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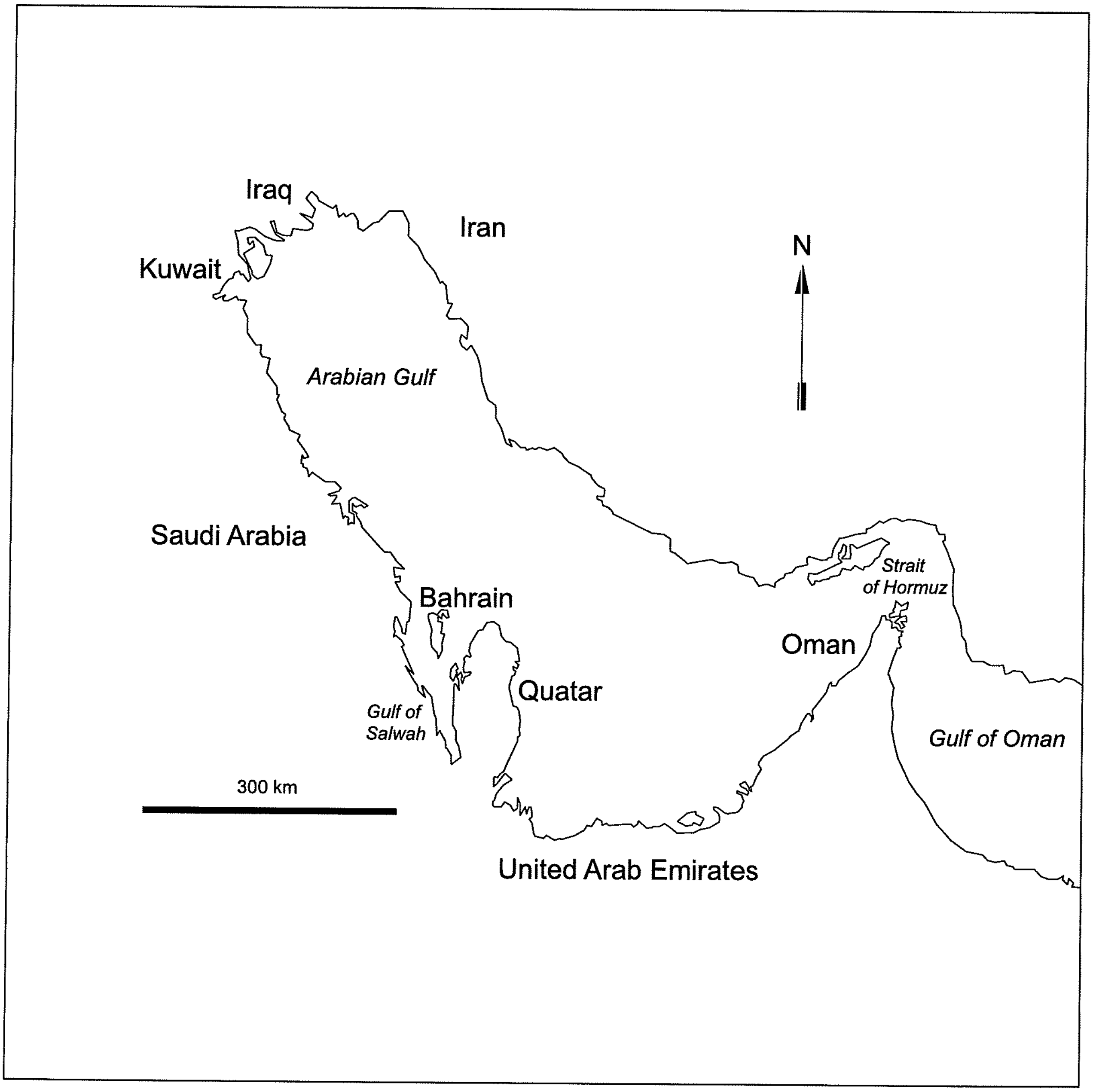
Water exchange and circulation of the Arabian Gulf

Preliminary study of suitability for seawater scrubber discharges



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REPORT

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Abstract

This report assesses the water exchange in the Arabian Gulf in relation to water demands for Flue Gas Desulfurization (FGD) plants based on available information from literature. The assessments are made for the whole Arabian Gulf, but also consider differences between the northwestern and southeastern parts of the Gulf and between specific areas on the coast of Kuwait, Saudi Arabia and Qatar.

Rough estimates based on available data and simple calculations indicate that accumulation of discharges from 10 plants distributed over the length of the coast from Kuwait to Qatar might at times give a background recirculation of between 1 and 3 %. If the plants are located closer together, i.e. within about 50-100 km, the high accumulation may at times amount to 5-10 % in the coastal waters around the plants.

The local accumulation for a single plant on top of this may be important if the discharge and intake is placed too close to each other. Based on the model calculations of near zone concentrations we recommend discharges to be located at least 2 km downstream of the water intake, in the direction of the mean residual surface current, i.e. towards the southeast. This should ensure that accumulation levels not exceed 10 %. It is important that sites considered for FGD plants are explored with regard to local topographical features and currents patterns under shifting conditions, as this may be vital for planning the intake and discharge to minimize the risk of water recirculation from the discharge into the intake.

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Water exchange and circulation of the Arabian Gulf

Preliminary study of suitability for seawater scrubber discharges

Preface

ALSTOM Power Norway AS has asked Norwegian Institute for Water Research to assess the water exchange in the Arabian Gulf in relation to water demands for Flue Gas Desulfurization (FGD) plants, based on studies of available literature. This report contains the results of this work. The calculations of near-zone dilution have been made by Jarle Molvær. Otherwise, the report is a result of the joint work of the two authors.

Oslo, 12 September 2000

Birger Bjerkeng

Contents

Summary

Norwegian Institute for Water Research has undertaken a commission for ALSTOM Power Norway AS to assess the water exchange in the Arabian Gulf in relation to water demands for Flue Gas Desulfurization (FGD) plants. The goal of the current project is to:

1. Collect and present available information about the water exchange and water quality in the Arabian Gulf.
2. Assess the water exchange for the whole Arabian Gulf in relation to water demand for FGD plants (macro assessment). The assessment will consider the water exchange through the Strait of Hormuz, but will also consider differences between the northwestern and southeastern parts of the Gulf inside the Strait of Hormuz.
3. Make similar assessments for more limited areas on the coast of Kuwait, Saudi Arabia and Qatar.

Topography and bathymetry

The Arabian Gulf is a relatively shallow basin, 900 by 300 km wide, with a maximum depth of 100 m, and average depth 36 m. The Arabian Gulf is connected to the much deeper Gulf of Oman through the Strait of Hormuz, which is only about 55 km wide in the narrowest cross-section south of the island of Qeshm. The Arabian Gulf is deepest in the eastern half, on the northern side along the coast of Iran. A trough with maximum depth about 100 m is separated from the Gulf of Oman by a more shallow region with maximum depths less than 80 m towards the Strait of Hormuz (map in Reynolds 1993).

Along the western and southern part of the Gulf, from Kuwait to Oman, there is a broad shallow shelf with sandy bottom, with the 20 m depth contour between 20 and 60 km from the coast.

Water masses in the Arabian Gulf

The Gulf water receives input of oceanic surface water through the Strait of Hormuz, and freshwater from the large rivers to the northwestern end of the Gulf and along the Iranian coast. These water masses are modified through mixing from wind and tides and by intense evaporation, thereby creating a time-varying hydrographic regime. Freshwater input in the northwest end of the Gulf creates a plume of relatively low-saline water (33-38) locally along the Kuwait coast with a more or less permanent, although weak, vertical stratification. The main parts of the western Gulf is vertically stratified only in summer, while the eastern half is permanently stratified. There is a permanent horizontal salinity gradient, with increasing salinity towards the west and across the Gulf towards the southern and southwestern shallow shelves. Surface temperatures are 15-19 °C in winter, lowest along the southwestern coast, and 30-32 °C in summer.

Data from 1977 show general good oxygen conditions in the main water body of the Gulf, also in deep waters, and data from 1982-83 show that this is also the case for the upper 10m of Kuwait waters.

Alkalinity is high in the freshwater-influenced waters. Salinity-specific alkalinity is reduced by carbon precipitation, but due to the evaporation the absolute alkalinity in the Gulf is higher than in the inflowing oceanic water.

Overall water balance of the Arabian Gulf

The freshwater input is estimated to an average of $110 \cdot 10^9$ m^3 annually according to newer estimates. This is higher than older estimates, but still only about 20-30 % of the estimated evaporation. The resulting water loss and salinity increase is balanced by a density-driven negative estuarine circulation

through the Strait of Hormuz, where high-saline waters leaving the Gulf through the deeper parts of the Strait with an inflow of less saline waters in the upper part. The overall mean residence time for the Gulf waters has been estimated to 3 years. The residence time is probably longer than this in the inner part of the Gulf and may be shorter in the outer parts.

Water circulation within the Gulf

The dominant feature of circulation in the surface layer of the Gulf is a seasonally changing system of counter-clockwise gyres. The inflow of oceanic water through the Strait of Hormuz continues along the Iranian coast, and circulates, partly within the eastern half, and partly (summer) also into the western part of the Gulf. This is balanced by a southeastern coastal flow on the Arabian side of the Gulf, driven mainly by wind. Dominant wind direction is north in winter, and northwest in summer. The intense evaporation in the shallow southern part creates a high-saline, dense water mass which sinks and flows into the central and deep part of the Gulf, where it forms the deep outflow through the Strait of Hormuz. The large-scale circulation pattern is a residual flow superposed on small-scale mixing due to tides, wind and surface evaporation. The residual current seems to be in the order 2-5 cm/s in the main parts of the Gulf, but according to a tidal model may be higher in shallow areas with sloping bottom, as along the Arabian Coast of the Gulf.

Advection and mixing along the coast from Kuwait to Qatar

Along the coast from Kuwait to Qatar, the surface water generally flows towards south-east, and mainly driven by wind (except for the influence from Shatt Al-Arab freshwater to the northwest). Typical mean current speed seems to be up to 10-15 cm/s at a distance 50-100 km from the shore, and lower within 20-30 km from the shore, with tidal fluctuations in the order of 50 cm/s. The residual current varies with wind, and may even be reversed during periods of southeast winds for up to two months.

In the Gulf of Salwah the circulation is different. Intense evaporation creates a circulation where in the order of 700 m^3/s of hyper-saline water sinks and flows along the bottom into the deep part of the Gulf. This outflow and the loss by evaporation are compensated by a transport of 900-1000 m^3/s surface water into the Gulf of Salwah. North of the Gulf of Salwah, at Ras Tanura, a north-going current of dense, high-saline waters are observed close to the bottom.

Consideration of specific coast sections

Three specific coast sections have been considered:

1. The coastline from Kuwait City to the Border between Kuwait and Saudi Arabia.
2. The coast at Ras Tanura
3. The north-eastern tip of Qatar.

All sections are situated along the same coastal current. The waters outside of Kuwait is influenced by the freshwater inflow through Shatt Al-Arab, creating an estuarine circulation, with a southward surface current with reduced salinity (33-38). At Ras Tanura the tidal currents are smaller than further north, and that residual currents also seem to be smaller. There is some density stratification in this area, a trace of the outflow of dense, hyper-saline from the Gulf of Salwah. According to wind statistics (John et al. 1990) the mean wind increases as one moves southeast along the coast.
The risk of recirculation of discharged water with the large-scale circulation in the Gulf seems to be rather small for all locations. For plants in Kuwait, there may at times be a local circulation within the northern end of the Gulf, for instance during episodes of southerly winds, but probably not lasting long enough to get discharged water recirculated back into the water intake. The evaporation on the southern side will contribute to prevent large-scale recirculation, since the water containing discharged effluent from the plants will increase in salinity, and be transported out of the gulf in the dense outflow

through the Strait of Hormuz. Further south along the Saudi Arabian coast the coastal currents may be smaller according to some of the measurements, and the residual currents may be more dependent on winds, with periods of up to 2 months with small residual currents. In this region, therefore, there may be larger risks of accumulation of discharges. For locations on the northeast coast of Qatar, the discharges will probably be transported southeast towards the shallow areas outside the United Arab Emirates, where evaporation will increase salinity and density. Such discharges will probably be taken out of the Gulf somewhat more efficiently than discharges from the locations in Saudi Arabia.

According to available large-scale information on topography found in literature, water depth increases about 1 m for each km for all the all three coast sections mentioned above. Although this is more than at other parts of the southern coast, it indicates that it may be necessary to locate plants a considerable distance from the shore to ensure sufficient access to process water and dilution water. However, we will emphasize that we do not have detailed knowledge of the bathymetry close to the shore.

Probable accumulation levels

Rough estimates based on available data and simple calculations indicate that accumulation of discharges from 10 plants distributed over the length of the coast from Kuwait to Qatar might at times give a background recirculation of between 1 and 3 %. If the plants are located closer together, i.e. within about 50-100 km, the high accumulation may at times amount to 5-10 % in the coastal waters around the plants.

The local accumulation for a single plant on top of this may be important if the discharge and intake is placed too close to each other. Based on model calculations of near zone concentrations we recommend discharges to be located at least 2 km downstream of the water intake, in the direction of the mean residual surface current, i.e. towards the southeast. This should ensure that accumulation levels not exceed 10 %. It is important that sites considered for FGD plants are explored with regard to local topographical features and currents patterns under shifting conditions, as this may be vital for planning the intake and discharge to minimize the risk of water recirculation from the discharge into the intake.

1. Introduction

Norwegian Institute for Water Research (NIVA) has undertaken a commission for ALSTOM Power Norway AS to assess the water exchange in the Arabian Gulf in relation to water demands for Flue Gas Desulfurization (FGD) plants.

