# IMPACT OF LONG TERM CONCENTRATED BRINE DISPOSAL ON THE ECOSYSTEMS OF NEARSHORE MARINE ENVIRONMENT – A CASE STUDY

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# IMPACT OF LONG TERM CONCENTRATED BRINE DISPOSAL ON THE ECOSYSTEMS OF NEARSHORE MARINE ENVIRONMENT – A CASE STUDY

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## Abstract

Despite remarkable developments of the Desalination industry in the Middle East region offering uninterrupted supply of drinking water to this water scarce region, the awareness about the impacts of concentrated Brine disposal on the ecosystem still remains very limited. Globally, it has however steered the environmental concerns. This Paper attempts particularly to examine all possible short-term and long-term impacts of the Brine disposal on the ecosystems adjacent to Desalination Plants, while discussing in detail various issues on the basis of extensive literature review and spatio-temporal data, collected from the sea adjacent to Marafiq's Power and Desalination Plant at Yanbu-I. It is one of the private sector Desalination Plants in the Kingdom of Saudi Arabia, situated at about 350 Km Northwest of Jeddah city on the Red Sea coast. Apart from 9 Gas Turbine Generators (GTG) coupled with Heat Recovery Steam Generators (HRSG) and 6 Steam Turbine Generators (GTG), this facility consists of 9 Multistage Flash Desalination (MSF) evaporators, 2 Multi-Effect Distillation/Thermal Vapor Compression (MED/TVC) units, 6 Seawater Reverse Osmosis (SWRO) and 3 Brackish Water Reverse Osmosis (BWRO) trains with a net installed production capacity of 226,560 $m^3$/day. The Plant started its commercial operation in several phases, 2 MSF Desal units in 1984, 2 MSF in 1987, 2 MSF in 1997 and 1 MSF in 1999. All SWRO trains were commissioned in 2006, BWRO in 2010 and MED/TVC in 2013.

Due to expected changes in the Physico-Chemical quality of live seawater resource, these changes are anticipated to affect the biodiversity and disrupt the distribution of marine production and food chains. Detailed accounts on all water quality parameters are likely to prevail near the shore and their influence on the ecosystem possibly resulting in some biological changes are discussed in this Paper. Biologically, the immediate Brine Discharge Zone was found slightly less productive than the ambient sea. Although, both the zones showed similar composition of Planktonic population on the site but the density and frequency of incidence exhibited a slight deviation from the ambient conditions. Slight biological effects, such as impingement, entrapment and entrainment are discussed too. However, the Recovery Zones showed substantial replenishment and restoration of the population. Several other aspects of Brine disposal, such as mixing, dilution and dispersion have also been discussed in the light of regulatory requirements.

It is the first time the authors of this Paper studied the impacts of the Brine Discharge on the Biological Diversity in the adjacent marine environment thoroughly and presented enormous information. Based on data, this Paper ratifies that the Brine Discharge from the Marafiq-Yanbu-I Desalination Plants has nonthreatening (or in the worst case the minimal) impact on coastal environment: Despite the claim of some environmentalists that the Desalination Plant effluents pose potential threat to the marine environment and the diversity of aquatic species.

# 1. INTRODUCTION

## *1.1 Desalination in Middle East – An Affordable Solution to Water Scarcity*

The scarcity of water in the Middle East region has been a severe constraint for the development until a few decades ago, but Desalination has provided a spectacular opportunity for freshwater production. The Desalination industry has become a potential sustainable and affordable global solution to water scarcity by gradually developing technologies, lowering energy requirements, improving chemical treatment practices, achieving greater operational efficiency, enhancing environmental stewardship and cost optimization.

As per Thorthwaite's classification, the climate of West Asia that lies within latitudes 12 $^{o}$N and 32 $^{o}$N and longitudes 36 $^{o}$E and 60 $^{o}$E falls within an "Arid Zone" [Al-Sayari and Zotl, 1978]. It is the only region, where the largest number of Desalination Plants exist worldwide. These West Asian countries account for about half of the world's fresh water production, out of which over a quarter of the global installed capacity exists in the Kingdom of Saudi Arabia (KSA) alone that makes it the leader in Desalination, both at global and regional scales [Ozair, G. et.al., 2013].

The growth of Desalination industry in the GCC region over last few decades has been the principal reason for the phenomenal increase in the production of desalinated water registered on the global scale. The global Desalination capacity was about only 58,000 $m^3$/day in 1960 [Wangnick, 1998], which rose to a global online capacity of 5.095 $Mm^3$/d in 1980, 14.890 $Mm^3$/d in 1990, 26.863 $Mm^3$/d in 2000 and 88.56 $Mm^3$/d in 2016 [IDA Desalination Year Book, 2016-2017].

Until recently, the extensive literature on Desalination did not address the environmental impacts associated with the process. It was assumed that if the Plant is properly engineered, the Brine Discharge is environmentally safe with respect to Physico-Chemical properties that ultimately influences the biological diversity. But the accelerated growth of Desalination Plants, particularly in the Middle East during about last 15 years, captured the attention of environmentalists. Consequently, the subject turned into an important topic for debate at almost all conferences on Desalination. Chances of changes in the oceans, especially in the characteristics of coastal waters, which might pose risk to biological diversity of several marine ecosystems were studied. Various investigators addressed this issue in their Papers, but according to Kress Nurit and Galil Bella, (2012), when the environmental aspect was initially addressed, it was descriptive with little quantitative data. The number of published articles with actual measurements of the effects in situ remained very limited in scope and time. An overview on the impacts of Brine Discharges from Desalination Plants on environment was presented by World Health Organization (2007) and highlighted by Middle East Desalination Research Center (MEDRC, 2002), Lattermann and Hoepner (2003), Khordagui (2002), AMBAG (2006), etc., in their respective reports. But Lattermann, (2011) considered that Desalination, perhaps, is not the most pressing one because Desalination contributes to only a minor part of all industrial discharges, which cause thermal and chemical loading on nearby coastal ecosystems [Ozair, G. et.al., 2013]. Nevertheless, a Paper entitled, "The Gulf: A Young Sea in Decline", in which long-term cumulative changes in the regional coastal ecosystems were anticipated further intensified the issue [Sheppard, etal., (2010); Ozair, G. et.al., (2013)].

It was followed by another article "Are the world's Oceans on the Brink of Disaster?" which was a Summary Report of the Workshops organized by the International Program on the State of the Ocean (IPSO) and the International Union for Conservation of Nature (IUCN) at the Oxford University during 2011 and 2012. In these Workshops, the international panel of marine experts examined the combined effects of pollution, acidification, ocean warming, nutrients run-off from farming, increasing hypoxia (low Oxygen ($O_2$) levels), anoxia (absence of $O_2$, known as Ocean Dead Zones), etc. Although this panel did not explicitly include the Brine Discharge from Desalination Plants as an ocean stressor but warned that the world's oceans are at high risk of entering a phase of mass extinction of the habitat (e.g., *Mangroves* and *Seagrass* meadows) and marine species, such as Reef-forming Corals. The main stressors listed by the marine scientists were high Carbon absorption rate by the oceans; mass Coral bleaching that kills the tropical Coral Reefs; overfishing reducing some commercial fish stocks and populations of by-catch species; explosions of the invasive species including harmful algal blooms; changes in the behaviour, fate and toxicity of heavy metals with acidification that may reduce the limiting effect of iron availability on primary production; increased temperature and acidification that may increase the susceptibility of Corals to bleaching and acting synergistically to impact the reproduction and development of other marine invertebrates; increased uptake of plastics by *fauna*; increased bioavailability of pollutants through adsorption onto the surface of micro-plastic particles; impacts of climate changes on the oceans, such as temperature rise, sea level rise, loss of ice cover, increased storm intensity and methane release; physical disturbance and pollutants dumping (e.g., flame retardant chemicals and synthetic musks from detergents, etc.). These threats mean that the ocean and the ecosystems within are unable to recover [Rogers, A.D. and Laffoley, Dan, (2011, 2012); Are the world's Oceans on the Brink of Disaster? (2011)].

The KSA has taken proactive initiatives to protect its marine environment. For example, the General Authority for Meteorology and Environmental Protection (GAMEP) hosted a Workshop in Jeddah in collaboration with World Bank as a part of the framework of Gulf Environmental Partnership and Action Program (GEPAP), a regional initiative aimed at promoting sustainable development in the Gulf and its water conduits. The Workshop evaluated the preliminary results of a diagnostic analysis project of the Arabian Gulf basin, studied the regional cost of environmental degradation, identified the top coastal and marine issues, prioritized possible intervention procedures and formulated the environmental strategy and action plan [English Daily, Arab News, (2017), Issue: 31 Jan.].

Further, the environmental studies conducted by Regional Authority for Environment Protection of Red Sea and Gulf of Aden (RAEPRSGA) in cooperation with the Presidency of Meteorology and Environment Protection (PMEP) reveal that the quality of water and marine along Saudi coasts is generally good. The former Authority has started a sustainable environment program in the Gulf of Aqaba, south of Jordan to monitor the quality of water along the coast of Saudi Arabia and other Gulf countries using a floating station that relays information about environment changes above and under the seawater [English Daily, Saudi Gazette, (2017), Issue: 04 Jan.]. Similarly, the General Port Authority (GPA) authorized PMPE to control marine pollutants resulting from oil disposals by the ships and boats. Developing a mechanism to follow-up on environmental pollution accurately was felt required. KSA joined the International Marine Organization (IMO) in 1969 to increase the efficiency and environmental sustainability in KSA waters [English Daily Arab News, (2016), Issue: 27 Sept.]. Further, the PME proposed a plan to the Ministry of Interior to create an environmental police unit for monitoring environmental violations and investigating perpetrators and ensuring that the environmental laws and regulations are enforced [English Daily Arab News, (2013), Issue: 12 Nov.].

A comprehensive database for environmental planning and management and taking up the studies to resolve the environmental problems emerging from Desalination Plants need to be realized by the entire Desalination community.

### *1.2 Unique Characteristics of the Red Sea*

The Red Sea, also known in Arabic as 'Al-Baḥr Al-Aḥmar' or 'Baḥr Al-Qalzam', is unique in characteristics amongst other deep-water bodies in the world. It is a seawater inlet of the Indian Ocean, lying between Africa and Asia. It has a natural connection with the Gulf of Aden in south through Bab Al-Mandeb, a 28 km wide opening with a sill depth of 130 m. In south a line exists joining Husn Murad (12°40′N43°30′E12.667°N 43.500°E12.667; 43.500) and Ras Siyyan (12°29′N 43°20′E12.483°N 43.333°E12.483; 43.333), whereas in north, there are Sinai Peninsula, the Gulf of Aqaba and the Gulf of Suez, which connects the Red Sea with Mediterranean Sea through Suez Canal. The Gulf of Aqaba is a line running from Ras Al-Fasma southwesterly to Requin Island (27°57′N 34°36′E27.950°N 34.600°E27.950; 34.600) through Tiran Island to the southwest point thereof and thence westward on a parallel (27°54'N) to the coast of the Sinai Peninsula and Gulf of Suez is a line running from Ras Muhammed (27°43'N) to the south point of Shadwan Island (34°02'E) and thence westward on a parallel (27°27'N) to the coast of Africa [Ozair, G. et.al., 2013].

The Red Sea has a surface area of roughly 438-450 × $10^2$ km². It is about 2,250 km long and its widest point is 355 km wide at Massawa (Eritrea). Its average width is 280 km and the minimum 26 km at Bab el Mandeb Strait (Yemen). Approximately 40% of the Red Sea is quite shallow (under 100 m) and about 25% is under 50 m deep. About 15% of the Red Sea is over 1.0 km depth that forms the deep axial trough. It has a maximum depth of 2.211 km in the central median trench and the average depth of 490 m. The center of Red Sea has a narrow trough (~ 1.0 km; some depths may exceed 2.2 km also). The continental slope has an irregular profile (series of steps down to ~500 m). There are extensive shallow shelf breaks marked by Coral Reefs. It is the world's northernmost tropical sea containing an estimated a volume of 233,000 $km^3$. 79% of the eastern Red Sea coastline has numerous coastal inlets [International Hydrographic Organization, (1953, 2010); Ozair, G. et.al., (2013)].

The Red Sea is thus critically placed between two marine systems. The Gulf of Aqaba is only 30 km wide, but very steep-sided and deep, reaching a maximum depth of 1.8 km near the east coast. It is separated from the Red Sea by the Tiran sill of about 250-300 m deep. There is a net inflow into the Red Sea from south and outflow in north into Mediterranean Sea in order to maintain the overall water balance, as reported by Edwards and Head (1986). The sea is underlain by the Red Sea Rift, which is part of the Great Rift Valley. An outstanding oceanographic feature of the Red Sea is that there exists a relatively stable double layered current system in which the surface water from the Gulf of Aden enters the Red Sea as a surface current and the deep water from the Red Sea flows out to the Gulf of Aden as a subsurface current. Thus, the Red Sea surface water maintains a constant drift towards the north bathing the coasts. Due to evaporation, the surface water becomes denser with salinity reaching up to 42.5 parts per thousand (ppt) in north, i.e., in the Gulf of Suez, while a thin layer of water flows out into Mediterranean Sea. The main layer, which is denser, cooler and more saline, sinks in the Red Sea at a depth of 250-300 m, returns southward and exits at Bab Al-Mandeb beneath the inflowing surface waters. The estimated renewal time for the upper 250 m water is 6 years and 200 years for the whole Red Sea water [Ozair, G. et.al., 2013].

