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Desalination of seawater in the Gaza Strip: the regional short-term low-volume (STLV) seawater desalination plant of Deir Al-Balah as a case study

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ABSTRACT

The situation of water sector in the Gaza Strip-is characterized by many parties as humanitarian crisis- where the underling groundwater, the only water resource, is used extensively to supply water for domestic, agricultural and industrial sectors. The major part of the groundwater is grossly exploited and contaminated with high levels of pollutants, e.g. chloride (Cl) concentrations range between 600–2000 mg/l and nitrate (NO_3) concentrations range between 50 and 200 mg/l, these levels exceed World Health Organization (WHO) and Palestinian Water Authority (PWA) guidelines for drinking water. In response to this water crisis, the PWA put a comprehensive plan to construct three short-term low-volume (STLV) seawater desalination plants to provide Gaza Strip by a total of 13 million cubic meters per year of freshwater. The regional short-term low-volume (SLTV) seawater desalination plant is considered as an urgent solution to mitigate the suffering from water crisis in the southern region of the Gaza Strip. Currently, the plant provides the water sector by 2.2 million cubic meters of freshwater per year. The plant will be upgraded to provide about 7.3 million cubic meters of freshwater per year for domestic uses. However, as a product from the reverse osmosis process, huge amount of brine, nearly 8.92 million cubic meters per year, with salinity reaches to 75,000 mg/L will be redirected to seawater. This paper employs the powerful of numerical modelling to suggest proper mitigation measures in order to minimize the negative environmental impacts of brine disposal on the marine ecosystems. This study uses the model of CORMIX v 9.0 to simulate the dispersion and dilution behavior of discharged brine through eight disposal systems classified under four classes of configurations: single port outfall, alternating multi port diffuser, unidirectional multi port diffuser and staged multi port diffuser. The sensitivity of change in the ambient conditions over the four seasons of the year plays a significant role in enhancing or inhibiting the process of brine mixing, dilution and dispersion. Taking salinity variations as an indicator, the simulation results of discharged brine via various outfalls configurations into the marine environment over the four annual seasons show that the fanned-out unidirectional multi port outfall of option (7) is the optimal design configuration, where discharging the produced brine from the regional STLV plant via option (7) can meet the disposal standard at RMZ in the worst ambient condition of autumn at low astronomical tide (LAT) by reducing the brine's excess salinity at the edge of mixing zone to less than 1.25% (488 mg/L) above seawater salinity.

Keywords: Gaza strip; Water supply; Seawater desalination; Short-term low-volume (STLV); Brine disposal modelling; Environmental impact assessment (EIA), Public health assessment