More specifically, the goal of the current project is to:

1. *Collect and present available information about the water exchange and water quality in the Arabian Gulf.*
2. *Assess the water exchange for the whole Arabian Gulf in relation to water demand for FGD plants (macro assessment). The assessment will consider the water exchange through the Strait of Hormuz, but will also consider differences between the northwestern and southeastern parts of the Gulf inside the Strait of Hormuz.*
3. *Make similar assessments for more limited areas on the coast of Kuwait, Saudi Arabia and Qatar.*

2. Topography

The main topographical features of the Arabian Gulf are shown in Table 1 and in Figure 1.

Table 1. Main topographical characteristics of the Arabian Gulf inside the Strait of Hormuz. Data from Reynolds (1993) and Chao et al. (1992).

Length	990 km
Width	240 km
Average depth[1]	36 m
Maximum depth	100 m
Surface Area	$2.39\ 10^{11}\ m^3$
Volume	$8.63\ 10^{12}\ m^3$

The Arabian Gulf is connected to the much deeper Gulf of Oman through the Strait of Hormuz, which is only about 55 km wide in the narrowest cross-section south of the island of Qeshm. No direct description of this cross-section has been found in the literature, but from a topographical map in Reynolds (1993) it seems that the maximum depth in this cross-section is about 100 m, and that the strait is more than 40 m deep over a width of 40 km. The cross-sectional area is about $2.9 \cdot 10^6\ m^2$, and about half of this area appears to be above 30 m depth.

The Arabian Gulf is deepest in the eastern half, on the northern side along the coast of Iran. A trough with maximum depth about 100 m is separated from the Gulf of Oman by a more shallow region with maximum depths less than 80 m towards the Strait of Hormuz (map in Reynolds 1993).

Along the western and southern part of the Gulf, from Kuwait to Oman, there is a broad shallow shelf with sandy bottom. Maps and figures with bottom cross-sections are shown by Reynolds (1993).

[1] *Average depth given in the literature varies from 25 m (Brewer and Dyrssen 1985) to 50 m (Blain 1997), but most sources give a value of 36 m.*

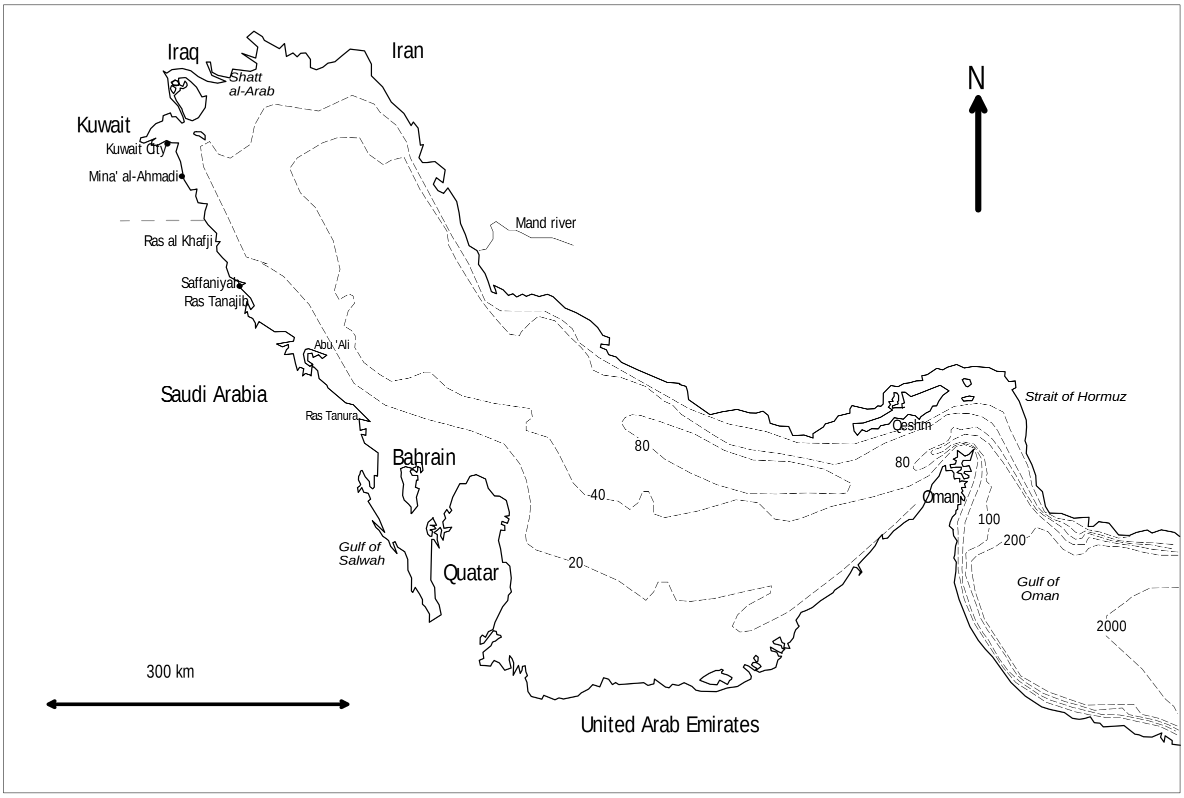


Figure 1. Map of the Arabian Gulf (Topography based on maps in Reynolds 1993).

More details about the bottom along the coast from the Kuwait/Saudi-Arabian border to Ras Tanura are shown in maps by John (1992a). These maps show that about 140 km southwards along the coast from Kuwait City the water depth increases about 1 m pr. km from the coast, i.e. with 20 m depth about 20 km outside the coast. The 40 m depth contour is about 100 km from the coast in the inner part of the Gulf. Further south, from Ras Al Khafji to Abu Ali Island, the coastal waters are even more shallow, with the 20 m depth contour 40-60 km from the coast, and depth <10 m 35 km from the coast in some places. The 40 m contour comes closer to the coast further southeast. From Abu Ali to Ras Tanura (Ra's At-Tannurah) the 10, 20 and 40 m contours are found about 10, 25 and 80 km off the coast.

The Gulf of Salwah between Saudi Arabia and Qatar, with depths about 10 m (hydrographic profiles in John et al. 1990), is partly closed off from the rest of the Arabian Gulf by the island Bahrain. The area enclosed southwest of Bahrain is about 4,000 km^2, with shallow areas of about the same size connecting the Gulf of Salwah to the rest of the Arabian Gulf.

East of Qatar and north of the western part of the United Arab Emirates there is an area of roughly 30,000 km^2 mostly less than 20 m deep. According to Al-Hajri et al. (1997) and Blain (1997) there are some smaller troughs within this area where depths are >20 m, covering an area of about 3,000 km^2.

According to Blain (1997) a depth database with 5 minutes resolution (8-16 km) exists at the Naval Oceanographic Office, Stennis Space Center, MS, USA.

3. Water masses in the Arabian Gulf

Descriptions of the Gulf water masses in general are found in Brewer an Dyrssen (1985), in Chao et al. (1992) and Reynolds (1993), who presents data from the Mt Mitchell expedition in 1992 (Clark & Symons 1993). Al-Hajri et al. (1997) give a general description based on data from Emery (1956) and Brewer et al. (1978). These descriptions give a large-scale picture of conditions in different parts of the Gulf, including the Kuwait waters.

More information of oceanographic characteristics of Kuwait waters have been found in two reports from Kuwait Institute for Scientific Research (Lee, Arar, Shalash and Saif, 1985a,b) which present data from 1983-84. One may assume that their stations are placed inside or close to Kuwait waters, but the incomplete reports available to us do not include geographic coordinates or maps showing where in the Kuwait waters measurements were taken.

Basically the Gulf water consists of two water masses:

- Oceanic water, entering the Gulf through the Strait of Hormuz.
- Freshwater, mainly outflow from the large rivers to the northwestern end of the Gulf and the Iranian coast.

These two water masses are modified through mixing from wind and tides and by intense evaporation, thereby creating a time-varying hydrographic regime. In the following the basic elements are briefly discussed.

3.1 Salinity and temperature

The Arabian Gulf has a net evaporation much larger than the freshwater inflow. This increases the surface salinity towards the west along the Gulf and over the southern shallow shelves on the Arabian side of the Gulf.

Figure 2 and Figure 3 show the main characteristics of the Gulf surface waters based on measurements winter and summer 1992. Note especially the plume with relatively low salinity water (33-38) flowing southwards along the Kuwait shore, created by mixing between fresh water from Shatt-Al-Arab and more saline Gulf water and by evaporation. The other extreme is found in areas to the southeast where evaporation creates salinity levels in the range of 40-50. In this context the inflow through the Strait of Hormuz from Gulf of Oman have a relatively low salinity (36-37.5). Hassan (1994) show similar surface variations from September 1986, for the southern part of the Gulf, with temperatures exceeding 34 °C, and salinities above 44 southeast Quatar.

Along the Kuwait coast the freshwater inflow from Shatt Al-Arab seems to create a varying but permanent vertical stratification (Figure 4). However, during periods of strong wind in winter the stratification may break down also in this area. Lee et al. (1985a) conclude that a breakdown in stratification is common from January to April. The stations shown by Reynolds (1993) do only cover waters at least 10-15 km from the Kuwait coast where the depth is about 10 m. The available data from this station only shows weak stratification (salinity up to differences of 4 or 5 between surface and bottom). Farther east in the head of the Gulf, south of Iran, the stratification is much smaller, and more easily breaks down due to less freshwater influence, strong evaporation and mixing from wind and tides. Also for shallower waters closer to the Kuwait coast, the mixing may result in a more homogeneous water column.

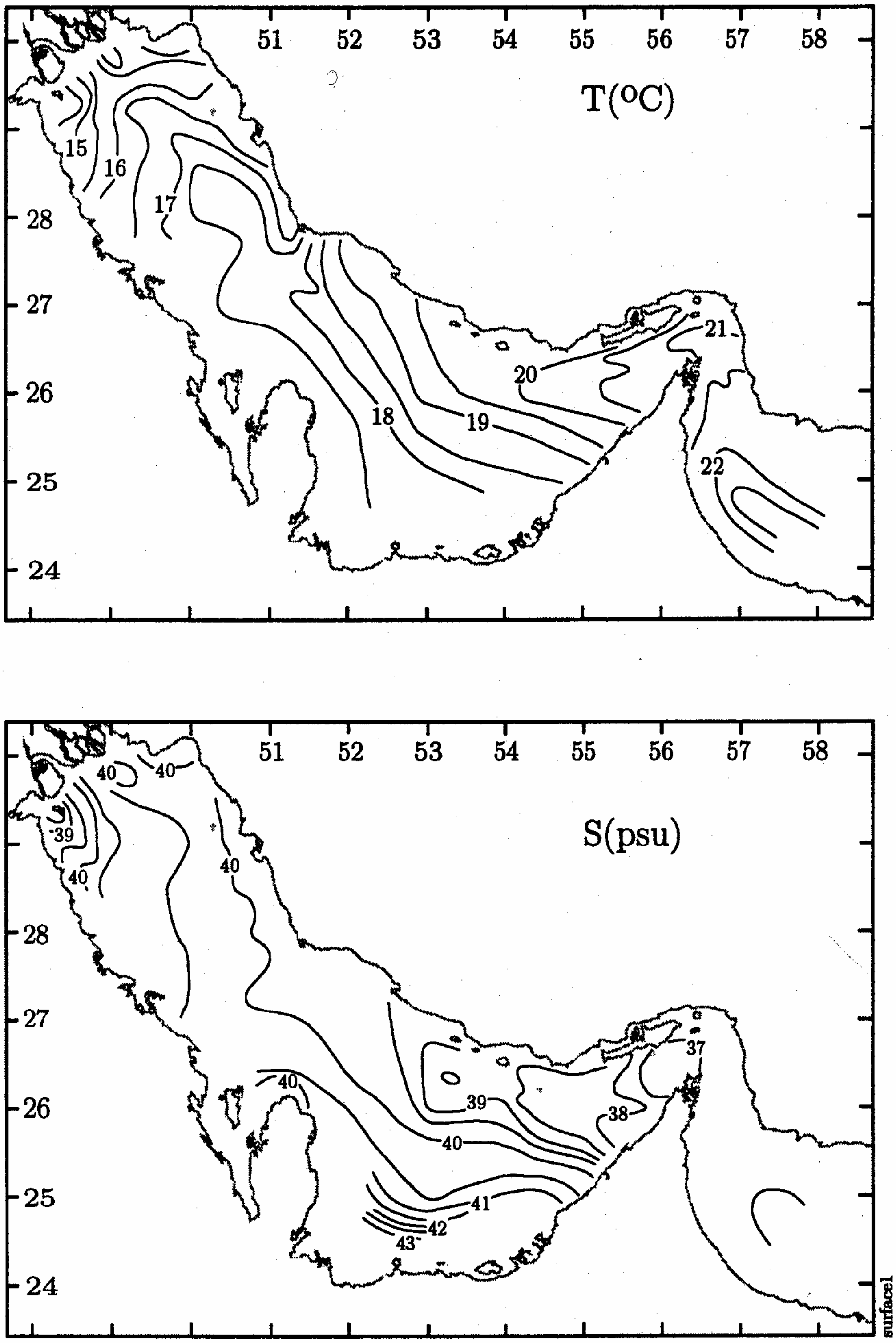


Figure 2. Map of surface temperature and salinity for winter 1992. Reprinted from Marine Pollution Bulletin, Vol. 27, Reynolds, R.M. (1993), with permission from Elsevier Science.