### *1.3 Salient Features of Marafiq-Yanbu1 Site on the Red Sea Coast*

The site under study is characterized by several special features, such as South to northwards bound water currents, high Biological Activity in the ecosystem, unstable weather conditions, abruptly changing seawater conditions (particularly the Turbidity), 7 Desalination and Power complexes within a coastal stretch of about 20 km (viz., SWCC-Yanbu-I MSF, SWCC SWRO, SWCC-MED, SWCC Yanbu-III MSF, NOMAC SWRO Barges, Marafiq-YII MED and Marafiq-YI MSF, MED, SWRO), huge Petrochemical industries, nearby Aramco's oil-loading facility and a zone of heavy shipping/tankers' traffic.

The Control Site (CS) or the Point of reference and the Working Stations (WS1 and WS2) were selected nearer to the offshore of Marafiq-Y1 Power and Desalination complex (Fig. 1, 2). This Desalination facility was considered for the study to assess the long-term cumulative impact of the Brine disposal. Since Marafiq-Y1 has been operational for over 3 decades, there was potential that the plume characterized by elevated temperature, higher salt concentration and low velocity might have distinct detrimental effect on the marine ecology during this extended period. The WS1 and WS2 were selected at the outlet of the Outfall Channel; WS1 50 m offshore, WS2 100 m offshore and WS1 located 250 m south to SW2 and the CS 1.5 Km northwest to WS2 and 1.5 Km also from the seashore. Marafiq-Y1 has distantly apart Intake-Bay and the Outfall Channel to avoid mixing of the Brine Discharge with the Intake Water.


**Fig. 1: Location of Marafiq Facility**

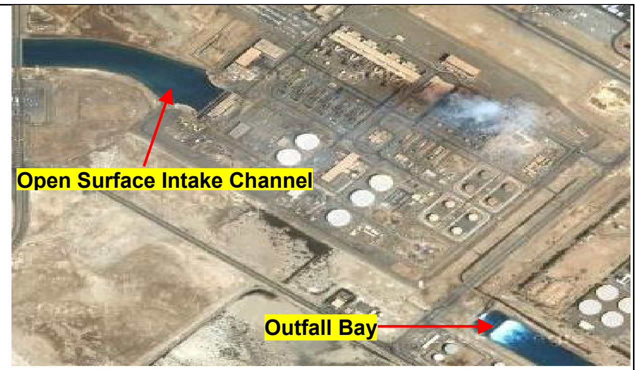



**Fig. 2: Close-up View of Marafiq Yanbu Facility**

## 2. OBJECTIVES & METHODOLOGY OF BRINE DISPOSAL STUDIES

The coastal discharges are believed posing serious risks to biological diversity of several marine ecosystems in the world. Because 70-90% of the living world still remains unknown to man (La Reiviere, 1992) and it is difficult to understand the importance of biodiversity to the functioning of marine ecosystem and their processes. In the context of growing desalination activity, there is a prodigious need for a scientific program to understand the marine biodiversity and its ecological significance so that the environmental impacts of releasing warm and concentrated Brine into the coastal waters bordering the region could be properly understood and managed at the species and ecosystem levels. The environmental impact on the aquatic ecosystems needs to be quantified, particularly based on the response of ecosystems, populations, communities and species. The potential to alter the species and community structure of organism living in the water column and on the sea floor needs to be examined besides conventional water quality measurements. The biodiversity has to be used as a reliable quantitative tool to evaluate the environmental impact of anthropogenic activities. Published ecological characterization of the marine sites where effluents from Desalination Plants are discharged is almost not available.

Marafiq-Y1 produces an average of ~ 950 $m^3$/hr (Min. 736.66, Max. 1,082.375) of Brine Discharge on annual basis (Fig. 20). In order to assess the prime effects of the Brine Discharge from Marafiq-Y1 on marine environment and degree of compliance with environmental regulations, the present study mainly covered following aspects:

- The Physico-Chemical impacts of the Brine Discharge on marine environment, such as changes in Temp., Salinity, Density, Stratification, Total Suspended Solids (TSS), Turbidity, discoloration due to residual Ferric Chloride ($FeCl_3$), etc.
- Transport and ultimate fate of discharged Brine
- Impacts of Brine Discharge on the primary production
- Impacts of Brine Discharge on *Chlorophyll* production, *Phytoplankton* and *Zooplankton*
- Overall impacts of Brine Discharge on Biotic Resources
- Short-term acute and Long-term cumulative impacts of the Brine Discharge.

Since conforming to environmental standards that would protect the species and ecosystems necessitates exigent attention of every Desalination facility to focus on the Physico-Chemical impacts of the Brine Discharge, detailed analyses on quarterly basis from WS1 and WS2 around Outfall Channel of Marafiq-Y1 for elevation in Temperature, Salinity, Turbidity, TSS, heavy metals, Disinfection By-Products (DBPs), Petroleum Hydrocarbons (PHCs), Persistent Organic Pollutants (POPs), Polychlorinated Biphenyls (PCBs), etc. were included in the scope of this study. The sampling depths selected were within 5 m (0+5), within 5-10 m (0+10), within 25-30 m (0+30). Also the impacts of Brine Discharge on living resources, such as bacteria, *Plankton*, *Benthos*, and *Seagrass* ecosystems in WS1 and WS2 and assessment of PHCs, POPs, PCBs and heavy metals accumulation in aquatic animal tissues and their Bio-geo-chemical cycling in the ecosystems were in the extended scope of the present study.

## 3. SIGNIFICANT PROPERTIES OF THE BRINE DISCHARGE

It is understood that the Brine Discharge from Desalination Plants is a highly altered fluid from physical, chemical and biological points of view compared to the raw seawater. It is generally characterized by a complex of multi component pollutants, such as high salinity, elevated temperature, residues or reaction products of a variety of chemicals used to control scaling, biofouling, foaming, cleaning, $O_2$ scavenging and leached corrosion products/heavy metals. Brine Discharge from RO Plants, though contains more solid wastes than the thermal Plants and residues or reaction products of a variety of chemicals, such as Disinfectants/Biocides, Antiscalants, Coagulants, Polyelectrolyte Flocculation-aids, Oxidant Scavengers, membrane cleaning/preservation agents, etc., but without temperature elevation. These water-born pollutants lead to affect the Physico-Chemical quality of the source water. So, the effects of these chemicals deserve special attention on long-term basis [Ozair, G. et.al., 2013].

### *3.1 Brine Transport & Sinking Patterns*

Obviously, the Brine Discharged from Desalination Plants is always denser than the ambient seawater with respect to higher salt loads, but due to elevated temperatures, it displays a reduced density, almost equal to that of open sea or seawater intake, and consequently has negative buoyancy. So, the dissipation of effluent depends largely on the bathymetry of the discharge site, prevailing tides, currents, waves and wind intensities in the Outfall Zone. The Brine Discharged from Desalination Plants, being denser than the receiving seawater, rapidly sinks in the Outfall Zone, attaining rapid dilution in an area immediately after the discharge point. But if the adjacent sea is shallow like Arabian Gulf, the Brine-plume up-wells to the surface due to elevated temperatures and spreads over depending on the prevailing currents and wind. The tides in diurnal rhythm move the Brine to-and-fro in the Discharge Zone, but when low tide cycle occurs, the discharge plume covers an extended area of the sea and hence the temperature and salinity tend to return to ambient conditions. This area of the sea is considered as a 'Natural Recovery Zone'. The extent of tidal ebb during each cycle determines the limit of Brine dispersion and consequently the dissipation of temperature and salinity [Ozair, G. et.al., 2013].

The most important aspect of Brine disposal is its ultimate sinking in the receiving water. Dilution is the best option to restore the Brine to normal salinity of the ambient sea but the extent of Mixing and Dilution Zone could be defined only after careful study of the Receiving Zone with respect to waves, currents and the ecological carrying capacity of the site. More importance is given on Brine sinking in the context of buoyancy effects of the warm and concentrated Brine discharged into the sea. The discharged Brine is thermally buoyant and also characterized by higher conductivity and density. When the Brine falls into cooler and less denser natural seawater, it undergoes rapid mixing and diffusion. After initial sinking, the Brine rises up and due to buoyancy effects tends to spread over the sea giving distinct coloration to the plume, which also enables visual tracking of the Brine. After spreading over a distance, the Brine sinks again and moves along the sea floor. The temperature and conductivity records indicate the behavior of this buoyant plume during different seasons [Ozair, G. et.al., 2013].

A deeper and open sea, like the Red Sea, adjacent to the Brine Discharge site serves better for rapid dilution and dissipation of the elevated parameters. Rapid mixing and dilution are vital for safe Brine disposal in the sea. The expected advantage of mixing, dilution and dispersion has been cited by many authors as site dependent [Everest et.al., (1995), Hoepner and Windelberg (1996), Abdul Azis, et.al., (1999), Ozair G. et.al., (2013)]. Brine disposal results in sinking of concentrated Brine in the sea. Once it descends to the bottom the potential rate of mixing minimizes. So, as Desalination Plants would continue to be a major source of coastal discharges, vigilant monitoring is desired to keep the adjacent seas free from pollution.

During Marine Survey near Marafiq-Y1 discharge site, the parameters monitored at 0-5 m, 0-10 m and 0-30 m levels in the 'Natural Recovery Zone' were found almost similar to the ambient seawater conditions (Table 1). The bathymetric features of Outfall areas of Marafiq-Y1 Desalination site also show that the region being deeper facilitates rapid mixing and dilution. However, a temporary stratified water column was observed due to density differences between the discharge and the receiving waters, but no thermocline was noticed. The elevation in temperature of the receiving marine environment and the point where surface water temperature returns to ambient conditions varied from season to season, but the trend of recovery brought about by mixing, dilution and diffusion caused by wind, waves, tides and incursion of water masses was found highly robust [Ozair, G. et.al., 2013].

### *3.2 Physico-Chemical Impacts of Brine Disposal*

The aspects of Desalination as an environmental friendly water treatment system have been discussed in detail by Buros (1994) in the context and nature of processes adopted in USA. However, the unfolding impact of surface coastal discharge has been highlighted by Friedland, et.al., (1980), Bushnak (1993), Al-Tayaran and Madany (1992), Shams El-din, et.al., (1994), Raveendran, (1995) and Ozair, G. et.al., (2013), from Red Sea and Arabian Gulf regions. The UNESCO (1995) has reported that the Desalination discharge has been a major source of marine pollution in the Red Sea coastal waters. It is assumed that multiple use of seas for various industrial and civil developments has transformed several coastal areas of the Red Sea, Arabian Gulf and Northern Arabian Sea into environmentally sensitive zones. KSA has identified 46 such sensitive areas on the Red Sea coast and 11 on the Arabian Gulf coast [MEPA, 1987 a, b].

All seawater Desalination Plants in the Middle East region are located on the shores of the Red Sea, Gulf of Aqaba and Arabian Gulf discharging their Brines into adjacent surface coastal waters of respective countries [Al-Awadi (1991), Al-Tayaran and Madani (1992), Al-Gobaisi (1994), Manna (1994)]. The volume of Brine Discharged in the Red Sea had increased from 6.4 $Mm^3$/day in 1996 to 6.8 $Mm^3$/day in 2008 [Ciocanea, et.al., 2013], which went on increasing further almost every year due to new installations, improved recovery ratios and development of highly efficient Desalination processes. But despite this phenomenal growth of Desalination industry worldwide, precise data on the Physico-Chemical impacts of the Brine Discharge in the adjacent marine environment are very limited [Friedland and Gat, (1976); Friedland, et.al., (1980); Al-Tayaran and Madany, (1992); Shams El-Din et.al., (1994); Raveendran, (1995); Al-Hajri and Ahmed, (1997); Khordagui, (1997); Hoepner, (1999)]. Lattermann, (2011) also articulates that marine pollution by Desalination Plants has been monitored and results published in only a few short-term, localized studies [Ozair, G. et.al., 2013].

Ozair, G. et.al., (2013) have studied and reported in detail some of the supposed influences of Temperature elevation, increased Salinity, Density elevation, Turbidity rise, higher TSS, depleted dissolved $O_2$ and residual waterborne pollutants, like Antiscalant additives, Antifoam additives, acids, Corrosion Inhibitors, cleaning agents, $O_2$ Scavengers, heavy metals, Disinfectants, DBPs, Biocides, Coagulants and Coagulant-aids, etc., on the Physico-Chemical quality of Marafiq-Y1 near-shore marine environment.