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1. Introduction

The availability of water is one of the main guaranties that sustain the life of humans and other beings on the planet of earth [1–3]. However, water covers approximately three-fourths of the surface of the earth but over 97% of the total water supply is contained in the oceans and other saline water bodies which is not readily usable for most purposes. A little over 2% of the remaining 3% of the available water is inaccessible which is tied in ice caps, glaciers, atmospheric and soil moisture. Thus, for their general livelihood and the support of their varied technical and agricultural activities, humans depend upon the remaining 0.62%, estimated by 8.5 billion cubic meters, that is found in freshwater lakes, rivers, and groundwater supplies [4]. The water scarcity crisis "as a result of water abuse, pollution, climate change and population growth" became the most pressing problem [1,5–7]. The impacts of water scarcity crisis severely affect the biodiversity of the living organisms by threating more than two-third of their natural habitats [8,6]. Desalination of seawater became one of the most feasible and promising solutions for supplying freshwater in regions suffering from lack of conventional water resources, especially for those areas located along the coastlines [1,8–11]. Worldwide, many states depend on desalinated water for more than 50% of their domestic uses in order to avert the real threats to resource sustainability and to satisfy the immediate need to increase the production and supply of potable water [12,13]. By the year of 2015, around 18,426 desalination plants have been installed and operated in 150 countries to provide more than 300 million people by about 86.8 million cubic meters of freshwater daily [14]. Generally, the Middle East is classified as the largest desalinated water consumer where the conditions of drought and desertification strongly push towards treating the unconventional water sources in order to balance the deficit in the water supply needs [13,15–17]. The Kingdom of Saudi Arabia (KSA) produces the largest part of the desalinated water in the world. KSA desalinates daily more than one-tenth of the globally produced desalinated water, about 75% of the desalinated water in the KSA is produced by operating seawater desalination plants [18]. United Arab Emirates (UAE) follows KSA as the second highest country employing desalination around the world with a desalination employing capacity of 8.4 million cubic meters per day, more than 85% of the desalinated water is produced by seawater desalination plants [15]. However, as it is gaining increasing importance for addressing water needs, desalination technology has its disadvantages of costly, energy intensive and further strains the environment with brine disposal and greenhouse gas emissions [19–22]. So, to safeguard sustainable usage of desalination technology, the impacts of desalination process, specially the wastes of brine, should be investigated and mitigated as far as possible using adequate instrument for this purpose under the frame of environmental impact assessment (EIA) by developing appropriate mitigation measures and alternatives, such as modifications to the process or alternative project sites [23]. Like other countries in the Middle East and North Africa, the availability of freshwater resources in the Gaza Strip is scarce and the deficit in water balance is increasing by the time. Hence, the orientation in the Gaza Strip trends toward desalinating seawater to meet the requirements of water for different purposes. This study highlights the possibilities of using seawater desalination plants as a strategic option to mitigate the deterioration in the water sector of the Gaza Strip, as well as this study demonstrates a case study of Deir Al-Balah seawater desalination plant.

2. Environmental impacts of desalination plants

The main obstacle that threats the sustainability of seawater reverse osmosis (RO) desalination technology as a promising solution to meet the gap in water needs is the challenge of brine disposal. As a sub product of RO process, this technology produces large volume of brine with salinity reaches more than twice the salinity of feed water that is usually redirected into seawater [13,19–21]. The discharged brine has the ability to change the nature of the marine ecosystem due to the presence of several constitutes of chemicals in conjunction with its high salinity [24–27]. The environmental management and monitoring tools became essential to control the integrity of environment and to gather accurate knowledge on the behavior of environmental phenomena to be controlled. Physical and numerical models are effective and practical prediction tools to minimize the negative environmental impacts by simulating the effects of taken mitigation measures on the diffusion and advection of disposed brine into marine under different ambient conditions [21,28,29]. Hence, in the desalination processes, brine needs to be properly discharged with minimum environmental impacts. In the light of EIA, the mixing efficiency of the brine disposal systems should be simulated so that to be used as mitigation measures to mitigate the negative environmental impacts of brine disposal.

3. Water sector in the Gaza Strip

The Gaza Strip (Fig. 1) is a coastal strip located on the south-eastern coast of the Mediterranean Sea with 42 km long, between 6 and 12 km wide, and covers an area of 365 km^2. The Gaza Strip consists of five governorates: North Gaza, Gaza, Deir Al-Balah, Khanyounis and Rafah governorates. The estimations of the Palestinian Central Bureau of Statistics (PCBS) for the year of 2017, show that the population of Gaza Strip was 1.94 million inhabitants [30].

The primary source of freshwater in the Gaza Strip is the underling groundwater that is grossly contaminated, and at present yields, almost no flow of acceptable quality for domestic use [31]. The Groundwater provides about 98% of all water supplies, while the remaining 2% of the waters are purchased from water companies [32,33]. At its present rate of deterioration, over 95% of the underling portion of the coastal aquifer on which the Gaza Strip relies on for its water needs is contaminated with unacceptable high levels of either nitrate (NO_3) or chloride (Cl), posing significant health risks to Gaza's residents [31,32,34]. The abstraction rate from the underling groundwater has increased markedly over the last three decades, due to a combination of inadequate available water imports to Gaza; the expanding population; and the drilling and use of unlicensed wells specially to provide irrigation for agricultural activities. The sustainable yield of the aquifer within the geographical boundary of the Gaza Strip is widely quoted as 55 million

