Red Sea - Dead Sea Water Conveyance Study Program
Additional Studies

Red Sea Study

Draft Final Report

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Annexes

Annex 1 Field and laboratory activities carried out during the study and their results

Annex 2 Modeling activities
Executive summary

This report summarizes the results achieved in the framework of the Red Sea Study project. Within this study we conducted various environmental monitoring activities concerning several aspects of physical oceanography and marine ecology in the Gulf of Aqaba/Eilat, as described in our Inception Report (June 24th, 2010). In addition we also adapted and applied numerical models to support the assessment of the effects of RDC project on the environment of the Gulf. Both the monitoring and modelling activities provided us with relevant information to help understand the state and functioning of the Gulf and insight into some still unknown conditions and processes. Such knowledge gave fundamental contribution to our assessment and evaluation.

The physical data (literature, historical, and new data from our study) suggest a picture of the Gulf in which low-frequency motions and turbulent motion exchange water particles across the Gulf over times ranging from a few days to a couple of weeks. Superimposed on these motions are energetic internal tides that have little effect on net transport, but can result in significant vertical displacements of isothermal surfaces, most notably at depths comparable to the contemplated RDC intake depths. The basic density stratification of the Gulf will tend to act to limit withdrawals from the deep water off take to regions below the surface mixed layer, where higher concentrations on plankton are found. In these cases, internal waves will act to smear the “selective withdrawal” layers over a greater portion of the water column.

Data from hydrographic cruises corroborate knowledge on the structure of the water column of the Gulf. Three layers can be identified: the upper layer, which experience significant seasonal fluctuations, and extends to about 200 m. The penetration of winter convection during 2009-2010 was about 200m. The intermediate layer (200-400m) is the layer of permanent pycnocline, where a stable decrease of temperature and increase of salinity were observed during the all four cruises. The deep water layer, which extends from 400m to the bottom, is quite homogeneous. Potential temperature fluctuated between 20.87°C and 21.0°C and salinity between 40.65-40.72. In certain respects however, the year 2010 which was the base year for our analysis was unusual. The extent of the winter vertical mixing was comparable to or even slightly weaker than in previous years. More notably, however, during the spring and summer the water column above 300 m was less saline than during the previous 8 years. This is most likely an indication of increased water exchange between the gulf and the northern Red Sea.

Sampling of coral reef larvae was also conducted to understand the spatial (horizontal and vertical) and seasonal variability of this important component of the marine ecosystem, since very limited data are available for the Gulf. Major findings revealed that fish larval abundance varied considerably across the months analyzed, but consistently peaked at depths of between 25 and 75m. To a large extent the pattern appears independent of distance from shore (bottom depth), with the two sides of the gulf close to mirroring each other. Both fish and invertebrate larvae exhibit a remarkable decline in abundance below the photic layer (> 120 m depth). During summer, only 7% of the total invertebrate larvae were found below 120 m depth, while during winter the average was 20%.

We also conducted genetic analysis on two important Red Sea coral species (Pocillopora and Seriatopora) and on the coral-pest snail Drupella. Our results demonstrated the absence of genetic structuring in the Pocillopora damicornis populations residing in the northern Gulf (Israel and Jordan) and
high connectivity between the sites sampled for this study. Population of all North Gulf are closely related one to each other. Analysis of genotypes of *Seriatopora hystrix* revealed similar results and pointed out moderate to low genetic differentiation among populations. Similarly, population analysis of *Drupella cornus* AFLP loci from Aqaba and Eilat revealed high similarities between the Israeli and Jordanian populations.

Biological surveys and sampling for benthic habitats (at the eastern site) and fish assemblages (at the northern and eastern sites) were also carried out. At the northern candidate site the benthic habitat is characterized by seagrass meadows and sandy bottoms.

Seagrass beds in this area play significant role in harboring juveniles of various commercial fish (e.g. Lethrinids, Siganids and Mullids), and contribute to the nursery functions of these habitats. In addition to being primary producers, the seagrass habitat also functions as a biofilter for pollutants. They are also important for reducing the water turbidity and mitigate the influence of increased sedimentation rates. The eastern candidate intake site is a coral reef area. The results of the surveys here have shown that there are about 20%, 18% and 25% coral cover at the reef flat, 9m depth and 15m depth, respectively. A narrow area in front of the pumps room was destroyed by dumping of rocks in the past. The rocks dumped cover an area of about 35m wide (parallel to the shoreline) and might extend to about 60m depth (exact distance was not measured due to depth limitations).

Based on the understanding above, our assessment can be summarized as follows.

The exchanges of water between the Gulf and the northern Red Sea through the Strait of Tiran are several orders of magnitude larger than those that would be induced by the proposed abstraction flows, such that the latter would likely be imperceptible except in the immediate vicinity of the sink. The expected effect of the abstraction on the heat budget of the gulf is also expected to be negligible.

Furthermore, since the proposed maximum abstraction rate is less than 0.5% of the exchange of water through the strait, the impacts on the gulf-wide scale will be minimal. The only possible change is an extremely weak increase in the stratification of the upper thermocline at a depth of 20-40 m for maximum abstraction from the northern intake. In the other scenarios the effect is even smaller and in March (maximum mixing) the effects of abstraction are not discernable due to the deep winter mixing. In any case the potential impact of the abstraction on the gulf wide scale will be overshadowed by the projected impacts of climate change. At the northern Gulf scale the impacts are not expected to be significantly different from the impacts at the gulf-wide scale. At the local scale effects on the circulation are expected to be confined to the vicinity (200-300 m) of the intake. Maximum induced current speeds will occur at the location of the intake and for the maximum abstraction rate, these speeds will typically be between 4-11 cm/s, depending upon the intake location and depth.

Considering effects on water quality, the residence time of water is the major controlling factor on water quality in the GOAE, residence time in turn is affected by how strongly stratified the water column is. Therefore, increased stratification would increase the residence time of deep water in the GOAE leading to an accumulation of nutrients, which could be potentially harmful to the coral reef by triggering massive benthic algae blooms during winters with deep and prolonged convective mixing of the open sea water column. The modelling results of the different abstraction scenarios do not provide any evidence for significant changes in water column density structure. Therefore it is expected that water quality will not be negatively affected (deep reservoir nutrient accumulation) by abstraction of GOAE water at the maximal abstraction rate of $2 \times 10^9$ m$^3$/yr.
Considering the effects on marine environment, the assessment of pumping focused on five possible effects: (1) modification of heat flux; (2) changes in water-current intensity and circulation; (3) changes in nutrient fluxes; (4) local damage to benthic communities, and (5) entrainment of larvae and consequent repercussion to connectivity. Our physical and chemical oceanographic study suggests that the effects on heat flux and on nutrient dynamics will be negligible. The construction of the pumping station will undoubtedly cause substantial damage to the local community, over several hundreds of square meters. While surveys of the local communities at depth greater than scuba limit (>30 m) are yet to be done, damage by the pipes is expected over the shallow slope even if the pumping inlet itself will be deeper. The assessment of the abstraction’s regional effect on coral-reef larvae was based on extensive sampling across the northern Gulf and on Lagrangian particle-tracking simulations, validated with field measurements of the currents. The assessment was aided by a population-genetic study involving three species (2 corals and one snail), which indicated genetic homogeneity across the two sides of the Gulf (Aqaba and Eilat).

Based on above assessments our findings are for a "go" decision, as long as the intake configuration, location, and depth are selected properly.

To minimize the effect on the environment, we recommend that the pumping intake will be located at the eastern candidate site, based on considerations concerning morphology (relatively steeper bottom slope of eastern intake area), water circulation (currents along the east shore tend to be stronger and disturbance caused by the abstraction would be less significant), water quality (exposure to sediment resuspension, sediment load from the wadi in cases of flooding events), bottom habitats (at the eastern candidate site a barren submerged area was found), fish communities (Northern intake site is dominated by well developed sea grass meadows that can serve as nursery area for the successful recruitment, nursery and development of juvenile fishes, particularly for economically important species, this site can support fishery stock along the Jordanian coast), larval spatial distribution (measurements indicate that larvae and plankton are more abundant at the northern site than at the eastern site).

We recommend the intake to be placed below the photic layer and raised at least 25 m above the bottom. Based on the range of the photic layer depth, on the data on chlorophyll-a concentrations and the objective of avoiding withdrawal of water from the 60-120 m layer (where coral reefs larvae are common), we recommend to locate the intake at a depth of at least 140 m (bottom depth of 160-165 m). In so doing we expect that only a negligible proportion of the larvae reaching the region 3 km upstream of the intake will be removed. A somewhat higher proportion of those larvae (but still less than 1%) will be removed during the season when the water column is vertically mixed. Such values are at least one order of magnitude smaller than the present inter-annual fluctuations of the populations of corals and invertebrates at the local reefs.

Since results from our study show that some coral reef larvae are also present down to a depth of 180 m (limit of our sampling), to further refine and corroborate the selection of the precise depth, from an environmental point of view, we recommend conducting additional sampling, very focused in the vicinity of the proposed intake, down to a depth of approximately 250 m.

In addition, for precautionary reasons, we strongly recommend to expand the Jordanian and Israeli monitoring programs to continue operating in future years with add activities specifically designed to address possible RDC impacts.
One of the major goals of the proposed RDC is to provide, through desalination, much needed fresh water to meet the increasing needs of the population this very dry region. In this respect it is clear that to anticipate future needs it is most sensible to strive for the maximum availability of fresh water. For this reason in most of our analysis, especially concerning the impacts on water quality and the ecosystem, we concentrated on the maximum abstraction rate of 2 billion m$^3$/yr. In this sense our recommendations are cautious and conservative and represent a worst case option. The impacts of varying abstraction rates were assessed mainly in terms of the speed of the currents induced by the abstraction. Not surprisingly, for any given intake configuration, location, and depth the impacts will increase with increasing abstraction rates. Modeling results at lower abstraction rates carried out according to the ToR and the agreed scenarios allow to evaluate different combination of intake configuration, location, and depth and could certainly be refined in a future study, running modeling scenarios aimed at directly supporting next design phases.

As requested by ToR we also assessed cumulative effects with other abstraction. The only other major abstraction that is known is the Jordan Red Sea Project (JRSP) in which it has been proposed to abstract water from the same location as the northern intake that we considered in this study. Based on the available information and the recommendation of the SMU, it was assumed that the abstraction rate of the JRSP will be 0.4 billion m$^3$/yr. It was also recommended that the total combined abstraction of the RDC and JRSP not exceed 2 billion m$^3$/yr. Thus there are potentially two cumulative scenarios that should be considered in which the JRSP abstracts 0.4 and the RDC abstracts 1.6 billion m$^3$/yr, respectively. Not surprisingly, the results are very similar to the results for each individual intake considered separately.

Cumulative effects with climate change global warming will cause the water column in the GOAE to be more strongly stratified likely resulting in a longer deep water residence and an increase of the deep water nutrient reservoir. As a result of deep convective mixing during exceptionally cold and prolonged winters nutrient rich water will be transported into the surface layer and massive macro algae blooms could be triggered causing coral mortality in coastal fringing reefs. According to the modelling results the incremental effect of water abstraction on the warming and the stability of the water column are expected to be negligible.
1 Introduction

This report represents the Draft Final Report due in the framework of the Red Sea Study. Aim of the study is to identify and assess all relevant oceanographic and environmental impacts of sea water abstraction from the Gulf of Aqaba/Eilat, under different intake and abstraction rate scenarios. Hydrodynamics, water quality aspects and marine habitats are to be considered within the study.

According to the requirements of the Term of Reference, this Draft Final Report provides:

- summary description of existing environmental conditions (for most important component) and predicted future environmental conditions in the no action case, based on integration of available data and new results acquired in the framework of this study (chapter 2 and 3);
- description of the effects of abstraction on the Gulf of Aqaba/Eilat on most important environmental components (chapter 4);
- remarks addressing best option for Red Sea Dead Sea Conveyance Project intake (chapter 5).

Annex 1 reports in details on the field and laboratory activities carried out during the study and their results, while Annex 2 describes the modeling activities.

Data and considerations presented in the following previous reports prepared in the framework of Red Sea Study as been considered:

- Inception report;
- Best Available Data report;
- Mid Term report.

The report addresses the comments on previous reports from the Study Management Unit and the Independent Panel of Experts, particularly concerning those provided to the Mid Term report.

Outcomes from the present reports were anticipated through meetings and discussion to the Feasibility Study Consultant (Coyne et Bellier), providing essential elements for the completion of the Feasibility Study in due time. The anticipated results are essentially confirmed by the outcomes presented in this report, and refined on the basis of a detailed analysis of experimental and modelling results.

As described in the Inception report some experimental activities (physical oceanographic measurements and coral reef larvae sampling) are still on-going and their results will be included in the Final report due on August 2011. We expect that the new results will corroborate and confirm the conclusion presented in this report.
2 Description of the existing and predicted future environmental conditions of the GOAE in the No Action case

2.1 Currents

2.1.1 Introduction: basic characteristics of circulation and mixing

The Gulf of Aqaba is a semi-enclosed ocean basin connected via a narrow, relatively shallow, energetic tidal strait to the rest of the Red Sea. From past studies of the Gulf, several major features of the current physical behaviour of the Gulf can be discerned (all will be discussed in more detail later in this chapter):

1. Like much of the world’s ocean, the Gulf exhibits a seasonal cycle of stratification formation in spring, maintenance of a shallow thermocline in summer, and subsequent deepening of the thermocline to produce deep mixed layers in winter (Figure 2-1). As will be discussed below, much of the seasonal stratification variability is determined by exchanges with the rest of the Red Sea (Biton and Gildor, 2011a,b). Nonetheless, inter-annual variability in wintertime temperatures appears to set the depth of maximum mixing (Genin et al., 1995).

2. Because of being generally warm (T>21 deg C), and subject to dry winds much of the year, the Gulf is the site of high evaporation rates, estimated as between 0.5 cm/day to 1 cm/day, with recent estimates (Ben Sasson et al., 2009; Biton et al., 2011a) finding lower values than did earlier ones (Assaf and Kessler, 1976). Given a surface area of the Gulf of ca. 1.7 x 10^9 m^2, this implies a net inflow to the Gulf of ca. 54 m^3/s, i.e. a value comparable to the proposed abstraction rates for the RDC.

3. Because the densities of the Gulf and the rest of the Red Sea are different, there are strong density-driven flows. These exchange flows through the Straits of Tiran are substantially larger than are the net flows through the Straits, with Murray et al (1984) estimating flows of nearly 3 x 10^7 m^3/s entering (near the surface) and leaving (at depth) the Gulf through the Straits. More recent calculations by Biton and Gildor (2011a) suggest that the exchange varies annually between a maximum of nearly 4 x 10^7 m^3/s (April) to a minimum of 0.5 x 10^7 m^3/s (Sept. to Nov.), with an annual mean of 1.8 x 10^7 m^3/s. From a dynamical perspective, it is more correct to compare the rate of abstraction to the rate of exchange flow. This is because evaporation will also affect the circulation by increasing the salinity which in turn affects the density structure and the pressure gradient. The effect of abstraction is similar to exchange flow in the sense that it takes the water out with the salt. Since the gulf is a semi-enclosed concentration basin, the combined effects of exchange flow through the strait and evaporation produce a characteristic salinity profile with a noticeable subsurface salinity minimum in summer (Figure 2-2).
4. The currents in the northern Gulf are largely driven by the prevailing down-Gulf winds (Berman et al., 2000) and by semi-diurnal internal tides generated in the Straits of Tiran (Berman et al., 2000; Monismith and Genin 1984) and are typically low (10 cm/s). Notably, surface (barotropic) tides are negligible. These internal tides vary annually and are stronger in deep water than nearshore.

5. The combination of winds and buoyancy forcing as modified by the earth’s rotation produces a series of horizontal gyres throughout the Gulf (Berman et al., 2000, Biton and Gildor, 2011a) although in the narrower northern Gulf (north of 27.5 deg N), they tend to be less organized and more variable than in the south (Gildor et al., 2009; Gildor et al., 2010a). As seen in computations and HF radar data (surface velocities), these energetic features can be as strong as 80 cm/s (Gildor et al., 2010a).

These basic features can be used to develop a conceptual model of how the RDC abstraction might be expected to influence the ecosystem of the northern Gulf of Aqaba, by affecting (a) the physical environment directly; (b) influencing larval connectivity; and (c) by direct entrainment of larval organisms as well as other plankton.

At a most direct level, it is clear that the existing flows in the Gulf are much stronger than would be the currents induced by the RDC abstraction. For example, in the August 2010 500m mooring data, typical internal tidal currents of 10 cm/s averaged over the upper 120 m and across the Gulf (7km) give flows of approximately $7 \times 10^5$ m$^3$/s. The amplitude of the principal axis (standard deviation of the currents rotated to maximize variance in one direction – see Emery and Thompson 2005) of the measured currents averages 6 cm/s in the upper 120 m, giving a flow of $4 \times 10^4$ m$^3$/s, i.e. $10^3$ to $10^4$ times larger than the abstraction flows.

Similar behaviour is clear for the larger-scale exchange flows that exchange water properties between the Gulf and the rest of the Red Sea. We can make this more concrete. Suppose that the temperature difference between the northern Red Sea and the northern Gulf is 2 deg C, then the abstraction flow implies an additional net heat flux into the Gulf of $50 \text{ m}^3/\text{s} \times 4.2 \times 10^5 \text{ Joules/deg C m}^3$ (the heat capacity of water) x 2 deg C = $4 \times 10^8$ Watts, or, when distributed over the entire surface of the Gulf ($2 \times 10^9 \text{ m}^2$) = 0.2 W/m$^2$. This should be compared with the estimated average net heat flux through the Straits of 55 W/m$^2$ with a seasonal range of 0 to 150 W/m$^2$ (Biton and Gildor 2011a). Thus, it is clear that the abstraction flows will have no discernable effect on the thermal structure of the Gulf.
Figure 2-1 Temperature profiles in the northern Red Sea (black) and northern Gulf of Eilat (red) for February (left) and August (right). The effect of the abstraction on the heat budget can be estimated from the temperature difference.

Figure 2-2 Salinity profiles in the northern Red Sea (black) and northern Gulf of Eilat (red) for February (left) and August (right). The effect of the abstraction on the salt budget can be estimated from the salinity difference.

The influence on larval connectivity and entrainment is more subtle in that the oscillatory tidal currents may not effect large exchanges because in one limit, they may primarily produce motion of the same water parcels (and organisms) back and forth over the intake, so that what is important is the net exchanges they produce.

The RDC abstractions can be viewed as having an effect like catch or predation on the aquatic organisms of the Gulf. Thus what matters is the rate at which organisms are extracted, a number that can be compared to other rates such as growth, mortality or existing catch pressure. If we assume
that all organisms in a given volume are equally likely to be entrained, i.e. that the volume of interest is well mixed\(^1\), in the present case by the net effects of internal tides and gyres, then the “mortality” rate, \(r\), due to removing fluid is computed as

\[
 r = \frac{Q}{V} \left( 1 - \frac{C_{\text{outside}}}{C_{\text{inside}}} \right)
\]

where \(Q\) is the abstraction flow, \(C_{\text{inside}}\) is the concentration of organisms inside the volume of interest which has volume \(V\), and \(C_{\text{outside}}\) is the concentration of organisms outside that are drawn into the volume by the abstraction flow. Thus if \(C_{\text{outside}} < C_{\text{inside}}\), \(r\) is negative (abstraction decreases organisms in the volume) whereas if \(C_{\text{outside}} > C_{\text{inside}}\), \(r\) is positive (abstraction increases organisms in the volume). Note that if \(C_{\text{outside}} = C_{\text{inside}}\), abstraction has no effect.

A conservative estimate of \(r\) can be obtained assuming \(V\) equal to the upper 100m of the entire Gulf (\(V=2 \times 10^{11} \text{ m}^3\)), and assuming that there are no organisms of any kind south of the Straits of Tiran. Then \(r = 4\times10^{-9} \text{ s}^{-1}\), a rate that is much smaller than typical growth rates of virtually any conceivable aquatic organism corresponds to a timescale \(r^{-1} \approx 126 \text{ years}\).

On the other hand, the exact mixing mechanisms operating in the Gulf are likely more complicated than this simple estimate would suggest. From the modeling work reported in the literature and that was done for this project, the best conceptual model would appear to one in which there is rapid mixing in gyres – note that at an advective speed of 10 cm/s, the gyres can recirculate across the Gulf in ca. 1 day – and that north-south mixing is supported by exchanges between the gyres, in particular by transport of particles across gyres by the internal tides. This is in essence the model discussed by Ridderinkhof and Zimmerman (1991) examining tidal mixing in the Wadden See.

Hence, the consequences, to connectivity, of the abstraction would be best evaluated in light of the results of the modeling. Indeed, detailed and accurate determination of net exchanges and residence times for a particular system like the Gulf cannot be done using limited fixed oceanographic moorings, rather, they are best pursued using numerical models. Indeed that was the rationale for the modeling activities pursued in this project - they will be discussed in detail subsequent sections and chapters.

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\(^1\) In the chemical engineering literature this is known as a Continuously Stirred Tank reactor (CSTR).
2.1.2 Water column structure

Figure 2-3 and Figure 2-4 show average monthly temperature and salinity profiles measured at station A (black), ~10 km south of the north shore of the Gulf, and the climatological hydrographic profiles at the same location (gray) from the model of Biton and Gildor (2011a).

Figure 2-3 Comparison between the model and observations: Monthly average temperature profiles measured at station A based on monthly measurements courtesy of the Israeli National Monitoring Program for the years 2003-2009 (black), and the climatological temperature profiles at the same location (gray) of the model of Biton and Gildor (2011a). Shaded areas indicate the inter-annual variability over 7 years.

Figure 2-4 Comparison between the model and observations: Monthly average salinity profiles measured at station A based on monthly measurements courtesy of the National Monitoring Program for the years 2003-2009 (black), and the climatological salinity profiles at the same location (gray) of the model of Biton and Gildor (2011a).
Three layers characterizing the Gulf water column can be distinguished: (1) a deep and quasi-stagnant layer; (2) the intermediate water, and (3) the surface water. The deep layer is slightly colder than 21°C and fills the Gulf below 600 m. The intermediate water temperature slowly increases from 21°C to 21.9°C, and the surface layer has a temperature above 21.9°C. Unlike the deep water layer, the two upper layers are highly active and undergo strong seasonal changes. The year can be divided into two phases, the restratification phase (April-August) and the mixing phase (September-March). During the restratification phase the surface layer is rebuilt, increases its temperature and volume, and pushes the 21.9°C isotherm from the surface down to ~200 m. In August the temperature in the stratified surface layer at the northernmost Gulf increases almost linearly from 21.9°C at its base to SST ~27°C (Figure 2-3) and comparably close temperature profiles exist throughout the rest of the Gulf. From September to December, the surface layer increases its volume at a much slower rate and the strong stratification starts to erode due to atmospheric cooling, until the surface layer is vertically mixed, and a relatively thin (stratified) layer separates the surface layer from intermediate water everywhere along the main axis. From January to March the surface layer is mixed with the intermediate layer almost completely and the sea surface temperature in mid-February is below 21.9 deg C in most places in the Gulf (Biton and Gildor 2011a; Plähn et al., 2002; Klinker et al., 1976). In severe winters, the water column can mix down to the bottom (~700) at the northernmost end of the Gulf, where the deep water is formed via both open water convection and shelf convection [Wolf-Vecht et al., 1992; Genin et al., 1995; Biton et al., 2008a].

The seasonal cycle of stratification is controlled by the exchange flow between the Gulf of Eilat and the Red Sea, and by surface fluxes.

Figure 2-5 Seasonal cycle of the exchange flow between the Red Sea and the Gulf of Eilat [After Biton and Gildor, 2011]. 1Sv = 10⁶ m³/s.
The observed warming of the surface layer during the restratification phase (April-August) is mainly due to advection of heat through the Straits, with a smaller contribution from surface heating (Biton and Gildor, 2011a). During this phase, the water entering the Gulf through the Straits gradually re-constructs the stratification in the surface layer with increasing temperatures, while pushing the Gulf intermediate water level downwards. The water reaches the northernmost Gulf, and the time it takes varies from ~12 days in April to ~40 days in July, due to the substantial reduction in the exchange flux through the Straits. Eventually, the whole upper ~150 m in the entire Gulf is replaced with northern Red Sea surface water.

Figure 2-6 Average modeled temperature profile throughout the entire Gulf (down to 400 m in depth). Colored shaded areas indicate the seasonal mixing (gray) and restratification (light gray) phases in the evolution of the Gulf stratification. The isotherm 21.9°C separates the Gulf intermediate water and the surface water.

During the mixing phase a small amount of advected heat from the Straits and large heat loss to the atmosphere leads to efficient erosion of the stratification at the surface (note the increasing mixed layer depth during this time in Figure 2-6).

2.1.3 Insights from field measurements

In order to improve the data available for calibration of the circulation model used to evaluate the effects of abstraction on particle entrainment, as well as to improve gaps in our knowledge of flows in the Gulf, a series of deployments of oceanographic instruments to measure currents, temperatures, and salinities were carried out for 3 separate periods on the 200 and 500 m isobaths on the Israeli side of the Gulf offshore of the Steinitz Marine Lab. On each of these moorings, one 600 KHz and one 150 KHz Teledyne RDI Acoustic Doppler Current Profilers (ADCPs) were installed at 50 to 60 m depths looking upwards and downwards respectively. Likewise, a single 600 KHZ ADCP was deployed for shorter periods of time at shallow-water sites around the northern end of the Gulf, notably at the proposed intake sites. Other details of these deployments are given in Annex 1.
2.1.3.1 Deep ADCP moorings

Measurements by the ADCPs mounted on the deep moorings show that while the averaged currents are only 1-2 cm/s, instantaneous currents in the upper 200 m can be as high as 20 cm/s and the dominant period is the tidal M2 component. The amplitudes of the averaged currents are similar in all deployments and over both 200 and 500 m water depth, as can be seen from the following figures. Assuming an averaged velocity of 5 cm/s during each tidal cycle, a passive tracer will move a distance of ~2 km, which is well beyond the region affected directly by the abstraction.

Zero to positive northwards components were found for the averaged currents at all water depths at all times, with the only exception of the January 2011 deployment, when an average southwards current was measured at depths below 200 m.

Another characteristic of the averaged currents is non-zero east-west components, eastward in the upper layer during all deployments, and westward in the lower layer. These non-zero averaged currents suggest a link between the two sides of the gulf, over a time scale of few days assuming passive-tracer behavior.

Figure 2-7 August 2010 deployment: The east/west component of the flow (measured by both the upward looking 600 kHz ADCP and the downward looking 150 kHz ADCP) at the 500 m mooring location. The color scale corresponds to speeds in cm s⁻¹: positive values represent eastwards currents. White patches indicate missing data.
Figure 2-8 August 2010 deployment: Similar to Figure 2-7, but for the north/south component of the flow. Positive values represent northwards currents.

Figure 2-9 August 2010 deployment: Averaged velocity component at each depth bin at the 500 m Mooring location. The averages were computed over the entire deployment period (~34 days during August-September 2010).
Figure 2-10 October 2010 deployment: The east/west component of the flow (measured by both the upward looking 600 kHz ADCP and the downward looking 150 kHz ADCP) at the 200 m mooring location. The color scale corresponds to speeds in cm s⁻¹: positive values represent eastwards currents. White patches indicate missing data.

Figure 2-11 October 2010 deployment: Averaged velocity component at each depth bin at the 200 m Mooring location. The averages were computed over the entire deployment period of October 2010).
Figure 2-12 October 2010 deployment: Averaged velocity component at each depth bin at the 500 m Mooring location. The averages were computed over the entire deployment period of October 2010).

Figure 2-13 January 2011 deployment: The east/west component of the flow (measured by both the upward looking 600 kHz ADCP and the downward looking 150 kHz ADCP) at the 200 m mooring location. The color scale corresponds to speeds in cm s⁻¹: positive values represent eastwards currents. White patches indicate missing data.
2.1.3.2 Implications for selective withdrawal

The temperature measurements made on the moorings can also be used to infer vertical isotherm displacements associated with internal waves. Figure 2-16a shows the temperature measured at 120 m depth on the 200m mooring in August 2010. Using the temperature profile measured in the August 2010 (similar to that seen in Figure 2-3), these were converted to isotherm positions (Figure 2-16b) by inverting the dependence of temperature as a function of depth.

The standard deviation of the displacement seen at this mooring was 14m, with maximum displacement of up to 40m up or down. These displacements will have the effect of spreading the selective...
withdrawal effect discussed in section 2.2 over a wider range of depths than calculated above. For example in summer, the effective withdrawal layer might expand from 20m above and below the intake to ca. 40m above and below. As will be discussed below, the effects of internal waves on particle entrainment in the model will also appear in a broadening of the “capture” zone of the intake.

\[ u = \frac{Q}{2\pi r \delta} \]

For \( \delta = 20 \) m, the induced velocity would be 0.2 cm/s at a distance of 100 m from the intake, i.e. at distances slightly larger than the withdrawal layer thickness the induced velocities would be essentially negligible.

Finally, the observed velocities can be used to examine the spatial scale at which the abstraction flow might be discerned. Note that a point sink in a withdrawal layer of thickness \( \delta \) (an idealization) will induce a flow at distance \( r \) of \( u = \frac{Q}{2\pi r \delta} \). For \( \delta = 20 \) m, the induced velocity would be 0.2 cm/s at a distance of 100 m from the intake, i.e. at distances slightly larger than the withdrawal layer thickness the induced velocities would be essentially negligible.

Figure 2-16 (a) Temperatures measured at ca. 120 m on the 200 m mooring; (b) isotherm displacements at 120m depth.
2.1.4 Horizontal mixing and eddying

2.1.4.1 ADCP transects

The spatial structure of flows in the Gulf, at least as seen by current meters has been best revealed in observations made along the entire Gulf of Aqaba, during February-March 1999 using a 150 KHz ADCP mounted on the RV Meteor (Manasrah et al., 2004). These unique observations reveal a sequence of flow changes with time and space (Figure 2-17). These changes do not match the basic tidal motion, and represent in some parts a phase difference in the horizontal current components of about 90°. These appear to be a chain of cyclonic and anti-cyclonic eddies positioned along the Gulf axis and occupying at least the upper 300m of the water column (Manasrah et al 2004; Manasrah 2002). The diameter of the eddies ranged from 5 to 8 km with velocities ranging from 0 to 0.30 ms\(^{-1}\). Some of this spatial variability is seen in Figure 2-18, a plot of spatial variability in the northern Gulf taken from Manasrah (2002). This spring-time data show that the current in the upper 200 m in the western and eastern parts of the northern Gulf of Aqaba was dominantly directed to the NE, while in the center the current was mainly SE. Consequently, an anti-cyclonic circulation was observed in the upper 150 m between the western and central parts. Between 200 m to 300 m the NE current still dominated in the western part, while a transition from NE to SE can clearly be seen in the east. Obviously, the two opposite currents are parts of a larger anti-cyclonic circulation between eastern and western parts.