## 4. RESULTS & DISCUSSION

Hard data discussing the impacts of the Brine Discharge on the Biological Diversity in the adjacent marine environment are almost not available. It is the first time authors of this Paper took the initiative to study this aspect thoroughly. A series of monitoring exercise was undertaken on quarterly basis, including Marine Observational Survey, Lab analyses of replicate samples collected from raw Seawater (CS) and designated Working Stations from the Outfall area (WS1 and WS-2) for a number a Biological and

Physico-Chemical parameters. The Marine Surveys relate to the offshore monitoring adjacent to nearby site activities using professional divers and included observational approach to aquatic life monitoring.

## 4.1 Physico-Chemical Analyses

The need to understand the Physico-Chemical significance with respect to potential impacts of the Brine disposal on the near-shore marine environment and environmental compliance has been well considered by Marafiq-Y1 by continuous monitoring of the effluent quality using Auto-Sampler-Composite Samples for pH, Residual Chlorine ($Cl_2$), Copper (Cu) Content, Δ Salinity, Temp., Flow, Total Dissolved Solids (TDS), etc., which remain quasi identical. The average results on annual basis remained: For pH 8.027 (Min: 7.76, Max: 8.42), for Residual $Cl_2$ 0.0372 ppm (Min: 0, Max: 0.33), for Cu Content 25.552 ppb (Min: 6, Max: 34), for Δ Salinity 1.138 ppt, (Min: 0.73, Max: 1.4) and for Temp 35.53 $^oC$ (Min: 26.67, Max: 43.037), as represented in Fig. 15-19.

Apart from abovementioned continuous monitoring of Physico-Chemical quality of the Brine Discharge, detailed analyses were conducted at depths within 5 m (0+5), within 5-10 m (0+10), within 25-30 m (0+30) during 2012 [Ozair, G. et.al., 2013] and during 2016 also, samples were collected in triplicate on quarterly basis from WS1 and WS2 around Outfall Channel of Marafiq-Y1. The samples were collected from the depths as stated above and analyzed for elevation in Temp., Salinity, Turbidity, TSS, heavy metals, DBPs, PHCs, POPs, PCBs, etc. The results for 2016 are presented in Table-1.

Particular care was taken to assess the accumulation of DBPs, PHCs, POPs, PCBs and heavy metals in aquatic animal tissues and their Bio-geo-chemical cycling in ecosystems, but all results were absent or below detection limits.

## 4.2 Substrate Analyses

CS, WS1 and WS2 were subjected to Substrate Analyses on quarterly basis for Segments 1-4 (0-20 m, 25-45 m, 50-70 m, 75-95 m, respectively) for Hard Coral, Soft Coral, Recently Killed Coral, Rubble, Sponge, Rock, Nutrient Indicator Algae, Silt, etc. Table-2 represents the detail of the Substrate Analyses with color demarcation for different observation dates.

Similarly, the detailed Reef Examinations were conducted on quarterly basis for above-stated Segments 1-4. The results of Reef Examination Summary are presented in Table-3 with color demarcation for different observation dates.

## 4.3 Marine Data Collection

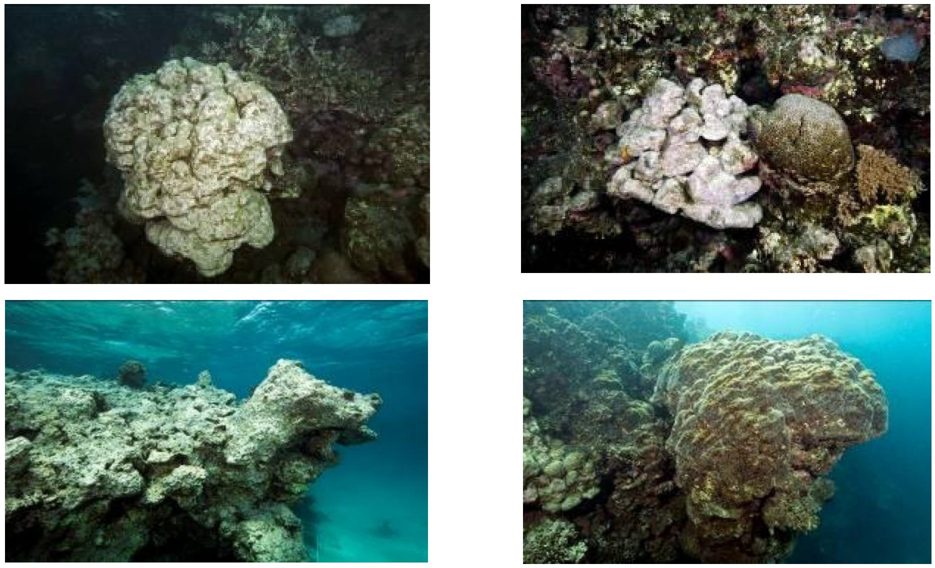
Table-4 represents Marine Data for Invertebrates, Coral Disease, Bleaching, trash and other impacts, fishes, count of *Serranidae* (Grouper) with size above 30 cm, rare marine life sighted, etc., with color demarcation for different observation dates.

## 4.4 Marine Observational Survey (Jan. 2016)

### *4.4.1 Control Site (10:00 Hrs)*

*Weather Conditions:* Wind speed: 7 Km/h, Northeasterly, partly cloudy, Air Temp: 31 $^oC$, Water Temp: 28 $^oC$ at surface and the depth, Visibility: 8-10 m.
*State of Coral Reef:* Dense coverage of algae up on the Reef crest, some Coral death on the Reef margin and outer Reef slope. Air Temp. out on the Reef was 28 $^oC$, at Surface 28 $^oC$ and Underwater 28 $^oC$. Underwater visibility was 8-10 m. Fig. 3 represents the underwater photographs at the CS.

**Fig. 3**

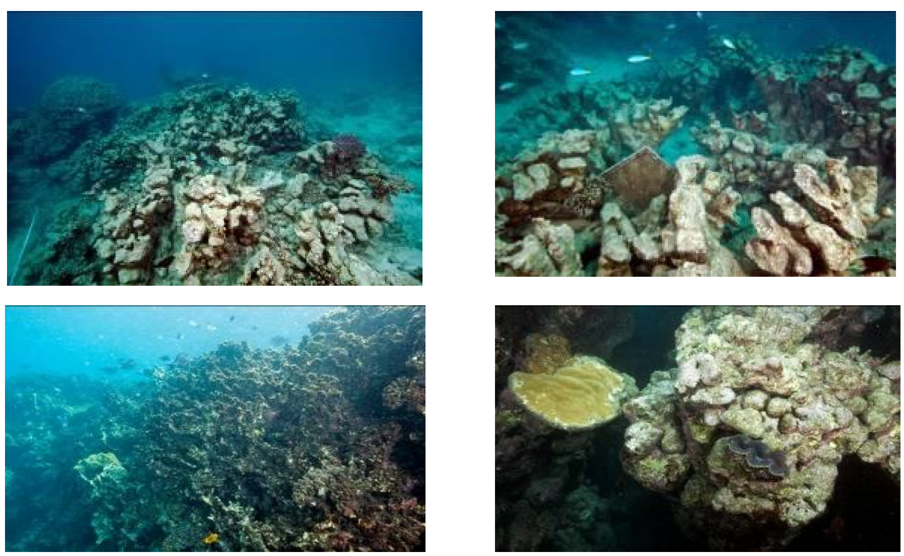


### *4.4.2 Working Station-1 (11:00 Hrs)*

*Weather conditions*: Slightly changed. Wind Speed: 11Km/h, Northerly, Air Temp: 28 $^{o}$C, Water Temp: 28 $^{o}$C both at surface and the depth, Visibility: 8-10m.

*Fish Population:* More fish life was witnessed in shallower water in the periphery of the WS1, including Groupers (*Serranidae*), such as Peacock grouper (*Cephalopholis argus*), Halfspotted hind (*Cephalopholis hemistiktos*), Redmouth grouper (*aethaloperca rogaa*) and from the family of Sweetlips (*Haemulidae*), Blackspotted sweetlips (*Plechtorhinchus gaterinus*) and Minstrel sweetlips (*Plectorhinchus schotaf*) with some species such as Schools of Orangespotted trevally (*Carangoides bajad*) and Bluefin trevally (*Caranx melampygus*) frequented this area looking for prey. There were a few additional healthy Coral Colonies, nurseries and associated Coral fish thriving in this heavily exposed area. Fig. 4 represents the underwater photographs at the WS-1.

**Fig. 4**



### *4.4.3 Working Station-2 (12:10 Hrs)*

*Weather Conditions:* Remained unchanged. Slightly turbid water from the Outfall was flowing near the bottom in a steady stream reducing the visibility to 3-4m, while above this layer or in the surrounding visibility was 8m.

*State of Coral Reef:* The Reef with once huge impressive Clownfish and Sea Anemone colony has so far no further Coral recruitment and leaves a dead Coral area behind.
*Fish Population:* There was a plenty of fish life in this Area with abundance of Indo-Pacific Sergeants (*Abudefduf vaigiensis*) tending the eggs. Fig. 5 represents the underwater photographs at the WS-2.

**Fig. 5**

## 4.5 Marine Observational Survey (April 2016)

### *4.5.1 Control Site (10:30 Hrs)*

*Weather Conditions:* Wind Speed: 8 Km/h, Northwesterly, Sunny, Underwater Visibility: 25 m. Air Temp: 31 $^{o}$C out on the Reef, Seawater Temp: 30 $^{o}$C near surface and 28 $^{o}$C at the depth.
*State of Coral Reef:* There were few sightings of Coral death along the drop of Reef slope, including species *Milipora*, *Acropora* and *Porites*. However, the pinnacles located few meters away from the Reef slope were healthier.
*Fish Population:* Diversity and density of fish population were observed higher as compared to the previous survey. Fig. 6 represents the underwater photographs at the CS.

**Fig. 6**

### 4.5.2 Working Station-1 (12:30 Hrs)

*Weather Conditions:* Wind Speed: Changed to 15 Km/h, Northwesterly, Underwater Visibility: 20-25m, Seawater Temp: 30 ºC near surface and 29 ºC at the depth.
*State of Coral Reef:* The siltation of Reef was with no or minimal change compared to the previous survey.
*Fish Population:* Fish populations appeared more abundant and diverse in the surroundings compared to the earlier survey. Large Sergeant Majors populations, Crown of Thorn individuals and small healthy Coral colonies with fish thriving in the previously exposed area were sighted. Some waste material, like paint buckets, tins, tyres, cables, and nylon ropes were observed on the seabed. Fig. 7 represents the underwater photographs at the WS-1.

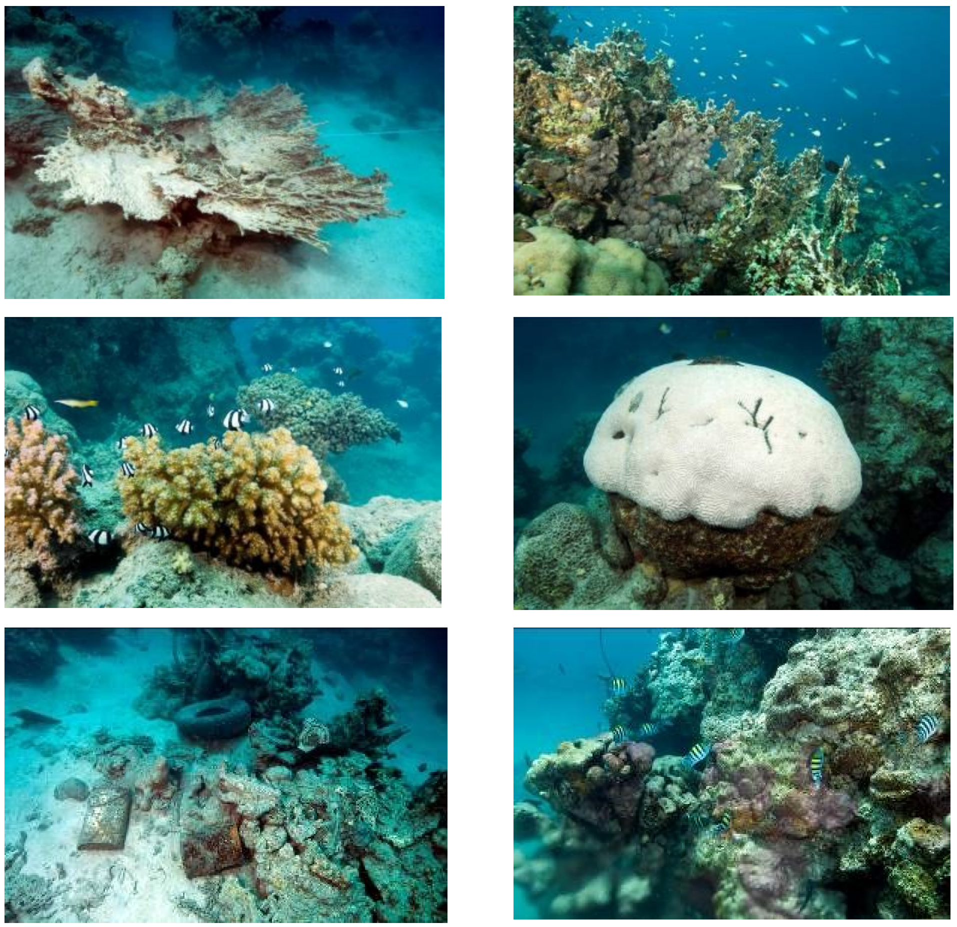
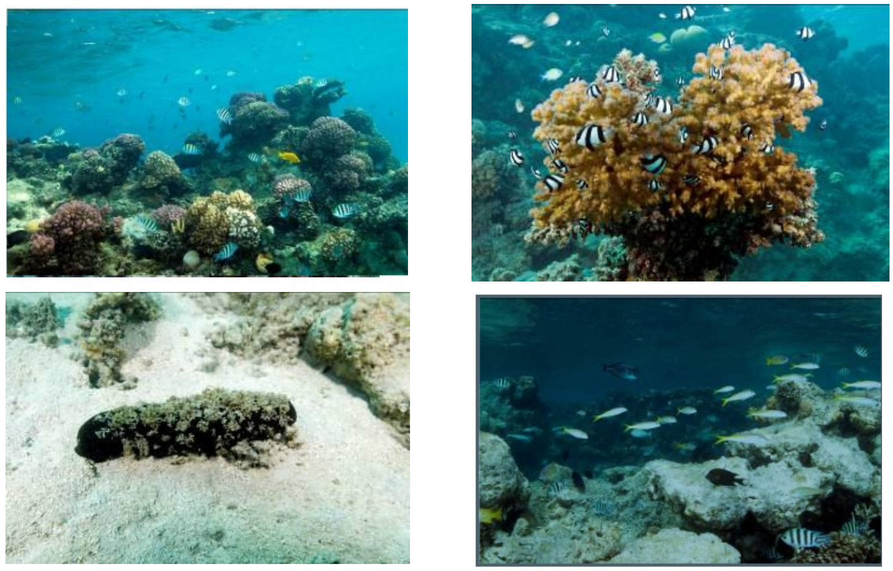


