Original Article

Effects of environmental change on phytoplankton in Kuwait Bay, Arabian Gulf: Emerging Critical Issues

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Abstract

Declining fluvial discharge, dust storms, salinity increases to ~44 PSU and anthropogenic activities impact the phytoplankton of Kuwait Bay, located in the hyper-arid desert climate of the north-western Arabian Gulf. Historical trends in phytoplankton dynamics in the bay are reviewed, which include decadal changes in phytoplankton communities and episodic algal blooms. The number of identified dinoflagellate species has increased from 45 to 213 since 1931, with increases in six categories of potentially toxigenic species, of which *Gymnodinium catenatum*, *Karenia papilionacea* and *Pyrodinium bahamense* pose the highest risk. A decline in chlorophyll *a* between 2002 and 2020, despite available nutrient sources, likely contributed to the decline in Arabian Gulf fisheries. Apart from declining pelagic fish catches, several mass fish mortality events have been reported for mullets, sobaity seabreams and sea cucumbers. Experimental manipulation of offshore Kuwait surface waters (~42 PSU) to salinities of 32, 37, 42 and 50 PSU resulted in phytoplankton bloom proportions in four days at 32 and 37 PSU. The measured trends in key ecosystem variables together with the decline in diatoms to dinoflagellates, and mass mortalities of fish, suggest a rapidly changing structure and functioning of phytoplankton communities in Kuwait Bay. Restoration measures are suggested to improve the ecological condition of the bay and surrounding Arabian Gulf, including greater regional collaboration to reduce the flow of brine and waste water nutrients into the Gulf.

Keywords: Environmental perturbations, desalination, eutrophication, remediation, oligotrophication, Arabian Gulf

Introduction

The Arabian Gulf (AKA. Persian Gulf) is a unique, subtropical, nearly enclosed, hyper-saline inland sea in a semi-arid region (Fig.1). The Gulf is approximately 1000 km long, 200-300 km wide, 2.39 x 10^5 km^2 in area, with an average depth of 35 m and 8630 km^3 volume (Al-Yamani, 2008). To quote Brewer and Dyrssen (1985), the Gulf experiences 'extraordinary neglect and tanker traffic'. Besides the hot climate, natural perturbations affecting the Gulf include the discharge from Shatt Al-Arab River - the only freshwater source, and dust storms. Shatt Al-Arab River- the confluence of the rivers Tigris, Euphrates, and Karun contributes 35-133 km^3 y^{-1} freshwater and 62.4 x 10^6 tons y^{-1} sediment (Reynolds, 1993). Several publications (Al-Yamani *et al.*, 2007, 2008, 2021; Jones *et al.*, 2008; Ben-Hasan *et al.*, 2018) addressed the importance of the Shatt Al-Arab River flow on the Gulf marine environment. Additionally, the dust storms contribute 60-200 x 10^6 tons y^{-} aeolian dust (Al-Dousari *et al.*, 2021).

Kuwait Bay (Bay) in the north-western Arabian Gulf, is a mesotidal hyper saline semi enclosed Bay with 130 km coastline, 720 km^2 area and ~3.76 km^3 volume.

The average depth of the Bay is 5.2 m, and its maximum is 30m. The Bay experiences natural and anthropogenic perturbations similar to those in the six Gulf Co-operation Council (GCC) countries.

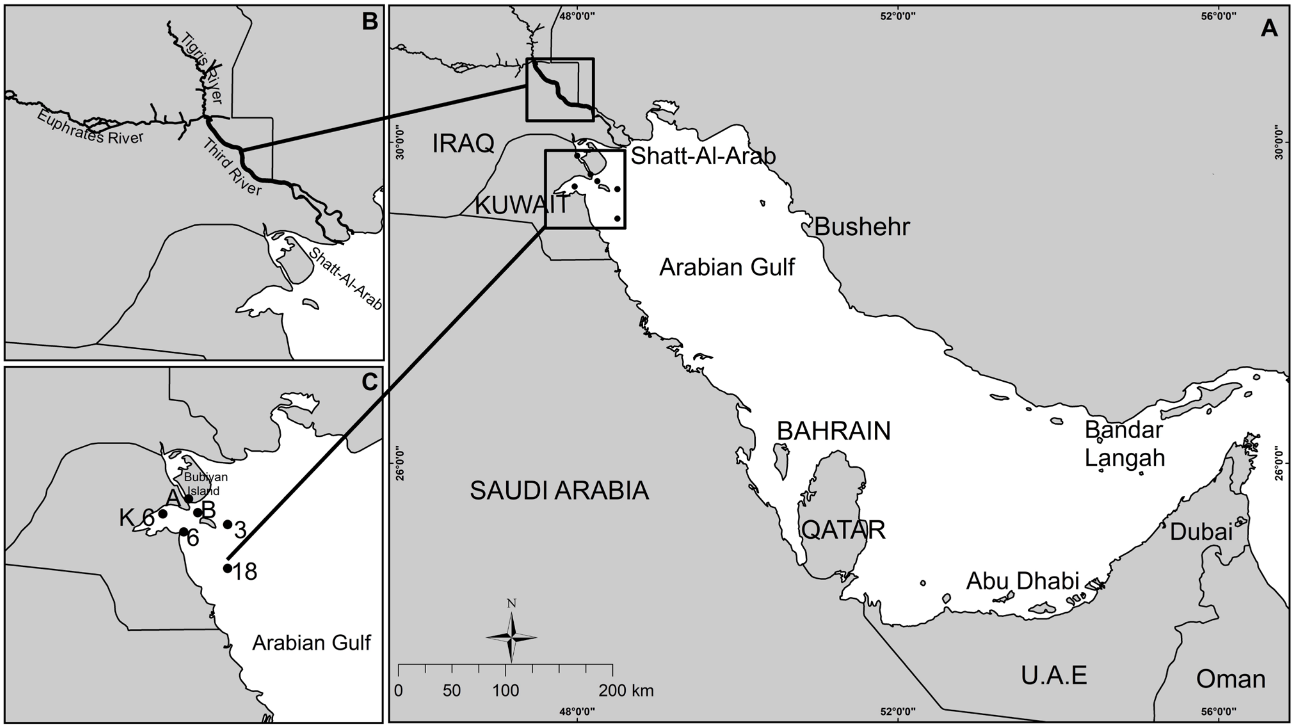

Figure 1. Location of Gulf countries, Euphrates and Tigris, Third River, marshlands of Mesopotamia (top left) and station locations in Kuwait Bay (bottom left).

The Gulf region is a harsh environment, and the high temperatures compound the stress caused by multiple perturbations that operate at multiple time scales. The present Gulf population of 43.2 million people is growing rapidly by 4 % y^{-1} and is expected to reach 59.8 million by 2050 (Le Quesne *et al.*, 2021). With an average <100 mm y^{-1} rainfall, decreasing flow from Shatt Al-Arab, Gulf Co-operation Council (GCC) countries receive much of their freshwater requirements from 1483 desalination plants that produce 9 x 10^9 hm^3 y^{-1}, and this figure is expected to grow substantially (Qureshi, 2020). Within the GCC, approximately 40 coastal towns with 300 wastewater treatment plants discharge 3455 hm^3 y^{-1} of which 73 % is treated and 39 % of this is reused, with the rest is discharged into the sea (Qureshi, 2020) . The socio-economic conditions in many regions of the Gulf are similar and accelerate the environmental stresses that would increase in future as a direct consequence. Common to the GCC countries, whose solid waste management practices are similar (Al-Hasawi, 1999), are the incessant anthropogenic environmental perturbations that have been on the rise and unabated for decades (Hosseini *et al.*, 2021). Intensive dredging, reclamation and infilling impact coastal habitats. Additionally, the Gulf acts as a receptacle for unintended spillage from oil tankers, discharges of ballast waters from shipping, sanitary wastewater, industrial wastes, effluents from slaughterhouses, dairy plants and mariculture operations which perturb the ecosystem (Table 1).

To protect water quality and further environmental deterioration and habitat loss in the Arabian Gulf, GCC countries established a Regional Organization for the Protection of the Marine Environment (ROPME) in 1979. ROPME is mandated to co-ordinate efforts of the eight member countries to protect the marine and coastal environment and ecosystems. However, much of the data generated from the Gulf are disparate and disorganized spatially or temporally, compared to data from the western countries. Of all the GCC countries, Kuwait has a more organized environmental database that incorporates environmental data from its monitoring program which began in 1967. In this paper these long-term series datasets are focused on, as a representative study indicative of the environmental issues in the Gulf.

Table 1. Natural and anthropogenic perturbation impacting the Gulf ecosystem.

Category	Perturbation	Contribution y^{-1}	Reference
Natural	Shatt Al-Arab out flow	35-133 km^3 freshwater and 62.4 x 10^6 tons sediment)	Reynolds, 1993
	Evaporation	~350-800 km^3	Swift and Bower, 2003
	Incursion of Indian Ocean Surface water Sverdrup	0.10 - 0.20 0.28 Sv	Swift and Bower, 2003 Johns *et al.*, 2003
	Aeolian dust due to Dust storms	60-200 x10^6 tons	Safar, 1985
Anthropogenic	Third River (Khor Al-Zubir -Khor Al-Sabiyah	6.57 km^3 Drainage from Salt encrusted fields	Richardson *et al.*, 2005
	Brine from 1483 Desalination plants km^3	1.264	Qureshi, 2020
	Wastewater x 10^{4}km^3	2.39 average	Qureshi, 2020; Chalit, 2009; GCC wastewater Report, 2020
	Waste water discharged into sea km^3	1.09	Al-Anzi *et a*l., 2012
	Sewage km^3	1.84	Aleisa and Al-Zubari, 2017b
	Discharge from slaughterhouses, diary plants	9125 tons	Bustillo-LeCompte and Mehrvar, 2017
	Spillage of oil	160 x 10^6 t	Jacob and Al-Muzaini, 1995
	Dredging, coastline encroachments, reclamation	Details not available	

Dorgham and Moftah (1989) published the first account on the plankton of the northwest Gulf based on data assembled by the Kuwait Institute. Subsequent studies discussed the environmental conditions and phytoplankton ecology (Subba Rao and Al-Yamani, 1998, 2000), and climatic factors regulating phytoplankton (Nezlin *et al.*, 2010). Sheppard *et al.* (2010) reviewed the large-scale activities impacting this shallow Gulf, and concluded that environmental conditions within this young sea were on the decline. Dorgham (2013) identified the achievements and limitations in plankton research in the Gulf. Essential gaps exist due to irregular collection of samples, sporadic studies in localized areas, the lack of integrated studies between the GCC countries, and the absence of comprehensive regular monitoring studies in the whole Gulf. After the Sheppard *et al.* (2010) study, new information on the Gulf has been published on water quality from 1983 to 2016, (Devlin *et al.*, 2015, 2019), diatoms, dinoflagellates, flagellates, and cyanobacteria (Al-Kandari *et al.*, 2009; Al-Yamani and Saburova, 2019 a and b), winter phytoplankton (Polikarpov *et al.*, 2016), hydrography (Al- Yamani *et al.*, 2017), and algal blooms (Al-Yamani *et al.*, 2012; Al-Yamani and Saburova, 2019 a; Polikarpov *et al.*, 2020) which are included in this review.

Despite the uncertainties in the data (Dorgham, 2013), reorganization of the metadata provides a valuable means to assess the environmental perturbations and their impact on the Gulf phytoplankton ecology. Based on a meta-analysis of data collected since 2010, this review was conducted to understand the combined impact of natural and anthropogenic perturbations, and increasing salinity on phytoplankton ecology, a crucial ecosystem component. It is hypothesized that the current high temperature and high salinity regime in the Arabian Gulf, the heavy loading of nutrients and chemical elements, and the longer residence times of bay waters are causing shifts in phytoplankton biomass to the detriment of the ecosystem. It is contended that the resultant breakdown of any seasonal phytoplankton cycle and the consequential loss of pelagic fish catch is an alarming sign of the shifting structure and functioning of this unique environment. This study is used to reiterate the need for more systematic time series data collections among GCC countries and for initiation of laboratory algal culture studies aimed at *understanding* the structure and physiological functioning of phytoplankton.

Sources of data

The physical, chemical and biological data presented here are based on various publications but were not balanced with regard to sampling. Temperature and salinity plots for 2004-2014 (Al-Yamani et al., 2014) were used to show their temporal changes. A Sea Bird electronic 25 profiler was also used to obtain profiles of temperature and salinity. Nutrients were analyzed using standard methods with an automated Auto-analyzer- Skalar SANplus Segmented Flow Analyzer Model. The precision obtained was greater than 0.2 % for nitrate, 1.1 % for phosphate and 0. 2 % for silicate. Phytoplankton biomass expressed as chlorophyll *a* (chl. *a*) was determined on duplicate samples using the fluorometric method utilizing a Turner Design Fluorometer Model 10-AU. Extraction of pigments was in 15 ml 90 % acetone + 5ml DMSU, in dark at 0 °C for 24 h (Barnes *et al.*, 1992). Water samples preserved with acidified Lugol solution were used for enumeration of phytoplankton by the Utermöhl method. These are described by Al-Yamani *et al.* (2006, 2012, 2017), Al-Yamani and Saburova (2019 a and b), Al-Said *et al.* (2017), Al-Kandari *et al.* (2009), and Polikarpov *et al.* (2016). Taxonomic nomenclature is based on WoRMS Editorial Board (2023).