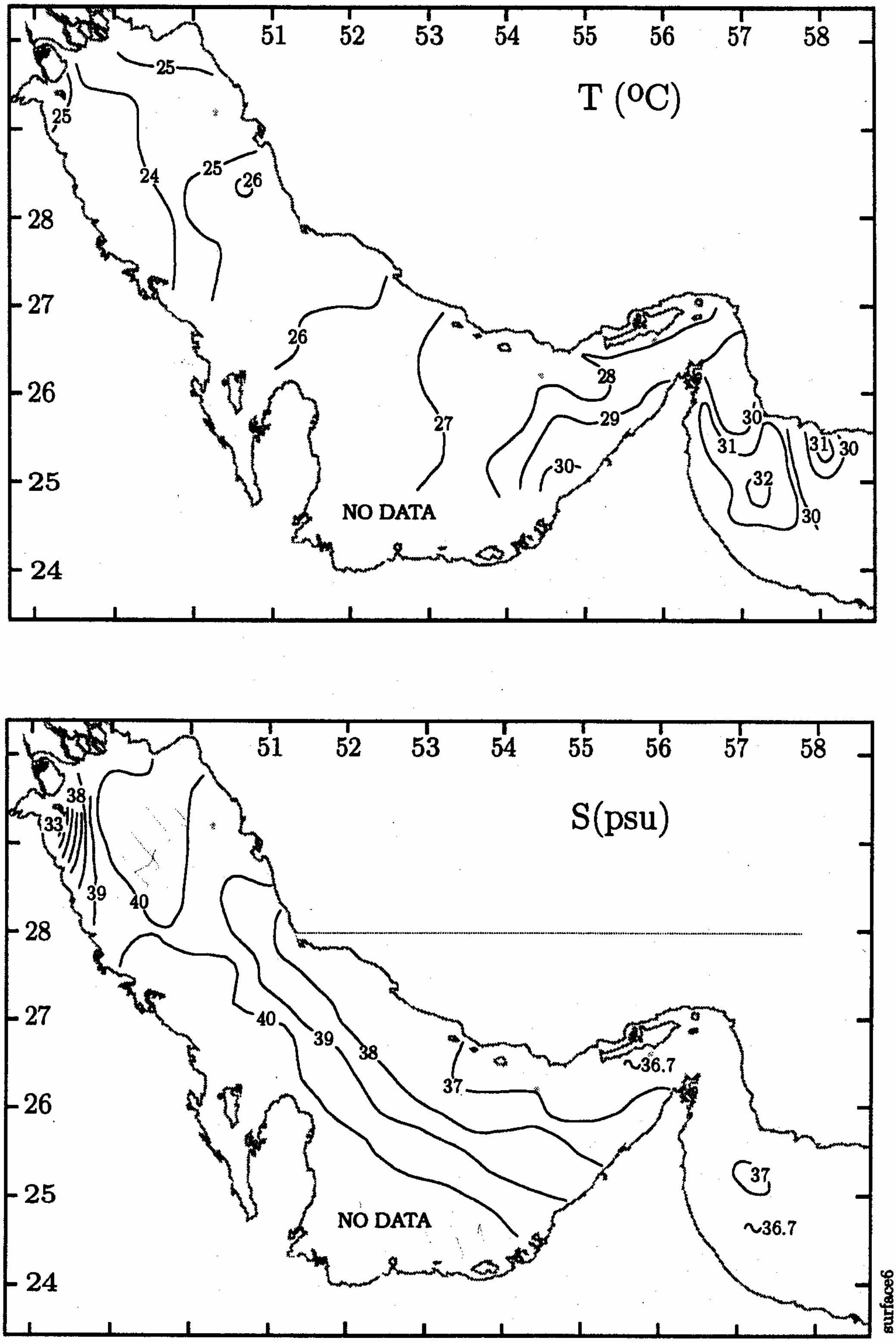


Figure 3. Map of surface temperature and salinity for early summer 1992. Reprinted from Marine Pollution Bulletin, Vol. 27, Reynolds, R.M. (1993), with permission from Elsevier Science.

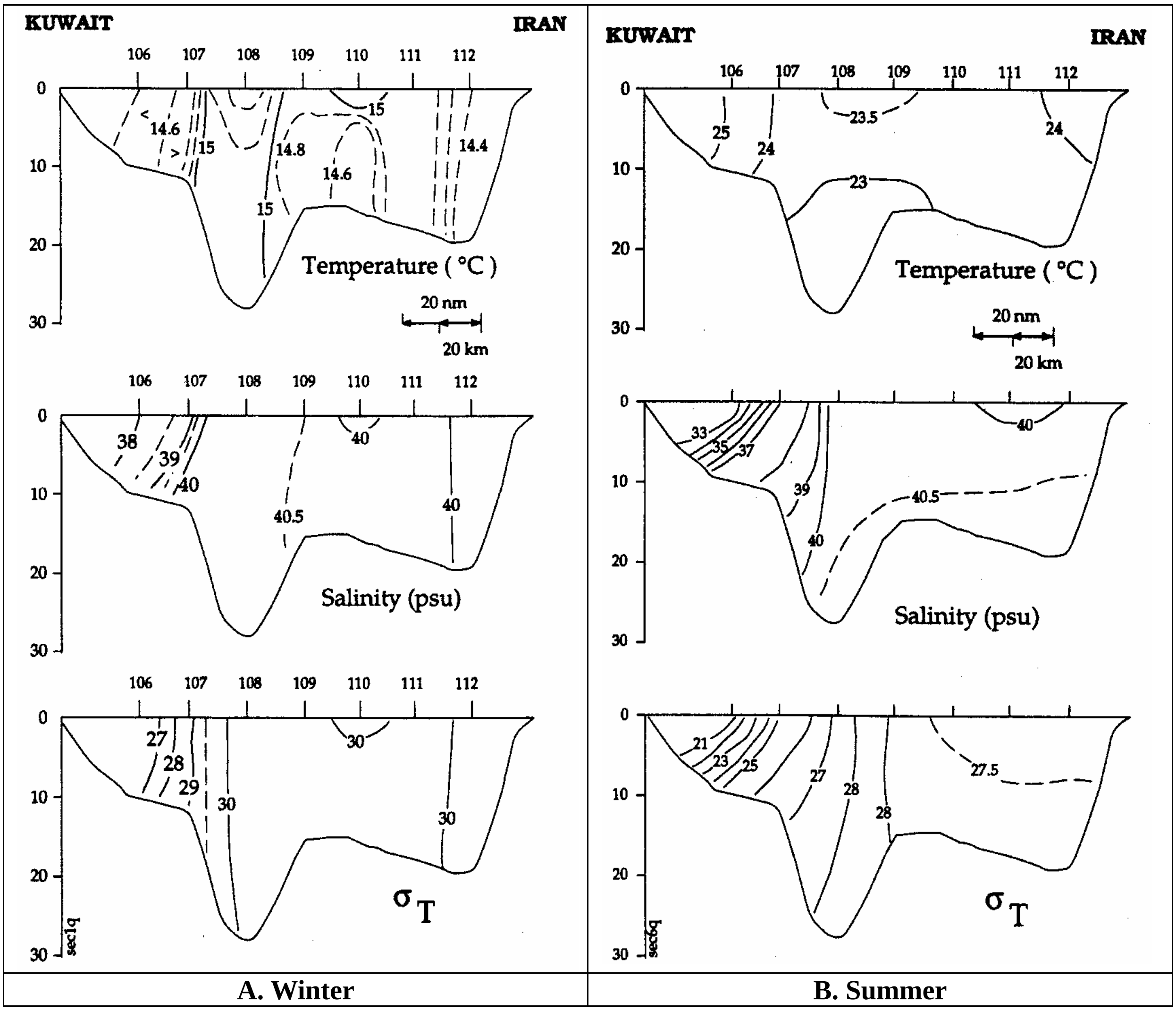
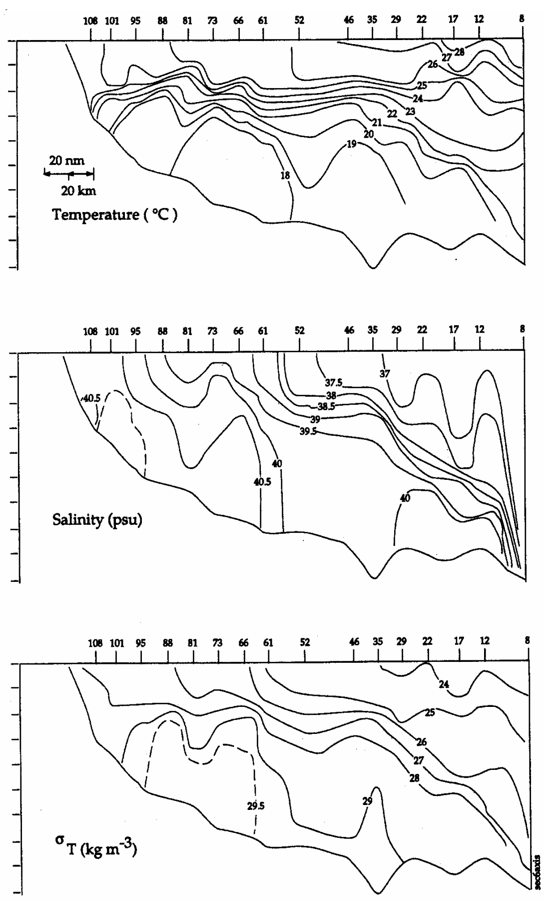


Figure 4. Cross section of temperature, salinity and density from Kuwait to Iran.
(A) Winter 1992. (B) during early summer 1992. Reprinted from Marine Pollution Bulletin, Vol. 27, Reynolds, R.M. (1993), with permission from Elsevier Science.

A cross-section along the axis of the Gulf from Kuwait to the Strait of Hormuz show a general picture of weak or absent stratification in winter and pronounced stratification due to surface inflow of low-saline water through the Strait of Hormuz and heating of surface water in summer (Figure 5). The main part of the Gulf northwest of Qatar has stratification during summer, but not in winter. Closer to the Strait of Hormuz and along the Iranian coast, the density difference between inflowing water from the Gulf of Oman and the high saline dense bottom waters formed by evaporation in the shallow areas of the Gulf usually maintains a stratification during all seasons, although it is weaker in winter. There is a general

The temperatures show marked seasonal variation. Water flowing into the Gulf through the Strait of Hormuz has temperatures around 21-22 °C in winter, increasing to about 30-32 °C in late summer. Inside the Gulf, the temperature variations are larger. In winter the temperatures drops to 15-17 °C in the head of the Gulf and along the south-eastern coast, and is in the range of 17-19 °C over large parts of the open Gulf, enhancing the horizontal density gradients caused by salinity. The surface waters are heated during summer, and this contributes to the vertical stratification of the Gulf. Emery (1956) found surface temperatures around 32 °C in the whole Gulf in August 1948. Hassan (1994) measured similar temperatures in the southern Gulf in September 1986.

It must be emphasized that variations in meteorological conditions and freshwater outflow are certain to create significant inter-annual deviations from this general picture. Further, since 1984-85 irrigation projects have been reported to reduce the freshwater outflow through Shatt-Al-Arab, and this would also influence the water masses in the (northwestern part especially) Gulf (Hassan & Hassan 1989). It is not clear from the cited sources how large this change is compared to the normal inter-annual variation in freshwater inflow (see chapter 4.2).



A. Winter	B. Summer

Figure 5. Cross section of temperature, salinity and density along the axis of the Gulf from Kuwait to Strait of Hormuz. Winter 1992. (B) during early summer 1992. Reprinted from Marine Pollution Bulletin, Vol. 27, Reynolds, R.M. (1993), with permission from Elsevier Science.

3.2 Oxygen

Oxygen is a fundamental and much-used parameter in biological, chemical and hydrophysical studies, and there may exist much information about the oxygen conditions in the Arabian Gulf. However, in our scanning through relevant literature no recent specific study of oxygen conditions has been found.

Brewer and Dyrssen (1985) reports data from February and March 1977 (Atlantis II cruise) for the whole Gulf. They found oxygen levels around 8-9 mlO_2/l in most of the Gulf, even in deep waters, with lower values, around 4 mlO_2/l, below 40 m depth on the north side of the Gulf close to the Strait of Hormuz.

Oxygen data from Kuwait waters have been found in Lee, Arar, Shalash and Saif (1985a,b), but as previously mentioned the position for the measurements is unknown as well as the maximum depth and the number of samples each month. However, we assume the stations are inside Kuwait waters or close outside, and that the values at 0-10 m depth are relevant for the water mass that may serve as recipient for discharge from a power plant. On the average the oxygen concentrations in the waters outside Kuwait were relatively high, with concentrations between 4.5 mlO_2/l and 6 mlO_2/l, and saturation between 95% and 110% between the surface and 10 m depth. High values occurred during winter months and then decreased gradually from March to July. This decrease was attributed to vertical stratification and probably also due to decomposition of an organic load from the plankton primary production. Minimum values in Kuwait waters were found in July (3.74 mlO_2/l, 79%) and in November 1983 (3.21 mlO_2/l, 99%). We point out that the measurements were made in 1982-83, and we do not know if they are representative for the current situation.

3.3 Alkalinity

The alkalinity of the Gulf waters has been measured by Brewer and Dyrssen (1985). The Gulf is an area of significant carbon deposition through biogenic carbonates ($CaCo_3$). This lowers the salinity-specific alkalinity of the Gulf compared to the inflowing water from the Gulf of Oman, but due to the evaporation, the alkalinity pr. water volume increases from around 2400 µeq/kg for inflowing water to about 2500 µeq/kg in the southern coastal waters of salinity 40-41. The river input from Shatt Al-Arab has high alkalinity, causing the water flowing south along the coast of Kuwait to have alkalinity around 2650 µeq/kg at salinity 39. The alkalinity decreases southeastwards along the coast, in parallel with the increase in salinity, as a result of carbon precipitation.