**Fig. 7**

### 4.5.3 Working Station-2 (15: 45 Hrs)

*Weather Conditions:* Wind: Northwesterly, Underwater Visibility: Reduced to 20 m due to slightly turbid and warmer water from the Outfall.
*Fish Population:* The fish populations observed on the top of Reef table included Sergeant majors, Blackspot Snappers and Sulan Ibrahim. Fig. 8 represents the underwater photographs at the WS-2.

Fig. 8

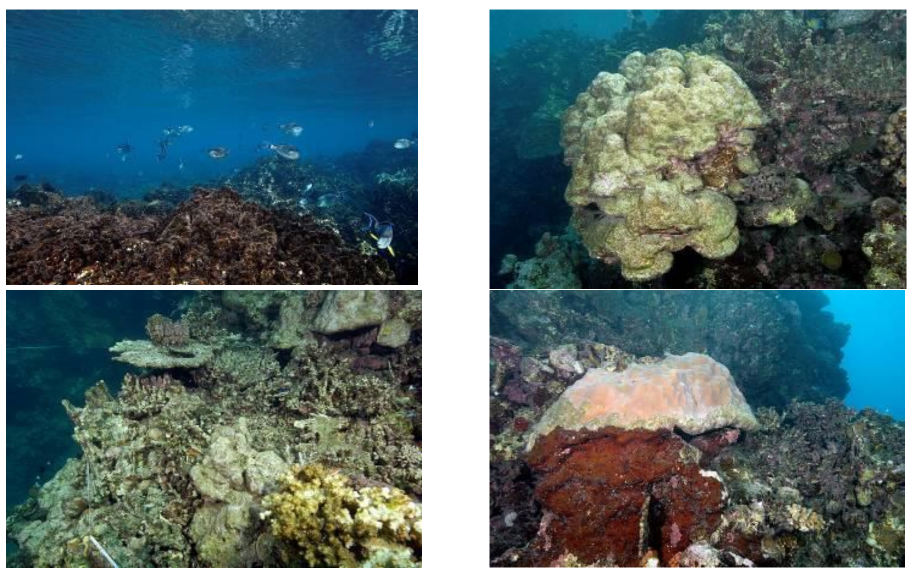


## 4.6 Marine Observational Survey (July, 2016)

### *4.6.1 Control Site (08:30 Hrs)*

*Weather Conditions:* Site was calm, Wind Speed: 5 Km/h, Southeasterly, Sunny, Underwater Visibility: 7m. Air Temp: 34 ºC out on the Reef, 30 ºC near surface and 29 ºC at the depth.
*State of Coral Reef:* Some additional Coral deaths sighted along the drop of the Reef slope, which is attributed to a combined effect of very warm summer and exceptionally high temp for much longer periods than normal in Yanbu. Fig. 9 represents the underwater photographs at the CS.

Fig. 9



### *4.6.2 Working Station-1 (11:00 Hrs)*

*Weather Conditions:* Wind: Changed to 7 Km/h, Southerly, Underwater Visibility: 8-12m, Plankton rich water, Seawater Temp: 30 ºC at depth and near the surface.
*State of Coral Reef:* Few more Coral deaths observed in the lower parts of the Survey area due to the effect from anchor damage with overturned heads. Less silt was noted. The adjacent Reefs to the west and east of Working Station-1 support live Coral in shallow areas.

*Fish Population:* Fish species Trevallys, Fusiliers, Humphead wrasse, Manta Rays and a Whale Shark were observed. Fig. 10 represents the underwater photographs at the WS-1.

**Fig. 10**

### *4.6.3 Working Station-2 (14:30 Hrs)*

*Weather Conditions:* Wind Speed: 12 Km/h, Southwesterly, Underwater Visibility: 5-7 m.
*State of Coral Reef:* Minor degree of Coral deaths was observed. The previous healthy community of sea anemones was seen exhausted with one Clownfish left.
*Fish Population:* Fish species Snappers, larger Parrotfish and few Sweetlips were observed.

**Fig. 11**

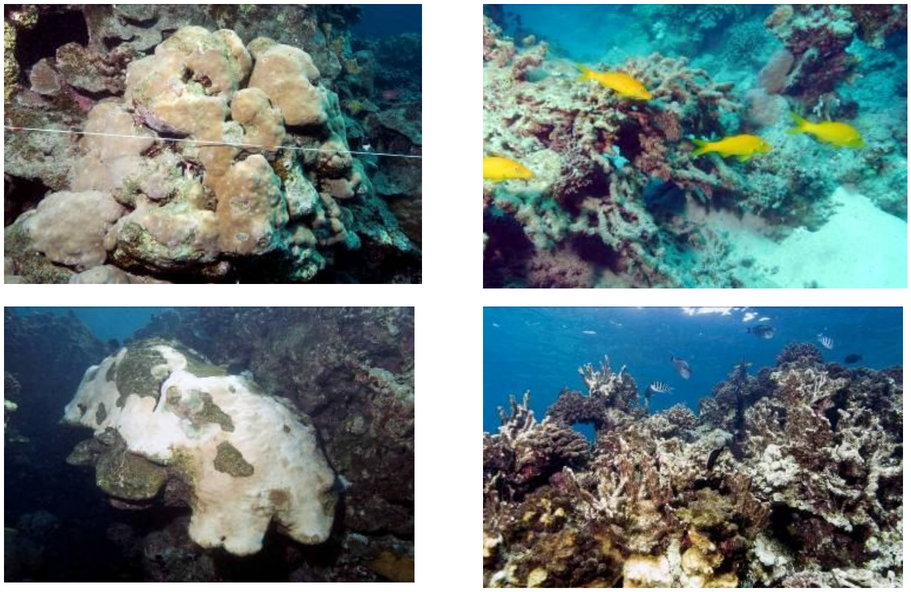
## 4.7 Marine Observational Survey (Oct. 2016)

### *4.7.1 Control Site (10:10 Hrs)*

*Weather Conditions:* Wind Speed: 2 Km/h, Northerly, Sunshine with cloud formations, Underwater Visibility: 8-12 m, Air Temp: 32 ºC out on the Reef, 30 ºC near the surface and 28 ºC at the depth.

*State of Coral Reef:* There were sightings of moderate Coral beaching and Coral death on many Corals, including Leather Coral and different species that were found affected to a certain extent in the previous Observational Diving Survey, such as Millepora, which has become extinct in the CS. Additional dead Coral was observed compared to earlier survey. Fig. 12 represents the underwater photographs at the CS.

**Fig. 12**



### *4.7.2 Working Station-1 (12:00 Hrs)*

*Weather Conditions:* Wind: Changed to a Northwesterly, Underwater Visibility: 15-20 m. Seawater Temp: 30 ºC near the surface and 28 ºC at the depth.
*State of Coral Reef:* The siltation of Reef was minimal as in the previous marine survey. However, more Algae were observed on the Coral colonies. The waste materials observed in previous survey might have moved away from the area by undercurrents.
*Fish Population:* The fish populations appeared more important in the surrounding areas compared to the earlier survey. A Hawksbill turtle was sighted in addition to small healthy Coral colonies with associated Coral fish in heavily exposed area. Fig. 13 represents the underwater photographs at the WS-1.

**Fig. 13**

### *4.7.3 Working Station-2 (15:00 Hrs)*

*Weather Conditions:* Wind: Northwesterly, Underwater Visibility: 8-12 m, Surface Conditions: Similar to the CS, Seawater Temp: 30 ºC underwater and 29 ºC near the surface.
*State of Coral Reef:* Algal growth and sedimentation on the Coral were observed. The sea anemones, which were noted distressed earlier had recovered with normal pigmentation.
*Fish Population:* Absence of large fish and many invertebrates was noticeable in all survey areas and none was sighted in the WS-2. Fig. 14 represents the underwater photographs at the WS-2.

**Fig. 14**

## 4.8 Biological Analyses

### *4.8.1 Impacts on Zooplankton*

The *Zooplankton* occupies a pre-eminent position in the marine food chain and represents a peculiar assemblage of organisms. There is a well-established correlation between commercial fisheries and *Zooplankton* abundance (Cushing and Dickinson, 1976). Any depletion of *Zooplankton* adversely affects the commercial fish and shellfish resources in the sea. During Jan., representatives of only six *phyla* in the *Zooplankton* were encountered but in July, this representation increased to ten *phyla* indicating a great shift in the population from one quarter of the year to another. The CS was found to be the richest for *Zooplankton* incidence among the designated Working Stations (WSs). *Tintinnida* is considered as highly environmentally sensitive but occurred in great density in the *Protozoan* community at all WSs. *Coelenterata*, which was absent in Jan., appeared during Apr.-Oct. July witnessed the incidence of Jellyfish in the CS. *Nematoda* made their first appearance in Apr. *Polychaeta* largely represented in the larval stages, which are temporarily *Planktonic,* but in adult stage they colonize the benthic habitat and occur among biofouling communities. *Cladocera*, *Copepoda* and *Cirripedia* mainly occurred during Apr.-

July but only first two groups occurred in Oct. The larvae of barnacles, *Cirripedia*, which are considered to be a hardy biofouler in Desalination Plants, was absent in Jan. in all WSs. The incidence of *Copepoda* in the Discharge bay and absence in CS points towards no impact of the Brine Discharge. *Pteropod* and *Bivalve molluscs* appeared in Apr.-July, whereas *Gastropod* and *Bivalve molluscs* appeared during July-Oct. The members of the *Molluscan* community in *Plankton* were mostly in larval stages or juveniles, drifted by the currents and waves. Although larvae are active associates in any biofouling assemblage, but the lower density shrunk their biofoulers' character. *Chordata* was represented by only *Larvaceae* (Appendicularia). In July, the community was composed of *Thaliaceae*, fish eggs and larvae, which occurred in large numbers. The largest abundance of fish eggs was seen near WS-2 and Intake Bay. A slight loss of fish larvae was noted in the Outfall Bay.

### *4.8.2 Impacts on Phytoplankton*

*Phytoplankton* contributes to ~ 95% of the marine primary production. The production of *Zooplankton* fish, shellfish, mammals, etc., depends on *Phytoplankton*. *Plankton* is used as indicators to assess the health of marine ecosystems [Haury and Piper, 1988]. Considering a long and vast Red Sea coast, *Phytoplankton* sustainability is of enormous importance. The *Phytoplankton* detected in WS1 and WS2 were composed of three taxonomic classes, viz., *Bacillariophyceae* (Diatoms), *Pyrrophyceae* (Dinoflagellates) and *Cyanophyceae* (Blue green algae), whereas 94% of the *Phytoplankton* in the Discharge Zone were *Baccillariophyceae*. Analytical data showed that the ecological conditions in the Brine Discharge Zone, which is characterized by elevated temperature and conductivity, as a whole did not limit the *Phytoplankton* incidence. Only a very limited drop was seen in the density at the immediate Brine Disposal site with rapid recovery at the adjacent WS1 and WS2. The mixing and dilution facilitated by cascading of the Brine Channel into discharge bay and richness of Marafiq-Y1 site in nutrients could be attributed for a relatively faster recovery of the *Phytoplankton*. However, the numerical abundance of *Phytoplankton* during July indicates the possibility of *Planktonic* blooms during the period. July was the most favorable for the incidence of several species of *Phytoplankton* followed by April and then Oct. Irrespective of months, the Discharge Zone experienced depletion of certain genera in Jan. However, in terms of species, the overall composition was not affected by the Brine Discharge.