Figure 2-17 Time-latitude distribution of the current vectors along the axis of the Gulf of Aqaba at 105 m depth on repeated tracks during February 21st-March 6th 1999.
Figure 2-18 Distribution of the horizontal current vectors in the Northern Gulf of Aqaba at selected depth levels during March 5th 01:40-March 6th 16:00 1999.
Conversely to what observed at the whole gulf scale, in the northernmost part (10 km) of the gulf HF radar measurements of the surface currents reveal that coherent eddies are very rare, and appear only few times a year between November and April (Gildor et al., 2010). Therefore, it is not clear how much such eddies contribute to horizontal mixing in this region.

### 2.1.4.2 High Frequency Radar current data

Since August 2005, Two 42 MHz SeaSonde HF radar systems have been operational in the northern gulf near the city of Eilat, and since July 2008 an additional station was installed on the Jordanian side near the MSS. This network is used to measure the complex surface circulation structure of the northern GOAE with very high spatial (300 m) and temporal resolution (30 min) (Gildor et al., 2009). Each of these stations measures the radial velocity of the surface currents. To reconstruct the velocity at a certain patch of water, at least two radar sites should measure the radial velocity there from two different angles (ideally with at least 15° difference). Strictly speaking, the radar measures the currents at the top few tens of cm of the water column. However, comparison to measurements by an Acoustic Doppler Current Profiler (ADCP) demonstrate that the shear in the top few meters is usually small, and most of the time the surface currents represent the upper 10-20 m.

The surface flow field can be quite complex and incoherent, as reported before (Fig. 2 of Gildor et al., 2009). Often it is more structured, with the main component aligned with Gulf axis, and smaller east-west component (Figure 2-19). However, due to the strong tidal signal, the direction of the flow changes twice a day.

![Figure 2-19 Two snapshots from the surface currents measured by the HF radar network during October 2010 and February 2011.](image)

Figure 2-19 Two snapshots from the surface currents measured by the HF radar network during October 2010 and February 2011.
Occasionally (about 30% of the time, Gildor et al., 2009), temporary barriers to mixing exist at certain sub-regions and can “trap” water masses for 1-3 days. This may have important implications for the dispersion of pollutants, nutrients, larvae, etc., and therefore for a wide range of predictions. The mechanism behind the barriers is still unknown and further analysis is required to better understand their evolution and their effect on the ecological system.

Rarely, only few times a year between November and March, a coherent eddy occupying most of the region and lasting for a day or so was observed (Gildor et al., 2010 and Figure 2-20). Although the shape and center of the eddies change in time, they are the dominant feature in the gulf when they are present. The associated velocities are relatively high, and can reach 100 cm s⁻¹ near the edge of the eddies, compared to the averaged velocities of 15 cm s⁻¹ observed over most of the year. In addition, such eddies appear usually under calm condition, when the wind is relatively weak. The mechanism behind the formation of such coherent eddies is yet unclear.

![Figure 2-20 An example of coherent eddy from November 2005.](image)

Large velocities appear also during strong storms, such as during February 15, 2011. An example can be seen in the following Figure 2-21.
Figure 2-21 Surface currents during the southern storm of February 15, 2011.

The HF radar data can also be used to estimate the connectivity between the two sides of the gulf by advecting virtual passive particles. In order to do that, we need to fill spatial gaps and filter outliers. As the data collected during this year is still under processing, we demonstrate the idea using data from 2006 that was used in Carlson et al., 2010. The spatial gaps at each HF radar measurement time were filled using open-boundary modal analysis (OMA)\(^2\), described by Lekien et al. (2004) for mapping total velocities and by Kaplan and Lekien (2007) for mapping radial velocities.

Figure 2-22 presents three examples for January 2006. Nearly 200 particles were released within the blue rectangles and their final locations after 36 hours are shown. The left and middle panels show that particles that were released on the Jordanian side on January 24 at 18:40 GMT and on January 10:40 GMT, were drifted toward the Israeli coast. On the other hand, particles that were released on the Israeli coast, on January 25, 10:40 GMT, stayed closed to the coast.

Figure 2-23 presents similar examples for August 2006. Here it is the opposite. Particles released on the Israeli side crossed to the other side while those released along the Jordanian coast stayed near the coast.

The above examples suggest that surface connectivity exists between the two sides of the gulf, although subject to strong variability in time due to the variability of the current fields.

\(^2\) The OMA procedure objectively maps the HF radar measurements using three sets of basis functions that are truncated at a specified spatial resolution. Dirichlet modes (with zero horizontal divergence) represent the flow’s vorticity structure. Neumann modes (with zero relative vorticity) account for horizontal divergence. Boundary modes are used to represent the normal flow through the analysis domain open boundaries. Radial velocities were objectively mapped using the procedure of Lekien et al. (2004) as detailed in Lekien and Gildor (2009), with a spatial scale of approximately 350 m. This spatial resolution threshold resulted in a set of 100 Dirichlet modes, 130 Neumann modes, and 40 boundary modes (Lekien and Gildor 2009).
Figure 2-22 Trajectories of virtual particles calculated based on the surface currents measured by the HF radar for few occasions during January 2006.

Figure 2-23 Trajectories of virtual particles calculated based on the surface currents measured by the HF radar for few occasions during August 2006.
2.1.4.3 Estimates of mixing times

The ADCP data shown in section 2.1.3.1 can be used to estimate horizontal exchange times associated with the observed flows. To do this, we can consider the time integral of the alongshore ($U$) and cross-shore ($V$) velocities in different regions of interest:

$$X_{z,T} = \int_0^T U_{z,t} \, dt$$
$$Y_{z,T} = \int_0^T V_{z,t} \, dt$$

with $z =$ depth and $t =$ time. Although flows must vary across the Gulf, these integrals can be used to make a first-order estimates of the time it takes for water particles at different depths to travel along and across the Gulf. In carrying out this analysis, we considered two velocities: (1) the velocity averaged over the upper 100m and (2) the velocity at 120m, about the depth of the potential intake.

A sample velocity record for the surface velocity measured on the 200m isobaths in August 2010 is shown in Figure 2-24. Here the velocity has been split into components that have been high-passed (the internal tides) and low-passed (low frequency currents) with a cutoff frequency of 0.4 cpd. These velocities translate into the displacements shown in Figure 2-25. Interestingly, the high-frequency motions contribute little to net displacements. For this case, water particles take ca. 4 days to traverse the Gulf. At the same time, at 120m, the pattern is more complicated (Figure 2-26), requiring ca. 25 days for particles to travel across the Gulf. A table of maximum cross-Gulf displacements for each ca. month-long deployment is given below.
Figure 2-24 Surface velocities on the 200m isobaths in August 2010. The East-North velocities have been projected onto 45 deg (along Gulf) and 135 deg (across Gulf) directions.
Figure 2-25 Surface displacements on the 200m isobaths in August 2010.
Figure 2-26 Displacements computed for 120m on the 200m isobaths.

Table 2-1 Computed displacements in the cross-gulf direction during 2010 deployments (about 1 month of duration each).

<table>
<thead>
<tr>
<th>Period</th>
<th>Surface/200 m</th>
<th>120m/200 m</th>
<th>Surface/500 m</th>
<th>120m/500 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 2010</td>
<td>30 km</td>
<td>10 km</td>
<td>21 km</td>
<td>9 km</td>
</tr>
<tr>
<td>October 2010</td>
<td>14 km</td>
<td>28 km</td>
<td>25 km</td>
<td>15 km</td>
</tr>
</tbody>
</table>

From Table 2-1, it can be seen that the time to transport particles across the northern Gulf (6.5 km wide) varies from about 5 to 20 days. Note that over 20 days (the longest period computed), the abstraction volume would be $8.6 \times 10^7 \text{ m}^3$. In contrast the volume of the Gulf mixed in this time is $9.5 \text{ km} \times 6.5 \text{ km} \times 100\text{m}$ (taking the upper portion of the water column where larvae are found) = $6.2 \times 10^9 \text{ m}^3$, i.e., the abstraction would take 1.5% of the mixed volume.
2.1.5 Insights from the circulation modeling

Within the context of this project we have developed a hierarchy of numerical circulation models to help assess the potential impacts of water abstraction from the gulf. The first set of simulations for this purpose consists of the control runs in which the models are used to reconstruct the present circulation. Since the models produce information at all locations and times, the control runs provide additional insight that the field measurements alone cannot. For example, Figure 2-27 shows the mean simulated temperature at a depth of 9.5 m (depth of the proposed northern intake) averaged over 60 M2 tidal cycles (~31 days) for the month of Aug 2010. In general the water in the gulf is cooler than the water of the northern Red Sea with a clear south to north temperature gradient. Two main features that clearly stand out are the inflow of the Red Sea water which forms a tongue that flows along the eastern shore, and the band of cooler temperatures along the eastern and northern shores which is indicative of the wind induced upwelling observed by Labiosa and Arrigo (2003) in satellite images.

![Figure 2-27 Simulated temperature at 9.5 m averaged over 60 tidal cycles for the month of August 2010.](image-url)
In Figure 2-28 (Mar 2010) and Figure 2-29 (Aug 2010) we show the residual currents at 25 m averaged over 60 tidal cycles. As noted above, it is the mean currents, not the high frequency tidal fluctuations, that are of primary importance since they will control most of the transport of dissolved and suspended particles in the gulf.

Figure 2-28 Simulated currents at 25 m averaged over 60 tidal cycles for the month of March 2010.

The intense inflow of Red Sea water is quite apparent. The appearance of a chain of alternating cyclonic and anticyclonic eddies aligned along the gulf is also quite apparent as reported in previous modeling studies (e.g. Berman et al., 2000; 2003) as well as in the ADCP measurements reported by Manasrah et al. (2004) and Manasrah (2002) and as shown above in Figure 2-17. In the meandering jet that forms the boundaries of these eddies, the mean current speeds can often exceed 20 cm/s. It is also interesting to note that no coherent eddy appears in the northernmost part of the gulf which is consistent with the HF radar measurements of near surface currents reported above in Section 2.1.4.2.
A similar map of the simulated, residual currents at 25 m for the month of Aug 2010 is shown in Figure 2-29. Here too the chain of eddies is apparent as is the intense inflow of Red Sea water which flows along the eastern shore. Similarly no obvious coherent eddy appears in the northernmost region. It is quite possible that the constricted width of the northernmost section precludes the formation of such persistent eddies.

![Residual Currents 25 m - Aug 2010](image)

Figure 2-29 As in Fig. 2.28 except for the month of August 2010.

The intermediate model was designed to provide a zoom of the circulation in the northernmost 10 km of the gulf which is the area most likely to be affected by the proposed abstraction. This model, with a horizontal resolution of 124 m, was nested in the full gulf model as described in Section 9.1.5. In the following figures we show some examples of the residual currents averaged over 60 M2 tidal cycles, as with the full gulf model results presented above.
Figure 2-30 Simulated currents from the intermediate model at 1.5 m below the surface, averaged over 60 tidal cycles for the month of March 2010.

Figure 2-30 shows the currents at 1.5 m below the surface for the month of March 2010. The circulation is dominated by a general cyclonic flow which mainly follows the shore and the isobaths. The strongest currents are found over the steep bottom slope on both the east and west sides although they tend to be somewhat stronger on the west side of the gulf. Typical speeds of the alongshore flow are around 10 cm/s. Weaker currents are found along the north shore and in the center of the gulf. In the southeastern part of the domain one can see a hint of the influence of the northern flank of a cyclonic eddy which is located to the south.
In Figure 2-31 we show the currents at 25 m. The pattern is almost identical to the near surface flow presented in the previous figure which is a result of the deep winter mixing at this time of the year. In fact the current pattern at 120 m (not shown) is also very similar as the winter mixing at this time extended from the surface to a depth of ~ 300 m.

The near surface mean currents for August are shown in Figure 2-32. In contrast to the winter case, here the response of the sea to the direct influence of the northerly winds is clearly reflected in the southwestward currents that appear over nearly the entire domain. This is due to the stratification of the water column which also leads to significant changes in the current patterns at various depths as will be seen in subsequent figures.
Figure 2-32 Simulated currents from the intermediate model at 1.5 m below the surface, averaged over 60 tidal cycles for the month of August 2010.

The mean currents in August at a depth of 25 m are shown in Figure 2-33. The pattern here is quite different than the surface currents (Figure 2-32) and is reminiscent of the general cyclonic pattern that characterized the March circulation with and an indication of the influence of the northern flank of a cyclonic eddy located outside the domain to the south. The flow along the eastern shore extends over a broader zone as compared to winter while along the western shore it is still restricted to the region over the slope.
Figure 2-33 As in Figure 2-32 except at 25 m depth.

The last figure that we present in this sequence is Figure 2-34 which shows the currents at 120 m below the surface. Here the pattern is quite different than the circulation in the upper layers. The general bathymetry-following cyclonic flow along the shores appears only in the northern half of the domain. The southern half of the domain, however, is dominated by a coherent anticyclonic eddy with inflow from the south along the western shore and outflow along the eastern shore. While we cannot quantitatively compare the results here to the HF radar measurements presented above in Section 2.1.4.2 (Figure 2-19 - Figure 2-21) due to the different time periods and averaging (the HF measurements presented were instantaneous snapshots), they do nevertheless share some common features. For example, the coherent eddies observed in the ADCP transects along the entire gulf (Section 2.1.4.1, Figure 2-17) and simulated by the full gulf model rarely appear in the HF measurements.
In this respect it is important to note that the HF measurements only sample the upper few meters of the water column while the ADCP transects in Figure 2-17 represent the circulation at a depth of 105 m. We also note that the domain covered by the intermediate model is roughly the same as the area covered by the HF measurements. In the intermediate model results presented here, no coherent eddies spanning the width of the gulf appear in the average currents in the upper layers (shallower than 25 m). The only occurrence of a coherent eddy appears in August at a depth of 120 m which is well below the layer sampled by the HF radar. The other common feature shared by the HF radar measurements and the model is the ratio between the mean and maximum current speeds. In both cases the ratio is a factor of 6 or more. The mean near surface currents simulated by the model are typically 10-15 cm/s while the maximum simulated instantaneous (1 hr mean) current speeds can reach 60-70 cm/s.

One feature of the observed circulation during 2010 that was not expected was the noticeable reduction of the salinity in the spring and summer in the layer extending from the surface to the depth of the subsurface salinity minimum. The salinity measured during the CTD cruises in May and August (Figure 2-35) was as much as 0.15-0.20 psu lower than observed in previous years as can be seen by comparing the red and black lines in the figure. The most likely cause of such a change is an increase in the amount of Red Sea water entering the gulf through the Strait of Tiran. A detailed analysis and study of this phenomenon is beyond the scope of this study especially in view of the lack of

Figure 2-34 As in Fig. 2.32 except at 120 m depth.
any field data from stations to the south. It may be an important change that could be transient or long term and which warrants future monitoring. It clearly means that 2010 was an unusual year in terms of the circulation.

Figure 2-35 Temperature and salinity profiles measured during the August CTD cruise (red lines), simulated by the intermediate model (blue lines), and means for the years 2003-2009 at Station A.

2.1.6 Summary

Overall, the physical data suggest a picture of the Gulf in which low-frequency motions (admittedly of uncertain origin) and turbulent motion exchange water particles across the Gulf over times ranging from a few days to a couple of weeks. Superimposed on these motions are energetic internal tides that have little effect on net transport, but can result in significant vertical displacements of isothermal surfaces, most notably at depths comparable to the contemplated intake depths. This is important in that the basic density stratification of the Gulf will tend to act to limit withdrawals from the deep water off take to regions below the surface mixed layer where higher concentrations on plankton are found. In these cases, the internal waves will act to smear the “selective withdrawal” layers over a greater portion of the water column (see Section 4.2.4).

Most importantly, the existing flows in the Gulf are seen to be several orders of magnitude larger than those that would be induced by the proposed abstraction flows (see Section 4.2.1), such that the latter would likely be imperceptible except in the immediate vicinity of the sink. The expected effect of the abstraction on the heat budget of the gulf is also expected to be negligible.

While our understanding of the general circulation of the gulf improved in recent year, we still lack mechanistic understanding of few small-scale circulation patterns. Examples are the barriers to mix-
ing (Gildor et al., 2009), the rare coherent eddies (Gildor et al., 2010), and the low frequency, non-
zero, cross gulf currents that were measured for the first time during this project. The spectrum of the
internal waves field is also not fully understood. Although it is clear that it is dominated by the M2
tide, many other frequencies are superimposed on it. In addition a noticeable reduction of the salinity
of the upper 300 m occurred during the year of measurements in comparison with previous years.
These yet unexplained characteristics of the circulation in the gulf would require additional investiga-
tions which are well beyond the scope of the present study.

2.2 Water quality

The shores of the GOAE are lined with well developed fringing coral reefs, which have grown suc-
cessfully despite the high latitude of the Gulf relative to where coral reefs are typically found. These
reefs are likely one of the most important components of the Gulf's ecological system. They provide
recycled nutrients that support open water productivity (Erez, 1990; Silverman et al., 2007), provide a
food source and together with sea grass habitats, they function as nurseries for many pelagic spe-
cies. Both coral reefs and sea grass meadows are very susceptible to changes in water quality es-
pecially in the GOAE considering that these habitats experience over an annual cycle naturally oc-
curring large variations in environmental conditions such as temperature, light penetration, aragonite
saturation and nutrient levels (Silverman et al., 2007a).

The waters of the GOAE are generally considered to be oligotrophic and have been characterized as
mildly productive with an annual average primary production of 80 g C·m⁻²·yr⁻¹ (Levanon-Spanier et
al., 1979). This state reflects the lack of regular supply of nutrients to the surface layer of the GOAE
(Lazar et al., 2008). Throughout the annual cycle the supply of nutrients to the surface layer of the
GOAE is very low except during the winter. The shallow sill (~250 m) at the Tiran Strait separating
between the GOAE and the northern Red Sea allow only warm nutrient poor surface water to enter
the Gulf (Reiss and Hottinger, 1984). Additionally, nutrient supply through terrestrial surface runoff is
limited to one or two flood events per year during the winter. More recent studies have shown that
the deposition of dust transported from nearby sources and subsequent biological fixation of nitrogen
acts as a significant nutrient source to the Gulf (Richter and Abu- Hilal, 2006), while others showed
no significant N-fixation at the northern part of GOAE (Hadas and Erez, 2004, IET Report).

Other than from scientific literature, data on water quality of the Gulf are available from the results of
various monitoring programs (Table 2-2). Location of monitoring stations is shown in Figure 2-36.

Dissolved inorganic nutrients

Stratification of the water column during the summer months (April-November) prevents recycled nu-
trients from the deep reservoir (>250 m) to enter the photic zone that accumulate there (Figure 2-37).
As a result the surface layer concentrations of inorganic nutrients, particularly nitrogen and phos-
phate, in the GOAE are especially low during summer (<0.05 and <0.01 µmol/l, respectively) (Al-
Qutob et al., 2002; Rasheed et al. 2003; Silverman et al., 2007b). However, during winter, deep con-
vective mixing (>250 m) in the GOAE results in nutrient enrichment (2-3 orders of magnitude) of the
open and coastal surface water (Rasheed et al., 2002; Manasrah et al. 2005; Silverman et al.,
2007b; Lazar et al., 2008). This enrichment supports phytoplankton and benthic macro-algae
blooms. The latter have a detrimental affect on the coral reefs lining the coast of the GOAE as a result of growing over and smothering the coral beneath them (Figure 2-48; Genin et al., 1995; Silverman et al., 2007b). In addition, high nutrient levels have also been associated with decreased rates of net CaCO₃ deposition by corals possibly resulting from an increase in CaCO₃ dissolution as a result of increased boring organism activity (Lazar and Loya, 1991; Glynn, 1997; Silverman et al., 2007b) or by directly affecting the corals and reducing CaCO₃ deposition rates in corals (Kinsey and Davies, 1979; Marubini et al., 1996).

During summer stratification the upper ~100 m of the water column are almost completely depleted of inorganic nutrients (e.g. Figure 2-37) and below this level a nutricline (Reiss and Hottinger, 1984; Badran et al., 2001; Lazar et al., 2008) develops indicating the threshold between nutrient uptake by primary production in the photic zone and the supply of recycled nutrients from deep water through diapycnal mixing. Above the bottom at station A there is sometimes an additional nutricline indicating the flux of recycled nutrients from the sediments (Figure 2-37). This pattern of repletion and depletion during summer stratification below 100 m depth in the GOAE is typical of nitrate, phosphate and silicate. These parameters have been measured in the open and coastal water by both the Israeli and Jordanian National monitoring programs for the last 10 years on a monthly basis. Prior to this period, measurements were made for short periods of time in the framework of scientific projects (see Table 2-2).
Table 2-2 Available data bases on water quality for use in this study.

<table>
<thead>
<tr>
<th>Data type</th>
<th>Source/Location</th>
<th>Period of measurement</th>
<th>Parameters measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Quality</td>
<td>Eilat coastal sampling stations (/From RSMPP and INMP (1999-2002, 2003-2010)/Only surface water sampled</td>
<td>1999 – 2010</td>
<td>Sal, DO, pH, Ar, NO2, NO3, Si(OH)4, PO4, Chl._a, Secchi depth, Temp</td>
</tr>
<tr>
<td></td>
<td>Eilat Stations FF and OS/From RSMPP (1999-2002) and INMP (2003-2010)/vertical profile measurements</td>
<td>1999-2010</td>
<td>Sal, DO, pH, Ar, NO2, NO3, Si(OH)4, PO4, Chl._a, Temp, PAR, fluorescence, Pico-plankton, PP (14C)*</td>
</tr>
<tr>
<td></td>
<td>INMP/Jordan station B1</td>
<td>2003-2010</td>
<td>Sal, DO, pH, Ar, NO2, NO3, Si(OH)4, PO4, Chl._a, Temp, PAR, fluorescence, Pico-plankton, PP (14C)*</td>
</tr>
<tr>
<td></td>
<td>JNMP/Jordan Reference Offshore Station</td>
<td>2003-2010</td>
<td>Sal, DO, pH, Temp, Sig T, NO2, NO3, NH4, Si(OH)4, PO4, Chl._a, Enterococcus, HC</td>
</tr>
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<td></td>
<td>JNMP/Jordan Coastal Stations</td>
<td>2003-2010</td>
<td>Sal, DO, pH, Transparency, Temp, Sig T, NO2, NO3, NH4, Si(OH)4, PO4, Chl._a, Enterococcus, HC</td>
</tr>
<tr>
<td></td>
<td>J-Industrial Complex Monitoring Program-South Boarder</td>
<td>2003-2010</td>
<td>Sal, DO, pH, Transparency, Temp, Sig T, NO2, NO3, NH4, PO4, SO4, F, TN, TP</td>
</tr>
</tbody>
</table>
Figure 2-36 Northern GOAE shoreline with sampling stations that are sampled by the Israeli (blue) and Jordanian (green) national monitoring programs at the surface (empty circles) and vertical profiles (filled triangles) on a monthly basis from 1999-2010.
Figure 2-37 Vertical profiles of nitrate (NO$_3^-$) and density calculated as a function of salinity and potential temperature ($\theta$) in sigma units measured a station A on a monthly basis during 2005.

Figure 2-38 Benthic macro-algae bloom smothering acropora coral head in the northern GOAE during winter of 2000. Under such conditions corals may suffocate and die. In 1992 an exceptionally deep mixing event occurred resulting in a benthic macro-algae bloom and large scale mortality of coral in the Eilat reef (Genin et al., 1995). Picture was taken by D. Zakai.
Some recent records of the monthly average total phosphate and organic nitrogen concentrations in the seawater of the Gulf of Aqaba are shown in Figure 2-39. Total phosphorus and organic nitrogen concentrations showed rather irregular month to month variations. Concentrations of these two species are associated with dissolved and particulate material, which can be either living or non-living. Concentrations are difficult to predict because they can be of either biogenic or anthropogenic origin.

![Graph showing total nitrogen and total phosphorus concentrations in the Gulf of Aqaba](image)

**Figure 2-39 Concentrations of total nitrogen and total phosphorus (mg/l) in the water of the Gulf of Aqaba – southern Jordanian area – in 2009.**

**Chlorophyll a**

Chlorophyll $a$ concentrations and primary productivity have been concurrently studied by Levanon-Spanier et al. (1979). The authors presented an annual cycle of the two parameters during 1976-1977 based on monthly measurements between the surface and 200 m in the north-western section of the Gulf. Phytoplankton succession has been studied by Kimor and Golandsky (1977) and more recently by Lindell and Post (1995) including the pico-fraction. Studies that included chlorophyll $a$ concentrations along the eastern coast of the GOAE were mostly restricted to coastal waters along the Jordanian coast or had temporal resolutions of 2-3 months (Leger and Artiges, 1978; Natour and Nienhuis, 1980; Mahasneh, 1984; Wahbeh and Badran, 1990; Badran and Foster, 1998; Richter et al., 2001; Rasheed et al., 2003; and Niemann et al., 2004). Badran et al. (1999) and Rasheed et al. (2002) reported significantly higher nutrient and chlorophyll $a$ concentrations in coastal coral reef waters as compared to water column waters just 3 Km offshore. This observation was supported by the results of a study conducted by Labiosa et al. (2003) who showed that upwelling of nutrient rich water along the eastern coast of GOAE resulted in an apparent cross-shore gradient in chlorophyll $a$ concentrations. This was demonstrated Using SeaWIFS and MODIS imagery, however no direct
measurements of upwelling have been made to prove this theory conclusively. From long term re-
cords of chlorophyll $a$ concentrations in the open water of the northern GOAE measured by the Is-
raeli National Monitoring Program at station A (Figure 2-40) it is evident that surface water concen-
trations vary between a low value of $0.03 \mu g/L$ during summer and $0.87 \mu g/L$ during the onset of
stratification at the end of March and beginning of April. During the summer months the water col-
umn is stratified, and a typical deep chlorophyll maximum (DCM) develops at $60–100$ m depth near
the limit of light penetration and close to the nutricline that begins at $\sim 100$ m depth. Unlike surface
concentrations, which are very low during the stratified season ($O 0.1 \mu g/l$), the concentration of
Chlorophyll $a$ at the DCM is relatively constant at $0.36 \pm 0.10 \mu g/l$. Nonetheless, the depth integrated
concentration of chlorophyll $a$ is greater by a factor of 2 Dec-Feb than the summer months Jun-Oct
(Stambler, 2006)

![Graph](image)

Figure 2-40 Successive annual cycles of chlorophyll $a$ measured in the 0-10 m surface layer
from 1999 to 2010 on a monthly basis at station A.

**Light penetration**

The depth of light penetration limits how deep a reef will grow because of the association between
endosymbiotic algae also know as zooxanthellae and their coral hosts. Under poor light conditions
corals aren’t able to sustain their energetic demands, which are provided for by photosynthates of
their algal symbionts. In the GOAE the average depth of maximum light penetration calculated ac-
cording to equation 1 following Kleypas et al. (1999) and using measurements made over a three
year period (1993-1996) in the GOAE of Iluz (1997) is 40 m (Silverman et al., 2007b). The minimum
and maximum depths are 10 m and 70 m, respectively. These values are very similar to those re-
ported by Kleypas et al. (1999) for oceanic waters inhabited by coral reefs.
\[ Z_{noon} = \frac{\ln(PAR_{min} / PAR_{noon})}{K_{490}} \]  

\( Z_{noon} \) – Depth of maximum light penetration, m  
\( PAR_{min} \) – minimum PAR necessary for reef growth, 250 \( \mu \)E·m\(^{-2}\)·sec\(^{-1}\) (Kleypas et al., 1999).  
\( PAR_{noon} \) – maximum daily PAR at sea surface, \( \mu \)E·m\(^{-2}\)·sec\(^{-1}\).  
\( K_{490} \) – diffuse extinction coefficient of light (\( \lambda = 490 \) nm), m\(^{-1}\).  

Light field measurements made at station A during 1996-2000 on a monthly basis indicated that the euphotic zone depths (1% of light at surface) varied between 80 and 115 m (Stambler, 2006). Regular measurements of Secchi depth and PAR in the coastal and open waters of the northern GOAE have also being made on a monthly basis the by national monitoring programs of Jordan and Israel since 2000.

**Carbonate chemistry**

It has been shown that the degree of aragonite saturation (\( \Omega_{arag} \)) also limits the latitudinal distribution of coral reefs (Kleypas et al., 1999) by limiting the rate of \( \text{CaCO}_3 \) deposition in corals (e.g. Langdon and Atkinson, 2005; Schneider and Erez, 2006). Thus, a coral will calcify at an increasing rate as \( \Omega_{arag} \) increases and visa-versa. Since \([\text{Ca}^{2+}]\) is relatively constant in the oceans it could be said that \( \Omega_{arag} \) is actually a measure of the carbonate ion concentration ([\( \text{CO}_3^{2-} \)]) according to equation 2.

Where, \( K_{sp-arag} \) is the apparent solubility product for aragonite that is the mineral deposited by corals.

The coral reefs in the GOAE are considered to be relatively high latitude reefs, i.e. at the northern latitudinal limit of coral reef distribution globally. However, since the Gulf is a terminal basin with high evaporation rates, the water is relatively saline (average ~40.7 PSU) compared to other oceanic regions inhabited by coral reefs (~35 PSU) resulting in comparatively high total alkalinity (~2500 \( \mu \)mol/kg). Therefore, the carbonate ion concentration is also relatively high. The average \( \Omega_{arag} \) in GOAE based on two years of measurements (2000-2002) on a monthly basis in the nature reserve reef, Eilat was 4.0 (Silverman et al., 2007). The minimum and maximum \( \Omega_{arag} \) values for this period were 3.7 and 4.4, respectively. These values are somewhat higher than the corresponding values for the global distribution of coral reefs (min = 3.3, mean = 3.8, max = 4.1) defined by Kleypas et al. (1999).

\[ \Omega_{arag} = \frac{[\text{Ca}^{2+}][\text{CO}_3^{2-}]}{K_{sp-arag}} \]  

Silverman et al. (2007) also showed that \( \Omega_{arag} \) varied seasonally with temperature and productivity in the adjacent open sea (Figure 2-41). More importantly this study showed that the rate of net calcification (\( G_{net} \)) of an entire reef was well correlated with ambient \( \Omega_{arag} \) demonstrating the importance of this parameter in assessing the water quality in coral reef environments.
Figure 2-41 Daily average degree of aragonite saturation in the nature reserve reef in Eilat plotted against daily average temperature. Filled data points indicate measurements made during open sea water column stratification (nutrient depletion) and empty markers indicate measurements made during open sea water column mixing depth >250 m (nutrient repletion). Note the positive correlation between $\Omega_{arag}$ and temperature for nutrient deplete conditions. Under nutrient replete conditions productivity offsets the expected reduction in $\Omega_{arag}$ with temperature due to increased uptake of CO$_2$.