3.4 Summary

The Gulf water receives input of oceanic surface water through the Strait of Hormuz, and freshwater from the large rivers to the northwestern end of the Gulf and along the Iranian coast. These water masses are modified through mixing from wind and tides and by intense evaporation, thereby creating a time-varying hydrographic regime. Freshwater input in the northwest end of the Gulf creates a plume of relatively low-saline water (33-38) locally along the Kuwait coast with a more or less permanent, although weak, vertical stratification. The main parts of the western Gulf is vertically stratified only in summer, while the eastern half is permanently stratified. There is a permanent horizontal salinity gradient, with increasing salinity towards the west and across the Gulf towards the southern and southwestern shallow shelves. Surface temperatures are 15-19 in winter, lowest along the southwestern coast, and 30-32 °C in summer.

Data from 1977 show general good oxygen conditions in the main water body of the Gulf, also in deep waters, and data from 1982-83 show that this is also the case for the upper 10m of Kuwait waters. This should be confirmed by more recent observations.

Alkalinity is high in the freshwater-influenced waters. Salinity-specific alkalinity is reduced by carbon precipitation, but due to the evaporation the absolute alkalinity in the Gulf is higher than in the inflowing oceanic water.

4. Overall water and salt balance of the Arabian Gulf

This chapter discusses the different sources and sinks of water in the Gulf, and presents estimates of the water exchange with the Arabian Sea through the Strait of Hormuz. This forms a background for the discussion of the circulation in the Gulf in Chapter 5, and for estimates of expected overall accumulation levels of FGD plant discharges in Chapter 7.

The evaporation in the Gulf is much larger than the freshwater input, so there is a net freshwater loss from the Gulf. This increases the salinity in the Gulf relative to water flowing in from the Gulf of Oman. The water loss is offset by a net surplus of inflow to outflow, and the salinity increase due to the evaporation is balanced by the outflow having higher salinity than the inflowing water.

4.1 Evaporation

The evaporation along the southwestern coast has been estimated from meteorological and hydrographic data to about 210 cm/s at Dhahran in Saudi Arabia (Ahmad and Sultan 1991), and to about 200 cm/year at Manama in Bahrain and Doha in Qatar (Meshal and Hassan 1986). For the open parts of the Gulf evaporation has been estimated to 144 cm/year (Privett 1959). Meshal and Hassan (1986) discuss the difference between the coastal and open-part estimates and concludes that it is to be expected due to differences in temperature and air humidity.

The evaporation varies through the year, with a max:min ratio of 3. The coastal evaporation is lowest in winter (December-March), and high in summer (May-August), mainly related to variations in surface water temperatures. The evaporation in the open parts have a largely opposite pattern, with high values from October to January, and low values in March to June (Meshal and Hassan 1986, Chao et al. 1992).

How the estimates should be weighted for a total mean is not discussed in the available literature. Hassan and Hassan (1989) use a simple mean of the coastal and open-part estimates, but probably the open-part estimate should be given more weight. A reasonably weighted mean for the whole Gulf might be around 160 cm per year, possibly relatively constant through the year, representing a water volume of about $3.8 \cdot 10^{11}$ m^3.

4.2 Fresh-water input and precipitation

The freshwater input is concentrated to Shatt Al-Arab in the Western end of the Gulf and along the Iranian coast. The discharge is normally at its largest from March to May and is low from August to December (Meshal and Hassan 1986).

According to Meshal and Hassan (1986) most of the fresh-water comes from Shatt Al-Arab, with additional input from some small Iranian Rivers. Meshal and Hassan (1986) state that annual estimates may vary from $5 \cdot 10^9$ m^3 to $100 \cdot 10^9$ m^3 between years, citing different sources (Sudgen 1963, Hartmann et al. 1971 and Ezzat 1985). The range corresponds to 2 to 40 cm/year over the Gulf surface. The yearly precipitation in the Gulf region is reported to vary between 1 and 5.5 cm over the years from 1972 to 1977.

Hassan and Hassan (1989) give the average precipitation over 17 years as 7.8 cm/year. They cite values for Shatt Al-Arab from Schott (1918) indicating a yearly flow on the order of $100 \cdot 10^9$ m^3, and a low estimate from Hartmann et al. (1971) of $5 \cdot 10^9$ m^3. This is the same range as given by Meshal and

Hassan (1986), but Hassan and Hassan interprets it differently as possible effects of dams and irrigation, leading to reduced outflow in recent years.

Ahmad and Sultan (1991) cite a value of 20-25 cm/year for precipitation and freshwater inflow over the Gulf surface area, and Al-Hajri et al. (1997) give a value of 0.14 cm/year for inflow from Shatt Al-Arab, including precipitation.

Reynolds (1993) gives the annual average inflow to Shatt Al-Arab as $46{\cdot}10^9$ m^3. This is reasonable compared to the range given by Meshal and Hassan (1986). He also reports additional inflow of $64{\cdot}10^9$ m^3 per year from Iranian Rivers, most of it from river Mand with outlet about 300km southeast of Shatt Al-Arab. This is based on new information from Iranian sources, and needs further verification according to Reynolds. The total annual mean freshwater runoff in Reynolds' estimate is $110{\cdot}10^9$ m^3, corresponding to a water column of 46 cm/year over the sea surface.

Thus, even if estimates are uncertain and varying, on can conclude that the freshwater inflow, precipitation included, is far less than the evaporation in most years.

4.3 Flow through the strait of Hormuz

As the preceding chapters show, the evaporation in the Arabian Gulf is about 3-4 times larger than high estimates for freshwater input through runoff and precipitation. The resulting water loss and salinity increase is balanced by a density-driven negative estuarine circulation through the Strait of Hormuz. High-saline, denser bottom waters leaves the Gulf through the deeper parts of the Strait, and a somewhat larger inflow of less saline waters enters the Gulf in the upper parts of the cross-section. Due to the earth's rotation, the inflow is often concentrated on the north side, i.e. the isopycnal[2] surfaces in the Strait slope downward towards the north, and the flow into the gulf continues along the Iranian Coast. The outflow is concentrated on the south side of the Strait.

According to Reynolds (1993) the flows in the Strait are complex, and hydrographic data from the Strait may indicate temporal variations in the flow pattern. Banse (1997), however, has concluded that there is no apparent seasonal component in the outflow of high-saline waters from the Gulf, based on hydrographic data in the Gulf of Oman from different years and different times of the year.

Direct data on currents in the Strait are sparse. Ahmad and Sultan (1991) give the flow estimates shown in **Table 2**, citing Koske (1972). The flows given there will have mean velocities of 12 cm/s when distributed over the estimated cross-sectional area in chapter 2, assuming that the two flows occupy proportional parts of the total area. This is close to modeling results of Lardner et al. (1993), and to the surface current velocity in the Strait given by Hunter (1982) based on ship drifts.

Table 2. Estimates of annual mean water flow through Strait of Hormuz - (Ahmad and Sultan (1991).

	Inflow	**Outflow**	
Temperature	24.1	19.5	°C
Salinity	37.1	40.2	
Flow	0.186	0.168	10^6 m^3/s

Results of drift buoy experiments in the beginning of March 1992 in the Strait of Hormuz show a different picture (Reynolds 1993). They indicate inflow along the northern part of the strait, continuing into the Gulf west of the island of Qeshm, but of much lower velocities, about 2.5 to 3 cm/s as vector

[2] *equal density*

means, and 7-8 cm/s as scalar means. A buoy on the southern side of the strait showed outflow at speed 15 cm/s. These measurements were done within 15 to 42 hours time intervals, and may be dominated by short-term deviations from mean flow. However, one buoy was placed in the middle of the cross-section about 100 km west of the narrow section, at a point were the Gulf is about twice as wide as at the Strait. This buoy was followed for about a month. During this time, it moved about within a radius of about 30 km, with a scalar mean speed of 20 cm/s, but almost no mean drift of less than 1 cm/s.

Thus, there are indications that flow into the Gulf through the Strait of Hormuz is lower than the estimate shown in **Table 2**, and confined to the northern half inside the Gulf. The difference between inflow and outflow in the table is $0.18 \cdot 10^6$ m^3/s, which is almost twice what appears to be the most probable net water loss according to the previous sections (water column of 100 cm/year).

4.4 Calculation of water and salt balance - negative estuarine circulation

The differences in salinity in **Table 2** appear to be confirmed by the large data compilation in Alessi et al. (1999). Based on this, an alternative estimate of exchange through the Gulf can be made.

For an inflow Q_1 of salinity S_1 and an outflow Q_2 of salinity S_2 balancing a net water loss E, we have the following relations for salt and water balance, respectively:

$$Q_1 S_1 = Q_2 S_2 \text{ and } Q_1 = E + Q_2$$

Combining the two equations results in:

$$Q_1 = E\frac{S_2}{S_2 - S_1} \text{ and } Q_2 = E\frac{S_1}{S_2 - S_1}$$

The residence time (T) of water in the Gulf of relevance for pollutant concentrations will be:

$$T = V / Q_2$$

where $V = 8.63\ 10^{12}$ m^3 is the total volume.

We use E=7,600 m^3/year, which corresponds to a lower limit estimate of net water 100 cm/year, and assume S_1=37.1 and S_2=40.2. The resulting flows are Q_1=98,300 m^3/s and Q_2=90,700 m^3/s. These estimates are roughly in accordance with the values Q_1=106,700 m^3/s and Q_2=98,600 m^3/s given by Hartmann et al. (1971), and cited by Brewer and Dyrssen (1985). The low estimates would result in speeds of magnitude 7 cm/s in each of the two flow, if they occupy proportional parts of the cross-section. If these estimates are correct, the mean residence time for water in the Gulf will be approximately 3 years.

Hunter (1982, 1983,1984) has calculated a 'flushing time' in the same way, and estimated it to be 230 days, but this is probably an under-estimation, being based on effective exchange by currents of 0.1 m/s over the full width of the Gulf, not taking the smaller width of the Strait into account. It is probably more relevant as an estimate of a circulation or mixing time within the Gulf. Hunter also refers to calculations by Koske (1972) of 3 years flushing time, and to an estimate of 5.5 years for '90 % flushing time' by Hughes and Hunter (1979). Since the residence time above would correspond to 65 % volume exchange in a well-mixed basin, and 90 % flushing in that case would be achieved in about twice the residence time, the different estimates seems to fit well. Thus, it seems reasonable to assume a mean residence time of about 3 years for the Gulf as a whole.

The residence time calculated in this way is most relevant for differences in concentrations between inflowing and outflowing water through the Gulf of Hormuz, and thus for concentrations in the outflowing water of dissolved pollutants added within the Gulf. For the western parts of the Gulf, one must also take into account the circulation within the Gulf, in particular the water exchange between the western and eastern parts, and the circulation pattern as a whole. The residence time is probably longer for the western part of the Gulf, and shorter in the outer, eastern part.

It should be emphasized that the estimates are quite uncertain, as the water transport through the Strait of Hormuz is considered complex, with very little available data on currents, and only isolated snapshots of hydrographic conditions.

4.5 Summary

The freshwater input is estimated to an average of $110 \cdot 10^9\ m^3$ *annually according to newer estimates. This is higher than older estimates, but still only about 20-30 % of the estimated evaporation. The resulting water loss and salinity increase is balanced by a density-driven negative estuarine circulation through the Strait of Hormuz, where high-saline waters leaving the Gulf through the deeper parts of the Strait with an inflow of less saline waters in the upper part. The overall mean residence time for the Gulf waters has been estimated to 3 years. The residence time is probably longer than this in the inner part of the Gulf and may be shorter in the outer parts.*

5. Water circulation within the Gulf

5.1 Residual circulation

Reynolds (1993) gives a general description of circulation in the Gulf, based on a large surveying expedition from February to June 1992 with the research vessel Mt. Mitchell (Clark and Symons 1993), as well as previous data and modeling efforts described in literature.

Figure 6 show the envisaged flow system schematically, in a simplified picture.

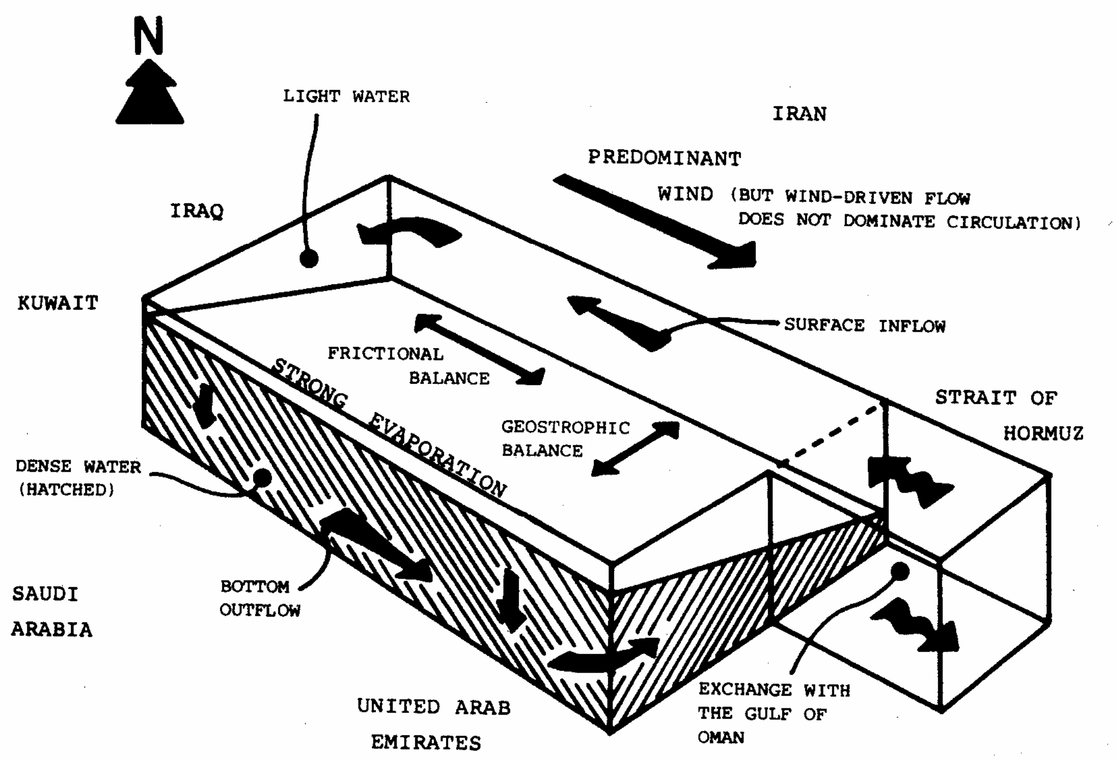


Figure 6. Schematic illustration of the circulation in the Arabian Gulf (from Hunter 1982)

The southeastern half of the Gulf is dominated by a counter-clockwise cyclic gyre in the surface layers, driven by inflowing surface water through the Strait of Hormuz. In winter, the inflow current in the surface layer is weakened by north-west winds (the Shamal) along the Iranian coast, and the northern Gulf becomes destratified. In summer, the inflow extends into the northern Gulf, which at this time of the year becomes stratified. The freshwater outflow from Iranian rivers creates a reverse circulation along the northern coast (Reynolds 1992).