Additionally, remotely sensed ocean color data from January 2002 to December 2002 were used for chlorophyll *a* estimations. Ocean color data was downloaded from Ocean color https://www.oceancolour.org site. The Ocean Color data sets consist of a time-series of merged and bias- corrected MERIS, MODIS Aqua, and SeaWiFS data at 4 km-by 4 km resolution (https://oceancolor.gsfc.nasa.gov.). Chlorophyll *a* data was processed using QGIS and ArcGIS Pro software for Geometric correction, and calibration. Data are downloaded in NetCDF format; the NetCDF file was converted to GeoTIFF format using QGIS. Final processing and analysis are performed in ArcGIS Pro for the chl. *a* distribution and final cartographic products are generated for 2020.

Results and Discussion

Natural perturbations

a) Fluvial discharge from Shatt Al-Arab

Strong inter annual variations in nutrient loading can be seen due to variations in riverine flow. The Shatt Al-Arab fluvial outflow contributes to the nutrient distribution (µ mol) in the Gulf (Table 2); nutrients were high and ranged from 1.82-7.07 µ mol PO_4-P, 365.9 – 733.8 µ mol NO_3-N, and 135.6 -306.9 SiO_2 -Si (Talling, 1980; Al-Ansari *et al.*, 2019; Al- Said *et al.*, 2017; Saad, 1985). An earlier study showed that in the Kuwait Bay, nutrients were not exhausted during 1985-89 when there was good river discharge; of the 28 instances, only on two occasions in Kuwait Bay waters and three instances in the offshore, SiO_2-Si was <11.32 **µ**m and chl. *a* ranged between 5.4 to 9.9 mg chl. *a* m^2 (Subba Rao and Al-Yamani, 1999). When freshwater inflow was moderate the SiO_2-Si: salinity (SiO_2:PSU) is usually about 1 and can be used as a tracer of freshwater. During 1997 the mean SiO_2: PSU in the Bay (sampling station K6) was 2.92 (Al-Yamani *et al.*, 2006) and the mean for 2006-2023 at station Z04 (located~ 48 ^{0} E and ~29 ^{0}.50N in the vicinity of K6) was 0.68 (Devlin *et al.*, 2015) suggesting a decrease in the flow of freshwater.

Nutrients in the Bay varied between 0-5.91 PO_4-P, 0 - 111.27 NO_3 N and 0.05-68.96 SiO_2-Si and are higher than those reported for 1983-2013 (Devlin *et al.*, 2015) (Table 2). A compilation of nutrient levels in the Gulf (Shatt Al-Arab, Basrah Estuary, Kuwait, Iran-Busheir, North of Iran, South of Iran, Qatar, UAE, Hormuz Strait, Gulf of Oman) shows existence of a large variation in the nutrient levels; i.e., 0-6.01 PO_4-P, 0-103.5 NO_3-N and 0-306.9 SiO_2-Si (Subba Rao and Al-Yamani, 2000). Compared to the northern Kuwait waters, nutrient levels in the south, near Hormuz and the Sea of Oman are low (Ismail and Al Shehhi, 2022; Emara, 2010) possibly due to reduced freshwater admixture. Besides the contribution by Shat Al-Arab, in these tidally well mixed shallow Gulf waters, the multiple sources of anthropogenic enrichments (Table 1) obliterate any seasonal trends, and account for large variations in nutrients.

Various sources contribute to elemental loadings to the Bay (Table 3). Kuwait surface water samples yielded high levels (µM) of Fe 670-28160, Cu 10260-23250, Ni 15.63- 23.25, Co 50-1340, Zn 5140-25330 and Mn 0.91-1.09, generally higher than in the offshore (Al-Said *et al.*, 2018 a). Shatt Al-Arab sediments are rich in Fe, Cu, Ni, Co and Zn and their ranges and mean (µ M) correspond to 0.00067-0.028 ($\bar{x}$ 0.0144 Fe), 0.0039-0.023 ($\bar{x}$ 0.014 Cu), 0.0078-0.0248 ($\bar{x}$ 0.0163 Ni), 0.00051-0.00134 ($\bar{x}$ 0.000925Co) and 0.005-0.025 ($\bar{x}$ 0.015Zn) (Al-Said *et al.*, 2018 b). Of interest is the existence of a gradient of Fe, Cu, Ni, Co, Zn Cr, Mn, V levels in the sediments, similar to the macronutrients, with high values in the north decreasing to the south (Basaham and Al-Lihaibi, 1993).

Although there was a reduction in the Shat al-Arab flow, the high level of nutrients is attributed to increased loading associated with industrial discharges and sewage outfalls. Devlin's analysis suggests several hypotheses related to the structure and functioning of phytoplankton in the Bay but data from perturbation experiments utilizing natural or cultured algae are required. Results of an experimental study in the Northern Arabian Gulf showed high denitrification 404±78 g NO_3-N ha day (Al Ghadban *et*

Table 2. Nutrient levels (µM) in the Arabian Gulf.

Region	PO_4 - P	NO_3 - N	SiO_2 - Si	Reference
Shatt Al-Arab	1.82-7.07	365.9 - 733.8	NA	Talling, 1980
	1.15-6.46	41.13- 114.52	135.6-306.9	Al-Ansari *et al*., 2019. Saad, 1985
Kuwait waters	0.07-0.59	0.29- 4.60	0.10-11.32	Al-Said *et al*., 2017
(mean 2000-2012)	Traces –5.91	Traces – 111.27	0.05-68.96	Al-Said *et al*., 2017
(monthly 1997-98)	0-5.16	0-14.12	1.19-52.48	Al-Yamani *et al*., 2006
(mean 1983-2013)	0.4-0.7	2.1-3.5	25.8-33.5	Devlin *et al*., 2015
Nov-Dec 2018	~3.1	~9	30.0	Ahmed *et al*., 2022
Qatar	0.03-1.23	0.12-0.90	0.66-5.12	Dorgham and Mofta, 1989
UAE	0.07-0.84	0.17-0.54	2.14-6.26	Emara, 2010
Strait of Hormuz	0.23-0.49	0.15-0.23	0.39-0.99	Dorgham and Mofta, 1989
Gulf of Oman	0.19-0.79	0.12-0.59	1.62-5.48	Dorgham and Mofta, 1989
Sea of Oman	0.08-1.65	0.08-3.44	2.49-22.47	Emara, 2010
Hormuzgan Sea	0.82-2.15	5.2-27.3		Esmaeili *et al*., 2021

al., 2012) corroborated by Al-Yamani and Naqvi (2019) who reported high nitrite levels in the euphotic zone of the Gulf. Hypoxia occurs in the Arabian Gulf due to oxidation of dissolved organic material. Similar to denitrification, there are no estimates of the sources of organic matter. The only work using clean sampling and analytical techniques is that of Al-Said *et al*., 2018 b, who suggested that anthropogenic inputs are important for Total Organic Carbon.

b) Dust Storms

The Gulf countries experience 15-20 dust storms per year that contribute 60-200 x10^6 tons of dust km^{-2} y^{-1}. This enormous quantity of dust is deposited over the land and sea (Prakash *et al*., 2015; Al-Dousari *et al*., 2021). The annul amount of dust received varies regionally; the Kuwait region experiences on the average 373 tons (Al-Dousari *et al*., 2017). The most abundant elements delivered by dust storms (Al-Awadhi, 2005) are Fe (19.62 g·kg^{-1}) and Al (9.672 g·kg^{-1}) followed by Cr (0.4318 g·kg^{-1}) and Mn (0.3941 g·kg^{-1}) besides large quantities of Si, Zn, P, Cu and Ni. The total dust fallout into the Kuwait Bay from August 2010 to July 2011 was estimated as 94,282.0 t that contributed 4569 t iron, 12,743 t clay, 99,818 t quartz, 14,177 t sulfate, and 169.167 t of ash (Neelamani and Al-Dousari, 2016).

Shatt Al-Arab sediments act as store houses of Fe, Cu, Ni, Co and Zn, and their ranges and mean (µM) are presented in Table 3. Dredging is an ongoing coastal activity for expansion of berths, deepening the approach channel, construction of marinas, and millions of tons of dredged spoil are redistributed. The Aeolian dust swept over the bays sinks to the bottom and is buried in the sediment. The surface one-meter layer of the Gulf sediments is rich in total organic carbon (TOC), Fe, Mn, Zn, V, Cr, Cu, Ni and Pb (Al-Ghadban *et al*., 1994, Al-Sarawi *et al*., 2002).

Dredging churns up the sediments and releases stored nutrients. Of interest is the existence of a gradient of Fe, Cu, Ni, Co, Zn Cr, Mn, and V levels in the sediments with high values in the north and decreasing to the south (Basaham and Al-Lihaibi, 1993). The surface one-meter layer of the Gulf sediments is rich in TOC carbon and heavy metals (Al-Ghadban *et al*., 1994). In Kuwait Bay during summer, TOC ranged between 101 -318.4 µM with a mean 161.2 µM (Al-Said *et al*., 2018 b) and is attributed to anthropogenic input. Sediments in Sulaibikhat Bay, an offshoot of Kuwait Bay, contained large quantities of Fe, Mn, Zn, V, Cr, Cu, Ni and Pb (Al-Sarawi *et al*., 2002), and are mostly derived from sewage. Large depositions of trace elements could be toxic to phytoplankton (Paytan *et al*., 2009). The dust, rich in several trace elements, stimulated phytoplankton growth when added to surface seawater in certain quantities (Subba Rao *et al*., 1999 b).

c) Other multiple sources of enrichment

In the Gulf Countries sewage disposal is a major form of coastal pollution that increases nutrient levels. Also,

Table 3. Elements (µM) in Kuwait Bay together with associated perturbations.

			Kuwait Bay			**Seawater**
			Anthropogenic			
			Brine (Kuwait Bay) [1,2]	**Sanitary water** [3,4]	**Kuwait Bay** [5,6,7]	[8]
	Quantity y^{-1} → **Element ▼**		1.264 km^3	2.39 x 10^{-4} km^3	3.76 km^3	
1	Nitrogen	Range	124.3-848.9	3142.9-7142.9	0-5.63	1107.14
		Mean	486.6	5142.9	1.53	
2	Phosphorus	Range	NA	451.6-2064.5	0-15.1	2.84
		Mean	NA	1258.1	0.355	
3	Silicon	Range	1.8-21749.4	NA	NA	103.25
		Mean	10875	NA	NA	
4	Iron	Range	0.5-799.8	-	71.95-182.6	
		Mean	400.2	1.3 x 10^{-3}	145.2	6.0 x 10^{-2}
5	Manganese	Range	0.9-76.9	-	2.2x10^{-2}-2.7x10^{-2}	
		Mean	38.9	4.0 x 10^{-5}	2.5 x 10^{-2}	7.3 x 10^{-3}
6	Copper	Range	0.8-635.5	-	8.7 x 10^{-2} - 0.57	
		Mean	318.1	11016	0.29	1.4 x 10^{-2}
7	Zinc	Range	0.8-91.5	-	0.28-3.44	
		Mean	46.15	30621	1.22	7.65 x 10^{-2}
8	Cobalt	Range	NA	NA	0.29-0.42	
		Mean	NA	NA	0.38	6.6 x 10^{-3}
9	Nickel	Range	0-0.17	-	0.72-2.13	
		Mean	8.0 x 10^{-3}	1891.2	1.6	0.112
10	Molybdenum	Range	NA	NA	NA	
		Mean	NA	NA	NA	0.411
11	Cadmium	Range			4.7 x 10^{-2} -5.0 x 10^{-2}	
		Mean		186.8	4.7 x 10^{-2}	9.8 xc 10^{-4}
12	Chromium	Range	0.38-675.9		0.37-0.78	
		Mean	338.13	1538.6	0.56	3.8 x 10^{-3}
13	Lithium	Range	NA	NA	1.44-1.96	
		Mean	NA	NA	1.73	24.50
14	Vanadium	Range	NA	NA	0.55-0.64	
		Mean	NA	NA	0.59	3.7 x 10^{-2}
15	Mercury	Range	NA	-	NA	
		Mean	NA	289.15	NA	7.5 x 10^{-4}
16	Lead	Range	NA	-	NA	
		Mean	NA	1626.4	NA	1.5x 10^{-4}
17	Aluminum	Range	NA	-	NA	
		Mean	NA	1.4 x 10^{-3}	NA	3.7 x 10^{-2}
18	Strontium	Range	56.6-498.2	NA	NA	
		Mean	277.4	NA	NA	92.45
19	Barium	Range	NA	NA	NA	
		Mean	NA	NA	NA	0.153

[1] Ahmed *et al.*, 2001; [2] Ahmed *et al.*, 2004; [3] Enezi *et al.*, 2004; [4] Aleisa and Al-Shayii, 2017a; [5] El-Anbaawy *et al.*, 2018; [6] Al-Mutairi *et al.*, 2014; [7] Al Said *et al*, 2018 b; [8] Anthoni, 2006. NA: Not Available

sludge from dredging the channels, discharge of ships' ballast water, slaughterhouse wastewater and effluents from mariculture operations enrich the Gulf. The annual wastewater collection in the Gulf is about 4.0 km^3 and 73 % is treated in 300 wastewater treatment plants (Qureshi, 2020). Many of the treatment facilities are either outdated or are exceeding their design capacity. Despite extreme water poverty, only 39 % of the treated wastewater is reused, and the remainder is discharged into the sea (Qureshi, 2020). Human influence enriches the Kuwait Bay with N, P, Zn, Ni, Al, Fe, and Mn (Aleisa and Al-Shayii, 2017a). Mean concentrations of NO_3 and PO_4 in the Bay were 14.9 and 52.5 **µg** $^{-1}$ (Al-Mutairi *et al.*, 2014). Estimated slaughterhouse wastewater (SWW) from the GCC countries is 9125 tons y $^{-1}$ (Qatar, 2015). Analyses of SWW (Bhunia *et al.*, 2022) showed these are rich in surfactants, volatile biosolids, chloride anions, carbon, nitrogen, heavy metals, and TOC impacts on the environment when discharged into the Gulf.