Total alkalinity reflects the concentration of dissolved minerals in seawater and therefore should be conservative with salinity, i.e. as salinity increases total alkalinity should increase linearly and visa-versa (Brewer et al., 1997). In the GOAE total alkalinity is generally lower than the calculated value as a function of salinity using the relations developed by Brewer et al. (1997) indicating that the entire Gulf is a net sink for Alkalinity, i.e. deposition of CaCO$_3$ (Figure 2-42). This is in agreement with the fact that there are many calcifying organisms in the GOAE primarily coral reefs, which reduce total alkalinity below conservation with salinity by precipitating their CaCO$_3$ skeletons. Measurements made at station A from 1989 to 2010 indicate that total alkalinity in the northern GOAE is increasing over time, getting closer to its conservation with salinity value. This could be the result of a number of processes: 1) reduction in calcification due to ocean acidification (e.g. Silverman et al., 2009). 2) Increase in dissolution of CaCO$_3$ in the deep water of the Gulf due to organic loading (see below). 3) Increase in salinity – values are not normalized to constant salinity.
Enterococcus in the Jordanian water was mostly not detectable except in the northern stations, which are near Tourist sites and the Port of Aqaba. Enterococcus was extraordinary higher near the middle Port and sometimes in the enclosed lagoon. The higher values at different stations might be caused by the livestock ship anchoring usually near Clinker Port or any uncontrolled discharge at different sites.

Table 2-3 Enterococcus (mpn$^3$) in the surface offshore and coastal waters of the Jordanian sector of the Gulf of Aqaba, Red Sea, during 2009. Data from Jordanian National Monitoring Program.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
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<tr>
<td>Northern Boarder</td>
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<td>Enclosed Lagoon-North</td>
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<td>75</td>
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<td>20</td>
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<tr>
<td>South Region</td>
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</tr>
</tbody>
</table>

$^3$ Most Probable Number
Fluoride and sulphate

Records of the monthly average fluoride and sulphate concentrations in the seawater of the Gulf Of Aqaba are shown in Figure 2-43. Fluoride and sulphate are two conservative species, their concentrations are not affected by the biological productivity. The values of fluoride and sulphate concentrations were usually in the normal range. Concentrations of the two species showed in 2009 only minor variations from one month to another.

![Sulphate Concentrations](image1)

![Fluoride Concentrations](image2)

Figure 2-43 Concentrations of sulphate (g/l) and fluoride, total in the water of the Gulf of Aqaba – southern Jordanian area – in 2009.

Dissolved trace metals and organic pollutants

Dissolved trace metals and organic pollutants in seawater at representative sites near potential pollution point sources and the coral reef along the Israeli coast of the GOAE were measured in 2002-2004 (Herut and Ludwik, 2004). The concentrations of all metals were very low, in the ppt/sub-ppb range, and all below Israeli standard for water quality. The results revealed low levels (below the analytical detection limits) of volatile organic compounds (<0.5 ug/L), PAHs (<0.1 ug/L), PCBs (<0.3 ug/L), and chlorinated pesticides (<0.03 ug/L, measured in 2002 only). However, significant, but low concentrations of tributyltin (TBT) and its degradation products) were measured at the ports.

Organochlorine pesticide concentrations in water of the Gulf of Aqaba (Table 2-4) were found to be very low ranged from below detection limit to 0.539 ug/kg (Al Masri et al. 2009).
Spatial changes were found in the concentration of the total hydrocarbon (THC) in the Gulf of Aqaba (Rasheeed et al. subm.). The concentrations of THC in water were generally low (less than 0.01 mg/l) except in the water of enclosed tourist lagoons that used for yachts and boats parking (average 0.02 mg/l).

Table 2-4 Organochlorine pesticides concentrations (µg/kg) in the water of the Gulf of Aqaba.

<table>
<thead>
<tr>
<th>Organochlorine Pesticide</th>
<th>HCB</th>
<th>Heptachlor</th>
<th>Aldrin</th>
<th>p,p’ - DDE</th>
<th>p,p’ - DDD</th>
<th>p,p’ - DDT</th>
<th>B-HCH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conc. µg/kg</td>
<td>&lt;d.l</td>
<td>0.001</td>
<td>&lt;d.l</td>
<td>&lt;d.l</td>
<td>&lt;d.l</td>
<td>0.539</td>
<td>0.201</td>
</tr>
</tbody>
</table>

2.2.1.1 Coral reefs effects on water quality

Coral reefs on the Jordanian and Israeli side of the GOAE have been shown to recycle particulate organic matter imported from the open sea into biologically available dissolved inorganic nutrients (Richter et al., 2001; Silverman et al., 2007). Rasheed et al. (2003) have also shown rapid recycling in carbonate sediments associated with the coral reef. Badran et al. (2001) & Rasheed et al. (2002) reported significantly higher nutrient and chlorophyll a concentrations in coastal coral reef waters as compared to water column waters just 3 Km offshore (order of magnitude during summer). Silverman et al. (2007) showed that the reef is actually a source of dissolved nutrients for open sea productivity during the summer, while during the winter it behaves as a sink (Figure 2-44).

![Figure 2-44](image_url)

Figure 2-44 Net production estimated from the diurnal cycle of NO$_3$⁻ (P$_{n-N}$) in the fringing reef at the Coral Beach Nature Reserve on the western side of the Gulf plotted against the open sea (1 km offshore) NO$_3$⁻ concentration for all studies conducted between 2000-2002. The black line indicates the calculated linear trend and the dashed lines indicate the boundaries of the 95% confidence interval. Positive values indicate that the reef is a source of dissolved nutrient and negative a source. During winter mixing nitrate levels in the open sea are high. During the stratified summer nitrate levels in the open sea decrease to <0.1 µM.
2.2.1.2 Long term trends in water quality of the northern GOAE

During the 1970’s a significant productivity gradient with increasing oligotrophy towards the north was observed from the Tiran Strait to the north end of the Gulf (Levanon-Spanier et al., 1979; Reiss and Hottinger, 1984). This situation reversed during the 1990’s and 2000’s as a result of significant nutrient input (250 tons N·yr⁻¹ during the period of maximum production) from fish farming in cages near the north shore of the Gulf on the Israeli side of the border (Lazar and Erez, 2004; Lazar et al., 2008). During the period of highest production (early 2000’s) the increasing nutrient reservoir in the deep water and decreasing oxygen concentrations in both the deep and surface layers of the northern Gulf were thought to be caused by the fish cages nutrient loading (Figure 2-45, Lazar and Erez, 2004; Lazar et al., 2008). Alternatively, much of the long term variability of the nutrient inventories and dissolved oxygen concentrations in the deep water of the GOAE may be due to fluctuations in the hydrodynamics of the Gulf. Specifically, the frequency of deep mixing events and the interaction between deep convective mixing and the horizontal circulation (Herut and Cohen, 2004; Atkinson et al, 2004, IET Report). Thus, nutrients in the deeper water of northern GOAE have been increasing with time, as part of a natural “cycle” and does not indicate accumulation of nitrogen from the fish farms (Atkinson et al, 2004, IET Report). Therefore, much of the long term variability of the nutrient concentrations in the deep water of the GOAE (and the water column nutrient inventories) may be due to fluctuations in the hydrodynamics of the Gulf. The frequency of deep mixing events and the interaction between deep convective mixing and the horizontal circulation may be especially important in this context (Atkinson et al, 2004, IET Report) and have implications on the water quality variations in this area.

Deep water nitrate levels increased from a typical value of 4 μmol/l (early 1990’s) to 7 μmol/l in 2003-2004, while dissolved oxygen decreased from 180 μmol/l to 150 μmol/l. After the deep mixing of the water column during the winter of 2007 oxygen levels in the deep reservoir (Figure 2-46) increased almost to the levels observed in the early 2000’s while nutrient levels decreased. Silverman and Gildor (2008) showed using a box model of the entire Gulf that an increase of nutrient levels in the deep northern basin of the Gulf could occur as a result of nutrient loading into surface water at its northern end. Additionally, they also showed that the frequency of deep mixing events or lack thereof can result in deep water nutrient accumulation as well. Thus, while the residence time of water in the Gulf is ca. 9 months in the surface layer and ca. 8 years for deep water (> 250 m), nutrients have a residence time on the order of 10’s of years. Hence, an increase in stratification in the water column of the GOAE will likely result in a nutrient build up and decreased oxygen levels in the deep reservoirs of the Gulf.
Figure 2-45 Contour plots of Dissolved Oxygen, NO₂, NO₃⁻¹, SiO₂, PO₄⁻³, and Chl_a measured at discrete depths at station A (in the middle of the GOAE, 10 km south of its northern shore) down to a depth of 750 m during the period 1999 – 2009 (including). The measurements were made within the frameworks of the Red Sea Marine Peace Park Monitoring Program (1999 – 2002) and the Israeli National Monitoring Program (2003 – to present).
Figure 2-46 Oxygen levels at different depths below the water surface at station A in the GOAE from 2000 to the end of 2009 (INMP annual report, 2009). The trend in the dissolved oxygen concentration is mainly controlled by deep mixing events (~600-700m) occurred in 2000, 2005, 2007, 2008 and horizontal circulation, and not related to fish cages operation in the past (Atkinson et al, 2004, IET Report; Herut and Cohen, 2004).

The decrease in dissolved oxygen in the deep reservoir until 2005 (Figure 2-47) was accompanied by a decrease in pH indicating the production of CO$_2$ due to recycling of organic matter through aerobic processes (data not shown). This decrease in dissolved oxygen was also observed in the surface layer (Figure 2-47), which could only be explained by the decrease in the deep reservoir concentration since there was no significant warming. Consistent with the decrease in deep water pH and surface dissolved oxygen, surface water pH also decreased significantly until 2005 (Figure 2-48). This decline (ca. 0.1 pH units) is somewhat larger than the expected decline due to ocean acidification (Caldeira and Wicket, 2003) in this short period of time. This decline in pH was not offset by the increasing trend in total alkalinity and caused a significant reduction in the carbonate ion concentration and $\Omega_{arag}$. This likely caused a reduction in coral reef calcification in the GOAE as shown by Silverman et al. (2007, 2009).
Figure 2-47 Dissolved oxygen concentration at the surface in station A from 1989 to 2009 indicating the long term decreasing trend.

\[ \Delta \text{DO}/\Delta t = -7 \text{ mmol} \cdot \text{L}^{-1} \cdot 10 \text{ years}^{-1} \]

Figure 2-48 Long term record of pH measured at a constant temperature (25°C) on samples of surface water from station A from 1996 to 2009. Since the pH was measured at constant temperature the decline reflects an increase in surface water CO₂ concentration, which is consistent with the decrease in surface dissolved oxygen concentrations.
2.3 Ecology

2.3.1 Marine ecosystems

The Gulf of Aqaba/Eilat (GOAE), which is part of the Syrian-African rift valley, is a long (180 km), narrow (5-25 km), and deep (average 800 m, maximum 1800 m) northward extension of the Red Sea. It is connected to the Red Sea through the Straits of Tiran where the sill depth is approximately 250 m. The Gulf is located in an arid region with annual rainfall of less than 30 mm and the surface runoff is practically zero. The best estimate for the annual mean evaporation from the surface is 1.6-1.8 m (Ben-Sasson et al., 2009).

The Gulf is a concentration basin in which less saline water enters through the straits in the upper layer and the more saline water, formed in the gulf due to excessive evaporation, flows out near the sill depth (Murray et al., 1984). Estimates of the water exchange through the straits, based on the observed thermohaline structure, vary between 30,000 – 70,000 m$^3$/s. More recent calculations by Biton and Gildor (2011a) based on model results suggest that the exchange varies annually between a maximum of nearly 4 x $10^4$ m$^3$/s (April) to a minimum of 0.5 x $10^4$ m$^3$/s (Sept. to Nov.), with an annual mean of 1.8 x $10^4$ m$^3$/s. Hence, the volume of surface water loss through evaporation is about two orders of magnitude smaller than the volume of water exchange through the Straits. In this respect, the situation is similar to other concentration basins such as the Mediterranean Sea. While the evaporative loss is compensated by inflow through the Straits, it is this small imbalance that drives the overall subtidal circulation. Salinity in the GOAE is among the highest in the world ocean and is around 40.68 ± 0.2 psu. Variations around the mean are due mainly to the high surface salinity in summer and the inflowing, less saline Red Sea water which appears as a subsurface salinity minimum in spring and summer.

Unlike open subtropical (and tropical) oceans, where the deep and intermediate water is cold, the deep water in the Gulf remains at just above 21°C throughout the year (NMP reports 2003-2010). The reason for this anomaly is the shallow sill at Bab-el-Mandeb, which effectively separates the deep waters in the semi-enclosed Red Sea from those in of the Indian Ocean. For comparison, water temperature at 1500m depth in the Gulf of Aden, which connects the Red Sea and Indian Ocean, is <10°C. The occurrence of warm water at depth substantially weakens the vertical stratification of the water column in the GOAE. For example, below ~300 m, the vertical gradient in temperature in the Gulf is ~0.09°C / 100 m, compared with more than an order of magnitude steeper gradient in “normal” oceans at similar latitudes (e.g., 1.07°C/100 m south of Bermuda, 1.67°C/100 m at the Central North Pacific). The weak stratification, together with low air temperature in winter, subjects the Gulf to unique (among warm, sub-tropical water bodies) seasonal vertical mixing that can exceed 600 m depth in cold winters (range of 250 to over 800 m) (Genin et al., 1995). Note that the occurrence of deep mixing is limited to the Gulf of Aqaba, at the northern end higher-latitude part of the Red Sea. Air temperature at lower latitudes, south of the Straits of Tiran, is too high to induce deep mixing, even during the winter (Paldor and Anati, 1979; Reiss and Hottinger, 1984).

Due to deep mixing, the concentrations of nutrients in the upper water column exhibit an unusually strong seasonality, changing from nutrient scarcity in summer to nutrient-replete conditions and phytoplankton bloom during winter-spring. Nearly each year a sharp nutricline exists, with relatively high
nutrient concentrations in the deep water (e.g. reaching 6-7 μM NO₃ at 500-700 m depth). The very deep mixing (>700 m) after cold winters causes substantial nutrient entrainment that brings about immense spring blooms of benthic algae. In some years those algae cover wide sections of the local reefs, causing substantial coral death (Genin et al., 1995). As such events occur in the GOAE every 5-20 years, the mechanism can be categorized as an “intermediate” disturbance (sensu Connel 1978), a process known to be important in the maintenance of the high species diversity. Indeed the diversity of reef corals in GOAE is among the highest in the world (Loya 1972; Connel 1978).

The year-round occurrence of warm waters is the key mechanism allowing coral reefs to flourish as far north as the northernmost end of the GOAE. Fringing coral reefs are the overwhelmingly dominant type in the shallow waters. At greater depths, down to approximately 100 meters, coral carpets covering marginal slopes are abundant. Growth of these deep reefs is facilitated by the clarity of the water that allows light penetration to that depth. Below 100 m the reef becomes more patchy, sandy stretches form greater proportion, and the corals are of different taxa and less abundant (Fricke and Knauer 1986).

While its connection with the Indian Ocean places the biogeographic origin of Red Sea fauna and flora within the Indo-Pacific domain, its setting and geological history make for unique conditions that have direct bearing on the development of reefs along the coasts of this elongated narrow sea. The reefs are dominated by stony, hermatypic corals, consisting of a diverse mixture of branching, foliose and massive species. Most abundant are corals belonging to the genera Acropora, Stylophora, Montipora, Pocillopora, Porites, Platygyra, Pavona, Echinopora, and Favia (Loya and Slobodkin 1971). The hydrozoan Millepora is very abundant in the shallow, sub-tidal zone. Soft corals are also abundant throughout the Red Sea, dominated by Sinularia, Sarcophyton, Lobophyton, and Xeniids, with magnificent thickets of nephtheids (mostly Dendronephthya) found on elevated substrates and vertical walls exposed to strong currents (Benayahu and Loya 1977(a) and (b)). Due to the clear water in the northern Red Sea, zooxanthellate corals reach at least 145 m in depth (Fricke et al. 1987).

The number of coral species found in the Red Sea is approximately 190, belonging to 70 genera (Head, 1987). While the total number of species is generally higher in other tropical Indo-Pacific reefs (e.g., ~360 species in the Great Barrier Reef- Veron 1986), the local, within-habitat diversity in the Red Sea is higher than in GBR (Loya 1972). However, almost any biological-ecological parameter studied at that northern Gulf reefs represents the property of high level of variation on a small geographic scale (reviewed in Rinkevich 2005). These geographically small scale variations were reflected in studies revealing rates of coral recruitment, population genetics of corals, interactions of algae and herbivorous organisms, natural catastrophe, substrate type, structure and topography, light intensity and sedimentation and more.

The fishes in the Red Sea coral reefs, like corals, share an Indo-Pacific origin. Especially abundant and diverse are the guilds of site-attached and mobile zooplanktivorous species, schooling and individual herbivorous fish, including acanthurids, siganids, and scarids, and many benthic predators, including serranids and balistids. Of the 462 reef-associated species (belonging to the ten richest families) that inhabit the Arabian Sea, 69% have crossed successfully into the Red Sea; of these, 55% have crossed into the Gulf of Aqaba. Present-day differences in the species richness of reef associated species among the Arabian Sea, Red Sea and Gulf of Aqaba appear to be the product of external, non-selective constraints on colonization (Kiflawi et al. 2006).
The Red Sea coral reefs are among the most studied reefs in the world. Detailed accounts of their structure and biological composition can be found in numerous publications. Useful references include Loya and Slobodkin (1971), Mergner (1971), Scheer (1971), Fishelson (1971), Benayahu and Loya (1977a; 1977b), and Edwards and Head (1987).

2.3.2 The coral reefs: status and trends

During the last four decades, the coral reefs of Aqaba and Eilat have undergone major changes resulting from increasing impacts due to human activities, coupled with those from natural disturbances (e.g., Genin et al., 1995; Meir et al., 2005, Rinkevich, 2005). Rapid developments in the cities of Eilat and Aqaba intensified the pressure on the coral reefs of the Gulf, including fishing, diving and boating activities, sand deposition on the coast, phosphate loading, and more. Fortunately, stricter rules are being applied on human activities near the coast and in the water in both cities to protect the natural ecosystems. Another major development was a decision made by the Jordanian and Israeli governments almost a decade ago to establish and support long-term marine monitoring programs in Aqaba and in Eilat. Those monitoring programs provide comprehensive data and information on both the water column and coral reef ecosystems in the region. That large set of data provides invaluable information for our assessment of the physical, chemical and ecological effects of RDC. Especially, the sections below on the present state of the coral reef and the role of larval recruitment in the population dynamics of reef corals, are based on our processing of the Israel National Monitoring Program (NMP) data base.

The NMP data base is open to the public for downloading of data and/or real-time measurements at the following website: http://www.iui-eilat.ac.il/NMP/Default.aspx

Last year (2010) was the NMP’s seventh year of standard monitoring operations, carried out using repetitive methods by mostly the same team. The abundance, diversity, sizes and health status of reef corals are measured using the standard 10 m line transect method, where the cover of corals (identified to genus or species), algae and other substrates are measured. The size of each coral under the line is visually sorted as belonging to one of the following categories: small, medium, large, and huge (1-5, 5-15,15-30, and >30 cm in diameter, respectively). A total of 121 such line transects were carried in 2010 at 3 different sites at 2-3 depths per site (in the range of 5-20 m depth). Likewise, invertebrates are counted (during the night) along “belt transects”, 1 m in width, 50 m in length. A total of 36 belt transect at 5 different sites (1-2 depths per site) were carried out in 2010. All the line and belt transects are randomly positioned at each site.

The results are presented in the following figures (Figure 2-49a. through Figure 2-49). See figure legends for the main points shown.

Overall, during the seven years of monitoring by the NMP (2004-2010) the coral reefs of Eilat were stable, exhibiting a slight growth in cover and health in 2007. Live coral cover has steadily increased since 2007, and the normalized cover in 2010, while not as high as it was in 2007, has stabilized on higher values than in 2004-6. Massive and encrusting forms of stony corals outnumber branching species, although a single genus (Acropora spp.) is the dominant taxon in percent cover (Figure 2-49e and Figure 2-49). Species composition and species diversity in the monitored sites are stable, with no significant changes in the past seven years of monitoring. The density of sea-urchins (an important group of algae grazers) is recently decreasing, concurrently with a decrease in algal cover. At most sites the abundance of sea urchins is the lowest encountered in the past seven years. The years 2009-10 the growth potential of benthic algae, as indicated by settlement over plates protected
from grazing, was unusually low, indicating relative scarcity of nutrients. The obvious reason is the shallower-than-normal vertical mixing in the past two years (280-350 m, compared with 350-800 in past years). Nutrient entrainment, hence algal growth, decreases after winters in which the mixing does not reach great depths. It is possible that the observed decrease in the size of sea urchin populations was driven bottom-up by the scarcity of their algal food.

Year-to-year changes in the percent cover (normalized to rocky substrate) and total number of colonies per transect had coefficients of variation (CV) of 13.3% and 14.5%, respectively. Much higher fluctuations (CV ranging 30% to 83%) was found for the common mobile invertebrates included in the survey.

Figure 2-49a Average live coral cover (excluding soft corals) at each site (percent cover of total area) in the years 2004-2010 at the different sites (Katza- oil terminal, NR- nature reserve, IUI- Interuniversity Institute). Note the temporal stability in coral cover within sites and the substantial variation among sites.

Figure 2-49b Average live coral cover on rocky substrate at each site (percent cover of total rocky substrate) in the years 2004-2010 at the different sites (Katza- oil terminal, NR- nature reserve, IUI- Interuniversity Institute). The normalization to percent cover on rocky substrate allows a comparison between the extent of coral cover compared with full (100%) coverage. The stability within site and the variation between site, observed in the non-normalized plots (previous figure) is obvious also in the normalized values.
Figure 2-49c Top - The average number of coral colonies per 10 m of line transect at each site. Bottom – coral density normalized to hard substrate.

Figure 2-49d The coral live tissue index (=percent of skeleton covered with healthy, polyp-bearing tissue) of each living colony calculated for each site. Overall, the extent of damaged tissue within colonies remains fairly stable with time since 2004, with substantial variation between sites.
Figure 2-49e The twenty most abundant coral taxa in the reefs of Eilat (according to their cumulative measured length in the line transects of 2004) in the years 2004-2010, arranged according to their abundance in 2010.

Figure 2-49f Frequency distribution of the main taxa groups comprising reefs at permanent photo-sites in 2010, according to the relative (percent) area which they occupy.
Figure 2-49g The average density (per m$^2$) of mobile invertebrates in the coral reefs of the Eilat Nature Reserve and off IUI in 2010.

Figure 2-49h The average density (per m$^2$) of crinoids (Feather Stars, top) and Holothurians (Sea Cucumbers, bottom) at the coral reefs of Eilat since 2004.
Figure 2-49i The average density (individuals per m²) of Diadema setosum (top) other urchins (middle) and all sea urchins (bottom) at the coral reefs of Eilat since 2004.
2.3.3  Are the local populations of corals limited by recruitment?

Starting in 2005, in the coral-reef line transects carried out by NMP, each stony coral falling under the transect tape was categorized as belonging to one of 4 size categories (small, medium, large, and huge- see above for definitions). Thereby, the sizes of about 2500 individual corals were obtained each year. This 6 year long data base allows a general evaluation of the importance of “supply-side ecology” in determining the population size of reef corals in Eilat. That is, assessing the degree to which the populations and cover of corals are limited by the supply of larvae. With a detection size threshold of ~ 1 cm, the group of “small” corals consists of colonies 1-5 cm in diameter. In the following discussion, members of this group are termed “recruits”, representing colonies that recruited during the recent few years (most of the branching ones during the past year) and all, if survived undisturbed, with grow with a few years (most of the branching ones within a year) into the next size category (“medium” colonies). The growth rate of branching corals is in the range of centimeters per year, while that of massive and encrusting corals is millimeters per year (based on the NMP photographic monitoring of individually marked colonies). Note that the following analysis can provide only a general assessment, as it has some caveats and limitations, as described below.

The results indirectly suggest that neither the percent cover of all corals (Figure 2-50a- upper panel) nor their abundance (number of colonies per area; Figure 2-50a- lower panel) are limited by recruitment. On the contrary, in both cases a negatively significant (P<0.0001) regression was found between the dependent variable (coral cover or the abundance of non-small corals per 100 m of line transect) and the density of recruits (on hard substrate). That is, sites/years having more corals in the category of small colonies had lower percent cover (of all corals) and lower densities of the sum of medium + large + huge colonies.

A major caveat of the above assessment is that our analysis uses data on recruitment during the past 6 years, whereas many of the larger corals included in the survey were older than 6 years, some are perhaps over 100 years old. That is, there is a temporal decoupling between the size of the population and the abundance of recruits (=small colonies). On the other hand, many of the surveyed branching corals grow in diameter by several centimeters per year, that is, move from the “small” to the “medium” size (5-15 cm) category in 1 year. Therefore, under condition of recruitment limitation, one expects a positive correlation between the number of recruits and mid-size colonies. No such correlation was found, neither with concurrent abundance (R²=0.02, NS) nor with the abundance of medium corals after a time lag of 1 year (R²=0.05, NS).

Another assumption underlying our analysis is that the abundance of recruits measured at the different sites is representative, i.e., prevailed as is relative to other sites for many years. Indeed, a surprisingly stable difference between the sites prevailed for at least 6 years (Figure 2-50b). That is, throughout that period, there have been sites that can clearly be identified as recruitment rich (for example UIU) and there are sites that are repetitively recruit-poor (e.g. NR 5 and 10).

Based on the above findings we cautiously conclude that corals in the three main reefs of Eilat are not limited by the recruitment of small colonies. Perhaps the main limiting factor for coral richness in the Eilat reefs is the survival of small and medium colonies, where density-independent factors (e.g., southerly storms, algal cover, sediment accumulation) may be the main cause of mortality. That populations of corals are not limited by recruitment is by no means unique to the reefs in Eilat, as similar findings were found in coral reefs in both the Caribbean’s (Hughes and Tanner 2000) and the...
Great Barrier Reef (Hughes et al 2000). However, no information is available to allow a similar assessment of recruitment limitation in populations of invertebrates in Eilat and Aqaba, for which the inter-annual variation in population size is substantial (Figure 2-49 g-i).

![Coral cover (on hard substrate)](image1)

![Coral abundance (medium + large + huge; on hard substrate)](image2)

**Figure 2-50a** Observed relationships between the abundance of small (<5 cm diameter) corals (“recruits”) and the total percent cover of all corals (upper panel) or the density of all other corals (mid, large and huge; lower panel) recorded in the NMP line transects in the years 2005-2010 at 3 different coral reefs sites in Eilat, 2-3 different depths per site (N=48). The negative regression in both panels is statistically significant (P<0.0001).
Figure 2-50b The dynamics in the abundance of small corals (“recruits”) at the different sites surveyed by NMP during the past six years 2005-2010. Note the long-term consistency in the difference between recruitment-rich and recruitment-poor sites (e.g., IUI-5 vs. NR-10).
2.3.4 Coral reef larvae: abundance and distribution

The objective of this chapter is to provide information on the distribution of fish and invertebrate larvae across the northern Gulf of Aqaba at different depths (in the range of 0-180 m) and in different months.

The planktonic larvae of fish and invertebrates were sampled using a Multiple Opening-Closing Net and Environmental Sensing System (MOCNESS), with a 1 m² mouth opening and equipped with a CTD, and a flow meter. Mesh sizes used were 600 µm for the fish larvae (towed at 1.7-2.3 knots) and 100 µm for the invertebrate larvae (towed at 1.4-2 knots). MOCNESS nets of 600 µm mesh-size are well within the range used for studies of fish larvae. Since plankton net tows (of all types) rarely report trapping of coral larvae (“planulae”), we experimentally tested the suitability of the 100 µm mesh net for their sampling. Several hundreds planulae were collected overnight from individual colonies of the coral *Stylophora pistillata*, using standard planulae traps (shaped like an upside-down funnel with a collecting jar at the top, positioned overnight above the coral). In the next morning, 100 planulae were separated under the microscope, transferred to a jar, taken to a boat, and inserted into a plankton net (100 µm mesh, single mouth) which was rapidly lowered to the water and towed under the same conditions (speed and duration) as our MOCNESS tows. At the end of the tow the planulae remaining in the net were collected and brought to the laboratory for microscopic screening. This experiment was repeated 2 times, with the result of both replicates showing that the planulae survived the tow with no apparent morphological damage, with some of the larvae being alive and active. Additional control tows with the MOCNESS were carried out to verify accuracy of discrete sampling (lack of “contamination” by plankton from non-targeted depths) and overall performance.

Fish larvae were collected twice a month (starting in June), whereas invertebrate larvae were sampled once a month (starting in July). For details, see Annex 1 “Larval sampling”. Each sampling expedition took 2 consecutive days. Figure 2-51 shows the sampling sites and depths. For fish larvae the upper 100 m were sampled at a resolution of 25 m, whereas the water-column between 100 and 180 m was sampled at 40 m resolution. For invertebrate larvae, the upper 180 m of the water column was divided into three layers, each 60 m wide (except the shallowest station, where the bottom depth was 50 m and the sampled layer was 0-25 m). Note that in order to minimize the risk of hitting the bottom (which could damage both the reef and the MOCNESS), an elevation threshold of 25 m was set. That is, the closest distance from the bottom in which larvae were sampled was 25 meters above bottom (25 mab).