It is generally agreed that there is a predominant counter-clockwise circulation also in the northwestern part of the Gulf inside Qatar. This is assumed to be partly due to the freshwater inflow from Shatt Al-Arab North of Kuwait, but mainly a result of wind forcing. Winds from N to NW dominate the region throughout the year. Mean wind at the coast increase from about 4 m/s at Saffaniyah to about 5.5 m/s at Dhahran (John et al. 1990). The prevailing wind drives a current along the coast from Kuwait to Qatar superposed on fluctuating tidal currents. Thus, water discharged near the surface along the coast from Kuwait or Saudi Arabia will in the long term be transported southwards along the coast with the mean residual current, but with short-term tidal fluctuation and stagnation periods or even reversals during southern or southeastern winds. Available data indicate that such stagnation periods may last up to 1-2 months (John 1992b).

An important factor in the water balance and for the hydrographic conditions described in Chapter 3.1 is the evaporation, which mostly affects the shallow shelf areas along the south-western coast, both because evaporation is somewhat higher there, and because of the smaller water depth. As a result of evaporation, the surface salinity increase from around 37 close to the Strait of Hormuz to 40 or higher in the northern end of the Gulf and over the shallow shelf along the southwestern, Arabian coastline of the Gulf. The evaporation thus creates a hyper-saline, dense water mass that flows from the shallow areas northwards and eastwards into the deeper part of the Gulf and forms the bottom outflow through the Strait of Hormuz.

Lardner et al. (1987, 1988a,b), Lardner and Das (1991) and Lardner et al. (1993) discuss circulation in the gulf based on 2-dimensional and 3-dimensional modelling. Their conclusion is that the density driven currents are most important near the Strait of Hormuz, and that the main circulation pattern in the main parts of the Gulf is dominated by wind forcing. The most recent of these papers, Lardner et al. (1993), conclude that during winter and early summer, the wind-driven component is much stronger than the density-driven component in the northern half of the Gulf as well as along the United Arab Emirates Coast. In late summer, the density-driven effects extends well into the northern half of the Gulf.

Even if the flow along the coast is mainly wind-driven, the exchange of water transversally to the coast is probably influenced to a large extent by evaporation. The evaporation counteracts stratification, and is probably an important factor in keeping the water column in the Northern Gulf well-mixed in winter. In summer, when evaporation in open areas is smaller, and surface water is heated to above 30 °C, this part of the Gulf is also stratified.

Eid and El-Gindy (1998) have calculated regional and seasonal variation in surface density currents based on hydrographic data. In winter they find ranges of 2-5 cm/s northwest of Quatar, and 2-10 cm/s in the southern Gulf winter, and 2-19 and 2-18 cm/s in the two regions in summer.

In reality the Gulf does not seem to have a dominant well defined two-layer flow system as indicated by Figure 6. The salinity/temperature distributions within the Gulf are characterized more by gradual changes of water characteristics horizontally and vertically (Figure 2 to Figure 5). The density increase at the surface due to evaporation will contribute to vertical mixing together with wind, and in shallow areas this is also enhanced by mixing energy from fluctuating tidal currents. The flows in Figure 6 should be seen as a residual current system, superposed on large and small scale mixing and circulation both vertically and horizontally.

The large fresh-water inflow at Shatt Al-Arab flows south along the Kuwait coast, and sets up a local positive estuarine circulation there, also contributing to the cyclonic circulation of the northwestern half of the Gulf. The impact of the fresh-water flow is apparent as a plume of reduced surface salinities outside the coast of Kuwait (Chao et al. 1992, Reynolds 1993).

5.2 Tides

Tides form a complex pattern of standing waves, in resonance with the tidal forcing through the Strait of Hormuz. The tidal elevation varies throughout the Gulf, from 0.5 to 1.5 m (Blain 1997). The oscillating currents, with velocities exceeding 0.5 m/s (Proctor et al. 1994, John 1992a), are considered to contribute to horizontal mixing within a length scale of 10 km. The residual currents from tides in the main part of the gulf are considered low and contribute little to large-scale transport, but may be important in certain areas. Blain (1997) has modeled tidal currents, and found that residual tidal currents are 2 cm/s or less in most of the Gulf, but can be up to 0.5 m/s in gradually sloped, shallow near-shore waters. The area around Bahrain, in the straits between the Gulf of Salwah and the main Arabian Gulf, is one such region with increased residual tidal current according to Blain's model. The tidal fluctuations also provide an important input of energy for vertical mixing.

5.3 Current measurements

Buoy drift experiments from the Mt Mitchell expedition from February to June 1992 (Reynolds 1993, Al-Rabeh et al. 1993) indicate a counterclockwise circulation in the inner end of the Gulf, from Iranian waters towards Kuwait along the coast, and continuing along the southwestern coast. Buoys deployed at various points in the middle of the Gulf, from 28.8°N to 26.6°N indicate an area with small net movement in the middle of the northern part of the Gulf, but otherwise a general southwards surface current, driving water outwards and across the Gulf towards the western coast. The flow past Qatar is in the SSE direction, towards the shallow areas outside United Arab Emirates. These buoys were followed over 1-3 months. The mean speed of the buoys were generally from 3 to 8 cm/s.

Results from current measurements by recording current meters during the Mt Mitchell cruise in 1992 are described by Reynolds (1993), Abdelrahman and Ahmed (1995) and Sultan and Elghribi (1998). Recording current meters were positioned at various location in the middle of the Gulf, north and east of Qatar, some at 10-30 m depth, and some in the deep waters at 56 to 84 m depth. Overall residual mean currents were around 5 cm/s. The surface measurements (10-30 m depth) show a residual westward current at a position in the northern half of the Gulf midway between Qatar and the Strait of Hormuz. In the middle of the cross-section north-east of Qatar there is a weak residual current (2 cm/s) in the WSW direction, i.e. with a crosswise component towards the south. East of Qatar the water at 21 m depth flows south with residual speed about 2 cm/s. The current meters also measured temperature. A temperature drop of about 1 °C in the bottom waters during the measurements reflects the southeast flow of cold, dense water formed in the head of the Gulf during winter.

5.4 Summary

The dominant feature of circulation in the surface layer of the Gulf is a seasonally changing system of counter-clockwise gyres. The inflow of oceanic water through the Strait of Hormuz continues along the Iranian coast, and circulates, partly within the eastern half, and partly (summer) also into the western part of the Gulf. This is balanced by a southeastern coastal flow on the Arabian side of the Gulf, driven mainly by wind. The intense evaporation in the shallow southern part creates a high-saline, dense water mass which sinks and flows into the central and deep part of the Gulf, where it forms the deep outflow through the Strait of Hormuz. The large-scale circulation pattern is a residual flow superposed on small-scale mixing due to tides, wind and surface evaporation. The residual current seems to be in the order 2-5 cm/s in the main parts of the Gulf, but according to a tidal model may be higher in shallow areas with sloping bottom, as along the Arabian Coast of the Gulf.

6. Advection and mixing along the coast from Kuwait to Qatar

The coastal waters from Kuwait to Qatar generally flows along the coast towards the south-east. The large fresh-water inflow to Shatt Al-Arab sets up an estuarine circulation outside the coast of Kuwait, with surface water flowing south, but in general the coastal current is considered to be driven mainly by wind. It is reasonable to assume that the evaporation contributes to a landwards component in the surface currents, driven by density gradients, but modified by tidal and wind mixing. Chapter 6.1 to 6.3 describes measurements from this area that can be used to draw conclusions about transport and mixing in this area. Chapter 6.4 summarizes the results.

6.1 Current measurements

El-Din (1988) measured currents and stratification at 6 stations along the Saudi coastal waters from Ras Tanjib (27.8°N) to Ras Tanura (26.5°N) (Figure 1). The measurements were done between 19 and 29 May 1985, and spanned 25 hours at each station. Unfortunately, it is not possible to use the detailed information about differences between stations from this paper, because of inconsistencies and contradictory information concerning station identification[3]. Measured current velocities were typically around 30-40 cm/s. At two stations the current was generally in the SSW direction, presumably at the off-shore stations about 50 km from the coast. At other stations, the current had more variable directions, with little net advection during a complete 25 h tidal cycle. The wind was light to moderate, and the currents are believed by the author to be mostly related to tides.

Al-Rabeh (1994) reports buoy drifting experiments that covered the southern-western half of the Gulf cross-section from outside Mina al-Ahmadi in Kuwait (29°N) and past Qatar to the shallow waters north of United Arab Emirates. 13 buoys where deployed in May-June 1983 and December 83-March 1984. Some of the buoys where deployed between 50 and 100 km from the coast between Mina-al-Ahmadi and Saffanyiah in Saudi Arabia, and at least one in the middle of the Gulf, about 110 km north of the northern tip of Qatar. Mean winds during deployment had directions WNW (298-320°) and the wind speeds ranged from 1.8 to 6.7. All buoys moved SSE (143° to 163°), with a deflection angle of about 30° relative to the wind. Mean buoy speeds ranged from 7 to 18 cm/s, with most results within 13-17 cm/s. The results indicate a large-scale current along the coast of surface speeds about 15 cm/s, with a certain drift of surface waters towards the coast. One buoy, deployed 50 km from the coast just east of the Kuwait/Saudi Arabian border, moved south at speed 13 cm/s, with most of its drift path within 30 km of the coast, and ended up close to the coast west of Abu Ali Island.

John (1992a) describes long-term current measurements in two transects along the coast. At Saffaniyah, recording current meters were placed 36 and 80 km from the shore, with bottom depths 5 m and 30 m, respectively, and outside Ras Tanura 3 and 60 km from land, with bottom depths 4 and 30 m. The current meters were positioned about 2-3 m below surface at each location, and additionally close to the bottom at the two outer locations. The measurements cover from 1 to 2 years at each location, but not all locations were measured during the same periods. John (1992a) presents the data as time series, and analyses the harmonic constituents of the currents. John (1992b) gives information about residual currents from these measurements by progressive vector diagrams and also shows current direction histograms. The measurements shows oscillating tidal currents. At Saffaniyah there were mainly semidiurnal tidal currents, with typical amplitude 50-60 cm/s (max. 1 m/s). At Ras Tanura, the oscillating tidal currents were weaker. Current directions were bi-directional ES - NW far from the coast at Saffaniyah, and close to the coast at Ras Tanura. At the other stations the direction varied more over all directions, but still with SE as the dominant direction, particularly for high current speeds (>20 cm/s).

Residual currents in these data varied between locations and over time. For the location 80 km outside Saffaniyah, the residual surface current was directed south, sometimes also southwest, with speeds 5-10 cm/s, and sometimes as low as 2.5 cm/s, over periods of 30 to 50 days. Residual bottom currents at this position, as well as the current closer to the shore at Saffaniyah, were mostly in the range of 1.5 to

[3] The bottom depths given in a Table of stations do not correspond to the placement of stations in the topographical map. There are also clear contradictions between the map and several of the couplings between stations and geographical names in the text. From the data-ranges in the different plots it appears that the station numbering is different in temperature and salinity time series plots and in temperature-salinity distribution plots). Also, the velocity/direction distribution plots and progressive vector plot for surface currents show completely different results for the same station number, again indicating mix-up of station numbers.

2.5 cm/s, and generally in the east/southeast direction. The location 60 km outside Ras Tanura had residual surface currents mostly in the range 3-7 cm/s, and in the south/southeast direction. However, there was a period of about two months with almost no net speed, only 0.5 cm/s, and reversed towards the northeast, due to the wind. At this location, the residual bottom current (1.2-4 cm/s) was directed east-northeast, away from the coast. This is interpreted as a sign of the outflowing dense waters from the Gulf of Salwah (see chapter 6.3). Closer to the shore at Ras Tanura the residual current in the range 1-3 cm/s is generally directed southeast along the coast.

It should be emphasized that the mean current at a fixed point over time , as calculated by the current meters, may not reflect the actual mean advection of water particles, following a drift path over time. Drift buoys may come closer to this, but even such data will not account accurately for any residual transport due to non-linear interaction between surface level variations and current speeds. A three-dimensional model taking such phenomena into account is described by Dortch (1990). The best empirical picture of advective transport and advection of discharged water would be achieved by large-scale tracer experiments, but no descriptions of such experiments in the region has been found in the literature.