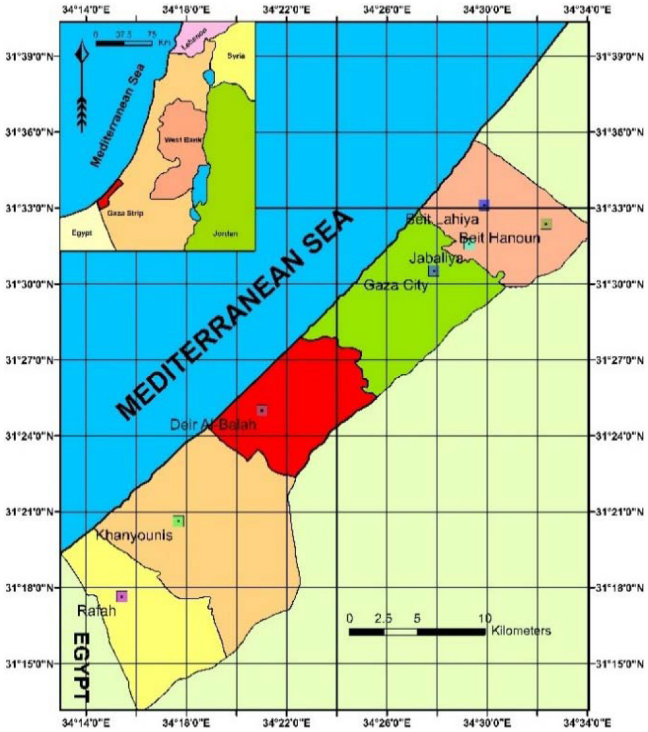

Fig. 1. Geographical location and governorates of the Gaza Strip.

cubic meters annually, however, the rate of pumping from the aquifer in the year of 2010 was estimated at 200 million cubic meters per year [35]. Generally, most of the wells show continuous chloride (Cl) increase as a result of intensive pumping, the major parts of the aquifer have a Cl concentration ranging between 600–2,000 mg/l, while along the coastal line Cl concentrations exceed 2,000 mg/l and can reach more than 10,000 mg/l at some spots due to effect of the seawater intrusion. As well, nitrate (NO_3) concentrations in the most of the groundwater range from 50 to more than 200 mg/l [35]. The baseline study of water quality and public health in the Gaza Strip that was conducted in 2015 by the Gaza-Program Coordination Unit (G-PCU) at the Palestinian Water Authority (PWA), to explore the health impacts of the existing poor quality of water in the Gaza Strip, highlights increasing in nitrate concentrations, which may cause Methemoglobinemia in infants. Most of the Gaza Strip, especially in the refugee camps, recorded high nitrate concentrations in the municipal supplied water of more than 200 mg/1 (higher than the less stringent drinking water quality standard of PWA). However, some areas are characterized by nitrate concentrations less than 50 mg/L (within the limit of the WHO Drinking Water Guidelines). This variation per locality could be explained by specific points of leakages from the sewerage network [36]. The majority of hepatitis A virus (HAV) infection still takes place in early childhood, where it is asymptomatic, self-limiting and leaves life-long immunity. In the year of 2014, a total of 860 HAV's cases were reported with an incidence of 48.8 per 100,000 population [37]. The main factor affects the geographical distribution of the incidence rate is the variation of bad infrastructures in some governorates and bad personal hygiene. Hence, the highest incidence rate per 100,000 population of reported cases in the year 2014 was reported in North governorate by 67.4, followed by Khanyounis governorate with 63. In Gaza and Deir Al-Balah governorates, the incidence rate was 42.5 and 40.3, respectively and in Rafah governorate the incidence rate was 25.3 as illustrated in Fig. 2. It has also reported an increase in the incidence of diarrhea during the period between 2009 and 2013. The rate was 4,017.1 per 100,000 in 2009, which increased to 6,909.1 per 100,000 in 2012. Data per governorate show that Deir Al-Balah (in 2009, 2010 and 2011) recorded the highest incidence rates of diarrhea compared to other communities, such as Gaza city. Bloody diarrhea is a potentially critical condition in which there is blood mixed with loose watery stools. Under this disease all cases with bloody diarrhea are included regardless the cause which could be bacterial infection or parasitic infestation. As shown in Fig. 3, during the year of 2014 a total of 7,112 cases of bloody diarrhea were reported with an incidence rate of 404 per 100,000 population representing a clear decrease compared to the year of 2013 where a total of 8,555 cases were reported with an incidence of 503 per 100,000. From the year 2006 to 2010, there were a continuous decrease of reported cases. Geographically, the highest incidence 847 per 100,000 of reported cases was in Deir Al-Balah governorate followed by North Gaza with an incidence of 527 per 100,000 population. In Khanyounis and Rafah governorates, the incidence was 495 and 259 per 100,000 while in Gaza governorate it was 148 per 100.000 population [37].