Counts were corrected for the volume of water sampled per net, and absolute abundance estimates are presented as larvae per 1 and 1000 m³, for invertebrate and fish larvae, respectively. Invertebrate larvae were sorted into 12 taxonomic groups (Table 2-5), defined based on the certainty in their microscopic identification as larvae of benthic animals (“meroplankton”), rather than “holoplanktonic” species. Therefore, at least one group of presumably abundant larvae, that of decapod larvae (e.g., crabs), for which such separation is complex, were excluded from our counts. A comparison of the distribution and abundance between invertebrate larvae and holoplanktonic animals was made based on concurrent counts in our samples of Chaetognaths (arrow warms) - a “classical” holoplanktonic taxon.
Fish larvae were pooled in a single taxonomic group. For the MSS and NR samples, the proportion of fish larvae belonging to taxa with a benthic adult phase (i.e. coral-reef associated) was estimated using depth-specific ‘conversion factors’. These factors (‘percent benthic’) were derived in an independent study, in which larvae collected along the NR site were identified to the family level (Figure 2-52) and separated from larvae of pelagic fishes. This analysis showed ranges of 60-80% and 20-90% of larvae of benthic species in the near- and far-stations, respectively.

The microscopic sorting of plankton is a slow and laborious process. By the time this report is written, we have completed the complete sorting of invertebrate larvae from 5 months (2 from the warm season – July, August, when the water column is stably stratified, and 2-3 from the cooling period when the vertical mixing gradually deepens – November, December, and March for invertebrates, September and November for fish. The counts of invertebrate larvae from February were partly completed during the writing of this report. The sorting work continues, aiming to be completed by August 2011.

Table 2-5 The 12 taxonomic groups used for sorting the invertebrate larvae.

<table>
<thead>
<tr>
<th>Taxon</th>
<th>Common name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bivalvia</td>
<td>Mussels, clams</td>
</tr>
<tr>
<td>Gastropoda</td>
<td>Snails</td>
</tr>
<tr>
<td>Polychaeta</td>
<td>Bristled warms</td>
</tr>
<tr>
<td>Tunicata</td>
<td>Sea squirts</td>
</tr>
<tr>
<td>Holothurians</td>
<td>Sea cucumbers</td>
</tr>
<tr>
<td>Asteroidea</td>
<td>Sea stars</td>
</tr>
<tr>
<td>Echinoidea</td>
<td>Sea urchins</td>
</tr>
<tr>
<td>Ophiuridae</td>
<td>Brittle stars</td>
</tr>
<tr>
<td>Crinoids</td>
<td>Feather stars</td>
</tr>
<tr>
<td>Planulae</td>
<td>Corals and other Cnidarians</td>
</tr>
<tr>
<td>Sipunculidae</td>
<td>Round warms</td>
</tr>
<tr>
<td>Brachiopoda</td>
<td>Shelled lophorites</td>
</tr>
</tbody>
</table>
Figure 2-51 Map showing a schematic chart of the MOCNESS sampling stations of coral-reef larvae. Triplicates of full circles along full lines indicate the path of consecutive samples at different depths. For the invertebrate larvae, at stations where the bottom was deeper than 250 or 400 m the sampled layers were 180 to 120, 120 to 60, and 60 to 0 m. At intermediate stations (bottom depth of 150 m) only the two shallower layers (120-60 and 0-60) were sampled, whereas at the shallowest stations (bottom depth of 50 m) only a single layer (0 to 25 m) was sampled. Thereby, 25 m above bottom was the closest distance the MOCNESS reached to the bottom. For fish larvae the upper 100 m were sampled at a resolution of 25 m, whereas the water-column between 100 and 180 m was sampled at 40 m resolution. An additional transect was regularly carried out for fish larvae (only) at the Israeli side of the north beach (with sampling locations being a mirror image of those along the Jordanian side).
2.3.4.1 Fish larvae

Larval abundance varied considerably across the four months analyzed (Figure 2-53), but consistently peaked at depths of between 25 and 75m (Figure 2-54). To a large extend the pattern appears independent of distance from shore (bottom depth), with the two sides of the gulf close to mirroring each other. Of the total abundance within the upper 140m, only a small fraction was found in the 100 to 140m depth strata (Figure 2-55); especially in the summertime when the water column is stratified. Focusing on the upper 25m, there does not appear to be a temporally consistent cross-shore gradient in larval abundance (Figure 2-56). However, the waters closest to the shoreline do seem to contain the highest abundances.

Across the north beach, abundances of fish larvae were similar along the Jordanian (eastern) and Israeli (western) sections (Figure 2-57). Similarly, abundances of larvae along the north beach follow a similar pattern as that along the MSS and NR sites; at least in the upper depth strata (0-75m), above bottom depth of 150m (Figure 2-58).

In summary, the majority of fish larvae in the vicinity of the proposed eastern intake site appear to be concentrated in the upper 75m; certainly within the upper 100m and mostly between 25 and 75m. The similarity in this pattern between the eastern and western shorelines suggests that it is relatively free of sampling noise.
Figure 2-53 Total larval abundance (per 1000m3) in the upper 100 meters. Averages and standard deviation are based on the MSS and NR profiles over a nominal depth of 250, and the mid gulf profile (i.e. n=3 per month). Abundances are corrected for benthic taxa.
Figure 2-54 Depth profiles of the relative abundance of fish larvae for casts made over the nominal bottom-depth specified (in parenthesis) by the x-axis label. Relative abundance is the proportion of the maximum number of larvae found in the specified cast. The maximum numbers themselves (larvae per 1000m³) are provided in the legend of each plot; corresponding to the 4 months specified in the general legend.
Figure 2-55 Percent of fish larvae found between 100 and 140 m of the total in the upper 140 meters. Averages and standard deviation are based on the MSS and NR profiles obtained in the station where the bottom depth was 250 m and at the mid gulf station where the bottom depth was 400 m (i.e. N=3 profiles per month). Abundances are corrected for benthic taxa.

Figure 2-56 Cross-gulf profile of relative larval abundance within the upper 25 meters. For each month (color), relative abundance per site (x axis) was calculated as the proportion of the maximum. Maximum numbers (per 1000m³) are provided in the legend.
Figure 2-57 Larval abundances along the north beach, east and west of the border (right and left panels, respectively). The depth stratum 0-25s was sampled over bottom depth of 50 m. The remaining strata were sampled over bottom depth of 150 m.

Figure 2-58 A comparison of log transformed abundances, between samples collected in the North Beach and along the eastern and western shorelines (blank and solid symbols, respectively). Data pertains to the upper three depth strata, above bottom depth of 150 m (i.e. three points per month, per side). No correction for benthic taxa was applied to the longshore abundances.
2.3.4.2 Invertebrate larvae

Larvae of mollusks (gastropods and bivalves) were by far the most dominant group, comprising together 91% of the total larvae counted (Figure 2-59). At the other extreme, planulae (larvae of corals and other cnidarians) were extremely rare, with an average of 0.3 m$^{-3}$, comprising 0.16% of the total larvae.

Figure 2-60 shows the distribution of the total number of larvae and the 3 most abundant taxa (echinoderms, bivalves, and gastropods) at the different stations and depths. In general, a remarkable spatial and temporal similarity is observed in the abundance and depth profiles of invertebrate larvae across the northern section of the Gulf, except some unique features in the north beach. That is, the abundance of invertebrate larvae is fairly similar across the northern Gulf of Aqaba except the north beach. Noteworthy is the similarity between the near-reef waters and that in the deep waters, suggesting strong cross-shore transport and mixing (see discussion below). The distribution of invertebrate larvae in north beach, on the other hand, exhibits a seasonal deviation from that pattern (Figure 2-61): during the cooling months (November, December) abundances in the north beach are significantly higher (paired t-test, $P<0.006$) than those along the east and west coast, whereas no such difference ($P=0.53$) is observed for the summer months (July, August). This pattern is explained by the occurrence of downwelling (water sinking) during the cooling months (Monismith et al., 2006) and upward swimming against the downwelling by depth-retaining zooplankton (Genin et al., 2005). This mechanism generates immense aggregations of zooplankton along oceanic fronts (e.g., Olson and Backus 1985; Olson et al. 1994; Shanks et al., 2000) including the north beach (A. Genin unpublished data). Apparently no such accumulation of plankton is observed in the summer when the water warms up and stratification strengthens, both of which inhibiting downwelling. The abundance of larvae of fish in the north beach, on the other hand, was similar to that along the west and east coast in all seasons (Figure 2-58).

A key pattern, most relevant to the question of the depth of the RDC intake, is the depth distribution of larvae. Both fish (Figure 2-53- Figure 2-55) and invertebrate larvae (Figure 2-62, Figure 2-63) exhibit a remarkable decline in abundance below the photic layer (> 120 m depth). During summer, only 7% of the total invertebrate larvae were found below 120 m depth, while during winter that average was 20%. This seasonal difference can be explained in terms of vertical mixing. The depth of the mixed layer (measured monthly by NMP and a concurrent study; results not shown), indicate vertical mixing depths of 102, 169 and 244 m on November 23$^{th}$, December 19$^{th}$, and February 14$^{th}$, respectively. Vertical mixing homogenizes the vertical distribution of small, weakly swimming plankters (Farstey et al., 2002), resulting in an extension of their vertical distribution to depths below the photic layer (which is 90±20 m depth in the northern Gulf of Aqaba). This extension to depths below the normal boundary, may be a result of direct, passive mixing of the animals themselves (by the physical mixing) or due to their tracking of their phytoplanktonic food, which, by itself, is passively mixed, or both.

As corals are a focal group in this study, noteworthy is our observation on the abundance of their larvae (planulae). Figure 2-64 shows the average abundance of planulae at different depths in August, the only month (of those for which the sample sorting has so far been completed) in which the average abundance of planulae exceeded 0.5 m$^{-3}$. No single planulae was observed in the samples taken in December, February and March, while their average density in July, August, and November was 0.13, 0.79, and 0.07 per m$^{-3}$, respectively. While the size and shape of the planulae sorted by us
indicated that they were coral larvae, we cannot exclude the (unlikely) possibility that some could have been the larvae of other cnidaria (e.g. hydrozoans, antipatharians). Possible explanations of the rarity of planulae in our samples are discussed below.

A pair-wise correlation analysis (Figure 2-65) between the main taxa, their total density, and "classic" holoplanktonic taxon (Chaetognaths) indicated that except bivalves all other taxa were not correlated with the holoplanktonic plankton. When the relatively uncommon Brachiopod larvae are excluded, of the 10 possible pairs of taxa, 7 were significantly correlated one with another (Pearson r>0.5; Bonferroni Probabilities P<0.0001). No significant correlation was found between Chaetognaths and the total invertebrate larvae. These findings suggest that the abundance and distribution of larvae is inherently different from that of holoplankton. Such a difference may be the outcome of different biology (feeding, behavior) and/or difference in their source location (coast vs. open water). However, these findings should be considered tentative, as a robust analysis of differences and similarities between larvae and holoplankton requires a much more elaborate analysis, especially of more holoplanktonic zooplankters (most important - copepods).
Figure 2-59 The abundance (absolute- upper panel, relative- lower panel) of different taxa of invertebrate larvae in our samples. Absolute values (upper panel) are indicated as the average (±sd) density in all the samples sorted so far (N=89). Note dominance of gastropods and bivalves and the rarity of coral planulae.
Total invertebrate larvae

Echinoderm larvae
Figure 2-60 Depth profiles of invertebrate larvae at all sampling station in all months for which the microscopic sorting has been completed, for the total larvae (upper panel), Echinoderm larvae (a group consisting larvae of sea urchins, brittle stars, sea cucumbers, sea stars and crinoids; 2nd panel from top), bivalve larvae (3rd panel from top), and gastropod larvae (lower panel). Note the uniform scale of the horizontal axes in all plots except some from the north beach.
Figure 2-61 A comparison between the abundance of invertebrate larvae at the north beach vs. their concurrent abundance along the west (NR) and east (MSS) coasts. A key feature observed in this plot is that during the cooling months (November, December; full blue circles) abundances in the north beach are significantly higher (paired t-test, P<0.006) than those along the east and west coast (that is, most of the points are above the Y=X line). No such difference (P=0.53) is observed for the summer months (July, August; empty red triangles).
Figure 2-62 Average (±sd) density of invertebrate larvae (color coded for total, gastropods, bivalves and echinoderms) at the three depth layers during the winter months (November, December, February; upper panel) and summer (July, August; lower panel). Note the decline with depth which is especially steep during the summer (see next figure).
Winter (mixing water column)

43%

37%

20%

Summer (startified water)

47%

46%

7%

Figure 2-63 The relative abundance (%) of total invertebrate larvae during the winter (upper panel) and summer (lower panel), based on abundances presented in Figure 1.3.4.11. Note that during the summer only 7% of the total larvae are found below 120 m depth, with a higher value (20%) observed in the winter.
Figure 2-64 The abundance of coral planulae at the three depth ranges sampled during the month of August 2010. Note the very low abundance of planulae (Y axis) and their sharp decline below the photic depth. August was the only month (of those in which the samples have so far been sorted) in which the average abundance of planulae exceeded 0.5 m⁻³ (see text). No single planula was observed in the samples taken in February and March. While the size and shape of the planulae sorted by us indicated that they were coral larvae, we cannot exclude the unlikely possibility that some could have been the larvae of other cnidaria (e.g. hydrozoans, antipatharians).
Figure 2-65 Matrix of pair-wise Pearson correlation between the main taxa of invertebrate groups, their total density, and a “classic” holoplanktonic taxon (Chaetognaths). Pairs indicated with a red asterisk indicate a significant correlation (Pearson r>0.5; Bonferroni Probabilities P<0.0001).

2.3.5 Genetic connectivity

Considering the limited extension of coral reefs in the most Northern tip of the Gulf, the foremost expected impact of RDSC project (except of possible major pollution events associated with the construction and/or the RDSC operation) is on larval supply and recruitment of coral reef species by affecting the connectivity among the Israeli and Jordanian reefs. The lifecycles of most coral reef species consist of a benthic, adult stage and a pelagic, larval stage. It is during the latter that dispersal is achieved. Moreover, it is the ‘recruitment’ of larvae back to the reef, which is largely responsible for defining the demographic dynamics of adult populations and structuring their communities. Thus, changes in dispersal routes would quickly cascade to the reef state.
Our preliminary observations suggest the existing of biological connectivity in the shallow-water marine assemblages. Circumstantial evidence for such possible connectivity may be seen by reappearance of several species, which had disappeared from Eilat's nature reserve area, on artificial objects in the northern tip of the gulf. Another support for connectivity is provided by Maier et al. (2005), suggesting that the coral nature reserve in Eilat is connected to southern reefs in the Sinai Peninsula. A population genetic study on the soft coral *Heteroxenia fuscescens*, a common shallow-reef brooding species in the Red Sea (Fucks et al., 2006), further revealed, by means of amplified fragment length polymorphism markers, no genetic structuring characteristic to a specific location, indicating extensive gene flow among specimens inhabiting the northern Gulf. A study on fish otoliths has also suggested that the northern tip of the Gulf forms a conduit for larvae that settle along the Eilat reefs after having passed along the Jordanian side (Ben-Tzvi et al., 2008).

It seems prudent, therefore, to consider the implications of any anthropogenic activity along the Gulf's tip that stands to affect the hydrology of these passageways. However, it is difficult to create from ocean current trajectories (usually mean trajectories) and larval duration a generalized framework to characterize larval dispersal because of the variability (between years, within a single year) of environmental situations and larval behaviors, becoming to be known at least as important as oceanography processes in determining population genetics of marine organisms. Various recent studies (in the Caribbean, Indonesia, etc.) have further indicated that larval dispersal can be more complicated than physical parameters. Many fish larvae, for example, actually recruit back to their natal reefs despite their ability to disperse. Recently, molecular genetics tools have contributed significantly to understanding larval dispersal and connectivity because dispersal patterns can be inferred by comparing patterns of genetic similarity between populations. As we have yet no clear evidence for the real existence of east-west, north-south types of connectivity trajectories (or their combinations) in the Gulf of Eilat/Aqaba, this study suggests that molecular biology tools, when performed adequately, may serve as the best tool for elucidating the net products of gene transfer directionalities between the northern Gulf populations, providing documentation for the prevailing type of biological connectivity in this area.

In view the above, this part of the study is focusing on the major question of biological connectivity in the northern Gulf. By using two types of molecular markers (polymorphic alleles on microsatellite loci and AFLP), this study suggests elucidating profiles of population genetics of selected reef organisms along both, Israeli and Jordanian coasts. Since developing any new set of microsatellite loci should take at least two years of work, which is unfeasible, we have used here sets of microsatellite loci that have already been developed for two important Red Sea coral species (*Pocillopora* and *Seriatopora*). We further used AFLP markers for an important reef organism residing along the Jordanian and the Israeli coasts (the coral-pest snail *Drupella*). By employing above molecular markers, we sampled DNA from organisms belonging to different populations of each selected species and elucidated their population genetics properties. These microsatellites and AFLP markers are also used to fill in the gaps in knowledge on population genetics profiles of the selected reef species in the northern Gulf of Eilat/Aqaba, providing the necessary background information for future monitoring and conservation measures.

The results of microsatellite analysis conducted on *Pocillopora damicornis*, demonstrated an absence of genetic structuring in the populations residing in the northern Gulf (Israel and Jordan) and high connectivity between the sites sampled for this study (Figure 2-66; see Annex 1 for location of sampling sites). Further analyses using clustering methodologies, each possessing a characteristic
set of allele polymorphisms on the basis of the genotyping data from microsatellite alleles have revealed that the 227 sampled individuals are divided to 11 clusters, each containing individuals from different collecting sites, showing, again, the genetic mixture of the corals' genotypes in all northern Gulf localities. Although the results of FST or clustering are informative for estimation of the genetic subdivision of coral populations between Israeli and Jordanian sites along the northern Gulf, these analyses cannot identify the direction of recruitment of coral larvae, nor are they informative about the recruitment level. Therefore, we performed an assignment test, which enables inference of the migration patterns of each colony. Population assignment test in which a sample is assigned to the population with the highest log likelihood was performed. The results showed that in total, 67% of the collected individuals in each location, possibly originated from a different location. Only Kisosky beach and Aqaba south showed high percentage of self-assignment (53% and 54% respectively). Individuals from Jordan were assigned with Israeli populations and vice versa. Pairwise population genetic distance and identity further revealed high genetic identities between sites, and very small genetic distance. These results demonstrated an absence of genetic structuring in the *Pocillopora damicornis* populations residing in the northern Gulf (Israel and Jordan) and high connectivity between the sites sampled for this study. These microsatellite-based population tests unambiguously identified only a single valid cluster in the northern Gulf populations.

![Figure 2-66 Population analysis of *Drupella cornus* Clade 43 COI sequences from Aqaba and Eilat- neighbour- joining tree for all populations.](image)

Analysis of genotypes of *Seriatopora hystrix* revealed similar results and pointed out moderate to low genetic differentiation among populations. In the same way, analysis of molecular variance showed no significant difference between Israeli and Jordanian sites, as most of the variance (98%) was accounted to the “within population factor”. Finally “distance tree” analysis indicated that all populations sampled in the study belong to a single large *Seriatopora hystrix* population residing in the northern Gulf.
The results of COI⁴ analysis conducted on Drupella cornus showed clearly, as in the two studied coral species that all North Gulf populations are closely related one to each other. Similarly, population analysis of Drupella cornus AFLP loci from Aqaba and Eilat revealed high similarities between the Israeli and Jordanian populations.

2.4 Pollution loads entering the Gulf

The coastal area of the upper Gulf of Aqaba is subject to strong anthropic pressures. The spectacular marine ecosystem and coral reef generate a massive and ever increasing demand of tourism, resulting in the non-stop construction of new touristic complexes and marinas. Moreover, as the only kingdom's seaport, the Aqaba zone offers unique development opportunities for Jordan's economy, resulting in the settling of ever growing industrial activities and in the continuous upgrade and expansion of port facilities and infrastructures, boosted by the launch, in 2001, of the Aqaba Special Economic Zone as a duty-free, low tax multi-sectoral development zone.

Several sources of contamination exist in the upper Gulf of Aqaba, acting as pollutant drivers. They generate the present pollution loads entering the sea (pressures), estimated according to the different mechanisms and paths (direct discharge; groundwater migration; atmospheric deposition etc.).

2.4.1 Distribution and characteristics of main pollution sources

Following a careful review of the relevant information available, the following main pollution sources have been identified for the upper Gulf of Aqaba:

1. The cities of Eilat and Aqaba, including the resident population and the touristic complexes located on the northern coast of GOA;

2. The peripheral touristic complexes (resorts) located far from the main cities;

3. The marinas and leisure craft traffic;

4. The industrial settlements;

5. Port activities and ship traffic;

6. Agriculture;

7. Fish farming.

Around the two main cities of Eilat and Aqaba located along the northern tip of the Gulf, residential and touristic settlements coexist in the highly populated coastal area.

The anthropic pollution generated in the area includes the domestic loads discharged with wastewaters both from private houses and touristic complexes and the diffuse urban pollution washed away

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⁴ Cytochrome Oxidase I gene
by stormwater. Moreover, some large touristic structures contribute by discharging to the gulf significant amounts of water withdrawn from the subsoil, after use for cooling in their air conditioning systems.

Both Aqaba and Eilat are served by municipal sewage systems connected to central wastewater treatment plants.

The current Eilat wastewater treatment plant, based on treatment in sand ponds and on a seasonal reservoir, was originally designed to guarantee “zero flow to the sea”: no leaks or planned percolation are allowed, and the treated effluents are recycled for direct irrigation some 40 km to the north of Eilat. Nevertheless, due to the recent tremendous growth in population, the quantity of sewage water currently surpasses the treatment and recycling facilities so that system overload has led to periodic breakdowns, resulting in untreated sewage spill to the Gulf (e.g. the event of September 2007, with an outburst of a main pipe in the sewage system, discharging about 500 cubic meters of raw sewage water into the Gulf).

As for Aqaba, the previous municipal wastewater treatment plant, also based on natural treatment in sand ponds, recently (2005) reached its full treatment capacity due to population growth. It was therefore upgraded with financial support from the U.S. Agency for International Development in order to ensure no discharge to the sea thanks to water re-use. It is not clear, though, if the rehabilitation of the existing natural plant included preventing further leakage of treated sewage into the groundwater, which was reported for the past (Bein et al., 2004).

While the whole of the domestic and touristic users located in the Eilat area are reported to be connected to the Israeli WWTP, the peripheral areas in Aqaba which are not connected to the central wastewater network are reported to be served by septic tanks, which are sealed and pumped out to tankers (ASEZA, 2008). Of course it is still possible that some (a minor part) of the domestic users, both in the Eilat and Aqaba, are neither connected to the WWTPs nor using sealed septic tanks, simply discharging their wastewater effluents to the groundwater. Anyway the lack of Kjeldahl nitrogen found in central Eilat groundwater seems to indicate that direct leakage of untreated sewage is negligible at least in that urban area (Bein et al., 2004).

As for the urban runoff, especially during the heavy rainfall events resulting in periodic floods to the cities of Eilat and Aqaba, the street dust is washed away with its load of contaminants accumulated in time during the dry weather period due to the different anthropogenic activities (mainly traffic and industry) carried out in the area. The rainwater from the urban areas is simply discharged to the main stormwater drainage channels, reaching the sea with no previous treatment to reduce urban contamination. Metal concentrations in street dust samples in Aqaba, are generally reported to be below the mean world-wide values, but nevertheless still significant (Al-Khashman, 2007).

Conversely to the touristic complexes located in the vicinities of Aqaba and Eilat city, which are served by the municipal sewage system, the ones located more to the south have local wastewater treatment plants.

According to the “zero flow to the sea” policy, the wastewaters are locally re-used after treatment, mostly for garden irrigation. However, they may act, although not proven, as a limited contamination source (Bein et al., 2004).
At present the main touristic settlements out of the city area are located in Tala Bay (Jordan) and Hof Almog (Israel). The Jordan coast, between the city of Aqaba and the Israel border, is also involved in the massive construction of luxury touristic resorts over previously inhabited areas (Saraya Aqaba resort, presently under completion and Ayla Oasis resort to be completed by 2017 in the area surrounding Saraya Aqaba).

Finally, The Marsa Zayed project needs to be recalled too, dealing with the transformation of the present area of the Aqaba main port into a $10 billion marina community that is the largest real estate project in Jordan's history.

The total design accommodation capacity of such new development projects largely exceeds the present treatment capacity of Aqaba municipal WWTP.

There are three marinas located at the northern tip of the Gulf of Aqaba/Eilat: the Eilat Marina, situated behind the beach in the Eilat hotel zone; the Aqaba Royal Yacht Club, lying on the waterfront of Aqaba and, more to the south along the Jordanian coast, the Tala Bay marina.

Moreover, more than 300 additional yacht berths are expected to be created by year 2017 along the Aqaba city waterfront with the implementation of the above mentioned Marsa Zayed project.

As wastewater collection and treatment facilities for boats and crews are reported to exist for the local marinas (at least in Eilat) and specific prohibition exists, minimum to null wastewater discharge to the gulf water is expected from leisure craft boats. Conversely, emission of contaminants to the air from the boats/yachts engines will be considered, as it can be reasonably assumed that, also due to the proximity of the exhaust pipes to the sea surface, most of the pollutants released to the air during navigation end up in the gulf waters.

Very few relevant industrial activities exist on the Israeli side of the gulf, apart from the Mekorot desalination plant, withdrawing brackish water from the subsoil, and the nearby operating salt company, both located in the area between the city of Eilat and the Israeli-Jordan border.

The main industrial settlement in the area is located on the Jordanian coast, in the vicinities of the Saudi Arabia border, and is served by port facilities.

Most of the existing industries at the site (the so called “South Zone”) are involved in the fertilizer business (Jordan Phosphate Mines Company), while the main remaining non-fertilizer related industries and facilities include the Red Sea Timber Factory, the Aqaba thermal Power Station, fueled by natural gas and by fuel oil, and East Gas Co., importing the natural gas from Egypt.

Although a dedicated wastewater treatment plant exists in the area, some leakage and leaching to the sea of liquid industrial waste from the industrial zone is deemed likely (ASEZA, 2008).

The industrial activities are planned to be expanded in the next future, involving:

- The expansion of the existing South zone: Aqaba Development Company intends to expand the already industrial district over 12 km² of vacant readily developable land, to create a bigger Industrial Estate (the ‘Southern Industrial Zone’). The area is adjacent to the site where the new Aqaba seaport will be built over the coming five to seven years. Moreover, a railway extension is about to be constructed to serve the new port and industrial area. Beside the integrated agro-
chemical/fertilizer cluster, the Southern Industrial Zone is intended to dedicate the remaining areas for heavy chemical industries, supporting industries and future industrial expansion (Jordan Investment Board: http://www.jordaninvestment.com/BusinessandInvestment/WhereToInvest/AqabaSpecialEconomicZoneASEZ/tabid/268/language/en-US/Default.aspx).

− The creation of a new industrial area: the Aqaba International Industrial Estate, covering 275 hectares, is presently under construction on a site 700 meters east of the Aqaba International Airport, offering investment opportunities for different type of activities (Aqaba Special Economic Zone Authority: http://www.aqabazone.com/index.php?q=node/527). The local infrastructures include, among the others, a storewater drainage system, flood protection drainage channels and full sanitary sewer network, connected to Aqaba municipal WWTP.

− The plan for the Kingdom’s first nuclear power plant: the Jordanian government is reported to be examining a coastal location near Aqaba for the establishment of the plant, expected to be built within eight years. (The Jordan Times: http://www.jordantimes.com/?news=12964).

Port structures exist both along the Israeli and the Jordanian coast. Port activities and ship traffic can contribute to the pollution of the upper gulf waters in many ways: through accidental release of contaminants, including oil spill, during loading and unloading operations, discharge of ballast and bilge waters, release (leaching) of toxic substances from the antifouling hull coatings, corrosion of the sacrificial anodes and finally fallout to the sea of the contaminants vehiculated by ship engine emissions.

The port facilities in the Eilat area (Israeli coast), operated by Eilat Port Company Ltd, include the North Jetty (a naval base and a ship repair facility) the South Jetty (a modern facility with cranes for handling general cargo and containers and a long quay for ship accommodation) and the Eilat Oil Terminal.

An additional cargo quay just north of the port of Eilat is 200 m long and can accommodate vessels up to 6 m draft. The port facilities include a specialized mechanical loading facility to handle bulk cargoes such as potash, salt and phosphates and serves as Israel’s southern gateway to the Far East, South Africa and Australia. Due to its peripheral location, though, to the lack of a railway connection and to the local competition of coastal tourism the ship traffic in the port is quite low.

The Eilat Oil Terminal, consisting of two jetties, forms the sea link of the Eilat-Ashkelon pipeline and is intended both for crude oil unload/load operations and for distillates load operations. The oil terminal has a storage capacity of 160'000 cubic meters of crude oil, with an additional storage facility for gas oil and fuel oil.

Along the Jordanian coast, three main ports exist: the Main Port, located close to Aqaba city; the Container Port, located some 5 km to the south, and the Industrial Port, located in the vicinities of the Saudi Arabian border, some 19 km to the south.

The industrial port consist of:

− an Oil Terminal, used for handling exports and imports of oil and oil products;

− a Timber Jetty, used in the past for the unloading of timber and livestock, but is not used extensively at the moment, as most of Jordan's timber imports come through the Main Port;
the main industrial terminal, consisting of a jetty constructed to serve the adjacent industrial complex mainly used for handling bulk fertilizer and ammonia, and chemical products.

At present an expansion of the Industrial Port is planned on an area of approximately 60 ha facing the Dirreh Bay, located between the existing port facilities and the Saudi Arabian border. The project includes the construction of a General Cargo and Ro-Ro Terminal, a Grain Terminal and a Ferry Terminal, aiming at replacing the existing Main Port of Aqaba, to be converted into a public waterfront area (Aqaba Development Corporation: http://www.adc.jo/pages.php?menu_id=37&local_type=0).

Stringent regulations exist to prevent pollution from ports and maritime activity in the study area, as the MARPOL convention recognizes the Red Sea and in particular the Gulf of Aqaba as a “special area” where the discharge into the sea of oil and oily mixtures from any oil tanker or ship of 400 DWT or more is prohibited, and any such ship is to retain on board all oil drainage, sludge, dirty ballast and tank washing waters, with discharges allowed only into accepted reception facilities. All the same the “noxious liquid substances” listed in MARPOL category X (products deemed to present a major hazard) are not to be discharged into the sea under any circumstances, including ballast water, tank washings or other residues or mixtures containing such substances. If tanks containing such substances need to be washed, the residues need to be discharged to a reception facility.