6.2 Observations and modeling of transport of 1991 oil spill

The transport of the large oil spills that were released from refineries and oil terminals in Kuwait during the Gulf War in 1991 are described in a number of papers, together with the results of modelling efforts. Although a major part of oil spills will be confined to the surface, and thus more strongly influenced by wind than dissolved substances, the results may also give useful background for considering transports of FDG discharges in the area. The following description is based on Al-Rabeh et al. (1992) and Proctor et al. (1994).

The oil spill started on January 19 at Mina al-Ahmadi, and the oil was transported southward along the coast. After 10 days, the oil slick was found with the leading edge about 150 km from the discharge point, outside Saffaniyah, and mostly between 10 and 30 km from the coastline. The propagation speed over the first 10 days was about 15 cm/s. The oil slick continued southeast along the coast, and after another 20 days had moved another 140 km down the coast, to the area around Abu Ali Island, i.e. with a propagation speed of 8 cm/s. The southward spreading stopped in the last part of February, as the wind turned from 5 m/s NW to SE direction.

Proctor et al. (1994) modeled the transport by a vertically integrated tide and surge dynamic model with additional wind surface drift. To get realistic oil slick movement they had also to add density driven flow, calculated to be in the range of 5 to 15 cm/s based on temperature and salinity transects from the coastal region.

Al-Rabeh et al. (1992) described the results of oil spill trajectory models GULFSLICK II and OILPOL applied to the oil spill. The models derive currents from 3-dimensional dynamic models. They made predictions both based only on tidal currents and on wind-driven currents, and found that the residual spread from tidal currents was insufficient to explain the observed transport, but that wind-driven currents gave realistic results. Al-Rabeh et al. conclude that transport is mainly due to wind-driven currents, and consider density driven currents to be small except for local areas close to Shatt Al-Arab. Venkatesh and Murty (1994) have simulated the oil spill with a 2-dimensional model including wind-driven and tidal currents, and found wind to be the dominant component.

We see that the modeling projects have different conclusions regarding the importance of wind versus density driven flow for the transport and spreading of oil. The observed propagation speed of the oil slick is of the same order as the surface currents measured by John (1992a,b) 80 km outside Saffaniyah, but higher than the currents measured 30 km from the shore.

6.3 Water exchange in the Gulf of Salwah

The Gulf of Salwah is a shallow water body between Saudi Arabia, Bahrain and Qatar. Here salinities in the range of 55-59 are observed (John et al. 1990), which is much higher than the rest of the Arabian Gulf. The open waters north of Bahrain typically has salinity around 40-42. The salinity gradient is mainly horizontal, with small vertical changes in salinity. Water temperatures in the Gulf of Salwah is about the same as in the rest of the Gulf (somewhat lower in winter). The evaporation can thus reasonably be assumed to be about H_e=200 cm/year as in other locations along the southern coast. The resulting high salinities are due to limitations in the horizontal water exchange. The water exchange can be calculated by using the continuity equations for salinity and volume described in chapter 4.3. The evaporation area inside Bahrain can be estimated to roughly A=4,000 km^2 and the evaporation thus calculated to $E= H_e \cdot A$=250 m^3/s. Using values 40 and 55 for salinity of inflowing and outflowing water (S_1 and S_2) respectively, the salinity/volume equations results in inflow Q_1 = 930 m^3/s and outflow Q_2 = 680 m^3/s. The flow Q_2 estimates the effective transport of hyper-saline water from the Gulf of Salwah to waters outside, and is valid no matter how the water exchange takes place (wind-driven advection, density-driven flows, horizontal mixing due to tides, wind, and circulation cells evaporation).

6.4 Summary

Along the coast from Kuwait to Qatar, the surface water generally flows towards southeast, and mainly driven by wind (except for the influence from Shatt Al-Arab freshwater to the northwest). Typical mean current speed seems to be up to 10-15 cm/s at a distance 50-100 km from the shore, and lower within 20-30 km from the shore, with tidal fluctuations in the order of 50 cm/s. The residual current varies with wind, and may even be reversed during periods of southeast winds.

In the Gulf of Salwah the circulation is different. Intense evaporation creates a circulation where in the order of 700 m^3/s of hyper-saline water sinks and flows along the bottom into the deep part of the Gulf. This outflow and the loss by evaporation are compensated by a transport of 900-1000 m^3/s surface water into the Gulf of Salwah. North of the Gulf of Salwah, at Ras Tanura, a north-going current of dense, high-saline waters are observed close to the bottom.

7. Water transport and mixing compared to water demand of FGD plants

7.1 Water demand and sulfur discharge pr. FGD plant

The water demand for FGD plants can be dimensioned according to the specifications in **Table 3**. For the Gulf as a whole, 10 such plants can be assumed.

Table 3. Discharges from one 600 MWe FGD plant

Total water discharge	152,000	m^3/h
"	42	m^3/s
Sulfur	10800	kg/h
Sulfur concentration in total water discharge	70	mg/l

Seawater with salinity 35 has a natural sulfate concentration of 2.7 g/l SO4 (Stumm & Morgan 1981), or about 0.9 g/l of sulfur. In the Gulf the concentration will probably be around 1.0 g S/l (1000 mg/l). In the undiluted discharge from an FGD-plant the added sulfur concentration is 7 % (70mg/l) of the natural concentration in the ambient seawater.

The sulfur addition, although small in relation to natural sulfur levels, can create a disturbance of the ionic balance, and decrease the pH, unless suficcient mixing and water exchange is ensured. Such discharges may be acceptable on a local scale (normally set forth in local EPA standards), with suitable location of water intake and discharge, giving sufficient dilution of discharges in recipient unaffected by the sulfur additions.

However, if there is a long-term accumulation of discharged water in the recipient due to limited large-scale water exchange, the levels of sulfur additions in the recipient could reach such high levels that it would affect the FGD process negatively and have environmental effects. This feasibility study focuses on the risk of such accumulation and recirculation in the Gulf. In the following chapters, we look at dilution of discharged water on different spatial and temporal scales, and discuss the risk of getting discharged water into the water intake as a basis for evaluating the feasibility of building FGD plants in the region. Environmental effects are not considered here.

7.2 Simulations of near-zone dispersion and mixing

In winter, with fairly homogeneous conditions from surface to bottom, a heated discharge from an FGD plant will initially spread as a plume at the surface. The high temperature will lead to higher evaporation than in the ambient waters, and this will cool off the water and increase salinity and density.

In summer, there may be a certain density stratification due to vertical changes in temperature and salinity. The initial discharge may then be entrapped at intermediate depth or be dispersed at the surface, depending on what depth the water is taken from. Entrapment is most likely to occur outside the coast of Kuwait, where the freshwater inflow creates a stratification. The coastal waters on the Arabian side of the Gulf are very shallow, with 10 m depth mostly found at least 10 km off-shore. The available data are only from stations further from the coast, and it is possible that the coastal zone is well-mixed all year, due to tidal currents, wind and the evaporation in the surface, which increases salinity and density at the surface. Any stratification must be expected to be rather weak, possibly within 1-2 sigma-t units, and would probably be overcome by the initial heating of the discharge water from the plant.

The local dispersion and mixing have been assessed by model calculations of the dispersion of plumes in an ambient flow. The calculations do not apply to a particular area, but use reasonable assumptions of flow, topography and stratification based on the available data. The range of current speeds are within the range of observed residual currents and tidal fluctuations. They should indicate what kind of near-zone mixing one may achieve. They do not take into account recirculation, this is considered in later sections.

7.2.1 Methods

Two types of discharges have been simulated:
- submerged discharge of 2x21 m^3/s through separate outfalls at 5-7 m depth
- a surface channel with outfall close to the shore

Mainly from lack of appropriate data, we have chosen two relatively simple, but robust models.

The submerged discharge has been simulated using the PLUMES model, distributed by United States Environmental Protection Agency (EPA) (Baumgartner et al., 1994). Discharge through a surface channel has been simulated using a 2D model (Boyce and Hamblin 1975), further developed by NIVA.

Both are "steady-state" models, and one must be careful using the results in an area with varying environmental conditions. In this case: especially wind.

7.2.2 Data

Table 4 shows the input data for the PLUMES model, most of them are also used as basis for the surface model.

Table 4. Main data input for the PLUMES model

Parameter	Value
Intake depth	2-3 m
Discharge	21 m^3/s [1)]
Discharge depth, submerged discharge	Approx. 5-7 m (average 6 m)
Excess temperature	9 °C
Vertical salinity profile	Increase with depth[2)]
Vertical temperature profile	Constant[2)]
Current speed	0.05, 0.1 and 0.3 m/s
Pipe diameter	Approx. 2.5 m

[1)] We assume there are two equal discharges (2x21 m^3/s) which do not interfere with each other.
[2)] Values have been chosen to give vertical density profiles with weak stability, and may be representative for a spring-summer situation with significant freshwater outflow through Shatt al-Arab and moderate or low wind speed. Stronger wind will probably break down the stratification.

7.2.3 Results

Submerged discharge through two pipes

For the diffusion coefficient in the Plumes model, which uses the 4/3-power law (diffusion coefficient proportional to length$^{4/3}$) we have chosen the diffusion parameter 0.000453 cm$^{2/3}$/s, according to EPA's recommendation for open coastal areas.

The complete computer output is shown in Appendix A. With our density profile, the discharge from – 5-7 m depth will reach the surface. With intake/outlet configuration in shallow water, one should assume that this generally will be the situation. This also implies maximal initial mixing, 5-10x as. shown in Figure 7. At a distance 2000 m downstream, the dilution in the center of the plume has been calculated to 530x for an ambient current of 0.05 cm/s and 50x with an ambient current of 0.3 cm/s.

This illustrates that:

- "Dilution increases with time", and at low current speed the dilution at a given distance from the discharge will in general be greater than with higher speeds, and the excess concentrations correspondingly lower.
- The dilution and the excess concentrations will vary with time, as both the current speed and the turbulent mixing does.

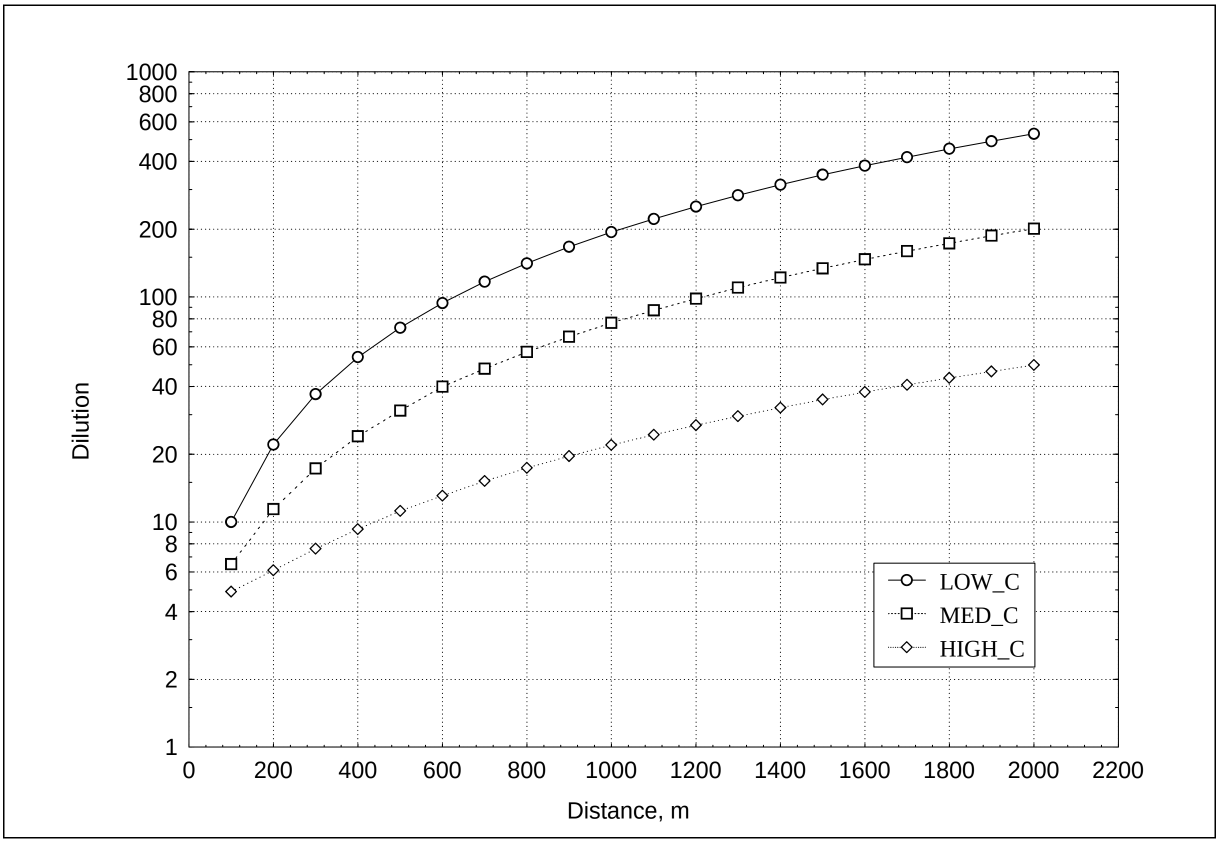


Figure 7. Model calculations of the centerline dilution for discharge through a single hole at 6 m depth, with ambient current from 0.05 m/s, 0.1 m/s and 0.3 m/s.