Accordingly, the main source of water in the Gaza Strip is grossly exploited, contaminated and a potential source for waterborne diseases. Hence, in response to this worsen-

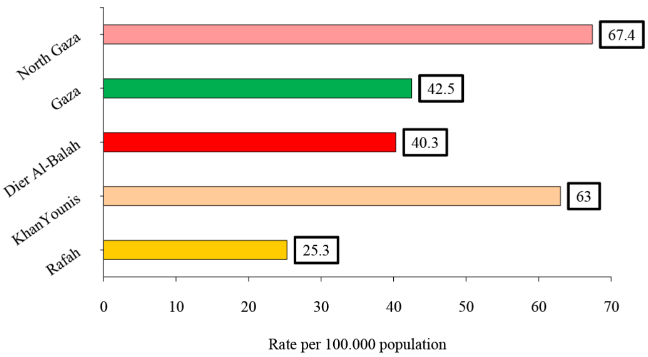

Fig. 2. Hepatitis A virus (HVA) incidence in Gaza Strip [37].

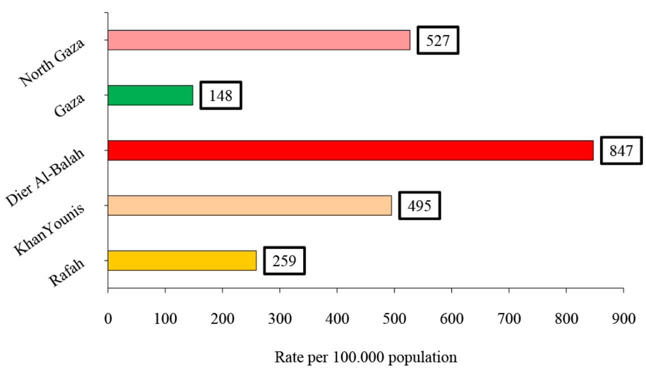

Fig. 3. Bloody Diarrhea incidence in Gaza Strip [37].

ing water crisis and in order to maintain the water balance to the positive condition and to fulfill the water demands in terms of quality and quantity, rapid and effective mitigation measures should be taken and applied to recover the underling groundwater by identifying new freshwater sources.

4. Desalination perspectives in the Gaza Strip

The current situation in the water sector of the Gaza Strip has been characterized by various parties as a humanitarian crisis. The primary source of freshwater is the underling groundwater that is grossly contaminated, and at present yields, almost no flow of acceptable quality for domestic use [31,32,38]. Seawater desalination exhibits feasible and long-term solution to fill the deficit in water demand and in remedying the depletion in the groundwater [39–43]. Accordingly, the Comparative Study of Options for an Additional Supply of Water for the Gaza Strip (CSO-G) highlights that a large-scale regional seawater desalination facility associated with number of short-term low-volume (STLV) seawater desalination plants, Table 1, can urgently mitigate the deterioration in both the quantity and quality of groundwater and can alleviate the current humanitarian and public health crisis in Gaza by improving the quality and increasing the quantity of the water available for domestic use [31,34,44].