Effluents from mariculture are another potential source of nutrient enrichment. A BLOOM ECO model developed (Bhunia *et al.*, 2022) for 73 cages for Seabream fish in Kuwait Bay yielded dissolved nutrient inputs (tons y^{-1}) of 9.27 inorganic nitrogen and 0.89 inorganic phosphate and particulates as well. However, the expansion of marine cage aquaculture operations in Kuwait were halted in 2008 because of several mass fish kills and this has been stagnant with production of around 412 tons y^{-1} (Almutawa and Alfraih, 2023). Under the New Kuwait 2035 Plan, several projects are being considered to provide technical help for growing fish and shrimp by 2029. In this GCC region aquaculture is on the increase and there are 80 mariculture farms (Feidi, 2009). Cage mariculture produces organic matter that could also increase the nutrient loads up to six-fold by 2050 (Islam, 2005) which may promote an increase in harmful algal blooms (Bouwman *et al.*, 2013). There are plans to establish 200,000 tons of cage fish production in the Arabian Gulf. Based on a nutrient model Risk *et al.* (2021) concluded that the resulting nutrient footprint could affect the entire Gulf raising ecological concerns. In the Kuwait Bay with a 5.2 m average depth and a 30 m maximum depth and a tidal range 3.5 to 4.0 m (Abu-Seedo *et al.*, 1990), the water column would be well mixed facilitating nutrient distribution. This could have devastating impacts on the AG ecosystem and it is emphasized that Environmental Impact Assessment (EIA) studies are important before embarking on this ambitious goal.

Thus, multiple perturbations enrich the Bay with several elements (Table 3); their range and mean levels are very high compared to the mean (µM) 0.0056 (Cd), 0.515 (Cu), 0.146 (Fe) 0.0073 (Mn), 0.019 (Ni) and 0.512 (Zn) reported in seawater of the Bahrain environment (Juma and Al-Madany, 2008). Some of these elements could be toxic to phytoplankton and all other forms of marine life depending on their speciation, i.e., oxidation state when they are more stable (e.g., Pb 0 +2 and +4, Mo +2 to +6, Cr +3 and +6, V +2, +3, +4 and +5, Mn +2, +4, and +7, Hg+1 and+2, As +3 and +4, Cu +1, +2). As estimates of these elements are not available for Kuwait wastewaters, values given by Baawain *et al.* (2014) in Oman waters were used; overall average levels of Cd, Cr, Cu, Pb, Mo, Ni and Zn in activated sludge (RAS) corresponded to 38,139,99,39,8,34 and 2800 mg/kg, and slightly lower in recycled activated sludge. Suffice is to say that natural and anthropogenic perturbations also impact waters in other regions of the Gulf and contribute N, P, Si, Fe, Mn, Cu, Zn, Co, Ni, Mo, Cd, Cr, Li, Va, Hg, Pb, Al and Sr.

d) Salinity

Decrease in the annual discharge of the Tigris and Euphrates Rivers affected the salinity in Kuwait Bay and the Gulf as well. The flow of these rivers decreased significantly (Al-Ansari *et al.*, 2019). Analysis of flow model data indicates that the average annual flow volume (10^9 m^3) is 80 for the period 1965–1973, and decreased to 55 by 1973–1989, to 50 by 1989–1998 (Jones *et al.*, 2008) and to 20 by 2010 (Abdullah, 2016). This decline is due to stream regulation in the riparian countries (Al-Yamani *et al.*, 2017) and will have a significant effect on the closely coupled phytoplankton ecology in Kuwait Bay and the Gulf. Gulf countries depend on intense activity of water desalination and the most relevant impacts are related to discharge of the brine. Discharges amount to 7.31 km^3 y^{-1} and may increase to 29.2 km^3 y^{-1} by 2050 (Le Quense *et al.*, 2021). Kuwait discharges 1.26 km^3 y^{-1} brine (Bashitialshaaer *et al.*, 2011). Multi-stage flash (MSF) desalination plants account for 86.7 % of the desalting capacity, while reverse osmosis accounts for only 10.7 % (Qureshi, 2020). Desalination results in an increase of salt concentration to 1.5 to >2 times than that of the seawater. Brine also contains 17 elements (µM), with chloride as the highest (1101749) followed by Na (354304), Mg (57188), Ca (15350), K (12349), and carbonates (7344) (Ahmed *et al.*, 2004). Nitrate (3804), Si (7.7), Fe (3.76), Cu (4.33), Zn (0.92) and Mn (1.09) were also present in concentrations higher than in normal coastal waters (Anthoni, 2006; Duxbury *et al.* 2020) and are known to impact micro algal growth (Ahmed *et al.*, 2004). During 2002 to 2020, salinity off Kuwait increased from about 37 to 44 PSU, which affected the phytoplankton community (Al-Said *et al.*, 2017). Surface temperature also increased during 2002-2020.

Kuwait Bay is impacted by the "Third River", a 565 km outfall drainage (Fig. 1) installed by Iraq to remedy the chronic salinity problem in the >7,750 km^2 farmland between Tigris and Euphrates Rivers (Al-Handal and

Hu, 2015). It collects wastewater and drainage from 1.5 x 10^6 km^2 salt-encrusted fields (Fig. 1) and discharges 0.018 km^{3}d^{-1} into the Arabian Gulf via Khor Al-Zubair and Khor Al-Sabbiya (Pearce, 1993). The international 'Basra Water Crisis" workshop 15-16 February 2024 Save the Tigris (coordinator @ savethetigris.org) discussed increase in salinity levels of Shatt al-Arab and the possible solutions to this salinity crisis. Details about the flow are not available.

Phytoplankton

There are two seasons in the Gulf: a 'cooler' December to February, and a hot April-October season. There are no distinct winter, spring, summer, and autumn seasons and therefore the local conditions influence the phytoplankton of the Gulf. In near shore Kuwait waters during 1985 to 1990, chl. *a* ranged between 1.6 to 8.1 µg chl. *a* l^{-1} (Fig. 2); biomass integrated in the column ranged from 3.8- 113.4 mg chl. *a* m^2 with the high values in the near shore (Subba Rao and Al- Yamani, 1999 a). Remotely sensed chl *a*. in the littoral Kuwait waters during 2020 ranged between 6.2 and ~8.1 µg *a* l^{-1} (Fig. 2). Albanai (2021) observed chl. *a* level (7 mg m^{-3}) during winter in Kuwait Bay that were higher than in the open Gulf (< 2.5) and <0.5 in the central Gulf. However, off Kuwait, their monthly averages for 2002 to 2020 ranged between 2.85 and 3.64 µg chl. *a* l^{-1} during June and September (Fig. 3). There was no pronounced seasonal progression; increases in chl. *a* were small and were during March-May, and August-October-December. During 2002 to 2020 as the Kuwait Bay warmed up and the salinity increased, chl. *a* decreased. These findings are consistent with earlier findings (Nezlin *et al.*, 2010); the seasonal maxima were during late summer-autumn on the western coast. Al-Naimi *et al.* (2017) pointed out that satellite data do not recognize the optical depth and the satellite sensors systematically over estimated chlorophyll; they suggested a need for a regionally calibrated algorithm to estimate chlorophyll in the Gulf.

Silica is related to river discharge and would impact diatom populations. In Kuwait Bay there have been qualitative and quantitative shifts in the dominant phytoplankton groups, particularly the halophytes (Al-Said *et al.*, 2017). In particular, perturbations in the silicon cycle caused by the decrease in river flow has impacted the growth of diatoms, and the increase in the amount of organic loading is now promoting blooms of dinoflagellates. Changes in salinity

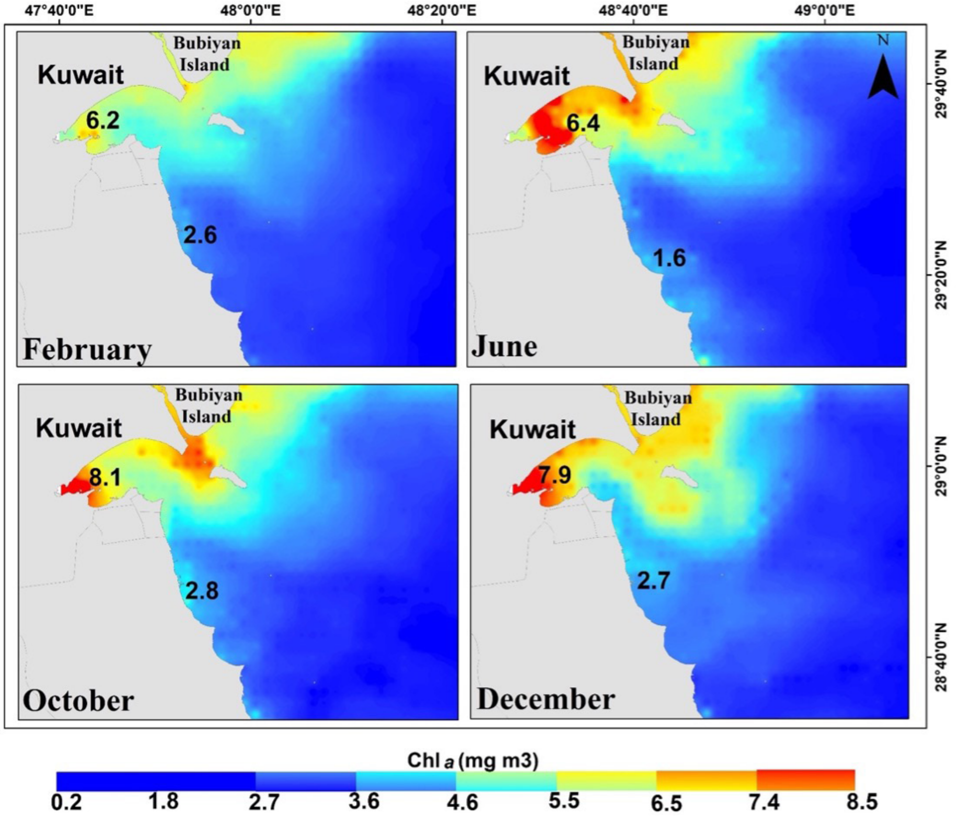

Figure 2. Distribution of average chlorophyll *a* (mg m^{-3}) in Kuwait waters during 2002 -2020. Based on *https://www.oceancolour.org site, https://oceancolor.gsfc.nasa.gov.*).

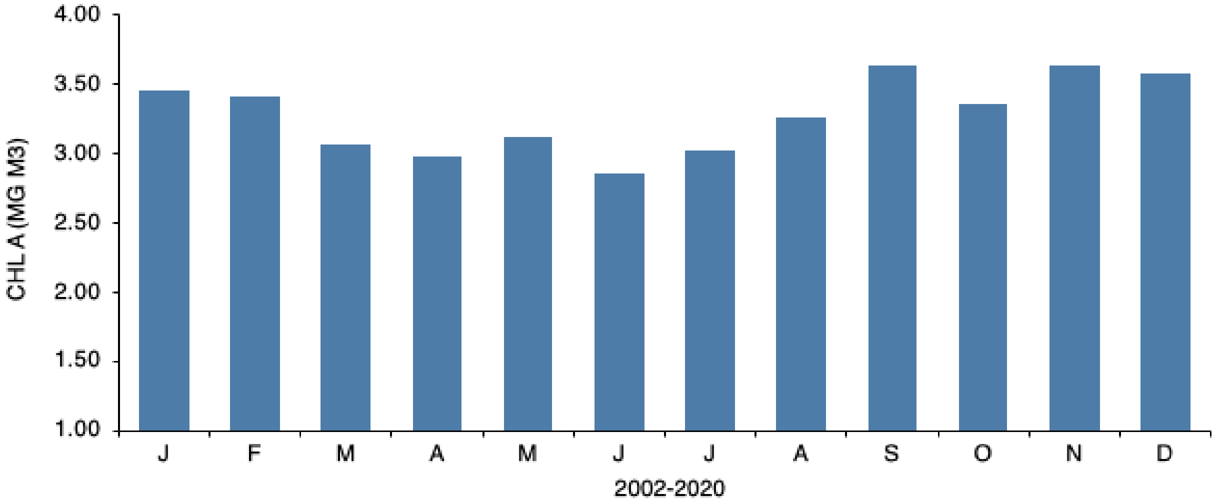

Figure 3. Distribution of average chlorophyll *a* in Kuwait waters during 2002 -2020 based on Ocean Color.

and anthropogenic perturbations seemingly impact the phytoplankton growth and species diversity in the inshore Kuwait waters. During 2000-2007 when the salinities were ~40 PSU, there were 243 diatom and 103 dinoflagellate species (Al-Yamani and Saburova, 2019 a) but by 2008 as the salinity increased to ~44 PSU their diversity decreased to 74 diatoms and 46 dinoflagellates (Al-Said *et al.*, 2017). In addition, in the offshore waters during 2005-2006 there were 108 diatom and 48 dinoflagellate species, but by 2012-2013 diatom diversity decreased to 83 species and dinoflagellates increased to 67 species. Members of Cryptophyceae and Prymnesiophyceae also increased. Such a replacement may be due to a physiological response of algae to salinity stress in these semi-arid, hyper saline, and warm Gulf waters. Brine salinity typically ranges from 1.6 to 2 times the salinity of seawater (Lee *et al.*, 2024) and part of the increase in salinity may be explained by the increased discharge of brine from desalination plants in the Gulf. Also, from thermal-based technologies brine could increase temperature to 1.37 to 1.82 times that of ambient seawater temperature (Lee *et al.*, 2024). Increased salinity and temperature resulted in a 32-60 % reduction in chlorophyll levels and total algal cell numbers in the AG waters (Omerspahic *et al.*, 2022). This corroborates with the results on osmotic and ionic effects due to NaCl resulting in the loss of activity of photosystems (Ps) I and II and loss of oxygen-evolving activity in *Synechococcus* sp. (Allakhverdiev *et al.*, 2000). Culture studies utilizing native microalgae in a salinity gradient would be necessary to establish that salinity is a crucial abiotic factor.