### *4.8.3 Impacts on Chlorophyll Production*

The economy of any aquatic biotope is dominated by *Chlorophyll* pigments. The production of *Chlorophyll* bearing plants sustains the multiplicity of food webs through *photosynthesis*, makes the seas a major source of food and vital sink for atmospheric Carbon Dioxide ($CO_2$). The samples collected showed that the production of *Chlorophyll* was impressive both in surface and bottom waters. The highest production was noticed in April and July and it was below detection limits during the Jan. Although a slight drop in *Chlorophyll* was noticed at the WS1, it soon regained the production level of the ambient sea in the Recovery Zone. The water in the discharge bay showed that the production of *Chlorophyll* has been active despite elevated temperature and conductivity. The productivity of *Chlorophyll* was vigorous because of the rapid replenishment of Dissolved $O_2$ that happens in the sea due to turbulent mixing. Brine Disposal has not impeded marine primary production, except in a very limited area of the immediate Brine Discharge site. The relatively high *Chlorophyll* production noticed in the CS and open sea suggests that the sea is biologically very productive despite the Brine Discharge.

### *4.8.4 Overall Impacts on Biotic Resources*

This study has brought out a clear understanding of the overall impacts experienced by biotic components of the sea associated with Marafiq-Y1 site. The impacts in process related water circuit are categorized in impingement, entrainment and entrapment. It has been a widely established ecological impact that a certain number of organisms are bound to be lost due to these impacts in any seawater based industrial process. Universally passive *Planktonic* organisms drawn into the Plant through intake pumps and screens are most likely to be mutilated and killed. Tis impact is called 'Impingement', whereas 'Embayment' is the deviation seen in the Intake Bay compared to CS or the open sea. Once seawater enters the Plants, the *Plankton* are in the state of 'Entrainment'. When the seawater passes through Plant equipment, organisms are exposed to various chemical laced environments, such as disinfectants, biocides, acids, etc., or damage and shear due to physical contact with mechanical parts, like pumps and valves or physical effects of pressure changes or mortality due to $O_2$ depletion as a result of deaeration or thermal shocks in condenser tubes followed by elevated salinity contact. All these factors exert a cumulative impact on *Planktonic* survival. But most of the *Phytoplankton* and *Zooplankton* can produce replacement generations within a matter of hours/days and the impact remains largely confined to the Brine Discharge site. Given a reasonable recovery period and an area, the situation tends to become normal.

Marginal increase in *Chlorophyll* production was noted as the in the Intake Bay during Jan.-Apr. as an impact of embayment, but encountered its substantial depletion compared to CS during Oct. When the production in Discharge Zone was compared to CS and the Intake Bay, there was loss of *Chlorophyll* production restricted to the point of immediate Discharge and very slightly in WS1 and WS2. The seawater after passing through Plant structures exits without usual concentration of the dissolved $O_2$ but the $O_2$ replenishment while passing through Brine Discharge Channel resulted in higher production of *Chlorophyll* pigments in the receiving sea. During July and Oct., the dry weight biomass of *Plankton* showed positive embayment effect but negative in Jan. The impingement and entrainment effects were evident during July. Compared to CS and open sea, a loss of major *Planktonic* groups (diatoms, dinoflagellates and blue-green algae) was noticed in the Intake Bay, whereas the total population of *Zooplankton* showed an increase of 58% in the Intake Bay compared to the CS. This increase was 8% for *Annelida*, 12% for *Appendicularia,* 15% for fish eggs, 40% for *Arthropoda*, 70% for *Chordata* and 375% for *Protozoa*. Unidirectional currents maintained by a huge battery of Intake Pumps and the sheltered nature of the Intake structure are attributed for the abundance of these groups in the Intake Bay. The stream of currents flowing into the Intake Bay brings in extra loads of passively floating *Plankton* into the Bay, where many groups flourish while others perish. Similar biological impacts affecting the Outfall Bay population for short durations attributable to impingement, entrapment and entrainment have been discernibly reported by many authors from other industrial institutions [Cheshire, (1975); Jensen, (1978); Majewski and Miller, (1979)]. The ecological characteristics in the receiving seawater dominated by temperature and salinity were not limiting the abundance of the abovementioned groups, but compared to Intake Bay and CS, the most abundant group of *Zooplankton*, such as the *Arthropoda*, *Chordata* and *Protozoa*, experienced some population loss in the area of receiving water.

## 4.9 Short-Term Acute Impacts

The short-term acute impacts of the Brine Discharges are reported by Cheshire (1975). These impacts are confined to the point of immediate and direct Discharge. The mortality of *Plankton*, benthos and fish in the Discharge Zones are normally attributed to thermal loading and elevated salt concentrations brought about by the warm Brine Discharges. The osmotic equilibrium of body fluids in many organisms gets disturbed by the perturbations in seawater salinity. The osmotic equilibrium of body fluids differs for different species. Kinne (1963) and Lange (1970) reported that in laboratory experiments, extreme perturbation in salinity was found to cause mortality of the organisms. Krishnan and Kanmpandy (1987) observed some other adverse acute effects on the marine organisms, such as larval mortality, shrinkage of body cells, slow development rate, failure of osmoregulatory mechanisms, etc. An acute toxicity of the ecosystem would occur only when Brine Discharges with unusual levels of temperature, salinity, metal ions, etc., are suddenly dumped into the sea. This short-term acute toxicity may lead to the mortality of *Plankton* and benthic animals in the exposed region.

### 4.10 Long-Term Cumulative Impacts

Price et.al., (1993) have implicated Desalination activity as a major environmental pressure on the Arabian Gulf ecosystem and it is anticipated that the ecological effect of coastal Power Plants have been an area of serious environmental concern. Mickley (1996) has indicated possible long-term cumulative effects of exposure to Desalination Discharges in a particular site. Ecologists [Price et.al., 1993] have noticed chances in the species composition, shifting of spawning seasons and reduction in the spawning stock size of *Prawns* due to environmental pollution. Several investigators have accepted the potential for ecological effects associated with the intake structures and processes related to the passage of seawater through the cooling and discharge circuits. According to USEPA (1976), large number of fish and invertebrates get killed on the travelling screens. Benda and Gulvas (1976) found a direct correlation between the species impinged, their abundance and seasonality in the seawater. Maryland Power Plant Siting Program [MPPSP, 1977] has reported the relative sensitivity of eight *estuarine* fish species to impingement stress. The impinged fish had reduced resistance to diseases following the loss of surface mucus or scales and were prone to even normal predator pressure.

## 5. CONCLUSIONS

- All Desalination Plants in GCC Countries depend on the regional seas for their feed and Brine Discharges and the principal method of Brine disposal is the coastal surface discharge.
- The track experience of Marafiq-Y1 with respect to Brine Discharge quality has been impressive and the review of the Discharges monitoring data demonstrates that Marafiq-Y1 is fully compliant with the Receiving Water Guidelines stipulated in the Environmental Protection Standards (MEPA 1409-01) of the PME.
- The impacts of the Brine Discharge from Marafiq-Y1 have been normal and very limited. Slightly elevated parameters rapidly return to ambient values in the Recovery Zones because greater and more intense oceanic circulations in the Red Sea have inherent advantages of faster diffusion, dissipation, mixing, dilution and dispersion.
- The cascading pattern of the Brine Discharge Channel plays beneficial role in normalizing the temperature.
- The absence of the traces of heavy metals, DBP, PHCs, POPs, PCBs, etc., in the tissues of Fishes and the dead and live Corals in WS1, WS2 and CS, indicates that the Brine Discharge from Marafiq-Y1 has no acute or long-term threat to the marine life and the abovementioned death of Corals is due to natural lifecycle process.
- The Brine Discharge has not impeded marine primary production except in a very limited area of the immediate discharge. The *Phytoplankton* population did not show much deviation in the Outfall from the Control Site throughout the year. There was a little drop only in the density at the Discharge site with rapid recovery. The overall species composition was also not found to be affected by the Brine Discharge.
- The *Zooplankton* community in the Discharge Bay are occasionally, but slightly, influenced by entrapment, entrainment and impingement effects. The elevated temperature and salinity did not limit the occurrence of *Coelentoreta*, *Aschelminthes*, *Annelida*, *Mollusca*, *Appendicularia* and fish eggs.
- Beneficial effects of mixing was obvious in the rapid restoration of *Planktonic* organisms in the Recovery Zone.

## 6. RECOMMENDATIONS

- The trend of establishing large capacity Plants along the coasts of the Red Sea, Arabian Sea and Arabian Gulf deserves a review by all GCC countries sharing these water bodies considering the local bathymetry, circulation and currents, sufficiently deep and suitably designed outfall Mixing Zone to carry the Brine plume rapidly to the deep sea.

- Since Mixing Zone is a shifting entity, from season to season and one tidal cycle to another, each Plant requires a well-designed Mixing Zone to allow the Brine Discharge mixing rapidly and return the seawater conditions to ambient levels with respect to aquatic life.

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## 8. TABLE

### Table-1: Environmental Analyses Results from WS1 and WS2 (Average of Jan., Apr., July, & Oct. - 2016)

| Constituents | Units | Allowable Effluent Levels | Average | | |
|---|---|---|---|---|---|
| | | | 0 + 5 m | 0 + 10 m | 0 + 30 m |
| **Physio-Chemical Pollutants** | | | | | |
| Floatables | Visual | None | ND | ND | ND |
| pH | - | 6 - 9 | 7.1 | 7.5 | 8.18 |
| TSS | mg/l | Max. 15 | < 5 | < 5 | < 5 |
| DO | mg/l | Min. 70% Saturation | 7.3 | 7.4 | 7.55 |
| Turbidity | NTU | Max. 75 | < 1 | < 1 | < 1 |
| BOD | mg/l | 25 | 5 | 4 | 4 |
| COD | mg/l | 150 | 11 | 11 | 10 |
| Total Kjeldahlnitrogen (TKN) | mg/l | 5 | 3.5 | 2.5 | 1.2 |
| Total Chlorinated Hydrocarbons | mg/l | 0.1 | < 50μg/l | < 50μg/l | < 50μg/l |
| Oil & Grease | mg/l | 8 (should not exceed 15 mg/l in any individual discharge) | < 10 | < 10 | < 10 |
| Phenols | mg/l | 0.1 | < 50μg/l | < 50μg/l | < 50μg/l |
| **Non-Organic Pollutants** | | | | | |
| Ammonia as N | mg/l | 1.0 | 0.125 | 0.090 | 0.055 |
| As | mg/l | 0.1 | < 0.004 | < 0.004 | < 0.004 |
| Cd | mg/l | 0.02 | < 0.0002 | < 0.0002 | < 0.0002 |
| Res. $Cl_2$ | mg/l | 0.2 | < 0.1 | < 0.1 | < 0.1 |
| Cr | mg/l | 0.1 | < 0.003 | < 0.003 | < 0.003 |
| Cu | mg/l | 0.2 | < 0.002 | < 0.002 | < 0.002 |
| CN | mg/l | 0.05 | < 0.002 | < 0.002 | < 0.002 |
| Pb | mg/l | 0.1 | < 0.003 | < 0.003 | < 0.003 |
| Hg | mg/l | 0.001 | < 0.001 | < 0.001 | < 0.001 |
| Ni | mg/l | 0.2 | < 0.0004 | < 0.0004 | < 0.0004 |
| Total Phosphorous | mg/l | 1.0 | < 0.020 | < 0.016 | < 0.018 |
| Zn | mg/l | 1.0 | < 0.004 | < 0.004 | < 0.004 |
| Fe | mg/l | 1.0 | 0.028 | 0.026 | 0.015 |
| **Biological Pollutants** | | | | | |
| Total coliform | MPN /100ml | 1000 | ND | ND | ND |
| **Mixing Zone** | | | | | |
| Temp. | ºK | ≤ 1 ºK above receiving water | 32.7 ºC | 31.1 ºC | 29.6 ºC |

*Notes:* All above parameters are within the permissible limits.