No ballast water reception facilities presently exist at the Port of Eilat, though, where only 2 small road tankers for removal of oily bilge water are located (Unishipping Israel: http://www.unishipping.co.il/eilat.html), while no operating waste reception facility at all exist for oil wastes, sewage, bilge or ballast water at the Jordan ports (ASEZA, 2008). As only clean ballast water from the segregated ballast tanks (SBT) is allowed to be discharged into the sea in the terminal area, ships entering the Port of Eilat are required to “change their ballast waters prior to arrival” (Eilat Ashkelone Pipeline co. Operations Division, 2004).

As for oil spill prevention during loading/unloading operations at port, strict safety measures and regulations exist at the Eilat Oil Terminal, while a marine pollution prevention station equipped with a marine pollution combat vessel was set up between the reef reserve and the Eilat Oil Terminal, with the capability of dealing with spills as large as a few hundred tons from large vessels.

An oil spill combat unit also exists at the Main Aqaba Port, so that according to ASEZA the main existing risk (due to its distance) in the area is related to the (unlike) possibility of leakage from the 300'000 DWT floating oil storage vessel – ‘Jerash’ at the Industrial Port (ASEZA, 2008).

About phosphate dust deposition during ship load activities, which were long considered to represent one of the major sources of nutrients to the upper Gulf, engineering improvements have been adopted since the late 90’s in the port of Eilat to limit the airborne dust (Atkinson et al, 2001). More recently the Aqaba Port Authority improved the operations in the Main Port in order to reduce the phosphate dust emissions, which in the recent past (2000-2001) had been evidenced to generate phosphate concentration in the local seabed sediments 2 orders of magnitude higher than elsewhere along the Jordanian coast (Badran and Al Zibdah, 2005). Following such improvements the previous typical dust pollution levels of 200 mg/m³ measured in the vicinities of the loading facilities are reported to have been reduced to levels less than 5 mg/m³ (Hub4: http://www.hub-4.com/news/1904/phosphate-loading-a-case-study ).
Concerning agriculture, releasing nutrients in the subsoil with irrigation, which eventually reach the Gulf waters via groundwater flow, a number of kibbutzs exist along the southern Arava valley, withdrawing irrigation water from the regional alluvial aquifer. The treated effluents of Eilat municipal WWTP are also used for crop irrigation some 40 km north of Eilat.

Finally, fish farms are no longer a major source of pollution (Atkinson et al., 2001; Israel Environmental Bulletin, January 2005) since the two commercial fish farms (floating fish cages) which used to be located close to the Jordanian-Israeli border at the northern tip of GOAE, were completely removed from the sea in 2008, after an eight years long public debate about their impact and role in the deterioration of the local coral reef ecosystem. Alternative land based solutions are now being developed. At present the main fish farming facility in the area is the inland based ARDAG mariculture facility in Eilat, producing 100-120 tons per year in a semi-closed system and discharging treated waters to the upper gulf through the Kinnet canal.

### 2.4.2 Pollution and sediment loads estimates

The pollution loads generated by the many sources identified in the above paragraph reach the sea following different paths, as reported in Table 2-6. Some loads are directly discharged with wastewater or rainwater, some leak into the subsoil and migrate to the sea with the groundwaters, some fall over the sea surface after being released into the air and some are directly released to the sea from ship and boat keels.
Table 2-6 Inventory of pollution sources, contaminant release mechanisms and discharge paths for the upper Gulf area.

<table>
<thead>
<tr>
<th>Source</th>
<th>Location</th>
<th>Mechanism</th>
<th>Path</th>
<th>Contaminants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eilat urban area</td>
<td>Northern coast</td>
<td>Spill of raw sewage from Eilat municipal system</td>
<td>Direct discharge to the sea</td>
<td>N, P, BOD₅</td>
</tr>
<tr>
<td>Aqaba urban area</td>
<td>Northern coast</td>
<td>Leakage of raw and treated sewage from Aqaba municipal system</td>
<td>Groundwater discharge through the upper unconfined shallow aquifer</td>
<td>N, P</td>
</tr>
<tr>
<td>Urban areas of Eilat and Aqaba</td>
<td>Northern coast</td>
<td>Groundwater contamination through irrigation with reclaimed wastewater</td>
<td>Groundwater discharge through the upper unconfined shallow aquifer</td>
<td>N, P</td>
</tr>
<tr>
<td>Urban traffic in Eilat and Aqaba</td>
<td>Northern coast</td>
<td>Deposition of contaminants to the ground in the urban areas</td>
<td>Urban runoff</td>
<td>P, N, BOD₅, trace metals, PAHs</td>
</tr>
<tr>
<td>Hotel cooling systems</td>
<td>Northern coast</td>
<td>Abstraction of nutrient-enriched groundwater</td>
<td>Direct discharge to the sea</td>
<td>N, P</td>
</tr>
<tr>
<td>Touristic resorts</td>
<td>Hof Almog; Tala bay</td>
<td>Groundwater contamination through irrigation with reclaimed wastewater</td>
<td>Groundwater discharge and saline submarine groundwater discharge</td>
<td>N, P</td>
</tr>
<tr>
<td>Marinas and leisure boat traffic</td>
<td>Eilat Marina; Royal Yacht Club; Tala bay Marina</td>
<td>Release of contaminants from (antifouling) boat keel paint</td>
<td>Direct release into the water at berthing place</td>
<td>Cu</td>
</tr>
<tr>
<td>Leisure boat traffic</td>
<td>Northern tip of GoA</td>
<td>Engine exhaust gas emission while in motion</td>
<td>Quick fallout over the sea water</td>
<td>Trace metals; PAHs</td>
</tr>
<tr>
<td>Eilat industries</td>
<td>Eilat</td>
<td>Discharge of treated wastewater and brine</td>
<td>Kinnet canal</td>
<td>N, P</td>
</tr>
<tr>
<td>Industrial manufacturing</td>
<td>Jordanian coast</td>
<td>Gas emission into the atmosphere</td>
<td>Fallout over the sea water</td>
<td>Trace metals</td>
</tr>
<tr>
<td>Export of fertilizers</td>
<td>Port of Eilat; Main Port of Aqaba; Southern Port area</td>
<td>Resuspension of ore dust into the air during ship loading activities</td>
<td>Deposition over the sea water in the close vicinities of the loading facilities</td>
<td>P</td>
</tr>
<tr>
<td>Ship traffic</td>
<td>Northern Gulf of Aqaba</td>
<td>Diesel engine exhaust gas emission while in motion</td>
<td>Fallout over the sea water</td>
<td>Trace metals, PAHs</td>
</tr>
<tr>
<td>Ship traffic</td>
<td>Port of Eilat; Main Port of Aqaba; Southern Port area</td>
<td>Corrosion of sacrificial anodes</td>
<td>Direct release into the water at port (and while in motion)</td>
<td>Zn</td>
</tr>
<tr>
<td>Ship traffic</td>
<td>Port of Eilat; Main Port of Aqaba; Southern Port area</td>
<td>Release of contaminants from (antifouling) ship hull coating</td>
<td>Direct release into the water at port (and while in motion)</td>
<td>Cu, Zn</td>
</tr>
<tr>
<td>Agriculture</td>
<td>Northern coast</td>
<td>Groundwater nutrient enrichment through irrigation</td>
<td>Groundwater discharge through the regional alluvial aquifer and the upper unconfined shallow aquifer</td>
<td>N, P</td>
</tr>
<tr>
<td>Fish farming (ARDAG mariculture facility)</td>
<td>Northern coast</td>
<td>Wastewater discharge from the facility</td>
<td>Direct discharge through the kinnet canal</td>
<td>N, P, BOD₅</td>
</tr>
</tbody>
</table>
The quantification of the pollution loads discharged into the upper Gulf waters from each pollution source and according to the best available data and information from ongoing and past environmental monitoring programs, is reported in Table 2-8. The table does not include the atmospheric deposition monitored in recent years (Chen et al., 2007, 2008, Table 2-7), as the related loads are estimated in terms of fluxes, which are loads per square meter.

Table 2-7 Nutrient and trace metals dry deposition fluxes to the upper Gulf of Aqaba Chen et al., 2007; Chen et al., 2008.

<table>
<thead>
<tr>
<th>Element</th>
<th>Deposition flux [mg m⁻² yr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>N⁺</td>
<td>194</td>
</tr>
<tr>
<td>P⁺</td>
<td>2.26</td>
</tr>
<tr>
<td>Al</td>
<td>342</td>
</tr>
<tr>
<td>Fe</td>
<td>216</td>
</tr>
<tr>
<td>Co</td>
<td>0.1</td>
</tr>
<tr>
<td>Mn</td>
<td>5.28</td>
</tr>
<tr>
<td>Cr</td>
<td>0.96</td>
</tr>
<tr>
<td>Cu</td>
<td>0.38</td>
</tr>
<tr>
<td>Ni</td>
<td>0.31</td>
</tr>
<tr>
<td>Zn</td>
<td>1.68</td>
</tr>
<tr>
<td>Pb</td>
<td>0.8</td>
</tr>
<tr>
<td>Cd</td>
<td>0.012</td>
</tr>
</tbody>
</table>

* Seawater soluble inorganic fraction only. The soluble inorganic nitrogen and soluble phosphate account for approximately 86% and 69% of total soluble nitrogen and total soluble phosphorus, respectively.

One of the most evident results from Table 2-8 is that the main sources for nutrient contamination in upper Gulf waters are by large the Kinnet Canal, the discharge of cooling groundwater from Le Meridien hotel and the groundwater flow at the northern tip of the Gulf. The ship ore loading operation at the ports of Eilat and Aqaba also represent one of the most relevant source of dispersion of phosphate to the sea.

Direct discharge of wastewater (including salt brine) through the Kinnet Canal concerns the Ardag fish farming facility, the NBT algae farming facility, the ISC Salt Terminal, the Mekorot desalination plant and IOLR test facility and is subject to authorization and monitoring by the Israeli Ministry for the Environment. According to the numbers provided by such Ministry, the average annual discharges of organic and nutrient loads were estimated for the period 2007-2009.

As for the future trends, the ARDAG fish farming test facility is expected to conclude the experimentations and to be stopped after year 2010. After that the nutrient loads vehiculated by the Kinnet canal are expected to reduce to about half the present ones.
Another relevant source of nitrogen and phosphorus is the direct discharge to the sea of groundwater extracted for cooling purposes (air conditioning) by touristic structures, carried out by the “Le Meridien” hotel in Eilat, as the local groundwater is contaminated with nutrients.

The load estimates reported in Table 2-8 are calculated according to the discharge rate supplied by the Israeli Ministry of the Environment for the years 2007-2009 (12.585 Mm³/yr ) and to the nutrient concentrations in groundwater for the Eilat area (11.3 mg/l N-NO₃, 0.017 mg/l P-PO₄).

Nutrient loads (mainly nitrogen) are also significantly discharged by groundwater through the regional alluvial aquifer and the upper unconfined shallow aquifer along the north coast.

The average nitrogen fluxes, both for the alluvial and for the shallow aquifer into the Gulf of Eilat were estimated in year 2004 by the Geological Survey of Israel based on the available relevant hydrogeological data and nitrogen concentration measured in groundwater in years 2002 and 2003.

Such calculations, giving an overall nitrogen load of about 6'790 kg/year, have been kindly revised and updated upon request by the Geological Survey of Israel according to more recent data from groundwater monitoring, yielding new preliminary estimates for the upper unconfined aquifer. Taking account for the previous estimate of alluvial aquifer contribution, the total annual underwater nitrogen discharge can be estimated in about 13'450 kg N/yr.

Assuming an average phosphate concentration in groundwater of 0.4 - 0.7 micromole per liter (source: Geological Survey of Israel), a total phosphorus discharge of 18 – 32 kilograms of phosphorus per year is obtained, almost negligible compared with the other sources.

Indeed, the most relevant loads of phosphorus are discharged to the sea during ship loading operations at Eilat and Aqaba ports, as calculated in year 2001 by the International Expert Team charged with the identification of the reasons for coral reef deterioration (Atkinson et al., 2001).

In that occasion the estimates were performed for the port of Eilat, based on direct sampling of dust and on the results of a plume distribution computer model, indicated that on average 3.7 grams of phosphorus were lost to the sea per ton of loaded ore. Although some further small improvement (e.g. installation of a new loading chute) was adopted at the Port of Eilat shortly after the above measurements and estimates were performed, it seemed reasonable to extend the above ratio of phosphorus lost to the sea to loaded ore to the present (year 2010) situation.

Taking account for the significant improvements recently introduced in the loading facilities at the Port of Aqaba to the aim of reducing phosphate loss to the sea, the same ratio of 3.7 grams of phosphorus per ton of loaded ore was adopted in our calculations for that port.

The resulting phosphorus loads are 1'961 kg/year for Eilat and 28'860 kg/year for Aqaba.

The direct discharge of spilled raw sewage from Eilat municipal system and from urban runoff with stormwater are other sources, though less relevant than the others described above, of nitrogen, phosphorus and BOD₅s. The urban runoff is also a source of contaminants as copper, zinc, lead and PAHs.

The nitrogen loads discharged to the sea due to the occasional failures of the Eilat municipal sewage system were calculated in year 2001 by the International Expert Team charged with the identification of the reasons for coral reef deterioration, based on the spilled volumes recorded in the period 1995-2001.
Although continuous work is being performed on the Eilat municipal sewage system to prevent further accidental spillage, the frequency of occurrence of failure events reported by the press for the recent past (3 events in year 2007) reveals that the present situation is still critical, also due to the increasing demographic trend in the area, and that the spillage problem is not likely to be definitively solved unless a thorough restructuring and upgrade of the sewage system is performed.

As long as no such intervention is performed, it is deemed reasonable to regard the pollution loads calculated in year 2001 as still representative of the present and future situation.

In absence of any direct measurement of pollutant concentration in runoff water in the study area, the loads (nutrients and micropollutants) discharged from the urban areas of Eilat and Aqaba with the stormwater were estimated according to:

− the results of the USA Nationwide Urban Runoff Program published by USEPA, providing an average estimation of the pollutant concentration in rainfall (USEPA, 1983);
− the overall yearly water runoff in the study area (runoff coefficient estimated by USEPA);
− the direct measurements for PAH performed in the same geographic area as the upper Gulf of Aqaba.

**Micropollutant** loads, especially copper and Zinc, to the Gulf waters are discharged firstly through the port activities along the Jordanian coast and secondly in the marinas from boat keels.

The direct release of copper (as antifouling agent) and zinc (hull coating and ship sacrificial anodes for the protection against corrosion) from **ship hulls at port and during navigation** were estimated considering:

− the Cu, Zn average release (\(\mu g \, cm^{-2} \, day^{-1}\)) in static conditions (in port), and when the ship is in motion, provided by the United States Environmental Protection Agency (USEPA, 2003);
− the current density requirement (A/m^2) and zinc capacity (amp.hrs kg^-1) for the zinc release from ship sacrificial anodes (Botha, 2000);
− the time of ship stay at port during unloading/loading operations and the navigation time through the gulf;
− the information supplied by ASEZA and by the private company running the port of Eilat, concerning the average annual number of cruises per ship type and to the available information concerning the respective port facilities.

Based on these information, the annual loads of copper from hull coating is estimated to be about 3695 kg/year; the annual load of zinc from hull coating and from ship sacrificial anodes is estimated to be respectively about 1465 kg/year and 12912 kg/year.

It must be stressed that, being based on the maximum ship size which can be accommodated by the berths, the total loads are likely to represent an overestimate or the actual ones. We are confident, though, that at least the order of magnitude (about 4 tons/yr of copper and 14 tons/yr of zinc as a total) has been correctly identified.

The keels of **leisure boat in the marinas** release copper and zinc from keel antifouling coatings just like the large vessels.
The total loads released in the upper GoA can be computed based on the number of boats/yachts per class of dimension hosted by the marinas in the area (Eilat Marina; Royal Yacht Club Aqaba; Tala bay Marina), assuming that the total number of hours of motion is small compared to the number of hours the boats stay in the marina and using the same release rates (USEPA, 2003) used above for the ship calculations.

As the keel wetted area depends on the boat size, and the private companies running the marinas are kind of reluctant to supply such feature, a rough estimate of the dimensional split of the boats hosted by the Eilat Marina (by far the largest in the area) has been worked out from the satellite imagery available on Google Earth and extended to the other two marinas.

Based on the above, the copper and zinc loads amounted respectively to 685kg/yr and 274 kg/yr.

Finally, micropollutant enter the Gulf also through deposition over the sea from engine exhaust gas emission of leisure boats.

It is assumed here that, given the close proximity of yachts’ and boats’ exhaust pipes to the sea surface, the trace metals and PAHs discharged with engine exhaust gas entirely fall over the sea surface shortly after the emission. The pollution emissions were estimated according to the methodology proposed by the Environmental European Agency (EEA, 2009), supplying specific emission factors (pollutant mass/ consumed fuel mass).

As the average engine type and power (HP) can be attributed (on a statistical basis) according to the boat size, the total loads discharged to the gulf waters were estimated based on the total number of boats/yachts hosted by the local marinas, per class of dimension, and on their average number of navigation hours in one year.
Table 2-8 Summary of the estimated pollution loads annually reaching the upper Gulf of Aqaba [kg/yr]. Atmospheric fluxes not included.

<table>
<thead>
<tr>
<th>Source of Pollution</th>
<th>N</th>
<th>P</th>
<th>BOD₅</th>
<th>Cu</th>
<th>Zn</th>
<th>Pb</th>
<th>Cd</th>
<th>Cr</th>
<th>Ni</th>
<th>PAHs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct discharge of spilled raw sewage from Eilat municipal system</td>
<td>880</td>
<td>110</td>
<td>6600</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct discharge through the Kinnet canal</td>
<td>9210</td>
<td>1667</td>
<td>7185</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge of urban contaminants with stormwater</td>
<td>564</td>
<td>86</td>
<td>2453</td>
<td>8.8</td>
<td>41.3</td>
<td>37.2</td>
<td></td>
<td></td>
<td></td>
<td>40.4</td>
</tr>
<tr>
<td>Groundwater discharge</td>
<td>13450</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct discharge of groundwater used for air cooling purposes</td>
<td>142210</td>
<td>214</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discharge from the periferal touristic resorts</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dispersion of phosphate to the sea during ship loading operations at port</td>
<td>30821</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct release of contaminants from ship hulls at port</td>
<td></td>
<td>3695</td>
<td>14377</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct release of contaminants from boat keels in the marinas</td>
<td></td>
<td>685</td>
<td>274</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deposition of contaminants from engine exhaust gas emission of leisure boats</td>
<td></td>
<td>2.2</td>
<td>1.3</td>
<td>0.01</td>
<td>0.07</td>
<td>0.09</td>
<td>3.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>166314</td>
<td>32923</td>
<td>16238</td>
<td>4391</td>
<td>14693.6</td>
<td>37.2</td>
<td>0.01</td>
<td>0.07</td>
<td>0.09</td>
<td>44.3</td>
</tr>
</tbody>
</table>
Finally, sediment loads reaching the upper Gulf of Aqaba with stormwater have to be considered as the coastal area of the upper Gulf of Aqaba is dotted with a number of alluvial fans composed of predominantly clastic materials deposited by infrequent but occasionally very powerful floods originating in the mountain catchments.

Although no studies have estimated the sediment load as a result from the flush floods along the Jordanian coast, long term (more than 40 years) monitoring of such phenomena have been undertaken in the small (0.6 km²) experimental drainage basin of Nahal Yahel, close to Eilat, which is a tributary of Nahal Roded (Schick and Lekach, 1993).

Moreover, sediment loads monitoring has been undertaken in a number of basins in the semiarid, arid and hyperarid Negev and Dead Sea regions, providing estimates for the mean annual sediment yield (Schwartz and Greenbaum. Extremely high sediment yield from a small arid catchment - Giv’at Hayil, northern Negev, Israel. Isr. J. Earth Sci. In press).

Taking account for these studies, a possible estimate of the annual sediment load to the sea has been proposed and reported in Table 2-9. The table reports the total sediment load vehiculated from each river catchment, the sediment fraction reaching the sea, ranging between 18 and 32% of total sediment load, and its fine fraction, creating long-lasting water turbidity at sea.

Due to the many assumptions and extrapolations forming the base for the calculation, this estimate is necessarily affected by a significant degree of uncertainty.

The different hydrological and geomorphological characteristics of the basins in fact have not been properly taken account for. This may be a significant source of inaccuracy in particular for Wadi Yutum, with its very large drainage basin extending to areas relatively far from the upper Gulf of Aqaba and involving both spatial variability of sediment load control parameters and very long routing of distant generated sediments, with an increasing probability of entrapment before reaching the sea.

We believe, nevertheless, that the above calculation may be regarded at least as a reliable estimate of the order of magnitude of the sediment loads reaching the upper gulf waters.
Table 2-9 Estimation of suspended sediment load and silt&clay component for the catchments draining in the Gulf.

<table>
<thead>
<tr>
<th>Catchment</th>
<th>Basin area [km²]</th>
<th>Mean annual sediment yield [ton km⁻² yr⁻¹]</th>
<th>Mean annual sediment load [ton x 10³ yr⁻¹]</th>
<th>Suspended sediment load [ton x 10³ yr⁻¹]</th>
<th>Silt and clay fraction of the suspended sediment load [ton x 10³ yr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nahal Roded</td>
<td>42</td>
<td>68</td>
<td>2.9</td>
<td>0.9</td>
<td>0.5</td>
</tr>
<tr>
<td>Nahal Shahmon</td>
<td>8</td>
<td>91</td>
<td>0.7</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Nahal Garof</td>
<td>3</td>
<td>108</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Nahal Shlomo</td>
<td>30*</td>
<td>72</td>
<td>2.2</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Wadi Yutum</td>
<td>1500</td>
<td>36</td>
<td>54.1</td>
<td>17.3</td>
<td>9.7</td>
</tr>
<tr>
<td>Wadi T</td>
<td>10</td>
<td>88</td>
<td>0.9</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Wadi Shalallah</td>
<td>10</td>
<td>88</td>
<td>0.9</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Wadi Jeisheik</td>
<td>9</td>
<td>89</td>
<td>0.8</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Wadi Mabruk</td>
<td>65</td>
<td>63</td>
<td>4.1</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>Wadi 9</td>
<td>28</td>
<td>73</td>
<td>2.0</td>
<td>0.7</td>
<td>0.4</td>
</tr>
<tr>
<td>Wadi 2</td>
<td>62</td>
<td>63</td>
<td>3.9</td>
<td>1.3</td>
<td>0.7</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td></td>
<td>23.3</td>
<td>13.1</td>
</tr>
</tbody>
</table>

* the extension of Nahal Shlomo Basin was roughly estimated. This is considered acceptable because the relative contribution to the overall load estimation is not so high.

2.5 Trends of environmental conditions (no abstraction scenario) and their effects on marine environment

Environmental conditions in the gulf have clearly changed over the past 20 years as shown in the previous sections. The causes of these changes have been natural and anthropogenic, local and global. It is likely that the environmental conditions in the gulf will continue to change in response to both global changes and local development and the resulting anthropogenic forcing, although it is difficult to precisely quantify the projected changes. Local development will include construction of new tourist facilities, artificial lagoons, residential buildings, industrial development, and port expansion. Each of these will be accompanied by increases in population, additional pollution loads, and other stresses on the ecosystem of the Gulf. Examples of major developments include the Ayla and Saraya projects along the northern shore, the proposed move and expansion of the port of Aqaba, the long-term plans for the “Southern Gate” of Eilat (moving the port to an artificial canal at the northern end), and the construction of additional power and water desalination facilities.
2.5.1 Physical conditions

A warming trend has already been observed in the northern GOAE. In the past 23 years (since 1988, when routine measurements were started in Eilat) the sea surface temperature has risen at a rate of 0.41°C/10 yr as shown in the upper panel of Figure 2-67. In fact the annual average of SST in 2010 was the warmest on record (since 1988). A similar warming trend has been observed in the deep water but the rate of 0.21°C/10 yr is only half that of the surface layer. Over a shorter period (since the start of the “Peace Park” program) similar trends have also been observed as shown in the upper panel of Figure 2-68. These trends are very similar to the warming observed in the central Red Sea from the ERS SST record over the last (~2°C/30 yrs; Cantin et al., 2010).

Figure 2-67 Warming trends in the temperature of the surface layer (20-40 m), upper panel, and in the deep water (below 400 m), lower panel, observed at station A in the northern GOAE over the last 23 years.
Figure 2-68 Time plots of temperature (upper panel) and salinity (lower panel) profiles at Station A, located in the deep waters near the Gulf’s center line approximately 10 km southwest of its end (bottom depth 700 m). Data are from NMP report 2010. Black dots represent the sampling depths.
In the past salinity has exhibited a clear seasonal cycle as can be seen in the lower panel of Figure 2-68. However a rather surprising and abrupt change appears to have started in the second half of 2009 with a very clear decrease in the salinity of the upper 300 m of the water column. This has already been discussed above in Section 2.1 in the context of potential changes in the water exchange through the Strait of Tiran. While it is too soon to tell if this represents a trend or a short-lived event, it clearly has implications for water quality and the ecosystem.

As far as natural or global forcing is concerned, climate change may become a significant factor (yet largely unknown). The region is a desert with no freshwater input other than the small amount of annual rainfall (<20 mm per year). Most climate projections for this region show this continuing. Topographically the gulf is an extension of the Arava Valley and surrounded by mountain ranges on both sides. This effectively channels the winds so that they blow mainly from the north-northeast more than 90% of the time. For this reason it is unlikely that the wind regime will change significantly in any of the future climate change scenarios. Thus, it is expected that the change will be felt primarily in terms of warming.

Based on the report prepared by Dr. Nick Brooks for the feasibility study consultant, the best estimate is that due to global climate change, the region of the gulf may be expected to warm by ~5 degrees by the end of the 21st century. While the rate of warming may change there is no definitive information available on this point. Therefore for the purpose of this assessment we assume that the trend is linear and that the air temperature may increase by ~1 degree over the next 20 years. This is rather similar to the observed recent trend.

A major concern is that the anticipated warming may strengthen the stratification of the gulf and subsequently reduce vertical mixing. In order to assess this possibility we ran the gulf wide model for the projected climate change of the year 2030. Historical meteorological measurements conducted at the IUI pier indicate that the warming trend of sea surface temperature reflects about 50-60% of the change in air temperature. Thus we constructed surface forcing fields for this situation by assuming that SST will warm by ~0.6 degrees over the next 20 years. The impact of the projected climate change is best illustrated by the profiles of the Brunt-Vaisala frequency which is a measure of the stratification (higher values indicate stronger stratification). Figure 2-69 shows the profiles for March at a point located in the southern part of the gulf (left panel) and in the north near Station A (right panel). The blue lines represent the model results for present conditions. The higher values above 300 m in the left panel clearly indicate that the southern part of the gulf remains stratified even in late winter. The very noticeable maximum at a depth of 20-30 m is due to the combined effects of higher surface temperature and the inflow of less saline Red Sea water in the upper layers which retains its identity since it has not yet fully mixed with the local water in the gulf. In contrast to this, in the northern part of the gulf (right panel) the values of the Brunt-Vaisala frequency above 340 m are relatively low and show very little variation with depth. This is indicative of the winter mixing which, in 2010, reached a maximum depth of ~300 m. By this point the signal of the less saline Red Sea water has disappeared. For the projected climate change scenario (red lines) the Brunt-Vaisala frequency increases at all depth. The implication of this is that the water column can be expected to be more stable in the future and the deep winter vertical mixing will be somewhat weakened.
Figure 2-69 Brunt-Vaisala frequency in the southern (left panel) and northern (right panel) gulf in March. The blue line is for present conditions (2010) and the red line is the projection for the year 2030.

Figure 2-70 As in Figure 2-69 except in August.
Figure 2-70 shows the Brunt-Vaisala frequency in August for the southern (left panel) and northern (right panel) parts of the gulf. These profiles are fairly typical for a stratified ocean in summer. The difference between the subsurface maximum (~ 40 m) and the deep water value is larger in the south indicating again that stratification is stronger here than in the north. For the climate change scenario (red lines) the most noticeable change will be a strengthening of the subsurface maximum and the associated suppression of vertical mixing.

### 2.5.2 Water quality

As reported in the above sections, trends were observed in the past years in the Gulf for some water quality parameters. Between 1999 and 2005, which coincided with the period of highest production in the fish cages (early 2000’s), there was a build-up of deep water nutrients and decline in oxygen levels both in the deep water and the surface water of the northern GOAE. This could have been a result of nutrient loading from the fish cages (Lazar and Erez, 2004; Lazar et al., 2008) or alternatively caused by changes in the frequency of deep mixing and or changes in advection through the Tiran Strait into the Gulf (Herut and Cohen, 2004). The decrease in dissolved oxygen in the deep reservoir until 2005 was accompanied by a decrease in pH, thus indicating the production of CO$_2$ due to recycling of organic matter through aerobic processes. This decrease in dissolved oxygen also became apparent in the surface layer, which could only be explained by the decrease in the deep reservoir concentration since there was no significant warming. Consistent with the decrease in deep water pH and surface dissolved oxygen, surface water pH also decreased significantly until 2005. The reduction in pH was shown to cause a reduction in the ability of coral reefs in the GOAE to calcify and maintain their CaCO$_3$ frameworks as shown by Silverman et al. (2007, 2008).

No evidences are presently available to foresee if such trends will continue in the future. In fact, from the beginning of the NMP in 2002 and until now substantial fluctuations were observed in the concentrations of oxygen, nitrate, phosphate, silicate, and chlorophyll $a$ and pH, but with no apparent trends (Figure 2-71). The annual dynamics of most of these parameters depend on the extent of vertical mixing in the winter, and mixing depth is a function of air temperature, water temperature, and stratification (as well as wind, humidity and solar radiation). Therefore, a continued warming may change the dynamics of these parameters. For example, shallower mixing due to warming, should weaken entrainment of nutrients, which, in turn, will reduce their concentration in the upper water column (the photic layer), with a concurrent increase of their concentration in the deep waters. Under that scenario, the upper part of the water column is expected to become more oligotrophic (lower concentrations of chlorophyll $a$). Furthermore, if the present decline in salinity (Figure 2-71) presents a trend (rather than a short-term event), and if it is a result of enhanced influx of Red Sea surface water (and an equivalent efflux of GOAE water to the Red Sea at greater depths above the sill at Tiran), it may decrease the influx of dissolved inorganic nutrients to GOAE; however the influx of nutrients within organic matter (plankton and POC) should increase. Which flux will be greater? The answer is yet unknown.
Figure 2-71 Dynamics of (from top panel down) oxygen, pH, nitrite and nitrate, phosphate, silicate, and chlorophyll a at Station A, located in the deep waters near the Gulf’s center line approximately 10 km southwest of its end (bottom depth 700 m). Data from NMP report 2010. Black dots represent the sampling depths.
2.5.3 Ecology

Considering the state of the coral-reefs, long-term studies indicate that the present situation is worse than it was 40-50 years ago, but the results of the NMP show that the coral-reefs in the northern Gulf of Aqaba have been in nearly stable conditions in the past 6-7 years. Coral cover, richness, and health in the reefs of Eilat have been quite stable. On the other hand, strong fluctuations are observed in the abundance of benthic invertebrates. Hence, under the assumption of no major environmental changes and disturbances, we foresee no major changes in the local coral reefs for the no abstraction scenario. Two global trends may nullify this forecast – (i) a continued sea-water warming may reach above some threshold for severe coral bleaching and/or (ii) acidification of sea water reaches below some pH threshold that can inhibit calcification by corals and other calcifying organisms in the reef. However at this stage, without apparent or explicable trends, no projections into the future are possible.