There is indirect evidence from Kuwait Bay to show that lowering of salinity is a highly effective stress reliever. Results of earlier microcosm experiments showed natural assemblages of phytoplankton positively responded to changes in salinity in real time. Incubations of offshore Kuwait surface water in a gradient of salinities 32, 37, 42 and 50 PSU, enriched with f/2 nutrients (0.2ml l^{-1}), showed a positive response only in samples with 32 and 37 PSU and not at salinities >37 (Madhusoodhanan *et al.*, 2018). Centric diatoms *Leptocylindrus, Lauderia, Streptotheca, Chaetoceros, Eucampia* and pennate diatoms *Thalassionema, Thalassiothrix, Nitzschia* and *Bacillaria* grew rapidly leading to a bloom in four days. At high salinities (42 and 50 PSU), algal growth was poor, indicative of their sensitivity to salinity stress. Also, results on the physiology of the chlorophyte *Clamydomonas plethora* and the naviculoid diatom *Nitzschia frustula* isolated from the coastal waters off Kuwait with 40 PSU but cultured in Atlantic Ocean water (34 PSU) medium f /2 are of interest. Results showed high growth rates μ max) of 2.5 for *C. plethora* and 3.4 for *N. frustule* (Subba Rao *et al.*, 2005). Their photosynthetic functioning measured as assimilation numbers (P^B_m: μg C [μg Chl *a*] $^{-1}$ h^{-1}): 22.8 for *C. plethora* and 18.1 for *N. frustula* and initial slopes (α^B: ng C [μg Chl *a*] $^{-1}$ $h^{-1)}$ [μmol m^{-2} s^{-1}] $^{-1}$ was also the highest observed so far, with 79.5 for *C. plethora* and 39.6 for *N. frustula* confirming their potential when cultured at lower salinity (Subba Rao *et al.*, 2005). Flash floods with a discharge 1400 of m^3 s^{-1}, exceeding the earlier records of 80 m^3 s^{-1}, lowered the salinity and promoted algal growth (4 -7 chl. *a* mg m^3) along the Kuwait coast (Alosairi *et al.*, 2019). Floodwater contributes silica and facilitates uptake of biogenic silica. Floods due to heavy rains in the winter of 1991-1992, lowered the salinity of the hyper saline waters of the Dead Sea to 70 % of their formal salinity, and a bloom of *Dunaliella parva* (15 x10^6 cells l^{-1}) developed (Oren *et al.*, 1995).

Aperiodic biomass

Unlike in the temperate seas that experience clear seasonal events such as the winter overturning, upwelling and monsoons that drive phytoplankton blooms, the shallow, semi enclosed, heavily nutrient enriched waters of the Arabian Gulf are not characterized by well-defined seasonal blooms. In the Gulf, multiple processes, prevailing high temperatures, salinities, nutrients, trace elements, aeolian dust, pollutants, and ballast water introductions operate at multiple time scales. Their interplay influences their constituents, when and where ephemeral phytoplankton pulses or blooms occur, and their duration and magnitude. Results of Winder and Cloern (2010) on the diversity of constituent species and their ephemeral nature in temperate and subtropical zones are relevant here. Of their 125-time series of phytoplankton biomass, about a third of them had a series of irregular pulses of biomass but no seasonal cycle. Anthropogenic perturbations, aperiodic weather events and strong coupling between phytoplankton and herbivores in Kuwait Bay may result in a high noise to signal ratio and probably masks any seasonal cycle.

There were 31 dinoflagellates reported from the Arabian Gulf and the Gulf of Oman (Bohm, 1931) and their numbers have increased since (Table 4). Using plankton nets with 55 **µM** pore size Dorgham and Moftah (1989) reported 88 diatom and 37 dinoflagellate taxa, 135 diatom and 9 dinoflagellate taxa in Kuwait waters during 1989, compared to 175 diatoms and 124 dinoflagellate taxa in the U.A.E and Qatar waters. A two-year study in the Gulf of Oman (Al-Azri *et al.*, 2010) showed a chlorophyll maximum of 3 mg^3, and the phytoplankton was dominated by diatoms and the dinoflagellate *Noctiluca*. From the coastal waters of Oman, Al-Hashmi *et al.* (2015, 2019) reported a high diversity of 130 diatom and 80 dinoflagellate species and their abundance related to the Northeast and Southwest monsoons. Maximum diatom abundance was 1832704 cells per m^3, four-fold less compared to the previous decade but dinoflagellates were dominated by *Noctiluca* (3x 10^6 m^3). There were 24 potentially harmful algal species identified, including 11 species of dinoflagellates and eight species of diatoms.

Long-term phytoplankton surveys in Kuwait waters (Al-Kandari *et al.*, 2009; Al-Yamani and Saburova, 2019 a) are more instructive than information from a few samples (Dorgham *et al.*, 1987). Diatoms were dominant in the unfractionated Kuwait water samples (Table 4). Recently, the ratio of diatoms to dinoflagellates was suggested to be a new environmental

Table 4. Phytoplankton diversity in Kuwait waters, ROPME Sea Area and the Arabian Gulf.

	Kuwait waters[1]	Kuwait waters[2]	Kuwait waters[3]	Kuwait waters[4]	Kuwait waters[5]	Central Gulf[6]	ROPME*[7]	Arabian Gulf[8]
Total species ▸	327	200	250		138	223	376	1220
Taxonomic group ▾								
Bacillariophyceae	202	134		250	125	134	171	888
Dinoflagellata	108	56	213		13	86	194	211
Cryptophytes	1	1	5				1	1
Cyanobacteria	2	2	2			2	2	
Dictiochales	2	2	3			1	2	15
Haptyophytes			3				1	15
Chlorophytes	6	3	6				4	90
Raphidophceae	1		4					
Chromista	5		1					
Ebriophytes		1	3				1	
Prasinophytes		1	4					
Prymnesiophyta			2					
Litostomaetea *(Myrionecta rubra)*			1					

[1] Al-Kandari *et al.*, 2009; [2] Polikarpov *et al.*,2009, [3] Al-Yamani and Saburova, 2019 a; [4] Al-Yamani and Saburova, 2019 b; [5] Dorgham *et al.*, 1987; [6] Dorgham *et al.*,1987; [7] Polikarpov *et al.*, 2016; [8] Jacob Al-Muzzaini, 1995

indicator; in the Baltic Sea due to eutrophication a shift from diatom to dinoflagellates is affected (Spilling et al., 2018). In Kuwait waters the diatom:dinoflagellate numbers corresponded to 202:108 (Al-Kandari *et al*., 2009), 134:56 (Polikarpov *et al*., 2009) 92:38 (Al-Yamani and Saburova, 2019a). Samples from ROPME areas (across the Arabian Gulf, the Strait of Hormuz, and the Sea of Oman) revealed 131 diatom and 194 dinoflagellate species (Polikarpov *et al*., 2016).

Besides the usual diatoms, dinoflagellates and other groups of microalgae, picoplankton is an integral component of phytoplankton biomass and responds to environmental perturbations. The relative contribution of picoplankton to the phytoplankton in Kuwait waters is not known but may be important.

Additionally, the results from this study on the impact of enrichment with aeolian dust in stimulating diatom growth are of interest (Subba Rao *et al*., 1999 b). Surface water 51.7 km off Kuwait with low phytoplankton collected during summer was enriched with aeolian dust comparable to the fall out levels 0-100 g m^2 sea surface (Gharib *et al*., 1986). Initial micronutrients (µM) were 1.4 - 4 NO_3, 6.6 -8.4 PO_4, and 18.3-28.1 SiO_2. Data from the present study showed the doubling rate of algal biomass increased from 0.56 to 1.42; in 5 days, 29 species of diatoms, mostly 6x3 µM naviculoids, grew rapidly and attained a maximum biomass (527 µg l^{-1} chl. *a*) (Subba Rao *et al*., 1999 b). Dust storms are a source of enrichment of Fe, Al, Cr, Mn, Si, Zn, P, Cu, and Ni (Al-Awadhi, 2005) some of which could stimulate phytoplankton growth. Satellite observations have shown that aeolian dust fertilizes the Gulf waters (Nezlin *et al*., 2010). The impact of these trace elements on marine phytoplankton is rather complex and could be either positive or inhibitory depending on the algal species, salinity of the medium, frequency of enrichment, stoichiometry, solubility state, oxidative reductive states, availability of chelators like organic ligands, siderophores, and on microbial feedbacks.

Episodic blooms

In these hyper saline Gulf waters, algal blooms are ephemeral, episodic, few and far between. They are atypical in respect of their non-seasonality, non-recurrence, and multi species in contrast to seasonal HAB blooms of *Dinophysis* sps., *Prorocentrum* sps. *Karenia brevis*, *Gamberidiscus* sps., *Pyrodiniumbahamense, Karlodinium venefiucum* and *Alexandrium tamarense* from other regions (Subba Rao and Durvasula, 2020). In Kuwait Bay there were significant short-term elusive pulses of red tides during 1987- 2000; both the constituent species and their abundance varied. Based on phytoplankton monitoring data for 2004-2017, Al-Yamani and Saburova (2019 a) recorded incidences of 50 algal blooms. About 29 species attained > 3 x 10^6 cells l^{-1} or 10 µg l^{-1}, within the blooms. Most blooms contained more than one species, that included *Chrysochromulina* sp., *Gymnodinium* spp, *Heterosigma akashiwo, Karenia papilionacea, Karenia selliformis, Karlodinium* sp, *Leptocylindrus* sp., *Prorocentrum* spp., *Nanoflagellates, Nitzschia cf. laevis, Nitzschia longissima, Nitzschia* sp., *Nitzschia* spp., *Phaeocystis globosa, , Leptocylindrus* sp., *Prorocentrum* spp., *Prorocentrum balticum, Pseudo-nitzschia seriata, Rhodomonas* sp., *Skeletonema grevillei, Takayama* spp., and *Thalassiosira* spp. Highly exceptional blooms contained 1008.9 x 10^6 l^{-1} cells and 4525.5 µg l^{-1} chl. *a* (Subba Rao *et al*., 2003). Monospecific blooms observed include *Chaetoceros socialis*, *Dunaliella salina*, *Myrionecta rubra*, *Noctiluca scintillans*, *Oltmannsiella lineata*, *Phaeocystis globosa*, and *Trichodesmium erythraeum*.

In September 2001, the globally invasive *Gymnodinium catenatum* and *Gyrodinium impudicum* were the main bloom-forming species (>10^6 cells/l) that suggests their ability to tolerate the prevailing high salinity (Glibert *et al*., 2002). Analyses of historical records of algal blooms in the Indian Peninsula (1908-2017) similarly showed a high variability; 24 genera and 30 species including Cyanophyceae, Bacillariophyceae, Dinophyceae, Raphidophyceae, Prymnesiophyceae, Trebouxiophyceae and Ciliates in the 154 events (Oyeku and Mandal, 2021). The non-recurrence of taxa and their biomass varied depending on the sea surface salinity, eutrophication and high nutrient conditions.