### Table-2: Substrate Data

| Date/Time | 10:00 Hrs | | | | 14:00 Hrs | | | | 16:00 Hrs | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | **Segment-1 (0-20 m)** | | | | | | | |
| 5-Jan-2016 | 0 | RC,SD,HC,HC | 10 | RC,SD,RC,RC | 0 | RC,RC,RC,RC | 10 | RKC,SD,SD,RC | 0 | RB,SD,SD,RC | 10 | SD,SD,SD,RB |
| 8-Apr-2016 | 0.5 | RC,HC,RC,RC | 10.5 | RC,SD,RC,RC | 0.5 | SD,RB,RC,RB | 10.5 | SD,HC,SD,RC | 0.5 | RB,SD,SD,SD | 10.5 | SD,SD,SD,SD |
| 3-July-2016 | 1 | RC,HC,RC,RC | 11 | RC,SD,RC,RC | 1 | SD,SD,RB,RB | 11 | RB,RC,RB,RC | 1 | SD,HC,SD,RC | 11 | SD,SD,RB,SD |
| 6-Oct-2016 | 1.5 | HC,SD,HC,RB | 11.5 | RC,SD,RC,RC | 1.5 | SD,RC,SD,RC | 11.5 | RC,RC,RC,RC | 1.5 | RB,SD,RB,SD | 11.5 | SD,SD,SD,RC |
| | 2 | RC,SD,RC,RC | 12 | RB,SD,HC,RC | 2 | SD,SD,SD,RB | 12 | RC,RC,RC,RC | 2 | RB,SD,RB,SD | 12 | SD,SD,SD,SD |
| | 2.5 | RC,SD,RC,HC | 12.5 | RC,SD,RC,RC | 2.5 | SD,SD,RB,RC | 12.5 | RB,RC,RC,RC | 2.5 | RB,SD,SD,SD | 12.5 | SD,SD,SD,RC |
| | 3 | RC,SD,SC,RC | 13 | RC,SD,RC,RB | 3 | SD,SD,SD,RB | 13 | RB,RC,RC,RC | 3 | SD,SD,SD,SD | 13 | RB,SD,SD,SD |
| | 3.5 | RC,RB,RC,RC | 13.5 | RC,RB,RC,RC | 3.5 | SD,SP,RC,HC | 13.5 | RC,RC,RC,RB | 3.5 | SD,RB,SD,SD | 13.5 | SD,RB,SD,SD |
| | 4 | RC,SD,RC,RC | 14 | RC,RB,RC,RC | 4 | SD,RC,RC,RC | 14 | RKC,RB,RC,RB | 4 | RB,SD,SD,RC | 14 | SD,RB,SD,SD |
| | 4.5 | RC,RB,RC,RC | 14.5 | RC,RC,RC,RC | 4.5 | SD,RB,RC,SD | 14.5 | RKC,RB,SD,RC | 4.5 | SD,RB,RB,RC | 14.5 | SD,RC,SD,SD |
| | 5 | RC,RB,RC,RC | 15 | RC,RB,RC,RB | 5 | RC,RC,RC,SD | 15 | RKC,RC,RC,RB | 5 | SD,RB,RB,RB | 15 | RC,RB,SD,SD |
| | 5.5 | RC,RB,RC,RC | 15.5 | RC,SD,RC,RC | 5.5 | RC,SD,RC,SD | 15.5 | RKC,RC,RB,RB | 5.5 | RB,RB,RC,RB | 15.5 | SD,SD,SD,SD |
| | 6 | RC,SD,RC,RC | 16 | RC,SD,RC,RC | 6 | RC,SD,RC,SD | 16 | RC,RC,RC,RB | 6 | SD,SD,RB,SD | 16 | SD,SD,RB,SD |
| | 6.5 | HC,SD,RC,RC | 16.5 | RC,RC,RC,RC | 6.5 | RC,RC,SD,SD | 16.5 | SD,RC,RC,RC | 6.5 | SD,SD,RB,RC | 16.5 | SD,RC,RC,SD |
| | 7 | RB,RKC,RC,HC | 17 | RC,SD,RC,RC | 7 | RC,RC,RB,RC | 17 | RB,RC,RC,RC | 7 | SD,SD,RB,RB | 17 | SD,SD,SD,RB |
| | 7.5 | HC,SD,RB,RC | 17.5 | HC,SD,RC,RC | 7.5 | RC,SD,RC,RC | 17.5 | RB,RC,RC,RB | 7.5 | SD,SD,SD,SD | 17.5 | SD,SD,SD,RC |
| | 8 | HC,SD,RC,RC | 18 | RC,SD,RC,RC | 8 | SD,SD,RC,RC | 18 | RB,RC,RB,RC | 8 | SD,SD,SD,RB | 18 | SD,SD,SD,RB |
| | 8.5 | RC,SD,RC,HC | 18.5 | RC,SD,RC,RC | 8.5 | SD,SD,HC,RB | 18.5 | RB,RC,RB,RB | 8.5 | SD,SD,RB,SD | 18.5 | RC,SD,SD,SD |
| | 9 | RC,SD,SC,HC | 19 | RC,SD,RC,HC | 9 | RC,SD,HC,SD | 19 | RB,RC,RB,HC | 9 | SD,SD,SD,SD | 19 | RC,SD,RB,SD |
| | 9.5 | RC,RKC,RC,RC | 19.5 | RC,SD,RC,HC | 9.5 | RC,RB,SD,RC | 19.5 | RB,RB,RB,RC | 9.5 | SD,SD,SD,RC | 19.5 | RC,SD,RB,RC |

| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Segment-2 (25-45 m)** | | | | | | | | | | | | |
| 5-Jan-2016 | 25 | RC,SD,RC,SC | 35 | RB,HC,RB,RC | 25 | SD,RB,RB,RC | 35 | RB,RC,RC,RB | 25 | SD,SD,RB,RC | 35 | SD,HC,SD,RC |
| 8-Apr-2016 | 25.5 | HC,RB,RC,RC | 35.5 | RB,RB,RB,RC | 25.5 | SD,RB,SD,RC | 35.5 | RC,RC,RC,RB | 25.5 | SD,RB,RB,RC | 35.5 | SD,RB,SD,RB |
| 3-July-2016 | 26 | HC,RB,RC,RC | 36 | RC,RC,RB,RC | 26 | RB,RC,RB,RC | 36 | RB,RC,RC,RB | 26 | SD,RB,RB,RC | 36 | RC,RC,SD,RB |
| 6-Oct-2016 | 26.5 | RC,RB,RC,RC | 36.5 | RC,RB,RC,RC | 26.5 | RC,RC,RB,RB | 36.5 | RB,RB,RC,RB | 26.5 | SD,RB,RB,RB | 36.5 | RC,RB,SD,RB |
| | 27 | RC,RC,RC,RC | 37 | RC,RC,RC,RC | 27 | SD,RC,RC,RB | 37 | RC,RB,RC,HC | 27 | SD,RC,RB,HC | 37 | RC,RC,RC,SD |
| | 27.5 | RC,RB,RC,RC | 37.5 | RC,RC,RC,RC | 27.5 | SD,RC,RC,RB | 37.5 | RC,RC,RC,RB | 27.5 | SD,RB,SD,SC | 37.5 | SD,RC,RC,SD |
| | 28 | RC,RB,RC,HC | 38 | RC,RC,RC,RC | 28 | RC,RC,RC,RB | 38 | RC,HC,RC,HC | 28 | SD,RB,RB,RC | 38 | SD,RC,SD,SD |
| | 28.5 | RC,SD,RC,RC | 38.5 | RC,RB,RC,RC | 28.5 | RC,RC,SD,RB | 38.5 | RC,RC,RC,RB | 28.5 | SD,SD,SD,RC | 38.5 | SD,RB,SD,SD |
| | 29 | HC,SD,RC,RC | 39 | RKC,RB,RC,RC | 29 | RC,RC,RB,RB | 39 | RB,RB,RC,RB | 29 | SD,SD,RB,HC | 39 | SD,RB,RC,SD |
| | 29.5 | RC,SD,RC,RC | 39.5 | RC,RB,RC,RC | 29.5 | RC,RB,RC,RC | 39.5 | HC,RB,RB,RB | 29.5 | SD,SD,SD,RC | 39.5 | SD,RB,SD,SD |
| | 30 | RC,SD,RC,RC | 40 | HC,SD,RC,RC | 30 | RC,RB,SD,RB | 40 | RB,RB,RB,RC | 30 | RB,SD,SD,RC | 40 | SD,SD,SD,SD |
| | 30.5 | RC,RC,RC,RC | 40.5 | RC,SD,RC,RC | 30.5 | RC,RC,SD,RB | 40.5 | RB,RC,RC,HC | 30.5 | SD,RC,RB,RB | 40.5 | SD,SD,SD,SD |
| | 31 | RC,RC,RC,RC | 41 | HC,RB,RC,RC | 31 | SD,RC,RC,SD | 41 | RB,RC,RC,SD | 31 | RB,RC,RB,RC | 41 | SD,RB,RC,SD |
| | 31.5 | RC,RB,RC,RC | 41.5 | HC,SD,RC,RC | 31.5 | RC,RC,RC,SD | 41.5 | HC,SD,RC,RC | 31.5 | RB,RB,SD,RC | 41.5 | SD,SD,RB,SD |
| | 32 | HC,SD,RC,RC | 42 | RC,SP,RC,RC | 32 | RKC,RC,RC,RC | 42 | RB,RB,RB,RB | 32 | SD,SD,SD,RB | 42 | RC,SP,RB,SD |
| | 32.5 | RC,SD,RC,RC | 42.5 | RC,SD,RC,RC | 32.5 | RC,RB,RB,RB | 42.5 | RC,SD,RB,RB | 32.5 | RB,SD,RC,RB | 42.5 | RB,SD,RC,SD |
| | 33 | HC,SD,RC,RB | 43 | RC,SD,RC,RC | 33 | RC,RC,RC,SD | 43 | RC,SD,RB,SD | 33 | RB,SD,SD,RC | 43 | RB,SD,RC,SD |
| | 33.5 | RC,RC,RC,RC | 43.5 | RC,SD,RC,RC | 33.5 | RC,RC,RC,SD | 43.5 | RC,RB,RC,RC | 33.5 | RB,RC,SD,RC | 43.5 | RB,SD,RB,SD |
| | 34 | RC,RB,RC,RC | 44 | RC,SD,RC,RC | 34 | RC,RC,RC,RB | 44 | RC,SD,RC,RB | 34 | RB,RB,SD,SD | 44 | RC,SD,RB,SD |
| | 34.5 | RB,RKC,HC,RC | 44.5 | RC,SD,RC,RB | 34.5 | SD,RB,SD,RB | 44.5 | SD,SD,HC,RB | 34.5 | SD,RC,SP,SD | 44.5 | RC,SD,RB,SD |
| **Segment-3 (50-70 m)** | | | | | | | | | | | | |
| 5-Jan-2016 | 50 | RC,SD,RC,RC | 60 | HC,SD,RC,RC | 50 | RC,RC,RC,RC | 60 | HC,SD,SD,HC | 50 | RC,SD,RC,SD | 60 | RB,SD,SD,SD |
| 8-Apr-2016 | 50.5 | RC,RC,RC,RC | 60.5 | RC,RC,RC,RC | 50.5 | RC,RC,RC,RC | 60.5 | SD,SD,SD,RC | 50.5 | RC,RC,RC,SD | 60.5 | RB,RC,SD,SD |
| 3-July-2016 | 51 | HC,RC,RC,RC | 61 | RC,RC,RC,HC | 51 | RC,RB,HC,RC | 61 | SD,RB,SD,RC | 51 | SD,RC,SD,SD | 61 | SD,RC,SD,SD |
| 6-Oct-2016 | 51.5 | RC,RC,RC,RC | 61.5 | HC,SD,RC,RB | 51.5 | HC,RB,RC,RB | 61.5 | SD,RC,RC,RC | 51.5 | SD,RC,SD,SD | 61.5 | SD,SD,SD,RB |
| | 52 | RC,RC,RC,RC | 62 | RB,SD,RC,RB | 52 | RC,RB,RC,RB | 62 | SD,RB,RC,RC | 52 | SD,RC,SD,SD | 62 | RB,SD,SD,RC |
| | 52.5 | RC,RC,RC,RC | 62.5 | RC,RC,RC,RB | 52.5 | RC,RB,RC,RC | 62.5 | SD,RB,RB,RC | 52.5 | SD,RC,SD,SD | 62.5 | RB,RC,RC,RC |
| | 53 | RC,SD,RC,RC | 63 | RC,RC,RC,RB | 53 | RC,RB,RB,RB | 63 | SD,RB,RB,RC | 53 | SD,SD,SD,RB | 63 | RB,RC,RC,SD |
| | 53.5 | RC,SD,RC,RC | 63.5 | HC,RC,RC,RC | 53.5 | RC,RC,RB,RB | 63.5 | RB,RB,RB,SD | 53.5 | SD,SD,SD,RB | 63.5 | RC,RC,RB,SD |
| | 54 | RC,SD,RC,RC | 64 | RC,RB,RC,RC | 54 | RC,RC,RB,RB | 64 | RB,RC,RB,RC | 54 | SD,SD,RC,RB | 64 | RC,RB,RB,RC |
| | 54.5 | RC,RC,RC,RC | 64.5 | RB,SD,RC,RC | 54.5 | RC,RB,RC,RB | 64.5 | SD,RB,RB,RC | 54.5 | SD,RC,SD,RC | 64.5 | RC,SD,RB,SD |
| | 55 | RC,SD,RC,RC | 65 | RB,RB,RC,RC | 55 | RB,RC,RC,RB | 65 | SD,RB,RC,RC | 55 | SD,SD,SD,RC | 65 | RC,RB,RB,SD |
| | 55.5 | RB,SD,RC,RC | 65.5 | RC,RB,RC,RC | 55.5 | RB,RC,RB,RB | 65.5 | SD,RB,RC,RC | 55.5 | SD,SD,SD,RC | 65.5 | RB,RB,RB,SD |
| | 56 | RC,SD,RC,RC | 66 | RC,RC,RC,RC | 56 | RB,RC,RB,RC | 66 | RC,RB,RC,RC | 56 | SD,SD,RC,RC | 66 | RB,RC,RC,SD |
| | 10.5 | RKC,SD,RC,RC | 20.5 | RKC,RC,RC,RC | 56.5 | RC,RB,HC,RB | 66.5 | RC,RC,RC,SD | 56.5 | RC,SD,RC,RB | 66.5 | RB,RC,RC,SD |
| | 57 | RC,RB,RC,RB | 67 | RC,RC,RC,HC | 57 | RC,RC,RB,RB | 67 | SD,RB,SD,SD | 57 | RC,RB,RB,RB | 67 | RC,RC,RB,SD |
| | 57.5 | RC,RB,RC,RB | 67.5 | RC,RC,RC,HC | 57.5 | RC,RC,RC,RC | 67.5 | RC,RB,SD,SD | 57.5 | RC,RB,RB,RB | 67.5 | RC,RC,RB,SD |
| | 58 | RB,RB,RC,RB | 68 | RC,SD,RC,RC | 58 | RB,RC,RB,RC | 68 | SD,RC,SD,RB | 58 | SD,RB,RC,RB | 68 | RC,SD,RB,SD |
| | 58.5 | RB,RB,RC,RB | 68.5 | RC,SD,RC,RC | 58.5 | RC,SD,RB,HC | 68.5 | SD,RB,SD,SD | 58.5 | SD,RB,RC,RB | 68.5 | RC,SD,RC,SD |
| | 59 | RC,RB,RC,RC | 69 | RC,SD,RC,RC | 59 | RC,SD,SD,RC | 69 | SD,RB,SD,RC | 59 | SD,SD,SD,RB | 69 | RB,SD,RC,SD |
| | 59.5 | RC,SD,RC,RC | 69.5 | RC,SD,RC,HC | 59.5 | RC,SD,SD,RC | 69.5 | SD,RB,SD,RC | 59.5 | RC,RB,SD,SD | 69.5 | RC,SD,RC,RC |
| **Segment-4 (75-95 m)** | | | | | | | | | | | | |
| 5-Jan-2016 | 75 | RB,RB,RC,RC | 85 | RC,RB,RC,RC | 75 | RB,SD,RB,HC | 85 | RC,RC,RC,RC | 75 | RC,RB,RC,RB | 85 | RB,RB,SD,SD |
| 8-Apr-2016 | 75.5 | RC,RB,HC,RC | 85.5 | RC,RB,RC,RC | 75.5 | RB,SD,RC,RC | 85.5 | RC,SD,RC,RC | 75.5 | RC,RB,RC,RB | 85.5 | RB,RB,SD,RC |
| 3-July-2016 | 76 | RC,RB,RC,RC | 86 | RC,SD,RC,RB | 76 | RB,SD,RC,SD | 86 | RB,SD,RC,RB | 76 | RC,RB,RC,RB | 86 | RB,SD,SD,SD |
| 6-Oct-2016 | 76.5 | RC,RB,RC,RC | 86.5 | HC,SD,RC,RB | 76.5 | RB,SD,RC,HC | 86.5 | RC,RB,SD,SD | 76.5 | RB,RB,RC,RB | 86.5 | SD,SD,SB,SD |
| | 77 | RC,RC,RC,RC | 87 | HC,SD,RC,RC | 77 | RC,SD,RC,RC | 87 | SD,RB,SD,RB | 77 | RB,RC,RB,RB | 87 | SD,SD,SB,SD |
| | 77.5 | RC,RC,RC,RC | 87.5 | RC,RB,RC,RB | 11.5 | RKC,RB,RB,RC | 87.5 | SD,RB,SD,RB | 77.5 | RC,RC,RB,RB | 87.5 | SD,RB,SB,SD |
| | 78 | RC,RC,RC,RC | 88 | RC,RB,RC,RB | 78 | RB,SD,RB,RB | 88 | RC,RC,RC,RB | 78 | HC,RC,RB,RB | 88 | RKC,RB,SB,SD |
| | 78.5 | RC,RC,RC,RC | 88.5 | RC,RB,RC,RC | 78.5 | RB,RC,RB,RB | 88.5 | RC,RB,RC,RB | 78.5 | RC,RC,RC,RB | 88.5 | SD,RB,SB,SD |
| | 79 | RB,RC,RC,HC | 23 | RKC,RC,RC,HC | 79 | RB,RB,RC,HC | 89 | SD,RB,SD,RB | 79 | RC,RC,RC,RB | 89 | SD,RC,SD,SD |
| | 79.5 | RB,RB,RC,HC | 23.5 | RKC,SD,RC,RB | 79.5 | RB,RB,SD,SD | 89.5 | SD,RB,SC,RB | 79.5 | RC,RB,RC,RB | 89.5 | RB,SD,SD,SD |
| | 80 | RC,RKC,RC,RC | 90 | RC,SD,HC,RC | 80 | RC,RB,SD,RC | 90 | SD,RC,SD,RB | 80 | RC,RB,RB,SD | 90 | RB,SD,SD,SD |
| | 80.5 | RC,RC,RC,RC | 24.5 | RKC,SD,RC,RC | 80.5 | RC,RB,RB,SD | 90.5 | SD,RB,SD,RC | 80.5 | RB,RC,RB,SD | 90.5 | SD,SD,SD,SD |
| | 81 | RB,RB,RC,RC | 91 | RC,RC,RC,RC | 81 | RB,RB,RB,RC | 91 | SD,RC,RC,SD | 81 | RB,RB,RB,SD | 91 | SD,RC,SD,RB |
| | 81.5 | RC,RB,RC,RC | 91.5 | HC,SD,RC,RC | 81.5 | RC,RB,RB,RB | 91.5 | SD,SD,RC,SP | 81.5 | RB,RB,RB,SD | 91.5 | RB,SP,SD,SD |
| | 16 | RKC,SD,RC,RC | 92 | SC,SD,RC,RC | 82 | RC,RB,RB,RC | 92 | SD,RC,RC,SD | 82 | RB,SD,RB,SD | 92 | RB,SD,RB,SD |
| | 16.5 | RKC,SD,RC,RC | 92.5 | HC,SD,RC,RC | 82.5 | RB,RB,RB,RC | 92.5 | SD,RC,RC,SD | 82.5 | RB,SD,RB,SD | 92.5 | RB,SD,RC,SD |
| | 17 | RKC,RC,RC,RC | 93 | RC,RB,RC,RC | 83 | RB,RC,RB,RB | 93 | RB,SD,RC,RC | 83 | RB,RC,RC,SD | 93 | RB,SD,RC,SD |
| | 83.5 | RC,SD,RC,RC | 93.5 | RC,SD,RC,RC | 83.5 | RC,RB,RC,SD | 93.5 | RB,SD,SD,RC | 83.5 | RB,SD,RC,SD | 93.5 | RB,RB,SD,SD |
| | 84 | RC,SD,RC,RC | 94 | RC,RB,RC,RC | 84 | RC,RB,RC,SD | 94 | RB,RC,RC,RC | 84 | RB,SD,RC,RC | 94 | RB,SD,RC,SD |
| | 84.5 | RC,SD,RC,HC | 94.5 | RC,RB,RC,RC | 84.5 | RC,RC,RC,HC | 94.5 | RB,RC,RC,SD | 84.5 | RB,SD,RC,RB | 94.5 | RB,RB,RC,RB |