Discharge through a channel

This discharge has been simulated by means of a 2-dimension model (Boyce and Hamblin 1975), which has been further developed at NIVA. We do not know the vertical mixing in the area, and have therefore assumed that at the discharge point the bulk of the plume is contained in a 0-4 m water mass, and that the depth of the plume on the average will increase with 1 m pr. 1000 m downstream distance until it is completely mixed vertically over 14 m depth after 10 km. If the maximum depth is smaller, the dilution in the last phase will be somewhat higher. For an open coastline the horizontal turbulent diffusion coefficient has been set to 6 m^2/s - being a constant in this calculation. The results for a discharge of 41 m^3/s near the shore, with ambient current speed of 0.1 m/s is shown in

Figure 8. Wind effects are not included in this calculation.

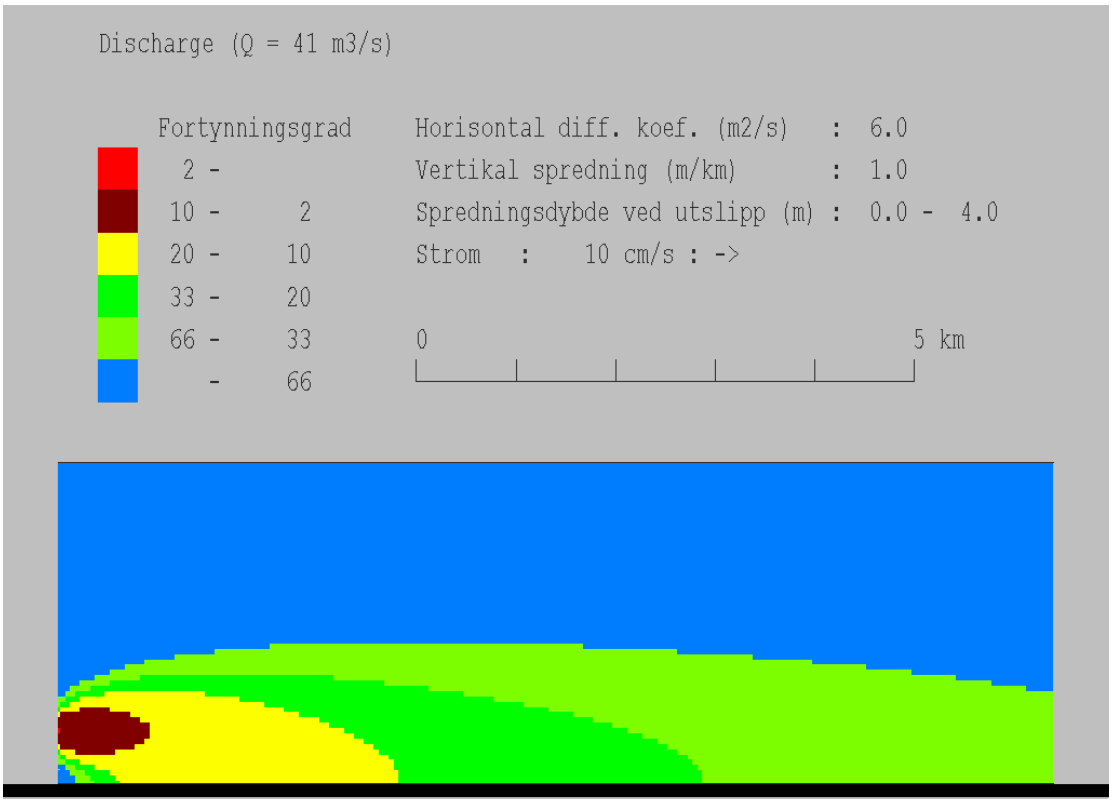


Figure 8. Simulation of dilution downstream of a surface discharge of 41 m^3/s with, ambient current speed 0.1 m/s.

7.2.4 Discussion

For a submerged discharge of 21 m^3/s through a single pipe, the PLUMES model give dilution factors in the range 5-10 about 100 m downstream, mostly as a result of primary turbulent mixing of the submerged jets. These results are based on "pure physics", and there should be little doubt that this indicates a realistic dilution. Different outfall design may increase or reduce the dilution.

The secondary mixing is far slower, and in the center of the plume the concentration may still be about 20-200 about 1 km downstream, varying with ambient current.

The downstream dilution is far more difficult to predict than the primary dilution, especially due to varying current speed, stratification and wind conditions. Relative to low current speed, higher speed will transport discharged water more rapidly along the coast - in a more narrow plume and with lower dilution/higher concentration at a given distance from the outfall. Our choice of 0.1 m/s may be a bit high compared to observed near-coast residual speeds, but is lower than fluctuation tidal currents.

The relevance of results from the surface model is more difficult to estimate. Compared to a submerged outfall of 21 m^3/s, the dilution is significantly lower. This may be explained by the larger volume and by lower primary dilution than from a submerged outfall. The plume may most of the time be moving alongshore, and the dilution will be strongly dependent on the local current speed, wind speed and direction together with wave effect on the mixing. This calls for using a model which has been calibrated for the area, and for simulation of a number of scenarios with combinations of wind speed and directions, wave height, current speed and direction.

A general conclusion might be that the dilution can be expected to exceed 10 outside of 1 km from the discharge point. Over time, the discharge will spread in shifting directions with shifting tidal currents, and over a tidal cycle (12.5 or 25 hours) may be expected to be dispersed over an area of width 10 km. The initial dispersion will depend on how far the discharge is from the shore; it should be as far out as possible, to get more dilution water available around the discharge.

7.3 Estimate of far- and medium-zone dilution

This section describes mixing, transport and risk of recirculation on different macro scales, i.e. outside the near-zone where the discharge has the character of a plume. The estimations here are of a general character. A discussion of the differences between specific parts of the Arabian coast from Kuwait to Qatar is given in Chapter 7.4.

7.3.1 Accumulation in the Gulf as a whole - discharge compared to water exchange of the Arabian Gulf

As described above, the outflow through the Strait of Hormuz has been calculated to 90,000-170,000 m^3/s. The lower of these estimates corresponds to an average residence time of about 3 years for Arabian Gulf waters, and over this period the discharge from a single FGD plant will theoretically give a net discharge of water of 0.05 % of the total volume. Thus the discharged water can be expected to be diluted by a factor of 2000 in the outflow from the Gulf. Correspondingly, if the discharge from 10 FGD-plants (theoretically) is mixed evenly in the Arabian Gulf waters, the effluent will be present in a concentration of 1:200.

7.3.2 Accumulation in the western part of the Gulf

Discharges from plants located along the Kuwait coastline and at Ras-Tanura will in summer most likely be mixed into the bottom outflow from the Gulf, partly directly from the western part of the Gulf, and partly by following the surface coastal current that continues past Qatar and into the southern areas with high evaporation and formation of dense, hyper-saline waters. In winter such discharges might mix into a local anti-clockwise circulation of the western Gulf. Assuming residual currents of 5-10 cm/s (based on the buoy experiments described above), and with a gyre circumference of about 800 km, the circulation time would be about 3-6 months, so recirculation of discharged water to the water intakes is conceivable. However, given the large tidal-and wind-induced mixing, and the absence of stratification, the water would probably be effectively mixed into the whole volume of the western Gulf, which can roughly be estimated to about $3{\cdot}10^{12}$ m^3. Even if we consider an accumulation period of 1 year in this part of the Gulf, the water discharge from 10 plants would amount to $1.3{\cdot}10^{10}$ m^3, thus the average dilution factor would be about 200.

7.3.3 Accumulation in the mean coastal current from Kuwait to Qatar

For FGD-plants situated on the coast from Kuwait to Qatar, water renewal is provided by the prevailing south-east coastal current, which is driven mainly by wind. Outside Kuwait, the estuarine circulation will also contribute to the flow. Along the coast of Saudi the water column will be well mixed due to tides, wind and evaporation, with increasing salinity as the water moves south.

Somewhat dependent on the discharge arrangements, it seems reasonable to assume that discharges in the coastal current will be dispersed during a few days in a width of about 20-30 km. The dominant landward component of the surface current will tend to keep the discharged water confined to a band along the coast, probably in a well-mixed water column, due to wind, tidal energy and evaporation. If the current speed is 10-15 cm/s along the coast, and we consider a band 20-30 km wide and with a mean depth of 10-15, the typical volume flux in the coastal current will be between 20,000 and 70,000 m^3/s. Discharges from one plant into such a coastal current will be diluted by a factor 500 to 1700. This is based on the higher estimates of the coastal currents indicated by the oil spill movement and the buoy measurements described in chapter 6.1. The recording current measurements along the coast indicate residual currents of 3-10 cm/s. In that case, the dilution under otherwise equal assumptions is in the range 200-500.

If 10 plants were to be located close to another, the downstream concentration of discharged water can be expected to be between 1:50 and 1:170 for the high estimates of residual currents, and 1:20-1:50 for the low current range.

If the plants are situated far away from each other, the most upstream (northwest) discharges will probably be more diluted before reaching the downstream plant due to transversal mixing. Such mixing may be enhanced by a rotational transverse component due to evaporation, with net advection towards the shore in the surface, and a net outflow of somewhat denser waters in the lower part of the water column.

7.3.4 Risk of local accumulation during reversals of the coastal current.

Even though N-NW winds prevail throughout the year, with coastal flow towards the south as described in chapter 7.3.3, both direction and strength of wind will vary, and periods of winds from S or SE will occur. In such periods the coastal flow will stop, and may even reverse.

Episodes may last for about one week (as observed during the oil spill in 1991), or according to John (1992b) up to two months. For a one-week episode it seems reasonable to assume that the discharges will be effectively distributed by tidal fluctuations over an area 30 by 20 km with mean depth 10m, that is, in a volume of $6{\cdot}10^9$ m^3. The accumulated discharged volume from one plant over a week, about $25{\cdot}10^6$ m^3, will be diluted by a factor 1:360 over such an area. If the stagnant current condition lasts for two months (9 weeks), and we assume that the length of the accumulating plume due to tidal fluctuations increases by the square root of time, the dilution would be 1:120. Thus, even for such an episode, the mean recirculation of water into a plant will probably be fairly small. Available meteorological data could probably be used to estimate the frequency of such episodes.

7.4 Consideration of various coastal sections

Based on the preceding chapters, some remarks can be made about the suitability of three specific coast sections that have been specifically mentioned as possible locations of FGD plants. The coast sections are:

1. The coastline from Kuwait City to the Border between Kuwait and Saudi Arabia.

2. The coast at Ras Tanura

3. The north-eastern tip of Qatar.

A preliminary judgement can be made based on a general consideration of what is known about the circulation in the Arabian Gulf and the currents along the south-west coast. All sections are situated along the same coastal current. The waters outside of Kuwait is influenced by the freshwater inflow through Shatt Al-Arab, creating an estuarine circulation, with a southwards surface current with reduced salinites (33-38).

Available data indicate that at Ras Tanura the tidal currents are smaller than further north, and that residual currents are also smaller. There is some density stratification in this area, a trace of the outflow of dense, hyper-saline from the Gulf of Salwah. According to wind statistics (John et al. 1990) the mean wind increases as one moves southeast along the coast.

The risk of recirculation of discharged water with the large-scale circulation in the Gulf seems to be rather small for all locations. For plants in Kuwait, there may at times be a local circulation within the northern end of the Gulf, for instance during episodes of southerly winds, but probably not lasting long enough to get discharged water recirculated into the water intake. The evaporation on the southern side will contribute to prevent large-scale re-circulation, since the water containing discharged effluent from the plants will increase in salinity, and be transported out of the gulf in the dense outflow through the Strait of Hormuz.

Further south along the Saudi Arabian coast the coastal currents may be smaller according to some of the measurements, and the residual currents may be more dependent on winds, with periods of up to 2 months with small residual currents. In this region, therefore, there may be larger risks of accumulation of discharges.

For locations on the north-east coast of Qatar, the discharges will probably be transported southeast towards the shallow areas outside the United Arab Emirates, where evaporation will increase salinity and density. Such discharges will probably be taken out of the Gulf somewhat more efficiently than discharges from the locations in Saudi Arabia.

Many of the discussions above are based on an assumption that water depth increases with about 1 meter for each km from the shoreline. The three specified coast sections all seems to fulfill this assumptions, from the large-scale bathymetric information we have had access to in the form of contour lines on maps of the Arabian Gulf. Based on this, it seems that even for those coast sections it may be necessary to locate plants a considerable distance (several km) from the shore to ensure sufficient access to process water and dilution water. However, we will emphasize that we do not have detailed knowledge of the bathymetry close to the shore.

7.5 Conclusions

Table 5 summarizes the estimated dilution factors on different temporal and spatial scales, based on the considerations in Chapter 7.2 to 7.4. It should be noted that each dilution factor in the table refer to dilution in ambient water that is unaffected by the discharge, so some of the estimates of concentrations in the table may be additive.

Table 5. Probable dilution factors on different temporal and spatial scales along the Arabian side of the western Arabian Gulf.

<table>
<tr><td>Source</td><td colspan="2">Spatial and temporal scale</td><td>Dilution factor</td><td>Concentration of discharged water</td></tr>
<tr><td rowspan="2">Discharge from single FGD plant</td><td colspan="2">Stagnation or reversal of coastal current - 1 week to 2 months.</td><td>120 to 360</td><td>0.3 to 1 %</td></tr>
<tr><td colspan="2">Local concentration about 2 km from single plant discharge (<1 day)</td><td>10 to 200</td><td>0.5 % to 10 %</td></tr>
<tr><td rowspan="4">Accumulated discharge from 10 FGD plants</td><td colspan="2">Overall background, water exchange through Strait of Hormuz - 3 years</td><td>200</td><td>0.5 %</td></tr>
<tr><td colspan="2">Large-scale circulation in western Gulf
1 year</td><td>200</td><td>0.5 %</td></tr>
<tr><td rowspan="2">Concentration downstream of 10 plants, 1-2 months</td><td>Current 10-15 cm/s</td><td>50 to 170</td><td>0.6 % to 2 %</td></tr>
<tr><td>Current 3-10 cm/s</td><td>15 to 50</td><td>2 % to 7 %</td></tr>
</table>

Accumulation of discharges from 10 plants distributed over the length of the coast from Kuwait to Qatar might be additive on the three large/medium scales, and at times give a background recirculation of between 1 and 3 %. This is based on the low estimates of accumulation in the coastal current (last two rows of Table 5). If the plants are located closer together, i.e. within about 50-100 km, the high accumulation estimates may apply at times, giving concentrations of up to 5-10 % in the coastal waters around the plants.