Due to continued perturbations in the Gulf, probably a few resistant species grew better. Based on a mechanistic competition theory, Flöder and Sommer (2015) showed that factors other than macro-nutrients affect the structure of macroalgal communities. Rengefors (2020) discussed adaptive C, S, R strategies (Competition, stress tolerance and disturbance tolerance) as a response to the environment, favoring distinct species. In the Bay that experiences incessant perturbations, competition for resources among phytoplankton species and groups can determine which species become dominant. Mesocosm experiments of 90 days duration with sequential pulse perturbations, showed the resistance and recovery index of algae, finally resulting in a failure of the community to recover (Stelzer *et al*., 2022). In addition to the salinity gradient studies mentioned earlier, experiments along the lines of Folt (1999) may be taken up by the GCC and utilize cultures of microalgae native to the Gulf to understand their response to synergism (increased stress) and antagonism (decreased stress). Not a single nutrient but an array of complex factors including optimal temperature and light and a mix or multiples of the macro, micro and trace elements regulate phytoplankton growth. If their levels are higher than the threshold, the nutrients become toxic to phytoplankton. The Fe, Cu, Co, Zn and Mn levels in Kuwait Bay (Table 5) are much higher than those in f/2 algal culture medium (Guillard, 1975). However, culture medium has much higher P, N, Si concentrations than in Kuwait Bay (Al-Said *et al.*, 2018a).

Elevated levels of PCBs, PBDEs and dioxins were reported near crude oil industries along the Kuwait Bay coastline. Alshemmari (2021) in a review of persistent organic pollutants in Kuwait sediments (g/ DW) reported ranges of TPH 40-240 µg, and PCBs 0.40 -81.7 ng. Further, elevated levels remain relatively high (426-459 µg) in industrial areas and near oil loading terminals. Their longevity, high hydrophobicity and resistance to degradation are a matter of concern. In the highly saline Kuwait waters these may be toxic for phytoplankton growth and may prevent progression of phytoplankton into blooms Studies such as that of Gallo *et al*. (2020) indicating that PAHs from sediment elutriate inhibit growth of *Phaeodactylum tricornutum*, *Skeletonema costatum* and the halophyte green alga *Dunaliella tertiolecta* are required for the AG region. In addition, precise physiological ecology studies utilizing cultures of native algae are required to understand their response and recovery to perturbations and to answer the question as to why the algal blooms in the Gulf are sporadic and not regular.

Ballast waters: microalgae

More than 17 million barrels of ballast water from various geographical regions are transported to the ROPME area annually and may have inadvertently introduced exotic microalgae (Al-Yamani *et al*., 2015) and heavy metals as well (Dobaradaran *et al*., 2017). Comparison of a list of dinoflagellate records from Kuwait waters shows a steady increase in dinoflagellate species from 39 (Dorgham *et al*., 1987), to > 108 (Al-Kandari *et al*., 2009; Al-Yamani and Saburova, 2019 a) and included several first-time records. In the whole Gulf the increase has been from <45 species in 1931 (Bohm, 1931) to 509 species (Subba Rao and Durvasula, 2020). It is plausible that ballast water from 50,000 ships visiting the Gulf annually from various geographic regions may have introduced species new to the Gulf. Of interest are the changes in the constituent species; 19 species from Dorgham *et al*. (1987) were absent in observations of Al-Kandari *et al*. (2009) while 155 species additional were reported by Al-Yamani and Saburova (2019 a). Only 33 species from the first study are common to those of the second. Assuming 60 % of these, particularly the athecate, were "poorly preserved" the remaining were thecate and well preserved. While such an increase in dinoflagellate diversity could be partly due to an underestimation of native taxa, it is plausible that at least some of the 40 % new of thecate dinoflagellates constitute the "suspect" transient species brought in by ballast waters. However, it appears that their physiological conditions and low abundance precluded their development into a bloom.

It has been observed previously that a few of the opportunistic species when "inoculated" in sufficient numbers in enriched coastal waters can result in aperiodic, episodic non-recurrent blooms as in *Karenia*

Table 5. Enrichment levels (µM) in f/2 algal culture medium compared to their range in Kuwait waters.

Enrichment	f/2 medium (Guillard, 1975)	Range in Kuwait waters (Al-Said *et al*., 2018)
Phosphorus	36.3	0.07-0.45
Nitrogen	883	0.08-2.85
Silica	107	0.26-9.72
Iron	10	670-28160
Copper	0.04	10260-23250
Cobalt	0.05	50-1340
Zinc	0.08	5140-25330
Manganese	0.9	-1.09

Additionally, *f*/2 contains 3 x 10^{-8} Molybdenum, Vitamin B_{12} (3.69 x 10^{-10} M), biotin 2.05 x 10^{-2}M. and 2.96 x 10^{-7} thiamine.

(*Gymnodinium*) *mikimotoi, Gonyaulax polygramma, Noctiluca scintillans*, *Pfiesteria piscicida*, *Prorocentrum cordatum* (Burkholder, 1998). *Heterocapsa circularisquama,* a species of hardy alien opportunistic and toxic dinoflagellate from the Western Pacific developed into blooms in Kuwait Bay during June-July 2020 (Saburova *et al*., 2022). During the blooms, chl. concentrations were 20 µg l^{-1} and cell concentrations were 267.9 x 10^6 cells l^{-1} along with the native blooming diatoms *Thalassiosira delicatula, T. exigua*, and *Minutocellus polymorphus* (Saburova *et al*., 2022). Their geographical distribution suggests introduction from Malaysia, Brunei, Philippines, New Guinea, Japanese waters, Australia, Belize, Russia, and South African seas, like the occurrence of Indo-Pacific dinoflagellates in the Mediterranean (Gómez, 2006). It is desirable to establish the viability of such suspect introduced alien species using culture methods (Subba Rao *et al*., 1994). In the enclosed Black and Caspian Seas some of the novel transient hardy species *Lingulodinium machaerophorum* and *Impagidinium caspienense* introduced by shipping activities bloomed (Sala-Perez *et al*., 2020; Lattuada *et al*., 2020). Clarke *et al*. (2020) reported the possible introduction of a wide range of 136 invasive non-native species of which 56 potentially invasive species from four microalgae to fish in the Arabian Gulf and Sea of Oman. Such bio-invasions could affect at local, regional and global scales.

Harmful algae

Species of algae reported harmful elsewhere causing Paralytic Shellfish Poisoning (PSP), Diarrhetic Shellfish Poisoning (DSP), Neurotoxic Shellfish Poisoning (NSP), Amnesic Shellfish Poisoning (ASP), Ichthyotoxin poisoning, Yesso toxin poisoning, are present in Kuwait waters (Devlin *et al*., 2019; Al-Yamani and Saburova, 2019 a; Saburova, *et al*., 2022). Out of a total of 62 harmful algal species, 43 are potentially toxic to humans and marine biota (Al-Yamani *et al*., 2012). These species are: PSP -, *Alexandrium acatenella, A. leei, A. ostenfeldii, A. pacificum, A. tamiyavanichii, Gymnodinium catenatum,* DSP - *Phalacroma rapa, P. rotundatum,* ASP -, *Pseudo-nitzschia seriata,* and *Halamphora coffeaeformis,* Neurotoxin - *Karenia brevis, Prorocentrum cordatum, Heterosigma akashiwo, Karenia papilionacea,* and Icthyotoxin–*Margalefidinium polykrikoides, Karenia mikimotoi* and Yessotoxin producer *Protoceratium reticulatum. Karenia selliformis* produces a compound gymnodimine in culture that may accumulate in shellfish with no effect proven for human health. Analysis of 214 species from a data set (2007-2016) listed 39 potential Harmful Algal Bloom (HAB) species (Devlin *et al*., 2019) in Kuwait waters. Species that produced phycotoxins are *Alexandrium minutum, A. tamarense, Gymnodinium catenatum, Pyrodinium bahamense* (PSP), *Dinophysis acuminata, D. acuta, D. caudata, D. fortii, D. miles, D. norvegica, D. tripos, Prorocentrum lima*, *P. mexicanum (*syn *P.rhathymum), P. concavum,* (DSP*), Gonyaulax spinifera (*Yessotoxin*), Karenia selliformis* (NSP), *Heterosigma akashiwo, Karenia brevis (*syn *K. papilionacea), Prorocentrum minimum,* (Neurotoxin), *P. reticulatum* (Yessotoxin), *Karenia mikimotoi* (Icthyotoxin), *Pseudo-nitzschia pungens*, and *Pseudo-nitzschia seriata*,(ASP). Additionally, Devlin *et al*. (2019) reported the occurrence of *Akashiwo sanguinea* a surfactant species, *Chaetoceros socialis, C. curvisetus, Chaetoceros* spp, *Cyclotella* sp., *Cylindrotheca closterium, Eucampia zodiacus, Guinardia flaccida, Leptocylindrus* sp., *Nitzschia laevis, Noctiluca scintillans Peridinium quinquecorne, Prorocentrum micans, Pseudo-nitzschia americana, Tripos furca, T. fusus, Dictyocha fibula, Dictyocha speculum* and *Trichodesmium erythraeum*. Cell densities (l^{-1}) of these were for the non-toxigenic diatoms *Eucampia zodiacus (*929,333), the toxigenic *Karenia brevis* (116,333) and *Pyrodinium bahamense* (110,667) and were probably sufficient to be toxigenic. Al-Yamani and Saburova (2019 a) listed 57 blooms in Kuwait waters during 1987-2017, and 22 dinoflagellate species were the constituents. Cell densities (l^{-1}) ranged between 0.4 x 10^6 and 1x 10^9 and chl. *a (*µg l^{-1}) between 4.1 to 4256 (Table 1 in Al-Yamani and Saburova, 2019 a). Of these only 14 had >10 chl. µg l^{-1} (Al-Yamani and Saburova, 2019 a). Biosynthesis and bioaccumulation of phycotoxins in *Pseudo-Nitzschia multiseries* (Pan *et al*., 1996) and *Prorocentrum lima* (Pan *et al*., 1999) is dependent on sufficient cell biomass and their growth phase. *Alexandrium pseudogonyaulax* that produces a mucous trap and *Scripsiella trochoidea* were also recorded in Kuwait waters. The bloom of *S. trochoidea* was nontoxic; however, their high blooms can negatively impact coastal ecosystems and cause mortality in marine biota (Hallegraeff, 1993; Hold *et al*., 2001). As discussed earlier it is possible that prevailing high salinity in the Gulf, inhibited growth of these toxic species preventing their growth into bloom proportions that are needed for elevating toxin levels in the water. It is recommended that culture studies are conducted on isolates from Kuwaiti waters and investigations are carried out at various phases of their growth for phycotoxin production in this harsh environment.

Mass mortalities

Marine mortalities in the Gulf include 25-30 tons of mullets *(Planiliza macrolepis)*, approximately 80,000 tons of farmed Sobaity (*Sparidentex hasta)* in floating cages in Kuwait Bay during 1999, Gilthead Seabream (*Sparus aurata)* in aquaculture cages, Fringescale (*Sardinella fimbriata)* in marinas in 2005, and Catfish (*Netuma thalassina* and *Policofollis tenuspinus)* in 2006, 2015, 2017 and 2019 (Al-Yamani *et al*., 2020). The most well-known fish kill of *Planiliza macrolepis* in Kuwait occurred in 1999, as a result of a bloom of ichthyotoxic *Karenia selliformis* (Heil *et al*., 2001, Al-Yamani *et al*., 2020). A large-scale fish kill event worthy of mention was associated with intensive heterotrophic bacterial activity (*Streptococcus agalactiae*) on dead algae in Kuwait Bay during August-September 2001 (Glibert *et al*., 2002). This study also reported various harmful algae including *Gymnodinium catenatum, Gyrodinium impudicum*, and *Pyrodinium bahamense* var. *compressum*. Cell numbers of *G. catenatum* and *G. impudicum* exceeded 10^6 l^{-1}, probably sufficient to deliver phycotoxins. But these algae were neither cultured nor phycotoxin production determined. Data are needed to conclude whether the fish mortality may have been caused either by a phycotoxin or due to hypoxic conditions that followed the bloom.

The Gulf acts as a topographical shelter and concentrates organic carbon in the water column ranging from 101.0 – 318.4 µM (Al-Yamani and Naqvi, 2019). Oxidation of this organic matter and bacterial heterotrophic activity on dead algae also exacerbate deoxygenation leading to formation of dead zones with low oxygen. The prevailing high temperatures, excessive pollutants, and bacterial action of *Streptococcus agalactiae* may have resulted in hypoxia caused by the die off from phytoplankton, leading to the mortalities. A three-dimensional numerical model (Alosairi and Al-Sulaiman, 2020) showed depletion of dissolved oxygen is local and near the pollution out falls limited to Kuwait Bay. A bloom of toxic *Heterocapsa circularisquama* in Kuwait's waters during June–July 2020 (Saburova *et al*., 2022) was associated with shellfish mortality.

In Kuwait's southern shore mass mortalities of pearl oyster *Pinctada radiata* and scallop *Chlamys livida* in 2013 was associated dredging activities. The mass mortalities of Sea Cucumbers, *Holothuria arenicola* in 2018 on Kuwait's southern shore are believed to be due to osmotic shock resulting from a drastic decrease in salinity from 45 PSU to 5 PSU (Al-Yamani *et al*., 2020). This change in salinity was caused by rainwater discharge and coincided with dominance of the nano flagellate *Plagioselmis prolonga* (Al-Yamani *et al*., 2020*)*. Nevertheless, to establish the causative factors it is stressed that it is necessary to conduct culture experiments. Richlen *et al*. (2010) established cultures of *Margalefdinium polykrikoides* isolated from coastal waters near Ras Al-Khaimah, located in the northern United Arab Emirates. In one study, Al-Muftah *et al*. (2016) isolated cultures of the ichthyotoxic dinoflagellate *Vulcanodinium rugosum* from the coastal areas of Doha, Qatar, and these strains contained between 603 and 981 ng pinnatoxin (PnTx) H per mg dry weight in addition to being positive for portimine. It is suggested that going forward, molecular analysis of organism-level gene regulation and transcriptiomics under hypoxic conditions would be illuminating.