HC = Hard Coral SC= Soft Coral RKC = Recently Killed Coral RB = Rubble SP = Sponge SD = Sand RC = Rock NIA = Nutrient Indicator Algae
OT = Other SI = Silt (Color Representation: Black = 5-Jan-2016; Red = 8-Apr-2016; Blue = 3-July-2016; Green = 6-Oct-2016)
*Note:* The percentage of recorded RKC is a result of Bleaching.

## Table-3: Reef Examination Summary

| Date/Time | | 10:00 Hrs | | | | | | 14:00 Hrs | | | | | | 16:00 Hrs | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Total S1 | Total S2 | Total S3 | Total S4 | Mean | SD | Total S1 | Total S2 | Total S3 | Total S4 | Mean | SD | Total S1 | Total S2 | Total S3 | Total S4 | Mean | SD |
| 5-Jan-2016 | HC | 5,2,3,7 | 8,1,1,1 | 4,4 | 4,2,4 | 5.25,0.75, 1.5,4 | 1.89, 0.96,1.29,2.45 | 1,2,2 | 2, 1,1,3 | 2,2,2 | 4 | 1,0.5,1.25 ,2.75 | 1.15,0.58, 0.96,0.96 | 2 | 1,2 | | 1 | 0.25,0.75,0.5 | 0.5,0.96,1 |
| 8-Apr-2016 | SC | 2 | 1 | | 1 | 0.25,0.5, 0.25 | 0.5,1,0.5 | | | | 1 | 0.25 | 0.5 | | 1 | | | 0.25 | 0.5 |
| 3-July-2016 | RKC | 2 | 1,1 | 2 | 6,1 | 2.25,1 | 2.63,0.82 | 5 | 1 | | 1 | 1.75 | 2.22 | | | | 1 | 0.25 | 0.5 |
| 6-Oct-2016 | NA | | | | | | | | | | | | | | | | | | |
| | SP | | 1 | | | 0.25 | 0.5 | 1 | | | 1 | 0.25,0.25 | 0.5,0.5 | | 1,1 | | 1 | 0.5,0.25 | 0.58,0.5 |
| | RC | 33,2,34, 30 | 28,8,36, 36 | 27,15,40, 28 | 25,9,38, 31 | 27.5,8.5,37, 31.3 | 3.79,5.32,2.58, 3.4 | 13,13, 21,20 | 21,22,2 5,8 | 18,14,1 4,22 | 13,11, 20,13 | 16.3,15, 20,15.8 | 3.95,4.83, 4.55,6.45 | 4,2,2,10 | 6,9,7,12 | 15,15, 14,8 | 8,9,15,2 | 8.25,8.75,9.5,8 | 4.79,5.32,6.14, 4.32 |
| | RB | 2,7,1,3 | 3,13,3,2 | 7,8,8 | 4,15,5 | 4,10.8,1,4.5 | 2.16,3.86,1.41, 2.65 | 9,11,9, 12 | 9,12,9, 23 | 6,21,13, 11 | 16,18, 10,12 | 10,15.5, 10.3,14.5 | 4.24,4.8, 1.89,5.69 | 8,7,13,7 | 10,13, 14,7 | 9,8,10, 10 | 23,15, 15,13 | 12.5,10.8,13,9.25 | 7.05,3.86,2.16, 2.87 |
| | SD | 27 | 16 | 17 | 15 | 18.8 | 5.56 | 13,14,8, 6 | 7,5,5,6 | 14,5,11, 5 | 10,11,9, 10 | 11,8.75, 8.25,6.75 | 3.16,4.5, 2.5,2.22 | 28,29, 25,23 | 24,16, 18,18 | 16,17, 16,22 | 7,15,10, 25 | 18.8,19.3,17.3,22 | 9.29,6.55,6.19, 2.94 |
| | SI | | | | | | | | | | | | | | | | | | |
| | OT | | | | | | | | | | | | | | | | | | |
| **Total No.** | | 40,40, 40,40 | 40,40, 40,40 | 40,40, 40,40 | 40,40, 40,40 | | | 40,40, 40,40 | 40,40, 40,40 | 40,40, 40,40 | 40,40, 40,40 | | | 40,40, 40,40 | 40,40, 40,40 | 40,40, 40,40 | 40,40, 40,40 | | |

*Note*: Total must be 40 for each Segment. (Color Representation: Black = 5-Jan-2016; Red = 8-Apr-2016; Blue = 3-July-2016; Green = 6-Oct-2016)