A noteworthy point regarding effect of climate change on marine environment is the absence (so far) of coral bleaching events in the GOAE, not even in 1998, when coral bleaching occurred throughout the Pacific and Indian Oceans. Therefore, under conditions of a warming world, where coral bleaching may become a major destructive cause in coral reefs, the GOAE may serve as an important refuge for corals, perhaps of global importance. However, warming does appear to have a delirious effect on coral growth as demonstrated by Cantin et al. (2010). According to their findings, the growth of heliopora coral decreased by almost 30% relative to the 1970s. Cantin et al. (2010) concluded that this reduction was caused by the warming and not ocean acidification. While, this conclusion is based on only three measurements of carbonate chemistry over the last 40 years in the central Red Sea it can be supported by the observations of total alkalinity increase over the last 22 years in the northern GOAE at station A (Fig. 2-52). Assuming that surface water is at equilibrium with atmospheric CO₂ the increase total alkalinity offsets the effect of increasing dissolved inorganic carbon and essentially maintains the concentration of CO₃⁻² at a constant level. Nonetheless, both laboratory and field observation clearly show that coral growth is strongly dependent on carbonate ion concentration. Therefore, the increase in total alkalinity could be the result of reduced coral growth following ocean acidification and not necessarily warming.
3  Description of present environmental conditions in the vicinity of the intakes

3.1  Currents from the shallow ADCP moorings

The current profiles in the vicinity of the eastern and northern intake sites were measured during summer (Aug-Sep 2010) and winter (Jan-Feb 2011) by Workhorse 600 kHz ADCPs installed on the sea bottom on a depth of about 34m.

The current measurements reveal that the current speed near the eastern intake site was slightly stronger than that near the northern intake site, with very different patterns at both sites. These data are described in greater detail in Chapter 8.3 and are only summarized here.

The average current speed and direction at the northern intake during summer and winter were 3.6 ± 0.23 cm/s; 5° ± 59.7° and 5.2 ± 0.38 cm/s; 312° ± 29.5°, respectively.

At the eastern site, the average current speed and direction during summer and winter were 4.4 ± 0.90 cm/s; 48° ± 19.9° and 5.6 ± 0.34 cm/s; 188° ± 59.1°, respectively.

The common feature of the current patterns near both sites was the presence of a current reversal, with flow parallel to the shoreline, that had an irregular periodic signal with an average of 2-4 days. In addition a difference in current direction in upper and lower water columns was observed during summer and winter. At the northern intake site, a counter-clockwise rotation in current direction profile was detected (75° at 7m – 240° at 31m in summer; 350° at 15m – 230° at 31m in winter), whereas a rapid change in current direction with depth was observed at the eastern intake site (southward in 7-11m to northward in 15-27m in summer; southward in 7-19m to westward in 21-31m in winter).

The vertical profiles of the mean currents at the two sites are shown in Figure 3-1.

The maximum current speeds in summer were 30 cm/s at 3 m and 15 cm/s near the bottom at the eastern site; 30 cm/s at 3 m and 20 cm/s near the bottom at the northern site. In winter, the maximum current speeds at the eastern site were 40 cm/s at 5 m and 30 cm/s near the bottom; 30 cm/s at 3 m and 20 cm/s near the bottom at the northern site. Thus the near bottom currents in the eastern near shore zone were stronger in winter than in summer. A comparison of the full time series at both locations is shown in Figure 3-5.

Spectral analysis of time series data of the average current speed over the overall entire coastal water columns during summer and winter at the Eastern and Northern Intake sites revealed that tidal current signals were significantly detected at the Eastern Intake compared to the absence of these signals at the Northern Intake site except for a semidiurnal signal (12.19 h) that was detected in summer. The common tidal current signals during summer and winter at the Eastern Intake site were the semidiurnal (12.19 h: principle lunar M2) and lunar or/and solar quarter-diurnal harmonics (6.10 h: M4; S4; MS4). Besides, other tidal signals of 4.06 h, 3.16 h and 2.51 h were detected only in winter at the Eastern Intake site, which is attributed to the (2MS6; 2SM6), (M8) and (M10) tidal constituents, respectively. Result of the spectral analysis are shown in Figure 3-3.

The general current pattern in both sites suggests the connectivity of water masses in coastal areas due to the current reversal that was detected during summer and winter seasons. The analysis of current records in front of the MSS and IUI support the major findings of coastal current pattern at
the Intake sites regarding the existing of the current reversal and water masses connectivity - par-
ticularly during winter- along the coastal waters (see Section 8.3).

Figure 3-1 Profiles of the average cross and long shore current [cm s⁻¹] components in
summer (upper panels) and winter (lower panels) at the northern (left panels) and eastern
(right panels) intakes. Cross shore currents are positive when directed shorewards.
Longshore currents are positive when directed clockwise at the northern intake,
counterclockwise at the eastern intake.
Figure 3-2 Cross and long shore current [cm s\(^{-1}\)] components of the raw data (10 minutes interval) at the northern (upper four panels) and eastern (lower our panels) intake sites in summer (left panels) and winter (right panels). Cross shore currents are positive when directed shorewards. Longshore currents are positive when directed clockwise at the northern intake, counterclockwise at the eastern intake.
Figure 3-3 Spectra of time series of the average current speed in over entire coastal water column in summer and winter at the northern and eastern intake sites.
3.2 Water quality

Water quality at the intake sites can be described by means of the water quality parameters recorded during 2010 in the framework of the Jordanian National Monitoring Program. The data are available for surface water (0-1 m). These data indicate that water quality of the two sites is very similar and similar to the open water values. Annual distributions of temperature, pH, particulate matter, oxygen, nutrients, and chlorophyll $a$ at the northern intake and eastern intakes sites are presented in Figure 3-4 and Figure 3-5. The results exhibit notable seasonal changes in all parameters with higher concentrations generally in winter for most parameters (accompanied by lower recorded temperature) except the pH, and particulate matter (Figure 3-4 and Figure 3-5). Particulate matter and pH showed no major time variations. Their values fluctuated mostly within the standard error of the measurements. The higher concentrations of nutrients during winter are attributed to deep water vertical mixing and perhaps cross shore mixing due to density current formation (Lazar et al., 2008). Increased nutrient levels in the photic zone enhance primary productivity resulting in higher phytoplankton abundance and increased chlorophyll $a$ concentrations (Op. Cit.). During the summer, thermal stratification of the water column results in a depletion of the inorganic nutrients in the surface layer leading to reduced phytoplankton biomass and chlorophyll $a$ levels.
Figure 3-4 Monthly average of temperature, particulate matter, pH (measured in situ) and dissolved oxygen values at the proposed north and east intake sites.

Figure 3-5 Monthly average of ammonium (NH₄⁺), nitrate (NO₃⁻), nitrite (NO₂⁻), phosphate (PO₄³⁻), silicate (SiO₂) and chlorophyll a concentrations at the proposed north and east intake sites.
### 3.3 Sediments

Field activities were carried out to investigate sedimentation rates and sediment characteristics at the two candidate sites.

Sedimentation rates were estimated using locally designed and manufactured simple sediment trap, which were moored to the sea bed at 5 and 15 m depth in the two candidate intake sites. Details on methods used are reported in Annex 1.

Surface sediment samples were collected from the two candidate intake sites by SCUBA diving. From each site, sediments cores (15 cm long) and grab samples were collected at three depths (5, 15, and 30 m). Each core was then sectioned into three sections representing the layers 0-5 cm, 5-10 cm, and 10-15 cm. The cores were analyzed for sediment physical properties (grain size analysis and mud content) and sediment chemical properties (calcium carbonate, organic carbon, ignition loss, redox potential, total phosphorus, total organic nitrogen, and heavy metals: Cr, Pb, Cu, Cd, Zn).

Results of sedimentation rates from the Northern intake site (averaged 2.6±0.6 mg.cm^-2.d^-1) were 4 times higher than those from the Eastern intake site (averaged 0.60±0.03 mg.cm^-2.d^-1). The values from deeper waters (e.g., 15 m) from both intake sites showed slightly higher rates when compared to shallow waters (e.g., 5 m) from the same site (Figure 3-6).

![Figure 3-6 Sedimentation rate (mg.cm^2.d^-1) at the Eastern and Northern intake sites along the Jordanian coast of the Gulf of Aqaba during the period May-June 2010. Bars represent the standard deviation from the mean values.](image)

The sedimentation rates from both sites are within the ranges reported along the Jordanian coast (range between 0.5 – 2.5 and average of 0.88 mg.cm^-2.d^-1). The higher values recorded at the northern intake site are expected and could be attributed to many factors including the construction and the infrastructure work that take place in the northern tip of the Gulf, as well as to the dredging and dumping activities for the establishment of the huge investment projects such as Al-Saraya, Ayla Oasis and other hotels. Tourist activities, including the continuous and intensive glass boats, skiing boats and swimming activities are other important factors, as they contribute to stirring the waters.
and to resuspending the fine sediment particles which are major components of sediments in the area of the traps.

Bottom surface sediments from different depths (5, 15, and 30 m) from the Eastern intake site showed almost similar textural composition. The most dominant fractions were the fine sand (125-180, 63-125 µm) which comprises about 53% of all sizes. The mud fraction comprises about 21% of sediment from this site (Figure 3-7). At the Northern intake site, the most dominant fractions were the medium sand (250-500, 180-250, and 125-180 µm) which comprises about 68% of all sizes. Mud fraction at these stations is low and comprises less than 5%. The differences between depths were minor (Figure 3-7).

Figure 3-7 Grain size distribution of sediment from the Eastern and Northern intake sites along the Jordanian coast of the Gulf of Aqaba. Bars represent the standard deviation from the mean values.
The process of deposition is of great importance in determining the physical characteristics of the sediments. The variations in textural properties and mud contents between the two sites could be ascribed to the variety of sediment sources, topography and their response during currents and waves, and the seasonal variability and activity of benthic infauna. The currents acting on the pre-existing sediments cause a large scale sorting into areas of gravel, sand and mud. The distribution is determined by topography and current strengths; that is, in areas of high current velocity there are areas of gravel left as lag deposits.

The sediments at the Northern intake site are homogeneous with low mud content (<5%), and rich in grains derived from land and nearby wadi (Wadi Araba). This is due to dynamic water conditions (active waves and relatively strong currents) in this terrigenous sand bottoms which leads to cleaning of sediments from very fine materials due to absence of coral reef and rock structures.

Simple and direct information about the sediment oxygenation state, which is one of the most important variables in determining the biological productivity and the trophic structure, could be obtained from the color, odor and redox potential values of the bottom sediments. Sediments from both intake sites (northern and eastern) exhibited negative redox potential values from all depths (Figure 3-8). The negative sign refers to poorer oxygenation states of the sediments.

![Figure 3-8 Redox potential (mV) of bottom surface sediment from Eastern and Northern intake sites along the Jordanian coast of the Gulf of Aqaba.](image)

Mean values for ignition loss in sediments from both sites ranged between 15-34 g kg\(^{-1}\) (Figure 3-9). The eastern intake site exhibited relatively higher values than the northern site. No significant differences can be observed between depths, and in different sections of the core (Figure 3-9). Ignition loss is indeed a simple and economic technique for estimation of total organic matter in sediment. However, ignition loss values here need to be interpreted with care.

The higher ignition loss values recorded at the Eastern intake site could be due nature of source of sediment in this site which is carbonate. Coral reef calcium carbonate sediment tends to lose weight upon ignition due to carbonate partial decomposition and conversion to calcium oxide or even being lost as carbon dioxide.
Figure 3-9 Ignition loss values (g kg\(^{-1}\)) in bottom surface sediments from different water depths (5, 15, and 30 m) and from different core sections (0-2, 2-6, and 6-10 cm) from the Eastern and Northern intake sites along the Jordanian coast of the Gulf of Aqaba. Bars represent the standard deviation from the mean values.

High calcium carbonate concentrations in the surface bottom sediment at the eastern intake site (more than 20%) were recorded (Figure 3-10). The northern intake site had considerably lower calcium carbonate concentration ranging between 5-11%, reflecting the nature of the bottom habitat. The eastern intake site is a coral reef site; while the northern site is a deposition environment and non-coraline sea grass bottom habitat. No significant differences could be noticed between depths and sections of the core (Figure 3-10).

Total phosphorus values ranged between 0.06 to 1.6 g kg\(^{-1}\) (Figure 3-10). The Eastern intake site showed significantly higher total phosphorus values (average 0.74 g kg\(^{-1}\)) compared to the Northern intake site (average 0.1 g kg\(^{-1}\)). For comparison the summary statistics of the chemical characteristics of sediment along the Jordanian coast of the GoA (Al-Rousan et al., 2006) reports average concentrations of 0.51 g kg\(^{-1}\), 0.22 g kg\(^{-1}\) and 0.33 g kg\(^{-1}\) for the Hotels area, the Marine Science Station and the Southern Industrial complex area respectively.
Figure 3-10 Calcium carbonate (wt %) and total phosphorus (g kg$^{-1}$) concentration in bottom surface sediments from different water depths (5, 15, and 30 m) and from different core sections (0-2, 2-6, and 6-10 cm) from the Eastern and Northern intake sites along the Jordanian coast of the Gulf of Aqaba. Bars represent the standard deviation from the mean values.

With respect to organic carbon (Figure 3-11), all values exhibited concentrations ranging between 1.15 to 3.15 g kg$^{-1}$. North intake site exhibited higher organic carbon concentration at 30m depth than the other stations (3.15 g kg$^{-1}$). Organic nitrogen concentrations (Figure 3-11) which refers here to Kjeldahl digestion ranged from 0.02 to 2.5 g kg$^{-1}$. The Eastern intake site exhibited the higher value averaging 1.5 g kg$^{-1}$, compared to 0.21 g kg$^{-1}$ the Northern intake site. For comparison the summary statistics of the chemical characteristics of sediment along the Jordanian coast of the GoA (Al-Rousan et al., 2006) reports average concentrations of 0.04 g kg$^{-1}$, 0.23 g kg$^{-1}$ and 0.07 g kg$^{-1}$ for the Hotels area, the Marine Science Station and the Southern Industrial complex area respectively.
Generally, bottom surface sediments at the two intake sites were quite different in some chemical properties. Sediment from the Northern intake site is terrigenous where it is admixture of both carbonate and terrigenous sediments in the Eastern intake site. The admixture sediment in this site is characterized by high CaCO₃, total phosphorus and organic nitrogen concentration as compared to terrigenous silicate sediments. Terrigenous (non-coralline) sediments in Northern intake site are composed largely of land derived materials (from surrounding rocks and alluviums) poor in CaCO₃ transported from shore and near shore area by winds, floods and waves.

The results of the heavy metal concentrations (cadmium, chromium, copper, lead and zinc) in bottom surface sediments from both intake sites are shown in Figure 3-12. Concentrations of cadmium and copper were generally low. Concentrations of lead, chromium and zinc relative to the other metals were generally high.
Values of Cu in bottom sediment are similar from both intake sites and ranging from 2 to 13 mg.kg$^{-1}$. Cd and Zn showed higher values at the Eastern intake site with average of 2.6 and 67 mg.kg$^{-1}$ compared to 0.07 to 48 mg.kg$^{-1}$ for the Northern site. However, Cr was higher at the Northern intake site (154 mg.kg$^{-1}$) compared to the Eastern intake site (91 mg.kg$^{-1}$).
Figure 3-12 Heavy metal concentrations (mg kg$^{-1}$) in bottom surface sediments from different water depths (5, 15, and 30 m) and from different core sections (0-2, 2-6, and 6-10 cm) from the Eastern and Northern intake sites along the Jordanian coast of the Gulf of Aqaba. Bars represent the standard deviation from the mean values.
The following Table 3-1 compares the average concentrations measured at the two proposed intake sites with the ones resulting from the Jordanian National Monitoring Programme for year 2009. Chrome was not included in the monitoring.

Apart from zinc (but much higher values - one order of magnitude - are reported for zinc in previous studies for the same areas monitored by the NMP) the heavy metal concentrations found in the sediments at the two proposed intake sites are not significantly different from the ones found elsewhere along the Jordanian coast.

Table 3-1 Average concentrations of heavy metals measured at the two proposed intake sites during this study and average concentrations measured at representative sites along the Jordanian coast in the frame of the National Monitoring Programme.

<table>
<thead>
<tr>
<th></th>
<th>Cd [mg kg⁻¹]</th>
<th>Pb [mg kg⁻¹]</th>
<th>Zn [mg kg⁻¹]</th>
<th>Cu [mg kg⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern intake</td>
<td>0.07</td>
<td>67</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td>Eastern intake</td>
<td>2.6</td>
<td>7.0</td>
<td>48</td>
<td>5.2</td>
</tr>
<tr>
<td>Hotels area</td>
<td>N.D.</td>
<td>2.2</td>
<td>N.D.</td>
<td>6.7</td>
</tr>
<tr>
<td>Phosphate loading berth</td>
<td>5.6</td>
<td>24.0</td>
<td>6.5*</td>
<td>10.3</td>
</tr>
<tr>
<td>Marine Science Station</td>
<td>N.D.</td>
<td>14.2</td>
<td>3.7*</td>
<td>8.0</td>
</tr>
</tbody>
</table>

The heavy minerals distribution patterns in sediments of the Gulf of Aqaba are correlated with the mineralogy of the source rock including sandstone, metamorphic and granitic rocks.

3.4 Benthic habitats

The Jordanian coast of the Gulf of Aqaba was subjected to an intense survey to assess the health of coral reefs in Jordan (Al-Horani et al., 2006). The benthic cover components were studied at three depths including the reef flat, the 8m and the 15m depths in eight sites along the Jordanian coast. It was found that hard corals distribution increase gradually from north to south and that the 15m deep transects had the highest coverage of hard corals. On the other hand, soft corals showed the highest coverage at sites where industrial activities are found. Coral death was low along the Jordanian coast. The “hotels area”, the “phosphate loading berth” and the “Tala Bay” sites had more than 40% seagrass coverage and were classified as seagrass habitats. It is generally concluded that the coral reefs in Jordan are in good condition, although pressure resulting from the fast development in the touristic, industrial and construction activities along the coast is adding to the pressure on the benthic habitats and may represent the major threats to this ecosystem in future.
Concerning the northern candidate intake site for RDC project, the site is located at the northernmost part of the Gulf (i.e. the Hotels Area). The benthic habitat is characterized by seagrass meadows and sandy bottoms. In addition to being primary producers bottom habitat, the seagrass habitat also work as biofilters for the pollutants and are important for reducing the water turbidity and decrease the influence of increased sedimentation rates. They are also important nursery ground for many fish species that live in such habitat. The sandy bottoms of less importance relative to the seagrass habitat, though it has many kinds of dwelling organisms that function in nutrient cycling and many works as biofilters and bioindicators. There are no coral reefs in the area, although some individual colonies can be found scattered in the area. Therefore no additional specific surveys have been carried out in this area.

The eastern candidate intake site is located in front of the old Thermal Power Station. Here additional survey has been carried out in the framework of Red Sea Study. Methods applied for the surveys are described in Annex 1.

The results of the surveys have shown that there are about 20%, 18% and 25% coral cover at the reef flat, 9m depth and 15m depth, respectively. This means that the area is in fact a coral reef area, although the narrow area in front of the pumps room was destroyed by dumping rocks in the past. The rocks dumped (Figure 3-14) cover an area of about 35m wide (parallel to the shoreline) and might extend to about 60m depth (exact distance was not measured due to depth limitations). The rocks are also covering the area to about 100m south to the pumps room. The detailed results of the
transects have shown that the area located north to the pumps’ room (Figure 3-14) has a very well developed coral reefs with a cover percentages of about 30% for the hard coral component. Contrary to this, the area located south of the pumps room, which was destroyed in the past by dumping rocks and rubbles in it, has much less coral cover percentages with 3%, 6% and 12% hard coral cover at the reef flat, 9m and 15m deep transects, respectively. This is of course due to the dumped rocks in the area.

Detailed results of the surveys are included in Annex 1.

Figure 3-14 Photo of the eastern intake location (the old thermal power station site) showing the pumps room (left) and underwater photo in front of the pumps room (right).

3.5 Fish Communities

Fish communities were surveyed at the northern and eastern candidate intake sites. Methods applied in the surveys and detailed results are reported in Annex 1.

Northern intake site

Dominant taxa and fish community parameters at the northern intake site have been found as follows:

*Lethrinus borbonicus* is the most abundant species on the surveyed area, followed by *Lethrinus variegatus*, *Trachurus indicus*, *Siganus rivulatus*, *Decapterus macrosoma*, *Scolopsis ghanam*, *Parupeneus forsskali* and *P. macronema*. The coral reef fish assemblages along the Jordanian coast showed completely different picture. The most abundant fish species along the Jordanian reef were *Pseudanthias squamipinnis*, *Pomacentrus tichorous*, *Chromis dimidiata*, *Dascyllus marginatus* (Khalaf and Kochzius, 2002).

In terms of relative abundance of families, the coral reef fishes along the Jordanian is dominated by Pomacentridae, followed by Anthininae (subfamily of Serranidae) and Labridae (Khalaf and Kochzius, 2002), while visual censuses of fish assemblages at the northern intake site revealed the dominance of Lethrinidae, followed by Carangidae, Mullidae, Siganidae and Nemipteridae.
The seagrass beds play a significant role in harboring juveniles of various commercial fish (e.g. Le-thrinids, Siganids and Mullids). Availability of food, shelter and protection from predators within the seagrass lattice contribute to the nursery functions of these habitats. Hence, understand well the contribution of grass beds to coastal fisheries in terms of fish distribution, species composition and spawning seasons.

Some major characteristics of fishes characterizing, inhabiting or utilizing the seagrass habitat at the northern most tip of Gulf of Aqaba are reported:

1. *Lethrinus borbonicus* (subnose emperor): It is the most abundant species in the studied area. It forms 38.56% of the total population. Fish juveniles live in schools in shallow seagrass beds. They use seagrass beds for shelter as well as for feeding. It feeds on crustaceans, mollusks and echinoderms. Size estimation of these juveniles was between 20 to 35 mm in the area. Adults are more solitary and lives at depth of about 15m or even more.

2. *Lethrinus variegates* (variegated emperor): It is the second abundant fish species. It forms 16.97% of the total population. Similar to *L. borbonicus*, this fish utilizes the sea-grass beds.

3. *Upeneus pori*: this is a common species and can only seen at the northern part of the Jordanian coast. It inhabits shallow coastal waters off sandy flats and the seagrass beds. This species lives at depth range of 1 to 20m. It feeds on benthic invertebrates.

4. *Parupeneus forsskali* (Red Sea goatfish) and *P. macronema* (longbarbel goatfish): these fish are distributed along through the Jordanian coast. Juveniles of both species live in mixed schools in seagrass beds and forms 3.67% and 3.28% of the total population, respectively within the studied area. Both fish use seagrass habitat for shelter and on the associated invertebrates for feeding. Adult fish may stay living in seagrass or may migrate to the sandy bottoms around the reefs. It feeds on a wide variety of small animals particularly crustaceans and worms.

5. *Scolopsis ghanam* (Arabian threadfin bream): this is a common species of inshore water usually found over sand flats. It forms about 4.15% of the total population in the studied area. Most of the recorded individuals of this species in the area are juveniles and with size range of 20 to 40 mm. The fish was seen hiding among the leaves of the seagrass beds and utilizes it for shelter as well as for feeding on the epiphytic invertebrates.

6. *Siganus rivulatus* (Rivulated rabbitfish) and *Siganus luridus* (Square tail rabbitfish): the two species live in schools and inhabit shallow water around sandy and seagrass meadows. They form 5.2 and 0.28% of the total population of the studied area. Most of the recorded individuals are juveniles observed to live among seagrass beds and use it for shelter and for feeding on the benthic algae.

7. *Teixeirichthys jordani* (Jordan’s damselfish): this species lives in aggregations over seagrass areas and sandy beaches. Juveniles are often found among the spines of the sea urchins in the studied area. This is the first report about its assemblages and their habitat along the Jordanian coast during a long term monitoring program carried out by the first author.
8. *Sparus aurata* (Gilt-head seabream): this is an exotic species found to inhabit the northern part of the Jordanian coast (Ayla). The individuals observed in the studied area are adults and were seen in site 3 at 9 meter deep. Individuals observed in the studied area are believed to be escaped from aquaculture plants at the Israeli side of Gulf of Aqaba.

9. *Heniochus diphreutes* (Pennantfish): this species is found in large aggregations in the water column above sandy flats or seagrass beds. In the studied area, juveniles were seen to live among the spines of the sea urchins or having shelters of solid substrates such as rocks, tires, etc..

10. *Dascyllus trimaculatus* (the Domino): this is a coral reef species found in the surveyed area. In their primary habitat, coral reef, the juveniles used to live in association with sea anemones. However, in the present studied area, it was seen hiding among the spines of the sea urchins with size range between 10 to 20 mm.

**Eastern Intake Site**

In this study 129 fish species belonging to 31 fish family have been counted from the eastern intake site. In the Jordanian waters of the Gulf of Aqaba 507 species of fish have been recorded to date, with around 51.1% of the fish species inhabit coral and boulders, 11.7% inhabits sandy bottoms and 8.3% live in sea grass meadows (Khalaf, 2004). Khalaf and Kochzius (2002) counted 198 fish species, whereas near Eilat, Rilov and Benayahu (2000) counted 142 species while in Dahab, 162 species were identified (Zajons, unpublished data). When comparing Literature data, differences between sites have to be taken with caution, because the observed species richness in a certain area is influenced by sampling intensity, and timeframe of the investigation.

*Pseudanthias squamipinnis* is the most abundant species on Jordanian coral reef and constitute (RA=25.07) of the total fish population followed by, *Paracheilinus octotaenias* (RA=16.59%) and *Nepomacentrus miryae* (RA=11.1%), *Chromis pelloura* (RA=9.54%). The 4 above mentioned species usually live in small aggregations few meters above the sea bottoms, and feeds on zooplankton (Khalaf and Disi, 1997). The most common species were *Pomacentrus trichourus*, followed by *Chae- todon paucifasciatus*, *Dascyllus marginatus*, *Thalassoma rueppellii*, *Chromis dimidiata*, *Pseudanthias squamipinnis*, *Parupeneus forsskali*, *P. Macronema*, *Amphiprion bicinctus* and *Anampses twistii*.

In terms of relative abundance, the ichthyofauna of the studied sites is dominated by the families Pomacentridae (RA=37.52%), followed by subfamily Anthiniini (RA=28.56) and Labridae (RA=21.48%), these three families’ form (RA=97.80%) of the total fish population.

The *Chromis pelloura*, which is an endemic species to the Gulf of Aqaba was only noticed at north transects at 15 m deep transects at the sandy bottom. Generally, fishes were most abundant at the 15 m transects followed by 8 m depth. The lowest number of individuals was found at the reef flat, may be because it is very difficult for some of the species to resist the unfavorable conditions exist within this area such as tides, wave action, food availability. The higher abundance in 15 m depth can be explained by the high primary productivity at this depth (Al-Najjar, 2000).

Finally, the analysis of the dominant taxa and fish community parameters revealed the following: (1) Labridae and Pomacentridae dominated the ichthyofauna in terms of species richness at all studied
sites, (2) Pomacentridae was the dominant family in terms of relative abundance, (4) abundance of fishes was higher at 15 m depth than at 8 m depth and reef flat.

**Conclusive remarks**

The fish community structure at the two candidate sites is different: the northern intake site is dominated by species inhabiting seagrass bed while the eastern intake site (Thermal Power Station) is dominated by coral reef fish species.

The analysis of the dominant taxa and fish parameters at the northern intake site revealed the following:

1) Labridae dominated the ichthyofauna in terms of species richness;
2) Economical important species such as Lethrinidae dominated the ichthyofauna in terms of relative abundance followed by Carangidae, Mullidae, and Siganidae;
3) The fish *Teixeirichthys jordani* (Jordan`s damselfish) is only present at this site;
4) The seagrass beds play significant role in harboring juveniles of various commercial fish (e.g. Lethrinids, Siganids and Mullids), and contribute to the nursery functions of these habitats;
5) This site is of importance to fishermen community.

The analysis of the dominant taxa and fish community parameters at the eastern intake site (Thermal Power Station) revealed the following:

1) Labridae dominated the ichthyofauna in terms of species richness;
2) Pomacentridae dominated the ichthyofauna in terms of relative abundance;
3) There are no endangered or threatened species at this site;
4) The number of species and number of families is almost similar to other coral reef sites along the Jordanian coast;
5) The fish *Chromis pelloura* which is an endemic species to the Gulf of Aqaba is highly abundant at the northern transect at 15m deep is of interest, but it is also reported in other sites such as Tala Bay and Phosphate Loading berth;
6) In general the northern transects host more number of individuals than middle and southern transects at all depths;
7) The sanddivers fish, *Trichonotus niki* and the peacock wrasse *Xyrichtys* sp. were observed outside the transect at the destructive area at more than 20 m depth;
8) The site is marked by a destroyed area (approximately 35-40 m) within the study site of Thermal Power Station starting from 2 m depth to more than 30m depth;
9) If this site is selected as intake point, this section might be suitable for deployment of the intake fittings material;
10) The area is considered as one of the sites for tourists.
4 Effects of RDC abstraction

Object of our study was to evaluate the effects on the environment of the Gulf of Aqaba/Eilat of abstraction of seawater ranging from 0.4 to 2 billion m$^3$/year.

The World Bank, through its Feasibility Study consultant, indicated two candidate intake sites to be considered for our study: the northern intake candidate site, located in Jordan in the immediate vicinity of the Israel/Jordan border and the eastern intake candidate site located in Jordan, close to so-called “old thermal power station”.