Fisheries

The natural and anthropogenic perturbations presented above resulted in concomitant changes in the hydrographical conditions during 2000-2013 that caused shifts in functional plankton groups. Phytoplankton biomass (chl. *a*) in Kuwait waters decreased from ~6 to 2 µg l^{-1} with a long term mean of 3.64 µg l^{-1} (Al-Said *et al*., 2017) and 1.01- 2.27 (Devlin *et al*., 2015). This in turn may have altered the pelagic trophodynamics evident from a drastic decline in the fish stocks. Fish and shrimp production declined (Alqattan and Gray, 2021). Off Kuwait, the landings (tons) of the pelagic feeders decreased during 2000 and 2012 (Al-Husaini *et al*., 2015); i.e., *Tenulosa ilisha* (Suboor) 642 to 72, *Carangoides* sp. (Hamam) 117 to 76, *Otolithes ruber* (Nowaiby) 728 to 535, *Parastromateus niger* (Halwaya) 50 to 42, and *Epinephelus coioides* (Hamoor) 262 to120. Correlation between the flow of the Tigris-Euphrates rivers and estimated finfish recruitment trends are positive (Ben–Hasan *et al*., 2018). Declining catches in the Northwestern Arabian Gulf indicate possible over-fishing. Ben-Hasan *et al*. (2018) on the other hand, allude to such declines as being the result of recruitment changes caused by reduced freshwater flow in the Tigris-Euphrates Rivers. In the Aral Sea where surface salinity increased from 10 PSU in 1960 to 92 PSU by 2004 (Zavialov, 2005), the commercial fish catch was decimated from 43,430 tons in 1960 to zero in 1980. It is to be noted that damming the Nile in 1965 reduced freshwater flow to the Mediterranean by 90 %, resulting in concomitant changes in the nature of the productive ecosystem and a collapse of the fishery within 15 years (Nixon, 2003). Changes in nutrient load caused by damming the Danube River similarly affected the food web structure in the Black Sea surface waters (Humborg *et al*., 1997).

Conclusions

Environmental protection practices in the Gulf countries are similar, and it is assumed that natural and anthropogenic perturbations like those in Kuwait would prevail in other Gulf countries. High sea surface temperature together with reductions in river flow, and enrichment due to natural and anthropogenic perturbations result in stressful environmental conditions for marine biota in the Gulf that have far-reaching consequences that need to be addressed. In the GC, 61 % of treated wastewater is not utilized but discharged into the sea (Qureshi, 2020). This study calls for a concerted effort by GCC for a systematic reduction in the release of treated wastewater in the AG for ecosystem restoration as was demonstrated in the highly eutrophicated Seto Inland Sea, Japan (Imai *et al*., 2006). Long-term reduction of nutrient inputs has been considered as the most effective pathway to mitigate eutrophication to improve the structure and functioning of the ecosystem (Imai *et al*., 2006). Prior to the reduction in wastewater outflow, about 299 harmful algal blooms developed and damaged a fishery worth US$ 60 million per annum. The causative microalgae included *Chattonella antiqua*, *C. marina*, *C. ovata* and *Heterosigma akashiwo* (Raphidophyceae), and *Karenia mikimotoi* and *Margalefidinium polykrikoides* (Dinophyceae) and in 1988 a novel red-tide of dinoflagellate species *Heterocapsa circularisquama*. The "Law Concerning Special Measures for Conservation of the Environment of the Seto Inland Sea" was legislated in 1973 and nutrient loading was systematically reduced to half the level of 1972. The incidence of harmful algal blooms also decreased to 100. A similar success story is that of Thau Lagoon, France, where a reduction of phosphorus loading as a means of 'de-eutrophication' resulted in a decrease in dinoflagellate abundance (Gowen *et al*., 2015).

The Arabian Gulf is experiencing "extraordinary neglect compounded in large part by excessive tanker traffic (Brewer and Dyrssen, 1985) and unabated discharge of pollutants from land. As a result of the warming trend and the prolific increase in the number of desalination plants all around its coast, the Arabian Gulf is emerging as one of the most thermohaline stressed environments. Compounding thermohaline stress, are both natural and anthropogenic perturbation levels of inorganic nutrients, nutrient stoichiometries, trace elements, heavy metals, and the PAHs, PCBs and PBDEs concentrations to the detriment of the environment. When several exogenous cumulative stresses exist beyond a threshold for biological tolerance, the threats to the ecosystem increase dramaticaaly. In order to maintain the integrity of the Gulf ecosystem, it is suggested that brine should not be discharged into the AG but pumped further inland on to the desert flat. Although this would decrease sea level, it would be compensated by incursion of relatively less saline (~35.4 PSU) Arabian Sea Water into the Gulf.

It is emphasized that it is time for all the GCC countries to come together to strengthen cooperation to implement of strategic management programs that reduce environmental stressors and build resilience of the Arabian Gulf ecosystem. This study calls for implementation of GCC-wide, sustained long term series data acquisition programs. Furthermore, research studies that include cultures of microalgae native to the Gulf and from ballast waters, improved screening of suspect toxigenic algal cultures for phycotoxins, and assessment of the impact of 'oligotrophication' to reduce nutrient loading and its impact on phytoplankton, are called for.

In addition a regional ecosystem-based nutrient management strategy plan is called for, like the HELCOM Baltic Sea Action Plan (HELCOM BSAP, 1974) in the Baltic Marine environment which has demonstrated the effectiveness of long-term and large-scale reduction of nutrient inputs to improve the Baltic Marine environment (OSPAR, 2020; Murray *et al*., 2019). Duarte *et al*. (2009) cautioned that coastal eutrophication results in shifting baselines and reduced chlorophyll, but prediction of trajectories of 'oligotrophication' of individual ecosystems is still a challenge and should be based on more long-term systematic data.

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References

Abdullah AD (2016) Modeling approaches to understand salinity variations in a highly dynamic tidal river: The case of the Shatt Al-Arab River. PhD thesis, Delft University of Technology and of the Academic Board of the UNESCO-IHE Institute for Water Education. 207 pp

Abu-Seedo F (1990) Tidal and turbidity effects on the shallow-water fish assemblage of Kuwait Bay. Marine Ecology Progress Series 65: 213-223

Ahmed M (2001) Brine disposal from reverse osmosis desalination plants in Oman and United Arab Emirates. Desalination 133: 135-147 [https://doi.org/10.1016/S0011-9164(01)80004-7]

Ahmed M, Hoey D, Shayya W, Goosen MFA (2004) Brine disposal from inland desalination plants: Current status, problems and opportunities. In: Zannetti P (ed) Environmental Sciences and Environmental Computing Vol. II. The Environmental Computing Institute [http://www.envirocomp.org]

Ahmed A, Al-Said T, Madhusoodhanan R, Wajih S, Naqvi A, Sarkar A, Fernandes L, Thuslim F, Al-Zakri W, Al-Yamani F (2022) Environmental impact of a series of flash flood events on a hypersaline subtropical system in the Northwestern Arabian Gulf. Marine Pollution Bulletin 175 (2): 113394 [doi:10.1016/j.marpolbul.2022.113394]

Al-Ansari N, Jawad S, Adamo N, Sassakian K (2019) Water quality and its environmental implications within Tigris and Euphrates Rivers. Journal of Earth Sciences and Geotechnical Engineering 9: 57-108 [http://www.diva-portal.org/smash/get/diva2:1199708/fulltext01.pdf]

Al-Anzi B, Abusam A, Shahalam A (2012) Assessment of wastewater reuse in Kuwait and its impact on amounts of pollutants discharged into the Sea. Journal of Environmental Protection 3: 935-939 [http://dx.doi.org/10.4236/jep.2012.328108]

Al-Azri AR, Piontkovski SA, Al-Hashmi K, Goes JI, Gomes HR (2010) Chlorophyll a as a measure of seasonal coupling between phytoplankton and monsoon periods in the Gulf of Oman. Aquatic Ecology 44: 449-456 [doi 10.1007/s10452-009-9303-2]

Al-Awadhi J (2005) Dust fallout characteristics in Kuwait: A case study. Kuwait Journal of Science & Engineering 32 (2): 135-152

Albanai JA (2021) Seasonal spatial and temporal distribution of Chlorophyll-*a* concentration over Kuwait and the Arabian Gulf using satellite and in-situ data. Preprints. 2021070232 [doi: 10.20944/preprints202107. 0232.v1.]

Al-Dousari A, Doronzo D, Ahmed M (2017) Types, indications and impact evaluation of sand and dust storms trajectories in the Arabian Gulf. Sustainability 9: 1526 [doi:10.3390/su9091526]

Al-Dousari A (ed.), (2021) Atlas of fallen dust in Kuwait. Springer International Publishing. ISBN: 978-030-6676-8 [doi: 10.1007/978-3-030-66977-5]

Aleisa E, Al-Shayii K (2017 a) Analysis on reclamation and reuse of wastewater in Kuwait. Kuwait Journal of Science and Engineering 7: 1-27

Aleisa E, Al-Zubari W (2017 b) Wastewater reuse in the countries of the Gulf Cooperation Council (GCC): the lost opportunity. Environmental Monitoring and Assessment 89: 553 [https://doi.org/10.1007/s10661-017-6269-8]

Al-Hashmi KA, Smith Sl, Claereboudt M, Piontkovski SA, Al-Azri A (2015) Dynamics of potentially harmful phytoplankton in a semi-enclosed bay in the Sea of Oman. Bulletin of Marine Science 91 (2): 141-166 [http://dx.doi.org/10.5343/bms.2014.1041]

Al-Hashmi K, Piontkovski S, Bruss G, Hamza W, Bryantseva YV, Popova E (2019) Seasonal variations of plankton communities in coastal waters of Oman. International Journal of Oceans and Oceanography 13 (2): 395-426 [https://www.ripublication.com/ijoo19/ijoov13n2_13.pdf]

Al-Ghadban AN, Jacob PG, Abdalli F (1994) Total organic carbon in the sediments of the Arabian Gulf and need for biological productivity investigations. Marine Pollution Bulletin 28: 356-362 [https://doi.org/10.1016/0025-326X(94)90272-0]

Al-Ghadban AN, Uddin S, Maltby E, Al Khabbaz A, Al Mutairi A (2012) Denitrification potential of the Northern Arabian Gulf- n experimental study. Environmental Monitoring and Assessment1 84 (12): 7103-12 [doi 10.1007/s10661-011-2483-y]

Al-Handal A, Hu C (2015) MODIS observations of human-induced changes in the Mesopotamian marshes in Iraq. Wetlands 35: 31-40 [http://dx.doi.org/10.1007/s13157-014-0590-6]

Al-Hasawi H (1999) Investigation of municipal solid waste management in GCC states. Thesis submitted for PhD. University of Sterling, U.K. 318 pp

Al-Husaini M, Bishop JM, Al-Foudari AF, Al-Baz AF (2015) A review of the status and development of Kuwait's fisheries. Marine Pollution Bulletin 100: 597-606 [doi: 10.1016/j.marpolbul.2015.07.053]

Al-Said T, Al-Ghunaim A, Subba Rao DV, Al-Yamani F, Al-Rifaie K, Al-Baz A (2017) Salinity-driven decadal changes in phytoplankton community in the NW Arabian Gulf of Kuwait. Environmental Monitoring and Assessment 189: 268 [http://dx.doi.org/10. 1007/s10661-017-5969-4]

Al-Said T, Madhusoodhanan R, Pokavanich T, Al-Yamani F, Kedila R, Al-Ghunaim A, Al-Hashem A (2018 a) Environmental characterization of a semiarid hypersaline system based on dissolved trace metal-macronutrient synergy: A multivariate spatio-temporal approach. Marine Pollution Bulletin 129: 846-858 [https://doi.org/10.1016/j.marpolbul.2017.10.009]

Al-Said T, Naqvi SWA, Al-Yamani F, Goncharov A, Fernandes L (2018 b) High total organic carbon in surface waters of the northern Arabian Gulf: Implications for the oxygen minimum zone of the Arabian Sea. Marine Pollution Bulletin 129: 35-42

Al-Sarawi MA, Massoud, MS, Khader SR (2002) Recent trace metal pollution in bottom sediments of Sulaibikhat Bay. Kuwait Technology 8: 38-50

Alshemmari H (2021) An overview of persistent organic pollutants along the coastal environment of Kuwait. Open Chemistry 19: 149-156

Al-Yamani F (2008) Importance of the freshwater influx from the Shatt-Al-Arab River on the Gulf marine environment. In: Abuzinada AH, Barth HJ, Krupp F, Böer B, Al Abdessalaam TZ (eds) Protecting the Gulf's marine ecosystems from pollution. Birkhäuser, Basel. pp 207-222 [https://doi.org/10.1007/978-3-7643-7947-6_11]

Al-Yamani F, Subba Rao DV, Mharzi A, Ismail W, Al-Rifaie K (2006) Primary production off Kuwait, an arid zone environment, Arabian Gulf. International Journal of Oceans and Oceanography 1: 67-85