The local accumulation for a single plant on top of this may be important if the discharge and intake is placed too close to each other. Based on the model calculations of near zone concentrations we recommend discharges to be located at least 2 km downstream of the water intake, in the direction of the mean residual surface current, i.e. towards the southeast. This should ensure that accumulation levels not exceed 10 %. It is important that sites considered for FGD plants are explored with regard to local topographical features and currents patterns under shifting conditions, as this may be vital for planning the intake and discharge to minimize the risk of water recirculation from the discharge into the intake.

8. Literature

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Appendix A. Calculations of dilution from a submerged discharge of 21 m^3/s at various ambient current speeds

Results are shown in ”bold font”, with arrows pointing to columns for distance (m) from the outfall and the corresponding centerline dilution.

Ambient current speed 0.05 m/s.

```
 Aug 24, 2000,   9:14:54  WED PROGRAM PLUMES, Ed 3.1, 8/7/95   Case:   1 of   3
 Title   Two pipelines,  current speed 0.05 m/s                          nonlinear

  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
        21         1     21.00        10      32.2        34       100      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
         6       2.5     2.500     4.278     4.278     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
         1       0.0       1.0   18.2320      1e-5         0     15.12  0.001859
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    10.000   21.5561   0.05000  0.000453      0.05     85.56   0.05662
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
         0      0.05   21.1044        32        25         0   0.02688   0.03202
         5      0.05   21.4808      32.5        25         0 buoy flux puff-ther
        10      0.05   21.8574        33        25         0   0.06723     62.15
                                                            jet-plume jet-cross
                                                                35.59     189.6
                                                            plu-cross jet-strat
                                                                 5379     18.78
                                                            plu-strat
                                                                13.64
                                                              hor dis>=

CORMIX1 flow category algorithm is turned off.
 0 day-1, 0.000 hr-1, 0.000 t90hr.                       0 to large day-1 range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: PLMSTUFF.VAR;
UM INITIAL DILUTION CALCULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                             m
     6.000     2.5000.00001000     1.000     0.000

     6.000     2.509 9.931E-06     1.007   0.04354 -> bottom hit
     5.387     10.11 2.415E-06     4.131     19.35 -> bottom hit -> merging
     5.266     10.68 2.300E-06     4.336     20.83 -> surface hit -> bottom h
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
```

Farfield dispersion based on wastefield width of 10.68m

--4/3 Power Law--			--Const Eddy Diff--					
conc	**dilution**	**width**	**conc**	**dilution**	**width**	**distance**	**time**	
		m			**m**	**m**	**sec**	**hrs**
9.85E-07	**10.1**	**34.4**	**1.48E-06**	**6.75**	**22.8**	**100**	**1580**	**0.44**
4.52E-07	**22.1**	**75.3**	**1.06E-06**	**9.45**	**32.1**	**200**	**3580**	**1.00**
2.71E-07	**36.9**	**126**	**8.65E-07**	**11.5**	**39.3**	**300**	**5580**	**1.6**
1.85E-07	**54.0**	**184**	**7.50E-07**	**13.3**	**45.3**	**400**	**7580**	**2.1**
1.37E-07	**73.1**	**249**	**6.71E-07**	**14.9**	**50.6**	**500**	**9580**	**2.7**
1.06E-07	**94.2**	**320**	**6.13E-07**	**16.3**	**55.5**	**600**	**11600**	**3.2**
8.56E-08	**117**	**398**	**5.68E-07**	**17.6**	**59.9**	**700**	**13600**	**3.8**
7.09E-08	**141**	**480**	**5.31E-07**	**18.8**	**64.0**	**800**	**15600**	**4.3**
5.99E-08	**167**	**568**	**5.01E-07**	**19.9**	**67.9**	**900**	**17600**	**4.9**
5.15E-08	**194**	**660**	**4.75E-07**	**21.0**	**71.6**	**1000**	**19600**	**5.4**
4.49E-08	**222**	**757**	**4.53E-07**	**22.1**	**75.0**	**1100**	**21600**	**6.0**
3.96E-08	**252**	**858**	**4.34E-07**	**23.0**	**78.4**	**1200**	**23600**	**6.6**
3.53E-08	**283**	**964**	**4.17E-07**	**24.0**	**81.6**	**1300**	**25600**	**7.1**
3.17E-08	**315**	**1070**	**4.02E-07**	**24.9**	**84.6**	**1400**	**27600**	**7.7**
2.87E-08	**349**	**1190**	**3.88E-07**	**25.7**	**87.6**	**1500**	**29600**	**8.2**
2.61E-08	**383**	**1300**	**3.76E-07**	**26.6**	**90.5**	**1600**	**31600**	**8.8**
2.39E-08	**418**	**1420**	**3.65E-07**	**27.4**	**93.3**	**1700**	**33600**	**9.3**
2.20E-08	**455**	**1550**	**3.55E-07**	**28.2**	**96.0**	**1800**	**35600**	**9.9**
2.03E-08	**492**	**1680**	**3.45E-07**	**29.0**	**98.6**	**1900**	**37600**	**10**
1.88E-08	**531**	**1810**	**3.36E-07**	**29.7**	**101**	**2000**	**39600**	**11**

Dilution

Distance

Ambient current speed 0.1 m/s.

```
Aug 24, 2000,   9:15:14  WED PROGRAM PLUMES, Ed 3.1, 8/7/95   Case:   2 of   3
 Title   Two pipelines,  current speed 0.1 m/s                        nonlinear

  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
        21         1     21.00        10      32.2        34       100      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
         6       2.5     2.500     4.278     4.278     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
         1       0.0       1.0   18.2320      1e-5         0     15.12   0.01487
 hor angle red space p amb den p current   far dif  far vel K:vel/cur Stratif #
        90    10.000   21.5561    0.1000  0.000453       0.1     42.78   0.05662
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
         0       0.1   21.1044        32        25         0   0.02688   0.03202
         5       0.1   21.4808      32.5        25         0 buoy flux puff-ther
        10       0.1   21.8574        33        25         0   0.06723     49.33
                                                           jet-plume jet-cross
                                                               35.59     94.78
                                                           plu-cross jet-strat
                                                               672.3     18.78
                                                           plu-strat
                                                               13.64
                                                             hor dis>=

CORMIX1 flow category algorithm is turned off.
 0 day-1, 0.000 hr-1, 0.000 t90hr.                      0 to large day-1 range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: PLMSTUFF.VAR;
UM INITIAL DILUTION CALCULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                             m
     6.000     2.5000.00001000     1.000     0.000

     6.000     2.509 9.931E-06     1.007   0.04407 -> bottom hit
     5.395     10.07 2.382E-06     4.188     19.55 -> bottom hit -> merging
     5.281     10.61 2.269E-06     4.396     21.01 -> surface hit -> bottom h
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      10.61m
       --4/3 Power Law--         --Const Eddy Diff--
     conc dilution    width     conc dilution    width  distance     time
                          m                          m         m      sec     hrs
 1.54E-06     6.47     21.3 1.83E-06     5.45     17.7       100      790    0.22
 8.75E-07     11.4     38.1 1.39E-06     7.19     23.8       200     1790    0.50
 5.77E-07     17.3     57.7 1.16E-06     8.61     28.6       300     2790    0.77
 4.17E-07     24.0     80.0 1.02E-06     9.84     32.8       400     3790     1.1
 3.19E-07     31.3      105 9.14E-07     10.9     36.4       500     4790     1.3
 2.54E-07     39.3      131 8.37E-07     11.9     39.8       600     5790     1.6
 2.09E-07     47.9      160 7.78E-07     12.8     42.8       700     6790     1.9
 1.76E-07     57.0      190 7.29E-07     13.7     45.7       800     7790     2.2
 1.50E-07     66.6      222 6.89E-07     14.5     48.4       900     8790     2.4
 1.30E-07     76.7      256 6.54E-07     15.3     50.9      1000     9790     2.7
 1.15E-07     87.3      291 6.24E-07     16.0     53.4      1100    10800     3.0
 1.02E-07     98.3      328 5.98E-07     16.7     55.7      1200    11800     3.3
 9.11E-08      110      366 5.75E-07     17.4     57.9      1300    12800     3.6
 8.22E-08      122      406 5.55E-07     18.0     60.1      1400    13800     3.8
 7.47E-08      134      447 5.36E-07     18.6     62.1      1500    14800     4.1
 6.82E-08      147      489 5.20E-07     19.2     64.2      1600    15800     4.4
 6.27E-08      160      532 5.04E-07     19.8     66.1      1700    16800     4.7
 5.78E-08      173      577 4.90E-07     20.4     68.0      1800    17800     4.9
 5.36E-08      187      623 4.77E-07     20.9     69.8      1900    18800     5.2
 4.98E-08      201      670 4.65E-07     21.5     71.6      2000    19800     5.5
```

Dilution

Distance

Ambient current speed 0.3 m/s.

```
 Aug 24, 2000,   9:20:11  WED PROGRAM PLUMES, Ed 3.1, 8/7/95   Case:   3 of   3
 Title   Two pipelines,  current speed 0.3 m/s                         nonlinear

  tot flow   # ports port flow   spacing  effl sal effl temp   far inc   far dis
        21         1     21.00        10      32.2        34       100      2000
  port dep  port dia plume dia total vel horiz vel vertl vel asp coeff print frq
         6       2.5     2.500     4.278     4.278     0.000      0.10       500
 port elev ver angle cont coef  effl den poll conc     decay  Froude # Roberts F
         1       0.0       1.0   18.2320      1e-5         0     15.12    0.4016
 hor angle red space p amb den p current   far dif   far vel K:vel/cur Stratif #
        90    10.000   21.5561    0.3000  0.000453       0.3     14.26   0.05662
     depth   current   density  salinity      temp  amb conc  N (freq) red grav.
         0       0.3   21.1044        32        25         0   0.02688   0.03202
         5       0.3   21.4808      32.5        25         0 buoy flux puff-ther
        10       0.3   21.8574        33        25         0   0.06723     34.20
                                                             jet-plume jet-cross
                                                                 35.59     31.59
                                                              plu-cross jet-strat
                                                                 24.90     18.78
                                                              plu-strat
                                                                 13.64
                                                               hor dis>=

CORMIX1 flow category algorithm is turned off.
 0 day-1, 0.000 hr-1, 0.000 t90hr.                      0 to large day-1 range
Help: F1.  Quit: <esc>.  Configuration:ATNO0.  FILE: PLMSTUFF.VAR;
UM INITIAL DILUTION CALCULATION (nonlinear mode)
 plume dep plume dia poll conc  dilution   hor dis
         m         m                             m
     6.000     2.5000.00001000     1.000     0.000

     6.000     2.509 9.931E-06     1.007   0.04630 -> bottom hit
     5.377     10.09 2.207E-06     4.520     21.15 -> bottom hit -> merging
     5.271     10.59 2.102E-06     4.744     22.68 -> surface hit -> bottom h
FARFIELD CALCULATION (based on Brooks, 1960, see guide)
Farfield dispersion based on wastefield width of      10.59m
       --4/3 Power Law--          --Const Eddy Diff--
     conc dilution    width     conc dilution    width   distance     time
                          m                          m         m       sec     hrs
 2.02E-06     4.93     13.8 2.05E-06     4.86     13.3      100       258   0.072
 1.64E-06     6.10     18.4 1.82E-06     5.48     16.2      200       591    0.16
 1.31E-06     7.63     23.4 1.62E-06     6.16     18.6      300       924    0.26
 1.07E-06     9.34     28.7 1.47E-06     6.81     20.7      400      1260    0.35
 8.93E-07     11.2     34.5 1.35E-06     7.42     22.7      500      1590    0.44
 7.60E-07     13.1     40.5 1.25E-06     7.98     24.5      600      1920    0.53
 6.57E-07     15.2     46.9 1.17E-06     8.51     26.1      700      2260    0.63
 5.75E-07     17.4     53.6 1.11E-06     9.01     27.7      800      2590    0.72
 5.09E-07     19.6     60.6 1.05E-06     9.49     29.2      900      2920    0.81
 4.55E-07     22.0     67.8 1.00E-06     9.94     30.6     1000      3260    0.90
 4.09E-07     24.4     75.3 9.63E-07     10.4     31.9     1100      3590    1.00
 3.71E-07     26.9     83.1 9.26E-07     10.8     33.2     1200      3920     1.1
 3.38E-07     29.5     91.2 8.93E-07     11.2     34.5     1300      4260     1.2
 3.10E-07     32.2     99.4 8.63E-07     11.6     35.7     1400      4590     1.3
 2.86E-07     35.0      108 8.36E-07     12.0     36.9     1500      4920     1.4
 2.64E-07     37.8      117 8.11E-07     12.3     38.0     1600      5260     1.5
 2.46E-07     40.7      126 7.88E-07     12.7     39.1     1700      5590     1.6
 2.29E-07     43.7      135 7.67E-07     13.0     40.1     1800      5920     1.6
 2.14E-07     46.7      144 7.48E-07     13.4     41.2     1900      6260     1.7
 2.01E-07     49.8      154 7.30E-07     13.7     42.2     2000      6590     1.8
```

Dilution

Distance