The approximate location for the two candidate intake sites are as follows (see Figure 4-1):

RDC EASTERN INTAKE APPROXIMATE LOCATION = 29°29’22”N - 34°59’06”E
RDC NORTHERN INTAKE APPROXIMATE LOCATION = 29°32’28”N – 34°58’40”E

Figure 4-1 Intake candidate sites approximate location (background: multibeam shaded colour bathymetry of the northern Gulf of Elat/Aqaba bathimetry map from Sade et al., 2008).
4.1 Scenarios considered for the evaluation

The scenarios to be considered for the evaluation of the RDC projects as presented, and approved, in the Best Available Data Report (and repeated in the Mid term Report) include 13 combinations of intake location, configuration, depth, and abstraction rates. For all scenarios considered, it was decided and agreed with the World Bank to include the Ayla and Saraya development projects along the north shore in Aqaba since both are already under construction. In both cases the plan is to circulate water through the respective lagoons to prevent potential problems of eutrophication. Thus neither of these projects will lead to a net abstraction of water from the northern gulf. Therefore they are both treated and a coupled sink-source pair. The inflow and outflow rates were taken as the maximum values as released by the developers. The values used were 8.5 and 3.5 m$^3$/yr for Ayla and Saraya, respectively. For comparison and assessment of the impacts it was also necessary to run a control simulation in which there was no RDC abstraction (see Section 2.1.5). Based on internal discussions and analyses of our team we added a fourteenth scenario with an eastern intake located at 200 m depth.

In addition to the RDC scenarios three cumulative abstraction scenarios including a proposed nuclear power plant and/or the Jordan Red Sea Project (JRSP) were to be considered.

Since the submission of the revised Best Available Data Report and the Midterm Report, several revisions have been made to the specifications of the cumulative scenarios. At the Donor Countries’ meeting held on 22 March 2011 in Milan, it was announced that the proposed nuclear power plant has been eliminated. Since we assume that the JRSP and the RDC northern intake are co-located, this means that the original Scenario 14 as listed in the previous reports is identical to Scenario 10 above and the original Scenario 15 is identical to Scenario 13 above. This leaves only one scenario in cumulative category, i.e., the original Scenario 16 which listed the RDC abstraction rate as 2 billion m$^3$/yr. Since then it has been agreed with the SMU and World Bank that the abstraction of the RDC eastern intake in this scenario should be reduced to 1.6 billion m$^3$/yr to give a cumulative JRSP+RDC abstraction rate of 2 billion m$^3$/yr.
Table 4-1 Modelling scenarios to be considered for the evaluation of the RDC project effects.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>Intake location</th>
<th>intake configuration</th>
<th>Intake depth</th>
<th>Height above the sea bed</th>
<th>Abstraction rate (per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONTROL</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>SCENARIO 1</td>
<td>RDC EASTERN</td>
<td>open channel</td>
<td>-</td>
<td>-</td>
<td>0.4 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 2</td>
<td>RDC EASTERN</td>
<td>open channel</td>
<td>-</td>
<td>-</td>
<td>1 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 3</td>
<td>RDC EASTERN</td>
<td>open channel</td>
<td>-</td>
<td>-</td>
<td>1.5 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 4</td>
<td>RDC EASTERN</td>
<td>open channel</td>
<td>-</td>
<td>-</td>
<td>2 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 5</td>
<td>RDC EASTERN</td>
<td>Submerged</td>
<td>- 25 m (to provide indications on preferred depth)</td>
<td>not less than 19 m</td>
<td>2 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 6</td>
<td>RDC EASTERN</td>
<td>Submerged</td>
<td>- 120 m (to provide indications on preferred depth)</td>
<td>not less than 19 m</td>
<td>2 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 7</td>
<td>RDC EASTERN</td>
<td>Submerged</td>
<td>best depth selected by the above analysis*</td>
<td>not less than 19 m</td>
<td>0.4 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 8</td>
<td>RDC EASTERN</td>
<td>submerged</td>
<td>best depth selected by the above analysis*</td>
<td>not less than 19 m</td>
<td>1 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 9</td>
<td>RDC EASTERN</td>
<td>submerged</td>
<td>best depth selected by the above analysis*</td>
<td>not less than 19 m</td>
<td>1.5 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 10</td>
<td>RDC NORTHERN</td>
<td>submerged</td>
<td>- 8 m</td>
<td>9.5 m</td>
<td>0.4 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 11</td>
<td>RDC NORTHERN</td>
<td>submerged</td>
<td>- 8 m</td>
<td>9.5 m</td>
<td>1 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 12</td>
<td>RDC NORTHERN</td>
<td>submerged</td>
<td>- 8 m</td>
<td>9.5 m</td>
<td>1.5 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 13</td>
<td>RDC NORTHERN</td>
<td>submerged</td>
<td>- 8 m</td>
<td>9.5 m</td>
<td>2 billion m$^3$</td>
</tr>
<tr>
<td>SCENARIO 14</td>
<td>RDC EASTERN</td>
<td>submerged</td>
<td>- 200 m</td>
<td>Not less than 19 m</td>
<td>2 billion m$^3$</td>
</tr>
</tbody>
</table>

*The results of the analysis of the hydrodynamic model simulations lead to the best depth selection of 120 m from the agreed scenario. However based on the latest results and the ecological analysis, which were not available at the time that the scenarios were fixed, indications are that the preferred depth of the intake should be deeper than 120 m (see par.4.4).
Table 4-2 Cumulative modelling scenarios to be considered for the evaluation of the RDC project effects.

<table>
<thead>
<tr>
<th>SCENARIO</th>
<th>RDC intake position</th>
<th>RDC abstraction rate</th>
<th>Jordan Red Sea Project abstraction rate</th>
<th>Nuclear power plant Aqaba Area abstraction rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCENARIO 15</td>
<td>EASTERN INTAKE -120 m</td>
<td>1.6 billion m³/yr</td>
<td>0.4 billion m³/yr</td>
<td>-</td>
</tr>
</tbody>
</table>

4.2 Effects on water circulation

4.2.1 Effects in the Northern Gulf

In terms of the circulation, the main topic to be addressed is what are the horizontal extent and magnitude of the local disturbance to the circulation pattern that is induced by the abstraction of water through the RDC. In order to answer this we present the following maps of the differences between the residual currents (averaged over 60 M2 tidal cycles; slightly more than 31 days) in the respective abstraction scenario and the currents in the control simulation (Section 2.1.5). All results presented here are based on the simulations with the intermediate model. However, in order to emphasize the effects of the abstraction, the maps are zoomed on the vicinity of the intake. The maps are presented for the three submerged intake scenarios using the maximum abstraction rate of 2 billion m³/yr (scenarios 5, 6 and 13 in Table 4-1). The results for lower abstraction rates and for the surface intake are summarized in Table 4-3.

We begin with Figure 4-2 which shows the horizontal extent of the effects of the abstraction on the mean currents in Scenario 5 (25 m eastern intake) at a water depth of 25 m below the surface for the month of March 2010. Figure 4-3 shows the corresponding vertical cross section of the induced current speed. Not surprisingly, the strongest impact occurs at the grid point of the intake where the maximum disturbance to the currents is 9.7 cm/s. The horizontal extent of the disturbance is limited to a radius of at most 2-3 grid points (~250-375 m). The main vertical disturbance extends less than 10-15 m above and 10-15 m below the intake depth but now a secondary maximum appears near the bottom indicating that the water is likely to be entrained from below. This near bottom disturbance may also have some implications for sediment resuspension.
Figure 4-2 Horizontal map of currents induced by abstraction for Scenario 5, March 2010.

Figure 4-3 Vertical cross section of currents induced by abstraction for Scenario 5, March 2010.
Figure 4-4 As in Figure 4-2 except for August 2010.

Figure 4-5 As in Figure 4-3 except for August 2010.
In Figure 4-6 and Figure 4-7 we show the horizontal and vertical extent of the disturbance for Scenario 6 (120 m eastern intake) for Mar 2010. As in Scenario 5, the horizontal extent of the impact at the depth of the intake is limited to within a radius ~250-300 m from the intake, although here it is elongated to the west probably due to the steep bottom slope to the east. The main vertical impact extends 20-30 m above and 20 m below the intake but its magnitude is less than half of that in Scenario 5 with a maximum of only 4.5 cm/s. The corresponding map and cross section for August are shown in Figure 4-8 and Figure 4-9, respectively.

As in the previous cases we again find that the horizontal extent of the induced currents is limited to a radius of ~250 m from the intake. A comparison of the March (Figure 4-6) and August (Figure 4-8) cases shows that in summer the disturbance is more symmetric than in winter although we do not believe that this is a significant difference. The vertical extent of the disturbance is somewhat more limited than in winter but the maximum here is 4.8 cm/s which is slightly stronger than in March.

Figure 4-6 Horizontal map of currents induced by abstraction for Scenario 6, March 2010.
Figure 4-7 Vertical cross section of currents induced by abstraction for Scenario 6, March 2010.

Figure 4-8 As in Figure 4-6 except for August 2010.
Figure 4-9 As in Figure 4-7 except for August 2010.

In Figure 4-10 we show the horizontal map of the disturbance to the current field induced by the scenario 13 (8 m northern intake) for Aug 2010. As with the east intakes, here too the impact is limited to 2-3 grid points from the intake (~250-375 m), although here the zone affected tends to be more elongated in the alongshore direction than in the eastern intakes. The vertical extent of the disturbance is restricted to a thinner layer than for the eastern intakes due to the shallower depth of the northern intake and the gentler bottom slope in this region. The maximum induced current here is 7.8 cm/s. In the nearshore zone this implies that the impacts of the abstraction may be felt over the entire vertical extent of the water column.

The March figures are very similar to those from August and therefore they are not shown here.
Figure 4-10 Horizontal map of currents induced by abstraction for Scenario 13, August 2010.

Figure 4-11 Vertical cross section of currents induced by abstraction for Scenario 13, August 2010.
The potential effects of the abstraction rate of water through the RDC are summarized in Table 4-3 where we show the maximum induced current for the different intake options. Not surprisingly there is a direct relationship between the abstraction and the impact – as the abstraction rate increases (i.e., reading down the rows in the table) so do the effects of the abstraction. We also note that the impact is usually stronger in summer since in the winter the effect is spread over a deeper layer due to winter mixing of the water column and weakening of the stratification. By using this parameter as the primary measure of the potential impact of the abstraction we can also rank the priority of the various intake options in the order from least desirable (highest impact) to most desirable (least impact): (1) 25 m east, (2) northern, (3) surface east, (4) 120 m east. This order of priority is the same for any of the abstraction rates considered. Thus from the circulation perspective, the recommended option from the scenarios considered is the 120 m submerged east intake.

Table 4-3 Maximum induced current speed due to abstraction (abstraction rate in billions m³/yr and current speeds in cm/s).

<table>
<thead>
<tr>
<th>Abstraction rate</th>
<th>Surface east</th>
<th>25 m east</th>
<th>120 m east</th>
<th>North</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4</td>
<td>1.4</td>
<td>1.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.0</td>
<td>3.1</td>
<td>3.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>1.5</td>
<td>4.9</td>
<td>5.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>2.0</td>
<td>5.8</td>
<td>6.8</td>
<td>9.7</td>
<td>11.6</td>
</tr>
</tbody>
</table>

For the 200 m intake with the maximum abstraction rate (Scenario 14), the results were similar to the 120 m intake with maximum induced current speeds of 3.5 and 5.2 cm/s in March and August, respectively. Thus based on considerations of minimizing the effects on the circulation, the deeper (120 or 200 m) are to be preferred.

### 4.2.2 Effects in the vicinity of the preferred intake location

The results of the intermediate model simulations show that the direct impact of the water abstraction on the currents is mainly localized horizontally to within ~300 m of the intake. Vertically, the disturbance typically extends 20 m above and 20 m below the intake, although during the maximum mixing in March it can be as much as 40-50 m (see for example Figure 4-7). In order to refine the assessment of the potential impacts of the abstraction a high resolution model (~25 m horizontal resolution), as described in Annex 2, was also adapted to the northern and eastern intake areas. Due to the extremely high computational demand of such a model it was not feasible to run it for the complete annual cycle. Instead, it was run for selected 10 day periods with initial and lateral boundary conditions extracted from the intermediate model. The first three days of the simulation are considered as the spin up or adjustment period. Thus results are shown which represent the averages for
the last seven days of the selected simulation. Here we present one particular example for the simulations initialized from 12 August 2010 for the 120 m eastern intake.

As with the previous figures in the section, Figure 4-12 shows the current differences between the abstraction simulation (Scenario 6) and the control run at 120 m depth in the vicinity of the intake in August. Except for the shorter time duration of the average, this is essentially a further zoom of Figure 4-8. As before, the maximum induced current speed appears at the grid point of the intake. The maximum speed is 4.5 cm/s and the disturbed zone is slightly elongated to the north. The vectors indicate that the induced flow consists mainly of a weak anticyclonic circulation around the intake. There is also a hint of a weak seaward flow in the region to the west of the intake.

![Figure 4-12 Mean current differences for 15-22 August at 120 m as simulated by the intermediate model.](image)

The corresponding results from the high resolution model are shown in Figure 4-13. The ratio of the high resolution to intermediate grids is ~ 5:1 and so the high resolution model is able to show the smaller scale details. Nevertheless the general picture is quite similar to the results provided by the intermediate model. Here too the maximum induced current speed appears at the grid point of the intake with a value of 5.3 cm/s. As in the intermediate model results, the vectors here confirm that the induced flow is mainly an anticyclonic circulation around the intake and a weaker seaward flow in the region to the west of the intake. We also note that the region affected by the induced currents is less symmetric and its horizontal extent is slightly smaller (<~ 200 m) than simulated by the interme-
diate model. Considering the differences between the resolutions of the two models, the comparison is quite good and indicates that for the purposes of the ecological and water quality assessment the intermediate model is adequate.

![Image](image.png)

**Figure 4-13** As in Figure 4-12 but from the high resolution model.

### 4.2.3 Effects at Gulf-wide scale

On the gulf-wide scale, the main concern is that the abstraction of water from the northern tip of the gulf will lead to an increase in the inflow of warmer and less saline Red Sea water through the Strait of Tiran and may thereby change the stratification of the gulf. As noted in Chapter 2, however, the proposed maximum abstraction rate is less than 0.5% of the exchange of water through the strait and therefore it is anticipated that the impact will be minimal, especially in comparison to the projected effects of climate change.

In Figure 4-14 – Figure 4-16 we show the potential impact of the abstraction at the maximum proposed flow rate on the stratification in terms of the profiles of the Brunt-Vaisala frequency\(^5\) (see discussion in Section 2.5 regarding the potential impact of climate change). The only noticeable change, although negligible, concerns the northern intake scenario and is a very weak variation in

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\(^5\) The Brunt-Vaisala frequency is a measure of the stratification: higher values indicate stronger stratification.
the stratification in the upper thermocline at a depth of 20-40 m, increasing in the southern regions and decreasing in the northern ones.

In March the effects of abstraction are not discernable due to the deep winter mixing. In any case the potential impact of the abstraction on the gulf wide scale will be overshadowed by the projected impacts of climate change (compare to Figure 2-69 and Figure 2-70).

Figure 4-14 Modelled vertical profiles of Brunt-Vaissala frequencies in the southern (left panel) and northern (right panel) regions of the GOAE in August. The blue line is for no abstraction and the red line is for the maximum abstraction rate at 25 m depth m from the eastern intake (scenario 5).
Figure 4-15 Modelled vertical profiles of Brunt-Vaissala frequencies in the southern (left panel) and northern (right panel) regions of the GOAE in August. The blue line is for no abstraction and the red line is for the maximum abstraction rate at 120 m depth m from the eastern intake (scenario 6).

Figure 4-16 Modelled vertical profiles of Brunt-Vaissala frequencies in the southern (left panel) and northern (right panel) regions of the GOAE in August. The blue line is for no abstraction and the red line is for the maximum abstraction rate from the northern intake (scenario 13).
4.2.4 Impact of selective withdrawal

In density-stratified fluids, it is well known that the withdrawal of fluid tends to be confined to a layer centered at the level of the withdrawal (Monismith and Maxworthy 1989). The process is known as selective withdrawal and has been used to manipulate reservoir water quality (Imberger and Patterson 1990). In the present case, it is worth considering whether or not the vertical extent of the flow induced by the possible RDC intakes might be of limited extent and so might avoid entraining any larvae from other depths.

To analyze this possibility, we can model the intake as a point sink (i.e. we neglect the details of the intake design) a case for which it is found experimentally that the thickness of the withdrawal layer \( \delta \) is determined by the relation

\[
\delta \approx 1.3 (Q/N)^{1/3}
\]  

(4.1)

with \( Q \) the flowrate and \( N = \left( \frac{-(d\rho/dz)}{\rho g} \right)^{1/2} \) is the buoyancy frequency (Spigel and Farrant 1984). However equation 4.1 has only been derived for linear stratifications, i.e. fluids with constant \( N \). To apply these results to the vertically variable stratification found in the Gulf of Aqaba, we applied 4.1 in modified form by noting that for layer of thickness \( \delta_e \) there is an average value of the buoyancy frequency

\[
N = \left( \frac{\Delta \rho (\delta_e)}{\rho g} \right)^{1/2} = \left( \frac{g' (\delta_e)}{\delta_e} \right)^{1/2}
\]

So that the withdrawal layer thickness equation could be written implicitly as

\[
\delta_e \approx 1.4 \left( \frac{Q^2}{g' (\delta_e)} \right)^{0.2}
\]  

(4.2)

It is reassuring that equation 4.2 is quite close to what is given as the two layer result in Wood (2001), i.e, the same functional form but with the constant equal to 1.45.

Equation 4.2 is solved by iteration using monthly density profiles measured at Station A by the Israeli NMP. For the surface and 25m intakes, we assumed that they operated at the surface and doubled the flow rate in equation 4.2 to account for the lack of a withdrawal layer above the intake. The results of these calculations are shown in Figure 4-17 (shallow intake) and Figure 4-18 (deep intake) and summarized in Figure 4-19.

The calculated withdrawal layer thicknesses suggest that for much of the year, the deepest intake will draw waters from depths of 70 m or more, whereas the upper intakes will generally be expected to draw above those depths. It also appears that selective withdrawal will be somewhat less likely in winter (e.g. January) when the surface mixed layer is quite deep.
Figure 4-17 Density profiles and withdrawal layer extent: Surface and 25m intakes. The solid line is the assumed location of the intake (10m) and the dashed line shows the bottom of the computed withdrawal layer.
Figure 4-18 Density profiles and withdrawal layer extent: 120 m intakes. The solid line is the location of the intake (120m) and the dashed lines shows the top and bottom of the computed withdrawal layer.

Figure 4-19 Monthly variation in calculated withdrawal layer boundaries. The top of the surface/25m intake layer is the free surface itself (depth=0).
4.2.5 Particle tracking – backward trajectories

In order to assess the source of water that reaches the intake we ran a series of backward (in time) trajectories for particles released from the intake. This approach is commonly used in air pollution assessments when assessing the source of air arriving at a receptor. In the case of the RDC the intake is the receptor. At each of the subsurface intakes considered, particles were released once every hour for an entire month. Each particle was tracked backward in time for 72 hr using the three-dimensional currents simulated by the intermediate model. Results are presented here for the maximum abstraction rate of 2 billion m$^3$/yr. All values shown in the following figures (Figure 4-20 - Figure 4-31) represent the percent of the total trajectory points that fall within a particular grid box of the intermediate model. Thus these figures effectively represent the distribution of the origin of water reaching the intake.

In Figure 4-20 and Figure 4-21 we show the horizontal distributions for the 25 m eastern intake for the months of March and August, respectively. Note that the horizontal distributions represent vertically integrated values. In both seasons the cloud of points is aligned mainly in the alongshore direction due to the dominance of the alongshore component of the currents. As the distance from the intake increases, the amount of water originating at a given location decreases. In March (Figure 4-20) nearly all of the water originates within a distance 2500 m from the intake, with a preference to water coming from the north. In August the area supplying water to the intake is smaller than in winter with nearly all of it originating from within a distance of less than 2000 m. Also the points are distributed more symmetrically along the shore although there is some indication of a slight preference for water originating in the south.

Figure 4-20 Horizontal distribution of the number of trajectory points falling in each grid box (expressed as percent of the total) for the 25 m eastern intake in March.
Figure 4-21 As in Figure 4-20 except for August.

Figure 4-22 and Figure 4-23 show the horizontal distribution for March and April, respectively, for the 120 m eastern intake. In general the results are similar to those for the 25 m intake in the sense that the water reaching the intake comes mainly from the alongshore direction with a clear preference for north in winter and nearly all of the water coming from within a distance of 2500-3000 m. In summer the area is once again smaller than in winter, but here there is also a clear preference for water to come from the north, unlike the shallower intake where it was more symmetric. We also note that compared to the shallow intake, there is somewhat more of a tendency to draw water from the off-shore region, most likely due to the blocking effect of the steep bottom slope.
Figure 4-22 Horizontal distribution of the number of trajectory points falling in each grid box (expressed as percent of the total) for the 120 m eastern intake in March.

Figure 4-23 As in Figure 4-22 except in August.
Figure 4-24 and Figure 4-25 show the results for March and August, respectively for the northern intake. Here too the tendency is for the water to come mainly from the alongshore direction. There is a clear seasonal preference for water to come from the area of Eilat in winter (Figure 4-24) and from the area of Aqaba in summer (Figure 4-25). The horizontal area supplying water to the intake is also smaller in summer than in winter as was seen for the eastern intakes.

Figure 4-24 Horizontal distribution of the number of trajectory points falling in each grid box (expressed as percent of the total) for the northern intake in March.

Figure 4-25 As in Figure 4-24 except in August.
In Figure 4-26 – Figure 4-31 we show the vertical distribution of the trajectory points for the three intake options (25 m east, 120 m east, northern) and for winter and summer. The values shown are radially integrated in the horizontal distance intervals of one grid box and therefore the two dimensional distribution as a function of depth and distance from the intake. The most important result from these figures is the central role of the stratification in controlling the layer from which the water reaching the respective intakes originates. In March (Figure 4-26, Figure 4-28, and Figure 4-30) the water can come from a layer with a much larger vertical extent due to the deep winter mixing of the water column. In contrast to this in summer (Figure 4-27, Figure 4-29, and Figure 4-31) the vertical extent of the layer supplying water to the intake is limited by the strong stratification. For the two shallow intakes (25 m east and northern) the water is supplied mainly by the layer extending from the surface to a depth of 40 m while for the deep intake (120 m east) the water reaching the intake originates in a 60 m thick subsurface layer extending from ~80 – 140 m. These results are consistent with the conclusion of the theoretical analysis of selective withdrawal presented in the previous section.

Figure 4-26 Vertical distribution of the number of trajectory points falling in each horizontal distance interval from the intake (expressed as percent of the total) for the 25 m eastern intake in March.
Figure 4-27 As in Figure 4-26 except for August.

Figure 4-28 Vertical distribution of the number of trajectory points falling in horizontal distance interval from the intake (expressed as percent of the total) for the 120 m eastern intake in March.
Figure 4-29 As in Figure 4-28 but for August.

Figure 4-30 Vertical distribution of the number of trajectory points falling in horizontal distance interval from the intake (expressed as percent of the total) for the northern intake in March.
4.2.6 Particle tracking – forward trajectories

The particle tracking module can also be used to assess the pathways that the larvae might follow assuming that their primary method of movement is advection by the currents. Thus neutrally buoyant particles were released at various locations and tracked for 96 hours using a Lagrangian particle tracking routine based on the three dimensional currents computed by the intermediate resolution hydrodynamic model. The particles were released along seven cross sections as indicated in the map in Figure 4-32. Each section extended outward from the coast for a distance of 1 km (eight grid points). The particles were released at each horizontal grid point (~124 km) at 5 m depth intervals from a depth of 5 m to 50 m (for deeper releases see at the end of section 4.4). In order to sample various circulation regimes, a time series was created by selecting different days from the months of March (maximum vertical mixing) and August (maximum stratification). Initial times were selected from the beginning, the second third, and the last third of each month. For each simulation, particles were release once every three hours over a period of 39 hours. Thus 9 tidal cycles were sampled for each case. Depending upon the bottom depths along the cross sections, approximately 3000 particles were released along each section for each month.

Figure 4-31 As in Figure 4-30 but for August.
A particle was considered to have been entrained into the intake if it reached the grid point of the intake and it was located within a 15 m thick layer surrounding the intake. According to the design provided by Coyne and Belliers, the vertical extent of the proposed intake is 5 m. Thus the 15 m thick layer that we specified assumes that if a particle enters to within +/- 1 intake thickness it is entrained. This is also consistent with the vertical extent of the maximum current disturbance around the intake as shown in Section 4.2.1. Results using an entrainment layer thickness of 20 m were not significantly different. The results are summarized in the Table 4-4 and Table 4-5, expressed as percent of particles from each section that are drawn into the intake. For each entry the values is the average percent removed for all three time periods in the month with the range for the individual days shown in parentheses. Results are shown for the maximum abstraction rate of 2 billion m³/yr.
### Table 4-4 Particle tracking results for March.

<table>
<thead>
<tr>
<th>Scenario/ Cross section</th>
<th># of particles</th>
<th>25 m East % removed (range)</th>
<th>120 m East % removed (range)</th>
<th>North % removed (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2808</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>2</td>
<td>2769</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>3</td>
<td>2262</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>4.2 (0-12.5)</td>
</tr>
<tr>
<td>4</td>
<td>1911</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>4.2 (0.16-8.9)</td>
</tr>
<tr>
<td>5</td>
<td>2808</td>
<td>0.32 (0-0.96)</td>
<td>0.28 (0-0.64)</td>
<td>0.50 (0-1.4)</td>
</tr>
<tr>
<td>6</td>
<td>2847</td>
<td>1.1 (0.21-1.7)</td>
<td>0.67 (0-1.3)</td>
<td>0.18 (0-0.43)</td>
</tr>
<tr>
<td>7</td>
<td>3003</td>
<td>0.53 (0-1.5)</td>
<td>0.23 (0-0.70)</td>
<td>0.23 (0-0.50)</td>
</tr>
</tbody>
</table>

### Table 4-5 Particle tracking results for August.

<table>
<thead>
<tr>
<th>Scenario/ Cross section</th>
<th># of particles</th>
<th>25 m East % removed (range)</th>
<th>120 m East % removed (range)</th>
<th>North % removed (range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2808</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>2</td>
<td>2769</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>0.11 (0-0.33)</td>
</tr>
<tr>
<td>3</td>
<td>2262</td>
<td>0.044 (0-0.13)</td>
<td>0 (0)</td>
<td>1.5 (0-3.1)</td>
</tr>
<tr>
<td>4</td>
<td>1911</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>9.1 (7.2-10.4)</td>
</tr>
<tr>
<td>5</td>
<td>2808</td>
<td>5.3 (1.7-9.6)</td>
<td>0 (0)</td>
<td>0.28 (0-0.75)</td>
</tr>
<tr>
<td>6</td>
<td>2847</td>
<td>2.2 (1.8-2.4)</td>
<td>0 (0)</td>
<td>0.11 (0-0.21)</td>
</tr>
<tr>
<td>7</td>
<td>3003</td>
<td>0.17 (0-0.4)</td>
<td>0 (0)</td>
<td>0.03 (0-0.10)</td>
</tr>
</tbody>
</table>
From the results it is clear that the largest loss of particles will occur in the immediate vicinity of the respective intake. The cross sections surrounding each intake were located ~500 m on either side of the intake and it is on the particles released from these sections that we see the largest impact. The loss of particles is typically a few percent but it can be as high as ~10-12% depending upon the circulation pattern. In general for the shallow intakes (25 m east and north) the loss in summer is larger than the loss in winter. In summer the water column is stratified so that most of the abstracted water is taken from the upper thermocline. In winter the water column is well mixed and therefore the water is abstracted from a larger volume consisting of the deep mixed layer. These results are consistent with the back trajectory simulations (Section 4.3) which indicate the region from which the water is primarily abstracted.

As noted at the beginning of this chapter, in response analysis to the results of the larval sampling that became available more recently and the resulting internal discussion of the team, we decided to run an additional scenario with an intake located at 200 m. We also run an additional set of particle tracking experiments based on these current fields. The results are presented below as part of Section 4.4.

### 4.3 Effects on water quality

#### 4.3.1 Effects of the abstraction on the water quality of the GOAE

In our assessment of the effect of abstraction on water quality at GOAE scale we were asked to consider the effects of abstraction at the site on the eastern shore of the GOAE at 25 m and 120 m depth. As discussed in detail in section 2.2 the water quality in the GOAE is mostly affected by the residence time of water in it, which in turn is affected by how strongly stratified the water column is. Therefore, increased stratification would increase the residence time of deep water in the GOAE leading to an accumulation of nutrients, which could be potentially harmful to the coral reef by triggering massive benthic algae blooms during winters with deep and prolonged convective mixing of the open sea water column. The modelling results of the different abstraction scenarios do not provide any evidence for significant changes in water column density structure (see section 4.2.3).

#### 4.3.2 Estimation of TSS and nutrients abstracted from RDC

The amount of suspended solids and nutrients abstracted through the RDC is a relevant information to understand the effects of abstraction on Red Sea ecosystems; from another point of view this information is useful to understand the quality of the brine water discharged into the Dead Sea.

In this section we consider the water quality near the eastern intake at the proposed intake depths of 25 and 120 m. The available nutrient and TSS data at the intake sites are very sparse (only surface measurements) and considering the relatively large depth range from which water is extracted at the
planned intake depths according to the backward trajectory passive tracer modelling results (see section 4.2.5) and since the horizontal distance of water from the intake being drawn is relatively large (~6 km), it was decided to use station A data, which are also relatively similar to the data from near the coast. For this analysis we calculated the monthly average nutrient levels at station A based on measurements made every month during the period 2007-2010 by the NMP (Figure 4-33 and Figure 4-34) and TSS data measured at station A on a monthly basis during 2002-2007 (Figure 4-35).