Al-Yamani FY, Bishop JM, Al-Rifaiae K, Ismail W (2007) The effects of the river diversion, Mesopotamian Marsh drainage and restoration, and river damming on the marine environment of the northwestern Arabian Gulf. Aquatic Ecosystem Health and Management 10: 277-289 [doi: 10.1080/14634980701512384]

Al-Yamani F, Saburova M, Polikarpov I (2012) A preliminary assessment of harmful algal blooms in Kuwait's marine environment. Aquatic Ecosystem Health and Management 15 (1): 64-72

Al-Yamani F, Stokozov N, Polikarpov I (2014) Oceanography Annual Report Card, OARC. KISR

Al-Yamani F, Skryabin V, Subba Rao DV (2015) Suspected ballast water introductions in the Arabian Gulf. Marine invasive species: Management of ballast water and other vectors. Journal of Aquatic Ecosystem Health and Management18 (3): 280-289 [https://doi.org/10.1080/14634988.2015.1027135]

Al-Yamani F, Yamamoto T, Al-Said T, Alghunainm A (2017) Dynamic hydrographic variations in northwestern Arabian Gulf over the past three decades: Temporal shifts and trends derived from long-term monitoring data. Marine Pollution Bulletin 122: 488-499

Al-Yamani F, Naqvi SWA (2019) Chemical oceanography of the Arabian Gulf. Deep-Sea Research. Part II: Tropical Studies in Oceanography 161: 72-80 [https://doi.org/10.1016/j.dsr2.2018.10.003]

Al-Yamani F, Saburova MA (2019 a) Marine phytoplankton of Kuwait's waters. Vol 1. Cyanobacteria, Dinoflagellates, Flagellates. Kuwait Institute for Scientific Research. 469 pp

Al-Yamani FY, Saburova MA (2019 b) Marine phytoplankton of Kuwait's waters. Vol 1I. Diatoms. Kuwait Institute for Scientific Research. 336 pp

Al-Yamani FY, Polikarpov IG, Saburova M (2020) Marine life mortalities and Harmful Algal Blooms in the Northern Arabian Gulf. Aquatic Ecosystem Health and Management 23 (2): 196-209 [doi: 10.1080/14634988.2020.1798157]

Al-Yamani F, Polikarpov IG, Saburova M (2021) Northern Gulf marine biodiversity in relevance to the river discharge. In: Jawad LA (ed) Southern Iraq's marshes. Coastal Research Library 37. Springer Nature Switzerland AG. pp 379-438

Baawain MS, Al-Omairi A, Choudri BS (2014) Characterization of domestic wastewater treatment in Oman from three different regions and current implications of treated effluents. Environmental Monitoring and Assessment 186 (5): 2701-2716 [doi:10.1007/s10661-013-3572-x]

Barnes IJD, Balaguer L, Mnrique E, Elvira S, Davison AW (1992) A reappraisal of the use of DMSO for the extraction and determination of chlorophylls *a* and *b* in lichens and higher plants. Environmental and Experimental Botany 22: 85-100 [https://doi.org/10.1016/0098-8472(92)90034-Y]

Basaham AS, Al-Lihabi SS (1993) Trace elements in sediments of the Western Gulf. Marine Pollution Bulletin 27: 103-107

Bashitialshaaer R, Persson KM, Aljaradin M (2011) Estimated future salinity in the Arabian Gulf, the Mediterranean Sea and the Red Sea. Consequences of brine discharge from desalination. International Journal of Academic Research 3 (1): 133-140

Ben-Hasan A, Walters C, Christensen V, Al-Husaini M, H. Al-Foudari H (2018) Is reduced freshwater flow in Tigris-Euphrates rivers driving fish recruitment changes in the Northwestern Arabian Gulf? Marine Pollution Bulletin 129 (1): 1-7 [https://doi.org/10.1016/j.marpolbul.2018.02.012]

Bhunia S, Bhowmik A, Mukherjee J (2022) Waste management of rural slaughterhouses in developing countries. Advanced Organic Waste Management: 425-449 [https://doi.org/10.1016/B978-0-323-85792-5.00019-8]

Bohm A (1931) Peridineen aus dem Persischen Golf und dem Golf von Oman. Archiv für Protestenkunde 74: 188-197

Bouwman L, Beusen A, Glibert PM, Overbeek C, Pawlowski M, Herrera J, Mulsow S, Yu R, Zhou M (2013) Mariculture: significant and expanding cause of coastal nutrient enrichment. Environmental Research Letters 8: 044026 [doi:10.1088/1748-9326/8/4/044026]

Brewer PG, Dyrssen D (1985) Chemical oceanography of the Persian Gulf. Progress in Oceanography 14: 41-55

Burkholder JM (1998) Implications of harmful microalgae and heterotrophic dinoflagellates in management of sustainable marine fisheries. Ecological Applications 8 (1): Supplement: Ecosystem Management for Sustainable Marine Fisheries (Feb. 1998): S37-S62

Bustillo-LeCompte, Mehrvar M (2017) Slaughterhouse wastewater: treatment, management, and resource recovery. In: Robert Farooq, Zaki Ahmad (eds) Physico Chemical Wastewater Treatment and Resource Recovery. pp 153-174 [doi: 10.5772/65499]

Chalit G (2009) FAO Report [Qatar.http://www.fao.org/nr/water/aquastat/countries_regions/qat/ QAT- CP_ara.pdf]

Clarke SA, Vilizzi L, Lee L, Wood LE, Cowie WJ, Burt JA, Mamiit RJE, Ali H, Davison PI, Fenwick GV, Harmer R, Skóra ME, Kozic S, Aislabie LR, Kennerley A, Le Quesne WJF, Copp GH, Stebbing PD (2020) Identifying potentially invasive non-native marine and brackish water species for the Arabian Gulf and Sea of Oman. Globe Change Biology 26: 2081-2092 [https://doi.org/10.1111/gcb.14964]

Devlin MJ, MS Massoud MS, Hamid SA, Al-Zaidan A, Al-Sarawi H, Al-Enezi M, Al-Ghofran L, Smith AJ, Barry J, Stentiford GD, Morris S, da Silva ET, Lyons BP (2015) Changes in the water quality conditions of Kuwait's marine waters: long term impacts of nutrient enrichment. Marine Pollution Bulletin 100 (2): 607-620 [https://doi.org/10.1016/j.marpolbul.2015.10.022]

Devlin MJ, Breckels M, Graves CA, Barry J, Capuzzo E, Huerta FP, Al Ajmi F, Al-Hussain MM, Lequesne WJF, Lyons BP (2019) Seasonal and temporal drivers influencing phytoplankton community in Kuwait marine waters: Documenting a changing landscape in the Gulf. Frontiers in Marine Science 6: 141 [doi: 10.3389/fmars.2019.00141]

Dobaradaran S, Soleimani F, Nabipour I, Saeedi R, Mohammadi MJ (2017) Heavy metal levels of ballast waters in commercial ships entering Bushehr port along the Persian Gulf. Marine Pollution Bulletin 126: 74-76 [https://doi.org/10.1016/j.marpolbul.2017.10.094]

Dorgham MM, Muftah A, El-Deeb KZ (1987) Plankton studies in the Arabian Gulf II. The autumn phytoplankton in the Northwestern Area. Arab Gulf Journal of Scientific Research B5: 215-235

Dorgham MM, Moftah A (1989) Environmental conditions and phytoplankton distribution in the Gulf and Gulf of Oman. Journal of the Marine Biological Association of India 31: 36-53

Dorgham MM (2013) Plankton research in the ROPME Sea Area, Achievements and Gaps. International Journal of Environmental Research 7 (3): 767-778

Duarte C M, Conley DJ, Carstensen J, Sanchez-Camacho M (2009) Return to neverland: Shifting baselines affect eutrophication restoration targets. Estuaries and Coasts 32: 29–36 [doi10.1007/s12237-008-9111-2]

Duxbury AC, Byrne RH, Mackenzie FT (2024) Seawater. Encyclopedia Britannica 5 Nov. 2020 [https://www.britannica.com/science/seawater]

El-Anbaawy E, Abdelhalim A, Al Ajmi D, Al Sarawi M (2018) Environmental assessment and evaluation of anthropogenic impacts on Sulaibikhat Bay tidal flat area, Kuwait. Journal of Health and Environmental Research 4 (1): 21-34 [http://www.sciencepublishinggroup.com/j/jher] [doi: 10.11648/j.jher.20180401.14]

Emara HI (2010) Nutrient salts, inorganic and organic carbon contents in the waters of the Persian Gulf and the Gulf of Oman. Journal of the Persian Gulf (Marine Science) 1: 33-44

Enezi G, Hamoda MF, Fawzi N (2004) Heavy metals content of municipal wastewater and sludges in Kuwait. Journal of Environmental Science and Health Part A-Environmental Science and Engineering and Toxic and Hazardous Substance Control A39 (2): 397-407 [doi: 10.1081/ESE-120027531]

Esmaeili FM, Mortazavi MS, Banadaki AD, Saraji F, Nozar SLM (2021) Algal blooms historical outbreaks in the northern coastal waters of the Persian Gulf and Oman Sea (1980–2015). Environmental Monitoring and Assessment 193: 648 [https://doi.org/10.1007/s10661-021-09413-3]

Feidi IH (2009) Aquaculture industry in the Arab World. Project report: FAO Aquaculture Industry in the Arab World. FAO, Rome. pp 12

Flöder S, Sommer U (2015) Competition of aquatic microalgae in variable environments: the disturbance effect. Chapter 15 In: Subba Rao DV (ed) Algal cultures, analogues of blooms and applications. Science Publishers, Enfield, USA. pp 1-42

Folt CL, Chen CY, M. V. Moore MV, Burnaford J (1999) Synergism and antagonism among multiple stressors. Limnology and Oceanography 44: 864-877

GCC Wastewater Report (2020) Water management in the GCC- statistics and facts. Statista Research Department.

Gallo A, M. Guida M, Armiento G, Siciliano A, Mormile N, Carraturo F, Pellegrini D, Morroni L, Tosti E, Ferrante MI, Montresor M, Molisso F, Sacchi M, Danovaro R, Lofrano G, Libralato G (2020) Species-specific sensitivity of three microalgae to sediment elutriates. Marine Environmental Research 156: 104901 [https://doi.org/10.1016/j. marenvres.2020.104901]

Gharib I, Al-Hashash, Anwar M (1986) Dust fallout in the northern part of the ROMPE Sea Area. I. Physical characteristics of the dust fallout in the northern part of ROPME Sea Area. ROMPE/GC 5/0 EES 66 KISR Technical report no 2058 p 193-195

Glibert PM, Landsberg JH, Evans JJ, Al-Sarawi MA, Faraj M, Al-Jarallah MA, Haywood A, Ibrahem S, Klesius P, Powell C, Shoemaker C (2002) A fish kill of massive proportion in Kuwait Bay, Arabian Gulf, 2001: the roles of bacterial disease, harmful algae, and eutrophication. Harmful Algae 1: 215-231

Gómez F (2006) Endemic and Indo-Pacific plankton in the Mediterranean Sea: a study based on dinoflagellate records. Journal of Biogeography 33: 261-270

Gowen RJ, Y. Collos Y, Tett P, Scherer C, Bec B, Abadie E, Allen M, O'Brien T (2015) Response of diatom and dinoflagellate lifeforms to reduced phosphorus loading: A case study in the Thau lagoon, France. Estuarine, Coastal and Shelf Science 162: 45-52 [https://doi.org/10.1016/j.ecss.2015.03.033]

Guillard RRL (1975) Culture of phytoplankton for feeding marine invertebrates. In: Smith WL, Chanley MH (eds) Culture of Marine Invertebrate Animals. Plenum Press, New York, USA p 29-60

Hallegraeff G M (1993) A review of harmful algal blooms and their apparent global increase. Phycologia 32: 79-99 [https://doi.org/10.2216/i0031-8884-32-2-79.1]

Heil CA, Glibert PM, Al-Sarawi MA, Faraj M, Behbehani M, Husain M, (2001) First record of a fish killing Gymnodinium sp. bloom in Kuwait Bay, Arabian Sea: Chronology and potential causes. Marine Ecology Progress Series 214: 15-23

HELCOM BASP (1974) Baltic marine environment protection commission [http://www.helcom.fi/1974 https://doi.org/10.1016/j.rsma.2020.101472]

Hold Gl, Smith EA, Rappé MS, Maas EW, Moore ERB, Stroempl C, Stephen JR, Prosser JI, Birkbeck TH, Gallacher S (2001) Characterization of bacterial communities associated with toxic and non-toxic dinoflagellates: *Alexandrium* spp. and *Scrippsiella trochoidea*. FEMS Microbiology Ecology 37 (2): 161-173 [doi:10.1016/S0168-6496(01)00157-X]

Hosseini H, Saadaoui I, Moheimani N, Al Saidi ,M, Al Jamali F, Al Jabri H, Ben Hamadou R (2021) Marine health of the Arabian Gulf: Drivers of pollution and assessment approaches focusing on desalination activities. Marine Pollution Bulletin 164: 112085 [doi: 10.1016/j.marpolbul.2021.112085]

https://www.oceancolour.org site

https://oceancolor.gsfc.nasa.gov

Humborg C, Ittekkot V, Cociasu A, Bodungen B (1997). Effect of Danube River dam on Black Sea biogeochemistry and ecosystem structure. Nature 386: 385-388