## Table-4: Marine Data

| Date | Species/Diving Time/Depth | 10:00 Hrs | | | | 14:00 Hrs | | | | 16:00 Hrs | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 0-20m | 25-45m | 50-70m | 75-95m | 0-20m | 25-45m | 50-70m | 75-95m | 0-20m | 25-45m | 50-70m | 75-95m |
| | **Invertebrates** | | | | | | | | | | | | |
| 5-Jan-2016 | *Stenopus Hispidus* (Banded Coral Shrimp) | | | | | | | | | | | | |
| 8-Apr-2016 | *Diadema* Urchins & *Echinothrix* spp. | | | | 3 | 1 | | | | | | 1 | |
| 3-July-2016 | *H. mammilatus* (Pencil Urchins) | | | | | | | | | | | | |
| 6-Oct-2016 | *Tripneustes* spp. (Collector Urchins) | | | | | | | | | | | | |
| | *Holothuridae* (Sea Cucumber) | | | | | | 1 | | | | | | 1 |
| | *Acanthaster plancii* (Crown of Thorns) | | | 1 | | 1 | | 1 | | | | | |
| | *Charonia tritonis* (Triton) | | | | | | | | | | | | |
| | *Palinuridae* (Lobster) | | | | | | | 1 | | | | | |
| | *Lambis truncate sebae* (Seba Spider Conch) | | | | | | | | | | | | |
| | *Tridacna* sp. (Giant Clam) <10 cm | | | | | | | | | | | | |
| | 10-20 cm | 3,2,1 | 1,1,1 | 2,1,1 | 1 | | | | | 1 | 1 | 1 | |
| | 20-30 cm | 4 | 2 | 2 | | | | | | | | | |
| | 30-40 cm | | | | | | | | | | | | |
| | 40-50 cm | | | | | | | | | | | | |
| | >50 cm | | | | | | | | | | | | |
| | **Total No. of Giant Clams** | | | | | | | | | | | | |
| | **Coral Disease/Bleaching/Trash/Other Impacts (0 = None, 1 = Low, 2 = Medium, 3 = High)** | | | | | | | | | | | | |
| 5-Jan-2016 | Coral Damage: Boat/Anchor | | | | | | | | | | | | |
| 8-Apr-2016 | Coral Damage: Dynamite | | | | | | | | | | | | |
| 3-July-2016 | Coral Damage: Other | | | | | | | | | | | | |
| 6-Oct-2016 | Trash: Fish Nets | | | | | | | | | | | | |
| | Trash: General | | | | | | | | | | | | |
| | Bleaching: % of Coral Population | | | | | | | | | | | | |
| | Bleaching: % of Colony | | | | | | | | | | | | |
| | Coral Disease: % of Coral Affected | | | | | | | | | | | | |
| | Rare Marine Life Sighted | | | | | | | | | | | | |
| | **Fishes** | | | | | | | | | | | | |
| 5-Jan-2016 | *Chaetodontidae* (Butterfly Fish) | 2,1,2 | 6,3,2 | 1,1,2 | 2,5,1 | 2,2,3,2 | 1,3 | 2,7 | 4,4 | 2,1 | 2,2,6,2 | 2 | 1,1 |
| 8-Apr-2016 | *Haemulidae* (Sweetlips) | | 1,1 | 1 | | | | | 1 | | 1,1,8,1 | 1 | 1 |
| 3-July-2016 | *Plechtorhinchus gaterinus* (Blackspotted Sweetlips) | | | | | | | | | | | | |
| 6-Oct-2016 | *Plectorhinchus schotaf* (Minstrel Sweetlips) | | | | | | | | | | | | |
| | *Lutjanidae* (Snapper) | 11,2,7 | 1,2,2 | 5 | 2,6,2 | 2 | 8 | 4,15,17,5 | | | 4,8,5 | 32,27,14 | 3,7,5 |
| | *Acanthuridae* (Surgeon Fish) | | | | | | | | | | 2 | | |
| | *Naso unicornis* (Bluespine Surgeon Fish) | | 1,1 | | | | | | 2 | | | | |
| | *Ctenochaetus striatus* (Lined Bristletooth) | 5,5 | 7,3,4 | | 4 | 12,5,7 | 8 | 2,5,5,5 | 4,7 | 1,7 | | 2,2 | 5 |
| | *Zebrasoma desjardinii* (Sailfin Tang) | | | 2 | | | | | 1 | 1 | | | |
| | *Zebrasoma xanthurum* (Yellowtail Tang) | | | | | | | | | 1 | | | |
| | *Acanthurus sohal* (Sohal Sugeonfish) | 3,25 | 7 | | | 5,5 | | | | 4,2 | | 7 | 5 |
| | *Pomacentridae* (Damselfish) | | | | | | | | | | | | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Abudefduf vaigiensis* (Sergeant Major) | 2,15,25 | 10,27,11 | 25,3,25 | 8,30,29,15 | | 7 | 16 | 20 | 2,12,35 | 12,85,45,25 | 8,7,25 | 10,15,45 |
| | *Chromis dimidiata* (Half & Half Chromis) | 25,21,5 | 3 | 10,5,5 | 7,5 | | 7 | | | 9 | | | 2 |
| | *Amblyglyphidodon indicus* (Whitebelly Damselfish) | 2,3 | 7,2,3,4 | 2,4 | 4,2 | 4,4 | 2 | | 5 | 80,3 | 2 | | 15,5,5 |
| | *Dascyllus aruanus* (Humbug Dascyllus) | 8 | 5 | 8 | 7 | 17 | 15,11,25 | 47,15,25 | 48,5,30 | 23 | 21,22 | 55 | 41,55,25 |
| | *Chromis viridis* (Bluegreen Chromis) | 10,110,19 | | | | 30 | 15 | 45,10,25 | | 7,5 | | 7 | |
| | *Stegastes Nigricans* (Dusky Gregory) | | | | | | | | | 10 | | | 15,5 |
| | *Amphiprion bicintus* (Red Sea Anemonefish) | | | | | 4 | | | | 19 | 2 | | |
| | *Pomacentrus sulfureus* (Sulfur damsel) | 2,4,7 | 1,2 | 1,3 | 3,1,5 | 3 | 2,2,2 | 1 | | 10,1 | | 1,1 | 2,2 |
| | *Amblyglyphidodon flavilatus* (Yellowside Damselfish) | 5 | 10,1,2 | 6,3 | 9 | 10 | 3 | 2 | | 1 | | 3 | 5 |
| | *Scaridae* (Parrot Fish) | 3 | 2,5 | 2,1 | 2 | 4,1,2 | 1 | 1,3 | 1 | 2,2 | 1 | 2 | |
| | *Holocentridae* (Squirrel Fish & Soldier Fish) | | | 1 | | | | | | | | | |
| | *Sargacentron spiniferum* (Longjawed Squirrel Fish) | | 1 | | 1 | | | | | | | | |
| | *Neoniphon samara* (Spotfin Squirrel Fish) | 1 | 1 | | | | 1 | | | | | | |
| | *Myripristis murdjan* (Blotchye Soldier Fish) | | 4,2,2 | | 1 | | | | | 1 | 2 | | |
| | *Pomacanthidae* (Angel Fishes) | 1 | 1 | | 1 | 1 | | | | 1 | 1 | | |
| | *Labridae* (Wrasses) | | | | | | | | | | | | |
| | *Halichoeres hortulanus* (Chequerboard Wrasse) | 1 | 1,1,2,2 | | | 1,1 | 1,1 | 1 | 1,1 | 1,1 | 1 | | 2,2 |
| | *Halichoeres iridis* (Rainbow Wrasses) | | 1 | | | | 1 | | | | | | |
| | *Gomphosus caerulus* (Indian Bird Wrasse) | | 1,1,1 | 1,2,2 | | 1 | | 1,2 | 5 | 1 | | | 1 |
| | *Thalassoma rueppelii* (Klunzingers Wrasse) | 2,4,4 | | 2,2 | 1 | 1 | 1 | 1 | | | | | |
| | *Thalassoma lunare* (Crescent Wrasse) | | 1 | 2 | | | | | 2,1 | 1 | | | |
| | *Cheilinus lunulatus* (Broomtail Wrasse) | | 1 | | | | | | | | | | |
| | *Cheilinus undulates* (Napoleeon Wrasse) | | | | | | | | | | | | |
| | *Chelinus abudjubbe* (Abudjubbe Wrasse) | | | | | 1 | | | | | 1 | 1 | |
| | *Chelinus quinquecinctus* (Redbreasted Wrasse) | | | 2 | | | 1 | | 2 | | 1 | | |
| | *Epibulus insidiator* (Slingjaw Wrasse) | | 1 | | 1 | 1 | | | | | | | |
| | *Cirrhitidae* (Hawk Fish) | | 1,1 | | 1 | | 1,2 | 3 | | | | | |
| | *Apogonidae* (Cardinal Fish) | | | | | | | | | | | | |
| | *Syngnathidae* (Pipe Fish) | | | | | 1 | | 1 | | | | | |
| | *Balistidae* (Trigger Fish) | 1 | | | | | | | | | | | |
| | *Blenniidae* (Blennies) | | | | | | | | | | | | |
| | *Mullidae* (Goat Fish) | | | 3 | | | | | | | | | |
| | *Caesionidae* (Fusiliers) | 10,25 | | 30,30 | | | 12 | | | 100 | | | |
| | *Arothron diadematus* (Masked Puffer) | | 1 | | 1 | | | 75 | | | 1 | | |
| | *Monotaxis grandoculls* (Bigeye Emperor) | | | | | 7 | 3,2 | 3 | | | 4,4 | | |
| | *Scolopsis ghunam* (Arabian Spinecheek) | | | | | | | | 7 | | | 1 | |
| | *Acanthopagrus bifaciatus* (Doublebar Bream) | | | | | | | 3 | | | | | |
| | *Cephalopholis argus* (Peacock Grouper) | | | | | | | 2 | 1 | | | 1 | |
| | *Cephalopholis hemistiktos* (Halfspotted Hind) | | | | | | | 2 | | | | | |
| | *Aethaloperca rogaa* (Redmouth Grouper) | | | | | | | | 1 | | | | |
| | Other Fishes | | | | | | | 1 Moray Eel | | | | 5 Orange spotted Trevally's | |
| | Great Barracuda | | | | | | | | | | | | |
| | **Count of *Serranidae* (Grouper) Sizes >30 cm** | | | | | | | | | | | | |
| 5-Jan-2016 | 30-40 cm | 1 | | 1 | | | 1,1 | | | | | | |
| 8-Apr-2016 | 40-50 cm | | | | | | | | | | | | |
| 3-July-2016 | 50-60 cm | | | | | | | | | | | | |
| 6-Oct-2016 | >60 cm | | | | | | | | | | | | |
| | **Total No. of Grouper** | 1 | | 1 | | | 1,1 | | | | | | |
| | Rare Marine Life Sighted | | | | | | | | | | | | |

(Color Representation: Black = 5-Jan-2016; Red = 8-Apr-2016; Blue = 3-July-2016; Green = 6-Oct-2016)

# 9. FIGURES

Fig. 15: Effluent Water pH

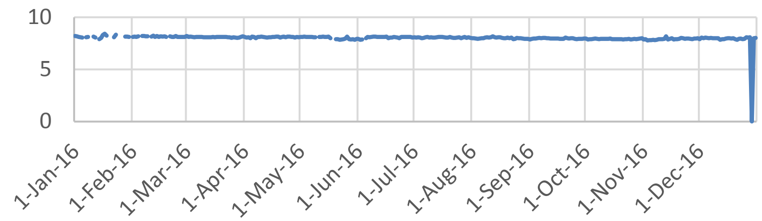


Fig. 16: Effluent Water Res. $Cl_2$ (ppm)

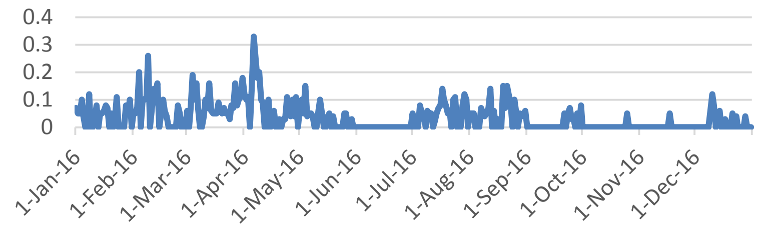


Fig. 17: Effluent Water Cu Concentration (ppb)

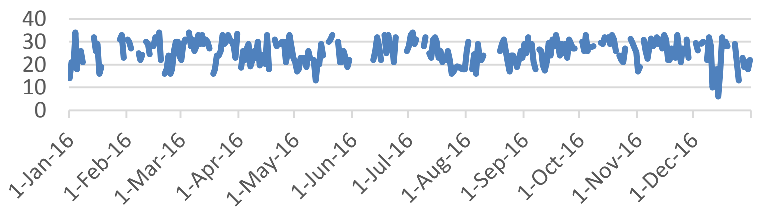


Fig. 18: Effluent Water Δ Salinity (ppt)

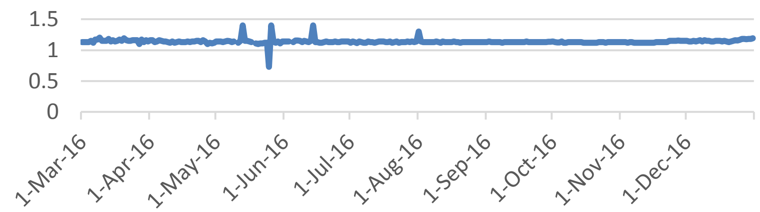


Fig. 19: Effluent Water Temp. (°C)

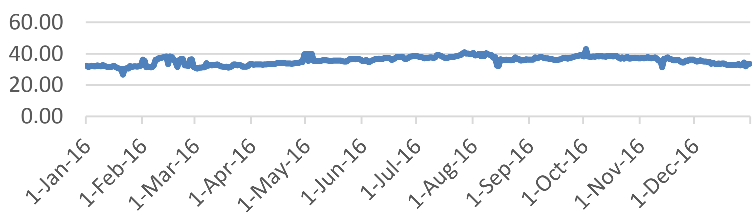


Fig. 20: Effluent Water Flow ($m^3$/Hr)