Figure 4-33 Multi annual monthly average values of nitrate levels measured at station A once a month during the period 2007-2010. The continuous line indicates the average and the shaded area represents the standard deviation of monthly measurements around the average. The dashed lines represent the theoretical range of depths from which water is extracted at the 25 m intake (red, from surface) and the 120 m intake (blue). These ranges were calculated by taking into consideration the stability of the water column (Brunt-Vaissala frequency, see section 2.5.1).
Figure 4-34 Multi annual monthly average values of phosphate levels measured at station A once a month during the period 2007-2010. The continuous line indicates the average and the shaded area represents the standard deviation of monthly measurements around the average. The dashed lines represent the theoretical range of depths from which water is extracted at the 25 m intake (red, from surface) and the 120 m intake (blue). These ranges were calculated by taking into consideration the stability of the water column (Brunt-Vaissala frequency, see section 2.5.1).
Figure 4-35 Multi annual monthly average values of TSS levels measured at station A once a month during the period 2002-2007. The continuous line indicates the average and the shaded area represents the standard deviation of monthly measurements around the average.

In order to calculate the loads of nutrients and TSS into the RDC we used the modeling results of passive tracer backward trajectories which were released at the 25 and 120 m depth intakes, as shown in Section 4.2.5. In addition to the March and August results, backward trajectories were also computed for May and November. These values were integrated for each depth level of the model to create a horizontal mean profile and used to calculate the weighted average concentration of nutrients and TSS of water arriving at the intake. These weighted averages were then averaged and considered to represent the annual average concentration of these parameters at the intake. The annual average weighted concentration of nutrients and TSS was then multiplied by the annual abstraction rate \((2 \times 10^9 \text{ m}^3/\text{yr})\) to obtain the loads into the RDC.

Thus, for the 25 m intake depth the expected annual loads of nitrate, phosphate and TSS into RDC are 12.9 T/yr, 8.2 T/yr and 10.7 kT/yr, respectively, while for the 120 m intake depth the expected annual loads of nitrate, phosphate and TSS into RDC are 19.0 T/yr, 10.4 T/yr and 10.5 kT/yr, respectively. The latter estimates contain large uncertainty due to the large variations in the nutrient levels throughout the water column annually and interannually.

Relative to the influx of nutrients through the Tiran Straits into the GOAE, the nutrient load into the RSDSC is less than 1%. Based on our current understanding of how nutrients affect the coral reefs in the GOAE this abstraction of nutrients is actually beneficial.
4.4 Effects on marine environment/coral reefs

The following section addresses the main concerns that have been identified as possible effects of the abstraction on the marine environment. For the sake of being cautious and conservative, the following discussion considers the scenario of maximum pumping rate (2 billion cubic meters per year).

a. Sea water warming

Since the northern end of the Gulf of Aqaba is close to the proposed pumping locations, the only source of water to replenish the abstracted quantity is from the south. Since the water in the south (lower latitude) is warmer, we were concerned that the RDC pumping would cause warming. If it occurs, such warming may have a major effect on the ecology of the Gulf’s open water and coral reef ecosystems through its effect on vertical mixing and stratification. As shown in the introductory section, the unusually deep mixing during winter is the key factor determining plankton and algal dynamics in the northern Gulf and, indirectly, the corals themselves (see Genin et al., 1995). However, based on the modelling results presented in Section 4.2.3 (see Figure 4-14 - Figure 4-16) the estimated effect of the abstraction on sea temperature and stratification is expected to be negligible, mostly due to the relatively large exchange of water between the Gulf and the Red Sea, which is two orders of magnitude or more larger than the proposed abstraction rate. The present and projected trends of sea water warming under the no abstraction case with projected climate change (Section 2.5) will overshadow any effects that might be expected due to the RDC pumping even at the maximum rate.

b. Change of circulation

As the general circulation is a key factor that determines the transport of key water-born commodities, such as nutrients, plankton, and larvae, abstraction-driven changes in the circulation may have far reaching effects on the ecology of the northern Gulf’s ecosystems. Based on the results presented from the intermediate model (Section 4.2.1) noticeable changes in the circulation are expected to be confined to the immediate vicinity (~300 m) of the intake. Therefore, circulation-driven ecological effects are hereafter classified under “local effects”, discussed in section (d) below. The larger scale effects of abstraction and change in circulation on coral-reef larvae are discussed in section (e) below.

c. Changes in nutrient fluxes

If pumping induces a perpetual upwelling, and the magnitude of that vertical current is substantial, it can augment eutrophication; conversely, if it induces downwelling it may reduce nutrient entrainment. Neither process is desirable, although the effects of eutrophication on the coral reef are of greater risk. However, the backward trajectory simulations presented in Section 4.2.5 indicate that the water entering the pumps during the stratified season will originate in a layer of no more than 20-30 m above and below the intake depth (Figure 4-27, Figure 4-29, and Figure 4-31). In the winter the
water enters from a thicker layer but at that time of the year the nutrient profiles are fairly uniform due to the vertical mixing. Hence no significant change in the vertical flux of nutrients is expected.

d. Local damage

We expect substantial damage to the local benthic community around the pumping facilities, especially during construction. The coral reef and/or sea grass meadows located along the path of the pipes and under the pumping hub will be sacrificed. For the eastern intake option, after construction, corals reef may be re-established on the hard artificial substrate (pipes, blocks, etc.), however, the re-established community on that substrate is expected to be different from the original, natural one (Perkol-Finkel and Benayahu, 2004, 2007; Perkol-Finkel et al., 2006). For example, in Eilat, soft corals tend to dominate raised substrates such as metal frames and pilings (Perkol-Finkel and Benayahu, 2004, 2007). For the option of North Beach intake, the sea grass meadow damaged by pipes is likely to be re-established around the pipes (but not on them) within several years.

As mentioned above, local changes in the flow may also induce perpetual changes in the benthic community structure. Enhanced flow in the 200-300 m around the pumps can augment the growth of corals and possibly other coral-reef organisms (Denison and Barns 1988; Atkinson and Bilger 1992; Atkinson et al., 1994; Lesser et al. 1994; Nakamura et al., 2003; Mass et al., 2010).

e. The effect of abstraction on coral-reef larvae

The removal of coral-reef larvae by pumping was considered a key factor to be investigated, as it can potentially disrupt the dispersal of coral reef species and break possible connectivity between coral reefs on the east and west coasts. As most benthic animals disperse via planktonic larval stage, the entrainment of larvae by the intakes may reduce the supply of larvae, possibly hindering the long-term maintenance of a stable reef community. That is, if larvae are transported along a route that crosses the abstraction site and the abstraction becomes a barrier to larval transport then, to the extent that the maintenance of a healthy reef community on one side of the Gulf depends on larval supply from the other side (hereafter “sink” and “source” sites, respectively), it (the abstraction) may put at risk the long-term maintenance of a rich community at the “sink” site. In some benthic communities, connectivity among neighbouring communities is a key “life-support” process, intensively studied under the heading of “supply-side ecology” (Underwood and Fairweather 1989; Hughes et al., 2000; and references therein).

It is because of the ecological importance of connectivity to coastal marine populations that substantial efforts were devoted in our study of the potential effects of abstraction on the coral reef larvae. The following section presents our synthesis and recommendations.

(e.1.) Minimizing the abstraction of larvae from the sea. Two types of planktonic larvae are found in the ocean: Lecithotrophic, which have a large amount of storage material and therefore do not need to feed during their planktonic stage, and planktotrophic, which have little storage and need to feed and grow prior to settlement. Members of the former type usually spend short time (hours to days) in the water column, whereas planktotrophic larvae usually spend weeks to months in the water prior to settlement. The larvae of corals (planulae) are lecitotrophic, whereas most of the other invertebrate
larvae sorted in our work are planktotrophic. Hence, for the vast majority of planktotrophic larvae, the photic depth (90 ±20 m in the Gulf), below which planktonic food is scarce (except during mixing – see below), is a lower boundary of distribution. Indeed the sub-photic layer we have sampled (180-120 m) had significantly less larvae than the photic layer, especially when the upper water column was stratified (see Figures at chapter 2.3.4). During summer less than 2% of the fish larvae sampled in the upper 140 m were collected below 100 m. Similarly, only 7% of the invertebrate larvae sampled in the upper 180 m were collected below 120 m. These percentages were higher during the months of deep mixing (November-February), with averages of 4.5% and 20%, for the fish and invertebrate larvae, respectively. As uni-cellular phytoplankton and microplankton (=the food of the larvae) are passively mixed throughout the mixed layer (Farstey et al. 2002), small larvae with weak swimming capability are expected to be passively mixed by the physical mixing. Alternatively, larvae (of all sizes) may extend their distribution throughout the mixed layer because their food is homogeneous throughout that layer.

Given the distribution of larvae along the water column it is clear that placing the intake below the photic layer should minimize the abstraction of larvae, especially during the months when the water column is stratified (April to October).

In order to minimize the risk of damage to the benthic communities and to our (very expensive) sampling gear, we avoided towing the MOCNESS closer than 25 m from the bottom. Hence, we have no information on the distribution and abundance of larvae in that near-bottom layer. Nevertheless, as ultimately planktonic larvae seek to settle on the bottom, the larvae which reach that near-bottom layer ecologically represent the most important portion of the larval pool. Many of those larvae are ready to metamorphose and settle after enduring the challenging period of planktonic stage (where survival is thought to be exceedingly low – e.g., Jackson and Strathmann, 1981), so that removing them from the benthic layer can aggravate the local damage incurred by abstraction. Pumping near the bottom should therefore be avoided.

During periods of water cooling, induced downwelling and/or downward vertical mixing lead to the accumulation of plankton (Genin et al., 2005) and larvae (Figure 2-61) in the waters off the north beach. Since the amount of larvae removed by pumping (at a given rate) is a linear function of their concentration, pumping at the eastern coast is preferred as the removal of invertebrate larvae will be lower compared with corresponding pumping at the north beach.

A noteworthy point is the rarity of planulae in our MOCNESS samples (on average 1 planula per 4.5 m³ of water), which may be due to the possibility that short time after being released, the larvae descend to the layer near the bottom (<25 m above bottom), a layer in which we had not towed the MOCNESS. Taking a cautionary approach, we recommend an avoidance of pumping in the 25 m layer above bottom. This conclusion strengthens the aforementioned recommendation to avoid near-bottom pumping based on the fact that larvae in that layer are ready to settle.

Overall, to minimize the abstraction of larvae from the sea we recommend that pumping will be done at the eastern coast, at a depth below 120-140 m (the deepest extent of the photic layer plus the thickness of the layer disturbed by the abstraction), using an intake elevated at least 25 m above bottom.
(e.2) Abstraction disruption of genetic homogeneity among the west and east populations. As described above (section 2.3.5), eastern and western samples of two coral species and one gastropod species were genetically homogenous. Results of Bayesian clustering of all individuals and particularly assignment tests (see Annex 1 for details) revealed that while cross-gulf larval trajectories are likely, the majority of biological connectivity occurs along the gulf’s coastal zones (north-south and east-west directions). However the lack of genetic structure is consistent with both our current measurements and the results of the model simulations. Cross-gulf larval movements can also add to the genetic homogeneity of the gulf. For example, direct measurements of current in the deep waters between Aqaba and Eilat (lower panel of Figure 2-24) show a prevalence of cross-gulf currents, fluctuating between Aqaba- and Eilat-ward flows with speeds of 1-2 cm/s. Under the influence of such currents it would take 3 to 7 days for a drifting larva to be transported from one side of the Gulf to the other. In previous studies, much stronger cross-gulf currents were measured using a ship-mounted ADCP (Figure 2-17 and Figure 2-18). In such cases larvae would cross the Gulf in several hours. Currents in the surface layer measured with a HF radar (Figure 2-19), as well as the associate particle trajectories (Figure 2-22 and Figure 2-23) also depict substantial cross-gulf exchanges. These direct measurements nicely match the pattern obtained from particle tracking simulations for particles released over an entire month from both sides of the gulf as shown in Figure 4-36. It is important to note that in both the direct measurements (Figure 2-17, Figure 2-19, Figure 2-22, and Figure 2-23) and the simulations (Figure 4-36) exchange of particles between the two coasts occurs throughout the length of the Gulf’s northern section. We also note that Figure 4-36 (especially the upper panel) shows some indication of a preference for alongshore trajectories, but ultimately these trajectories also lead to particle exchanges between the western and eastern coastal zones.

Hence, the abstraction of larvae at a single pumping point is unlikely to create a barrier to larval exchange (=connectivity) among populations at the two sides of the Gulf.
Figure 4-36 Simulated trajectories (96 hr long) of particles released once every 6 hrs along the eastern (top panel) and western (bottom panel) coasts at the 0-60 m depth layer in August 2010. The black segments show the position of the particle source transects.
(e.3.) Regional effects of larval abstraction.

A key question that can be addressed by particle (i.e. larva) tracking simulations is “what percent of the larvae released along the reef some distance upstream of the pumps will end up being abstracted by the pumps”? Results for particles released in the upper 50 m of the water column were already presented in Section 4.2.6. To further refine the estimates for deeper intakes, here we ran some additional particle tracking simulations using the same methodology as before except now we released particles at deeper layers and for the two deep intake scenarios (120 m and 200 m intakes). We also separately tracked the particles from the individual release depths. For the 120 m intake simulation particles were every 10 m from 60-170 m while for the 200 m intake scenarios they were released every 10 m from 170-230 m. We also limited the releases to four cross sections along the eastern shore at distances of 0.5 and 3 km north and south of the intake as shown in Figure 4-37. Table 4-6 and Table 4-7 list the results for March and August from the 120 m and the 200 m eastern intake respectively.

![Map showing the location of transects A, B, C and D (blue lines) along which simulated particles (=larvae) were released. Red X's indicates the location of the shallow and deep eastern intakes.](image-url)
Table 4-6 Percent of particles abstracted by a 120 m deep intake at the east coast from each release depth at each of sections (A,B,C, and D) shown in Fig. 4.32, in the months of August (stratified water column) and March (mixed water column). Note the generally higher abstraction when the water column is mixed, an outcome of both the tidal currents and vertical mixing (particles released in the photic layer are mixed down to the depth of intake). Overall the percent abstracted is very low, even for particles released only 500 m away from the intake (transects B and C).

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Table 4-7 Percent of particles abstracted by a 200 m deep intake at the east coast from each release depth at each of sections (A,B,C, and D) shown in Figure 4-37, in the months of August (stratified water column) and March (mixed water column). Note the generally higher abstraction when the water column is mixed, an outcome of both the tidal currents and vertical mixing (particles released in the photic layer are mixed down to the depth of intake). Overall the percent abstracted is very low, even for particles released only 500 m away from the intake (transects B and C).

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Consider the regional effect of the abstraction, with an intake depth of 120 m. Under the worst case scenario (maximum entrainment when the water column is mixed) a mere 0.18% of the larvae released within the 60-120 layer (where larvae concentration is highest) 3 km south of the intake will be removed. Of those released within the 121-170 m layer none will be removed. Given the depth distribution of larvae during mixing the total abstraction will be 0.06% of the total number of larvae reaching the site.

Even lower proportions will be abstracted if we consider the larvae released 3 km north of the intake and during the months of water column stratification (April-October).

For the 200 m intake the results are similar with the worst case being the abstraction in March from the section located 3 km north of the intake. Hence on a regional scale (kilometres) the effect on larval supply is expected to be negligible.

On a local scale (larvae released 500 m away from the intake), the worst case scenario (i.e. mixed water column) for an intake depth of 120 m amounts to the removal of 2.3% of the larvae released 500 m south of the intake, and for an intake at 200 m depth amounts to the removal of 4% of the larvae released 500 m north of the intake. While these are also small values, they must be added to other local effects (see above sub-section d).
The maximum proportion abstracted in the case of a shallow intake (25 m) is approximately twice that of the deep (120 m) scenario, especially during the season when the water column is stratified rendering the shallow intake option less desirable.

In our synthesis, we assume that larvae are passively drifting with the current. While this may be true for the vast majority of small, weakly swimming invertebrate larvae, some fish larvae can swim and orient in order to maximize their chances of reaching a suitable settling site (e.g., Paris and Cowen, 2004). Since the behaviour of larval fish is poorly known, no simulation can be of help in predicting the effects of abstraction of larvae that actively determine their location regardless of the ambient currents. Also, with time, the larvae grow and become better swimmer. Concurrently they also approach their settling place on the bottom. Therefore, for the sake of taking the more cautious approach, we recommend that the pumping will be done at 25 m above bottom at the depth of minimum fish larvae (in the 100-140 m deep layer, where 1-5% of the total fish larvae in our samples were found). This exceedingly low abundance, together with the fact that far less than 100% of the fish larvae in the region around the pump will end up in the intake, assures that such a deep pumping will likely be negligible on a regional scale.

Importantly, our synthesis of the expected effects of larval abstraction suffers from: (1) Short duration of larval sampling— one year; (2) Limited temporal (among-year) and depth resolution; (3) No larval sampling in the 25 m above bottom; (4) Simulation which are based on the assumption of passively drifting (non-behaving) larvae. Therefore, our recommendations for pump location are based on a most cautionary, conservative approach.

### 4.5 Future scenarios

#### 4.5.1 Cumulative impact of RDC and other future abstraction

The final scenario that was considered was the cumulative impact of the RDC and other planned abstractions from the gulf. The only other major abstraction that is known is the Jordan Red Sea Project (JRSP) in which it has been proposed to abstract water from the same location as the northern intake that we considered in this study. Based on the available information and the recommendation of the SMU, it was assumed that the abstraction rate of the JRSP will be 0.4 billion m$^3$/yr. It was also recommended that the total combined abstraction of the RDC and JRSP not exceed 2 billion m$^3$/yr. Thus there are potentially two cumulative scenarios that should be considered in which the JRSP abstracts 0.4 and the RDC abstracts 1.6 billion m$^3$/yr, respectively. The case in which the two intakes are co-located at the northern site is equivalent to our Scenario 13 in which a total of 2 billion m$^3$/yr are abstracted. The second case is with the JRPS abstracting 0.4 billion m$^3$/yr (from the northern intake) and the RDC abstracting 1.6 billion m$^3$/yr from the deep (120 m) eastern intake. The results are shown in Figure 4-38 - Figure 4-41 which for the induced currents at each of the two intakes (Figure 4-38, March, Figure 4-39, August, for the 120 m east RDC, and Figure 4-40, March, and Figure 4-41, August, for the JRSP). Not surprisingly, the results are very similar to the results for each individual intake considered separately (very close to Scenario 9 for the 120 m east RDC, and Scenario 10 for the JRSP). This is due to the fact that the impact of abstraction on the currents is a localized effect limited to within a few hundred meters. No specific or noticeable cumulative effects appear in this
scenario. Here the maximum induced current differences are 4.2 and 2.6 cm/s for the RDC and JRSP, respectively, in March and 3.9 and 3.2 cm/s in August. These are almost identical to the respective values for the separate scenarios as listed in Table 4-3. The main difference is that here the RDC abstraction is 7% stronger than in Scenario 9 (1.6 as compared to 1.5 billion m³/yr).

Figure 4-38 Horizontal map of currents induced by abstraction at the 120 m eastern intake for Scenario 15, March 2010.
Figure 4-39 As in Figure 4-38 except for August 2010.

Figure 4-40 Horizontal map of currents induced by abstraction at the northern intake (JRSP) for Scenario 15, March 2010.
Figure 4-41: As in Figure 4-40 except for August 2010.

4.5.2 Cumulative impact of RDC and climate change

As concluded in section 4.5.1 global warming will cause the water column in the GOAE to be more strongly stratified likely resulting in a longer deep water residence and increase of the deep water nutrient reservoir. As a result of deep convective mixing during exceptionally cold and prolonged winters nutrient rich water will be transported into the surface layer and massive macro algae blooms could be triggered causing coral mortality in coastal fringing reefs. According to the modelling results there appears to be very little to no additional affect of water abstraction to the effect of warming on the stability of the water column.

An additional water quality concern is the acidification of seawater due to increasing levels of atmospheric CO₂. Partial pressure of atmospheric CO₂ is expected to increase from a current level of 392 ppm to nearly 750 ppm by end of the 21st century according to the A2 “business as usual” scenario for CO₂ emissions (IPCC, 2007). This increase is projected to cause a decrease in oceanic pH on the order of 0.2 pH units. According to Kleypas et al. (1999) the effect of ocean acidification in Red Sea waters (including the GOAE) is expected to be the most pronounced because of its relatively high salinity/alkalinity. However, as seen in section 2.3, an increasing trend in total alkalinity as well as warming could partially buffer the increase in seawater dissolved inorganic carbon concentration resulting from the increase of atmospheric CO₂, thus reducing the effect of acidification on coral growth and other biological processes and organisms affected by it.
According to Silverman et al. (2007) community calcification rates are well correlated with degree of aragonite saturation and temperature. Thus, given a current annual average total alkalinity of 2520 $\mu$mol/kg, temperature of 23.9°C and salinity of 40.7 at atmospheric equilibrium with respect to CO$_2$, the aragonite saturation is 4.2. In 20 years the partial pressure of atmospheric CO$_2$ will be 472 ppm. Given the current warming and total alkalinity trends in 20 years both are expected to increase to 24.7°C and 2570 $\mu$mol/kg, respectively. The resulting degree of aragonite saturation will be 4.0, a reduction of only 0.2 (-5%). Using the empirical equation for community calcification developed by Silverman et al. (2007) yields a reduction in calcification rate of coral reefs of -3.5% relative to the current rate. If the alkalinity trend does not continue as suggested by the standardized measurements that have been made since 2005 then the decrease in aragonite saturation will be greater ($\Delta\Omega_{\text{arag}} = -0.34$) and the resulting decrease in calcification will be -10.8%. If the warming and alkalinity trends both don’t continue then the decrease in aragonite saturation will be even greater ($\Delta\Omega_{\text{arag}} = -0.43$) and the resulting decrease in calcification will be -20.6%. These anticipated changes in the carbonate system of the GOAE will be unaffected by the abstraction of water to the RDC.
5 Addressing best option for RDC intake

Based on the analysis and assessment of the various aspects of the RDC presented in the previous chapters, we can immediately eliminate the "no-go" options which we identify as any combination of intake configuration, location, and depth which are located within the photic zone. In the following chapter we therefore address the issue of the best option for a "go" decision.

Best option for intake configuration

The two options for intake configuration considered were an open channel at the surface and a submerged intake. While there are certainly engineering considerations that must be taken into account for either option, these are beyond the scope of our study which focuses on the environmental issues and impacts of the proposed water abstraction. In this respect there is a clear preference for a submerged intake under the assumption that it is located at an appropriate depth, as explained in the next subsection. The reasons for not recommending a surface intake are the following:

(1) Considerations concerning morphology

An open channel at the surface requires significant construction and development of infrastructure which will permanently affect the landscape.

(2) Considerations concerning water circulation

The largest disturbance of the circulation resulting from abstraction of water will occur when the intake is located in shallow water. In this respect there is little difference between a surface intake and a submerged shallow intake. The induced currents will be felt throughout the entire water column in the vicinity of the intake, and as with all options, the effects will be felt up to a few hundred meters from the intake. This may pose certain hazards to various surface operations such as boating, fishing, and recreational activities.

(3) Considerations concerning water quality

In shallow water the entire water column will be affected by the induced currents. In very shallow water around a surface intake the likelihood that the abstraction will cause resuspension of the sediments is much higher than even for a shallow submerged intake. This will lead to reduced water quality at the intake. In addition a surface intake may entrain floating or buoyant pollutants such as hydrocarbons which are not found at depth.

(4) Considerations concerning the ecosystem

A major conclusion of this study is that any intake for water abstraction should be located well below the maximum depth of the photic layer. In this respect the impact of a surface intake on the ecosystem will be similar to the impact of a shallow submerged intake and is therefore not recommended.
**Best option for intake location**

Concerning intake location, eastern candidate site is recommended for following reasons:

1. Considerations concerning morphology

   Since it is recommended to locate the intake well below the photic zone (see below), the relatively steeper bottom slope of eastern intake area versus northern intake implies that the desired depth can be achieved closer to shore.

2. Considerations concerning water circulation

   The local currents along the east shore tend to be stronger than along the north beach and therefore the disturbance caused by the abstraction would be less significant.

3. Considerations concerning water quality

   a. The proposed northern intake is located in relatively shallow water (bottom depth of 17.5 m with the intake located 9.5 m above the bottom), this characteristic, coupled with the presence of relatively fine sediments in the north, increase the likelihood that the currents induced by the abstraction will re-suspend the sediments. This may augment the damage to the local benthic community and the sea grass meadows. It could also adversely affect the invertebrate larvae population in this area. Finally, this may also lead to reduced water quality at the intake.

   b. During southerly storms, the typical wind speed is around 5 m/s. If we consider the most extreme southerly winds of 10-15 m/s, which occur at most once or twice a year (between October and May) and last for a period of 12 hours or less (meteorological data recorded at IUI station in Eilat), the estimated maximum significant wave height at the northern end of the Gulf could reach 2.6-4.3 m. These waves would break in water depth of less than 6 m and could cause some sediment resuspension in the nearshore zone. Thus wind and wave induced sediment resuspension is in general not expected to be a major factor even in the vicinity of the shallower northern intake location, except for the rare occasions when the water remains turbid for about 2-3 days after such storms (e.g., visual observations at the IUI station).

   c. After extreme events such as infrequent winter flooding some suspended sediments are introduced along the northern shore. These sediments may remain suspended in the water column for a few days (visual observations at the IUI station) and could be an issue for operation of the intake. However such events occur only once every few years.

   d. Several sources of potential contamination exist in the upper Gulf of Aqaba, close to the proposed northern intake, such as the cities of Eilat and Aqaba with their marinas, beaches and hotel areas. Untreated sewage spills to the Gulf due to failure of Eilat municipal wastewater treatment plant are not unfrequent, while emission of contaminants from the boats and yachts contribute to the depletion of local water quality. The new touristic developments of Ayla Oasis and Saraya Aqaba, presently under construction, are likely to add new potential contamination sources to the present situation. In this context the eastern intake, being far from relevant potential contamination sources (especially when considering the planned re-location of Aqaba port to the south) is by far a safer choice in terms of abstracted water quality.
(4) Considerations concerning bottom habitats

a. While in the past the sea grass meadows near Tala Bay (located south of Aqaba and previously known as the Big Bay) may have been a thriving sea grass site, after the construction of the Tala Bay resort, many of these sea grasses deteriorated (M. Khalaf personal observation). This indicates the clear risks posed by development and construction in the sea to the health of these meadows. Today the sea grass meadows in the “hotel area” located near the northern site is in much better condition. It is therefore important to preserve this important habitat from further anthropogenic disturbance.

b. At the eastern candidate site a barren submerged area (approximately 35-40 m) was found near the study site of Thermal Power Station, starting from 2m depth to more than 40m depth. This area was destroyed by previous construction and development activities and has never recovered. The construction of intake facilities in that area would not induce any significant additional impact.

(5) Considerations concerning fish communities

a. The Northern Intake Site is dominated by well developed sea grass meadows that can serve as nursery area for the successful recruitment, nursery and development of juvenile fishes, particularly for economically important species. This site can support fishery stock along the Jordanian coast. It is of great importance to protect this valuable fishery resource and to minimize any adverse impacts on the fishing community and industry in the city of Aqaba that may arise from any sea-based facilities including the RDC project.

b. *Teixeirichthys jordani* (Jordan’s damselfish) lives in aggregations over sea grass areas and sandy bottoms. Juveniles are often found among the spines of the sea urchins in the studied area. This species is only observed in this site only along the Jordanian coast. This should be taken into consideration if this site is to be decided as intake site.

c. The fish *Chromis pelloura* which is found at the eastern intake site is an endemic species to the Gulf of Aqaba, it is highly abundant in the northern zone of the eastern intake site at 15m depth. It has also been reported during previous monitoring programs in the Tala Bay area as well as at Phosphate Loading berth site.

d. At the eastern candidate site, the northern area show higher quality conditions in terms of number of species and number of individuals. The southern zone is of lesser importance. If this site will be selected as the intake site and the destroyed area mentioned above is not sufficient for construction and deployment of the intake, then it is recommended expand the construction and operation into the southern zone of the site rather than the middle or northern zone.

(6) Considerations concerning larvae spatial distribution

The measurements indicate that larvae and plankton are more abundant at the northern site than at the eastern site. Therefore the adverse impact of abstraction from the north will be higher.
**Best option for intake depth**

Based on the model simulations, the analysis of the available, and the new insights gained from the additional data collected within the framework of this project, it is recommended that the intake be located well below the deepest extent of the photic zone. To locate the intake within the photic zone would lead to a "no-go" recommendation. The maximum depth of the photic zone varies with the seasons as well as interannually. In Figure 5-1 we show the monthly variations of the depth of the 1% light level and the light attenuation coefficient for 2010 based on data collected at Station A as part of the NMP. The average depth is 86.3 m and it ranges from 59 m during the late winter bloom in March to 111 m in August. Considering the typical vertical extent of the current disturbance induced by the abstraction from the deep intake, which is +/-20 m, the implication is that the intake should be located even deeper than the proposed 120 m. Furthermore, chlorophyll-a is found in minute but measureable concentrations below the above mentioned depths of the photic layer, often at 120 m and occasionally even at 150 m. Thus based on the range of the photic layer depth, the chlorophyll-a concentrations, and our objective to avoid withdrawing water from the 60-120 m layer (where larvae are common), it is recommended to locate the intake at a depth of at least 140 m (bottom depth of 160-165 m). We are aware of high variability in plankton numbers, of the significant augmentation of larvae densities close to the shore and of other possible source of errors in the estimation. In addition to that, since our results show that larvae are also present down to a depth of 180 m (limit of our sampling), to further refine and corroborate the selection of the precise depth, from an environmental point of view, we recommend conducting additional sampling, very focused in the vicinity of the proposed intake, down to a depth of approximately 250 m. Finally to avoid entraining mature larvae and larvae that actively seek proximity to the bottom, we recommend the intake to be located 25 m above bottom.

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![Figure 5-1 Monthly variations of the depth of the 1% light level (red line) and the light attenuation coefficient in m-1 (blue line) at Station A during the year 2010.](image-url)
Abstraction rate

One of the major goals of the proposed RDC is to provide, through desalination, much needed fresh water to meet the increasing needs of the population this very dry region. In this respect it is clear that to anticipate future needs it is most sensible to strive for the maximum availability of fresh water. For this reason in most of our analysis, especially concerning the impacts on water quality and the ecosystem, we concentrated on the maximum abstraction rate of 2 billion m$^3$/yr. In this sense our recommendations are cautious and conservative and represent a worst case option.

The impacts of varying abstraction rates were assessed mainly in terms of the speed of the currents induced by the abstraction. Not surprisingly, for any given intake configuration, location, and depth the impacts will increase with increasing abstraction rates.

Modeling results at lower abstraction rates carried out according to the ToR and the agreed scenarios allow to evaluate different combination of intake configuration, location, and depth and could certainly be refined in a future study, running modeling scenarios aimed at directly supporting next design phases.
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