Imai I, Yamaguchi M, Hori Y (2006) Eutrophication and occurrences of harmful algal blooms in the Seto Inland Sea, Japan. Plankton Benthos Research 1 (2): 71-84

Islam MS (2005) Nitrogen and phosphorus budget in coastal and marine cage aquaculture and impacts of effluent loading on ecosystem: Review and analysis towards model development. Marine Pollution Bulletin 50: 48-61 [doi: 10.1016/j.marpolbul.2004.08.008]

Ismail KA, Al Shehhi MR (2022) Upwelling and nutrient dynamics in the Arabian Gulf and sea of Oman. PLOS ONE 17 (10): e0276260 [https://doi.org/10.1371/journal.pone.0276260]

Jacob PG, Al-Muzaini S (1995) Marine plants of the Arabian Gulf and effect of oil pollution. Mahasagar 28: 83-101

Johns WE, Yao F, Olson DB, Josey S, Grist JP, Smeed D (2003) Observations of seasonal exchange through the Straits of Hormuz and the inferred heat and freshwater budgets of the Persian Gulf. Journal of Geophysical Research 108 (C12): 3391

Jones C, Sultan M, Yan E, Milewski A, Hussein M, Al-Dousari A, Al-Kaisy S, Becker R (2008) Hydrologic impacts of engineering projects on Tigris-Euphrates system and its marshlands. Journal of Hydrology 353: 59-75

Juma HA, Al-Madany IS (2008) Concentration of heavy metals in the territorial sea water of Kingdom of Bahrain, Arabian Gulf. Arab Gulf Journal of Scientific Research 26: 19-32

Lattuada M, Wilke T, Raes N (2020) Caspian Sea environmental variables: an extension of the Bio-Oracle

Ocean data set. Ecology 101 (9): e03076 [https://doi.org/10.1002/ecy.3076]

Lee CH, Ho H-J, Chen W-S, Iizuka A (2024) Total resource circulation of desalination brine: A review. Advanced Sustainable Systems 8: 2300460 [https://doi.org/10.1002/adsu.202300460]

Le Quesne WLF, Fernand L, Ali TS, Andres O, Antonpoulou M, Burt JA, Dougherty WW, Edson PJ, El Kharraz J, Glavan J, Mamiit RJ, Reid KD, Sajwani A, Sheahan D (2021) Is the development of desalination compatible with sustainable development of the Arabian Gulf? Marine Pollution Bulletin 173: 112940 [doi: 10.10D16/j.marpolbul.2021.112940]

Madhusoodhanan R, Al-Yamani F, Subba Rao DV, Ahmed A, Fernandes L, Al-Said T, Madhavapeddi S (2018) Salinity and microzooplankton grazing as forcing variables affecting phytoplankton growth and primary productivity in the NW Arabian Gulf. Gulf International Conference, 5-7, November 2018 Al Aion, UAE

Murray CJ, Muller-Karulis B, Carstensen J, Conley DJ, Gustafsson BG, Andersen JH (2019) Past, present and future eutrophication status of the Baltic Sea. Frontiers in Marine Science 6: 2 [https://doi.org/10.3389/fmars.2019.00002]

Neelamani S, Al-Dousari A (2016) A study on the annual fallout of the dust and the associated elements into the Kuwait Bay, Kuwait. Arabian Journal of Geosciences 9: 210 [doi.10.1007/s/12517-2236-2]

Nezlin N P, Polikarpov IG, Al-Yamani FY, Subba Rao DV, Ignatov AM (2010) Satellite monitoring of climatic factors regulating phytoplankton variability in the Arabian (Persian) Gulf. Journal of Marine Systems 82 (1-2): 47-60

Nixon S (2003) Replacing the Nile: Are anthropogenic nutrients providing fertility once brought to the Mediterranean by a Great River? AMBIO: A journal of the human environment 32: 30-39

Omerspahic M, Al-Jabri H, Siddqui SA, Saadaoui I (2022) Characteristics of desalination brine and its impacts on marine chemistry and health, with emphasis on the Persian/Arabian Gulf: A review. Frontiers in Marine Science 9: 845113 [https://doi.org/10.3389/fmars.2022.845113]

Oren A *et al*. (1995) A bloom of *Dunaliella parva* in the Dead Sea in 1992: biological and biogeochemical aspects. Hydrobiologia 297: 173-185 [https://doi.org/10.1007/BF00019283]

OSPAR Commission (2020) Atmospheric deposition of Nitrogen to the OSPAR maritime area in the period 1995-2017. Publication 758, London, UK. pp1-94 [ISBN 978-1-911458-97-5]

Oyeku O G, Mandal SK (2021) Historical occurrences of marine microalgal blooms in Indian Peninsula: Probable causes and implications. Oceanologia 63: 51-70

Pan Y (1996) Changes in domoic acid production and cellular chemical composition of the toxigenic diatom *Pseudo-Nitzschia multiseries* under phosphate limitation. Journal of Phycology 32 (3): 371-381 [https://doi.org/10.1111/j.0022-3646.1996.00371.x]

Pan Y, Cembella AD, Quilliam MA (1999) Cell cycle and toxin production in the benthic dinoflagellate *Prorocentrum lima*. Marine Biology 134: 541-549 [doi:10.1007/s0022700505690xigenic]

Paytan A, Mackey KRM, Chen Y, Post AF (2009) Toxicity of atmospheric aerosols on marine phytoplankton. Thiemens MH (ed), University of California at San Diego, La Jolla, CA 106 (12) 4601-4605 [https://doi.org/10.1073/pnas.0811486106]

Pearce F (1993) Draining life from Iraq's marshes. New Scientist. 138: 11-12

Polikarpov I, Al-Yamani F, Saburova M (2009) Space-time variability of phytoplankton structure and diversity in the north-western part of the Arabian Gulf (Kuwait). BioRisk 3: 86-96 [https://doi.org/10.3897/biorisk.3.8]

Polikarpov I, Saburova, M, Al-Yamani F (2016) Diversity and distribution of winter phytoplankton in the Arabian Gulf and the Sea of Oman. Continental Shelf Research 119: 85-99

Polikarpov I, Saburova, M, Al-Yamani F (2020) Decadal changes in diversity and occurrence of microalgal blooms in the NW Arabian/Persian Gulf. Deep-Sea Research II 179: 104810 [https://doi.org/10.1016/j.dsr2.2020.104810]

Prakash PJ, Stenchikov G, Kalenderski S, Osipov S, Bangalath H (2015) The impact of dust storms on the Arabian Peninsula and the Red Sea. Atmospheric Chemistry and Physics 15: 199-222

Qatar (2015) [http://www.fao.org/nr/water/aquastat/countries_regions/qat/QAT-CP_ara.pdf]

Qureshi AS (2020) Wastewater to manage water scarcity crises in the Gulf Cooperation Council (GCC) Countries. Water 12: 1-16

Rengefors K (2020) Species assemblies and seasonal succession of dinoflagellates. Ch. 3 In: Subba Rao DV (ed) Dinoflagellates Classification, evolution, physiology, and ecological significance. Nova Science Publishers, Inc. New York. pp 63-84 [ISBN: 978-1-53617-888-3]

Reynolds RM (1993) Physical oceanography of the Gulf, Straits of Hormuz, and the Gulf of Oman: Results from the *Mt. Mitchell* Expedition. Marine Pollution Bulletin 27: 35-59

Richardson CJ, Reiss P, Hussain NA, Alwash AJ, Pool DJ (2005) The restoration potential of the Mesopotamian marshes of Iraq. Science 307: 1307-1311

Richlen ML, Morton SL, Jamali E, Anbiah R, Anderson DM (2010) The catastrophic 2008-2009 red tide in the Arabian Gulf region, with observations on the identification and phylogeny of the fish-killing dinoflagellate *Cochlodinium polykrikoides*. Harmful Algae 9: 163–172

Risk MJ, Haghshenas SA, Arab AR (2021) Cage aquaculture in the Persian Gulf: A cautionary tale for Iran and the world. Marine Pollution Bulletin 166: 112079 [https://doi.org/10.1016/j.marpolbul.2021.112079]

Saad MAH (1985) Distribution of nutrients in Shatt Al-Arab Estuary. Bulletin of the National Institute of Oceanography and Fisheries. Cairo Government 11: 24-72

Saburova M, Al-Kandari M, Polikarpov I, Akbar A, Hussain S, Rahmeh R, Al-Zakri W, Al-Yamani F (2022) Alien toxic dinoflagellate *Heterocapsa circularisquama* from the Western Pacific in Kuwait, NW Indian Ocean. Deep Sea Research Part II: Topical Studies in Oceanography 19: 6105027 [https://doi.org/10.1016/j.dsr2.2022.105027]

Safar MI (1985) Dust and dust storms in Kuwait. State of Kuwait Directorate General of civilization and Meteorological Department. 212 pp

Sheppard C, Al-Husiani M, Al-Jamali F, Al-Yamani F, Baldwin R, Bishop J, Benzoni F, Dutrieux E, Dulvy NK, Subba Rao DV, Jones DA, Loughland R, Medio D, Nithyanandan M, Pilling GM, Polikarpov I, Price ARG, Purkis S, Riegl B, Saburova M, Zainal K (2010) The Gulf: A young sea in decline. Marine Pollution Bulletin 60 (1): 13-38 [doi: 10.1016/j.marpolbul.2009.10.017]

Spilling K, Olli K, Lehtoranta J, Kremp A, Tedesco L, Tamelander T, Klais R, Peltonen H, Tamminen T (2018) Shifting diatom-dinoflagellate dominance during spring bloom in the Baltic Sea and its potential effects on biochemical cycling. Frontiers in Marine Science 5: 327 [https://doi.org/10.3389/fmars.2018.00327]

Stelzer JAA, Mesman JP, Gsell AS, de Senerpont Domis LN, Visser PM, Adrian R, Ibelings BW (2022) Phytoplankton responses to repeated pulse perturbations imposed on a trend of increasing eutrophication. Ecology and Evolution 12 (3): e8675 [https://doi.org/10.1002/ece3.8675]

Subba Rao DV, Sprules WG, Locke A, Carlton JT (1994) Exotic phytoplankton from ships' ballast waters: risk of potential spread to mariculture sites on Canada's east coast. Canadian data report of Fisheries and Aquatic Sciences 937: 51

Subba Rao DV, Al-Yamani F (1998) Phytoplankton ecology in the waters between Shatt-Al-Arab and Straits of Hormuz - the Arabian Gulf. Plankton Biology and Ecology 45: 101-116

Subba Rao DV, Al-Yamani F (1999) Analysis of the relationship between phytoplankton biomass and the euphotic layer off Kuwait, Arabian Gulf. Indian Journal of Maine Science 28: 416-423

Subba Rao DV, Al-Yamani F, Lennox A, Pan Y, Al-Said TFO (1999 a) Biomass and production characteristics of the first red tide noticed in Kuwait Bay, Arabian Gulf. Journal of Plankton Research UK 21: 805-810

Subba Rao DV, Al-Yamani F, Nageswara Rao CV (1999 b) Aeolian dust affects phytoplankton in the waters off Kuwait, the Arabian Gulf. Naturwissenschaften 86: 525-529

Subba Rao DV, Al-Yamani F (2000) Ch. 53, Arabian Gulf: In: Sheppard C (ed) Seas at the Millennium. Elsevier Science Ltd., UK. pp 1-16

Subba Rao DV, Al-Hassan JM, Al-Yamani F, Al-Rafiae K, Ismail W, Nageswara Rao CV, Al-Hassan M (2003) Elusive red tides in Kuwait Coastal waters. Harmful Algal News. IOC-UNESCO Newsletter 24: 10-13

Subba Rao DV, Pan Y, Al-Yamani F (2005) Growth and photosynthetic rates of *Chlamydomonas plethora* and *Nitzschia frustula* cultures isolated from Kuwait Bay, Arabian Gulf, and their potential as live algal food for tropical mariculture. Marine Ecology 26 (1): 63-71 [https://doi.org/10.1111/j.1439-0485.2005.00043.x]

Subba Rao DV, Durvasula R (2020) Ch. 15, Putting it all together: The Arabian Gulf dinoflagellates. In: Subba Rao DV (ed) Dinoflagellates, classification, evolution, physiology and ecological significance. Nova Science Publishers, New York. pp 527-569

Swift SA, Bower AS (2003) Formation and circulation of dense water in the Persian/Arabian Gulf. Journal of Geophysical Research 108: 3004 [doi:10.1029/2002JC001360]

Talling JF (1980) Water characteristics. In: Rzoska L (ed) Euphrates and Tigris: Mesopotamian ecology and destiny. Monographiae Bilogicae 38: 63-86

Winder M, Cloern JE (2010). The annual cycles of phytoplankton biomass. Philosophical Transactions of the Royal Society B 365: 3215-3226 [https://doi.org/10.1098/rstb.2010.0125]

WoRMS Editorial Board (2023) World Register of Marine Species [https://www.marinespecies.org at VLIZ; doi:10.14284/170]

Zavialov P (2005) Physical oceanography of the dying Aral Sea. Praxis Publishing Ltd., Chichester. pp 1-170