The large-scale regional Gaza central seawater desalination plant (GCDP) was set up as a strategic solution to alleviate Gaza's growing demand for freshwater. In the short term, the production capacity of GCDP shall be 150,000 m^3/d (55 million m^3/y) of freshwater from phase (I). In the future, phase (II), GCDP will be expanded by adding another desalinating stage to lift the long-term production capacity of freshwater to 300,000 m^3/d [45]. The three STLV seawater desalination plants are now under construction to provide the water sector by 13 million m^3/y of freshwater [31,46,47]. The geographical distribution of the three STLV seawater desalination plants along the Gaza Strip can be illustrated in Fig. 4. The regional STLV seawater desalination plant serves the southern part of the Gaza Strip, the Middle STLV seawater desalination plant provides its production to the middle regions, while Gaza STLV seawater desalination plant supplies the city of Gaza and the northern parts of the Gaza Strip. Nowadays, the regional STLV of Deir Al-Balah provides around 75,000 inhabitants of both Khanyounis and Rafah Western parts by 2.2 million cubic meters of freshwater per year [46–48]. The plant will be upgraded to produces 7.3 million m^3/y of potable water [31,47]. The middle STLV of Deir Al-Balah serves approximately 273,381 inhabitants of the Deir Al-Balah governorates. The STLV of Gaza is an important component of the STLV program that will improve the water supply quality for around 250,000 inhabitants in Gaza city [46].

Table 1
STLV seawater desalination plants in the Gaza Strip

STLV	Current capacity (m^3/d)	Full capacity (m^3/d)
Regional plant	6,000	20,000
Middle plant	2,600	6,000
Gaza plant	–	10,000
Total	8,600	36,000

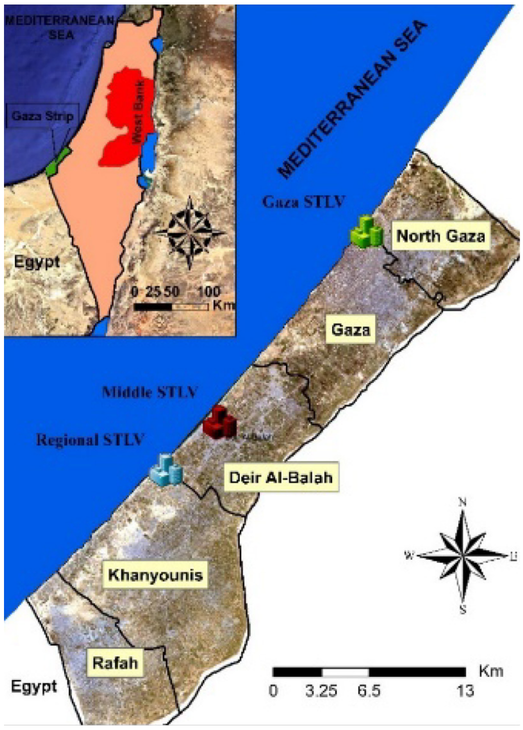

Fig. 4. Geographical locations of STLV desalination plants.

5. Environmental standards and regulatory aspects

Generally, the environmental standards that regulate the activities of effluent disposal into marine systems are not unified and clear. Hence, each country tends to formulate its own water regulations that are best for practice [13]. Currently, the regulations of effluent disposal are mainly formed based on the concept of mixing zones at the point of discharge. The dimensions and the standard of water quality at the border of these zones are defined according to the capacity of the receiving water body to dilute the effluent and to ameliorate both the spatial and temporal deterioration of aquatic systems [49]. In Palestine, the Palestinian environmental law (PEL) imposes standards, directives and conditions to control the coastal activities along the Palestinian beaches for the purposes of marine environment protection against pollution [50]. The PEL prevents any action which may affect the natural track of the beach [50]. Without contravention of the provisions of the PEL, the Palestinian water laws (PWLs) [51,52] give the rights to the PWA to participate in preparing special guidelines for the environmental impact assessment for any activity related to water resources which include the sea. However, until now, there are no clear standards that related to the regulations and criteria for discharging liquid effluents into the marine environment in Palestine. Recently, based on studying different alternatives for brine dispersion standard, the PWA recommended best practice regulations for the disposal of liquid waste based on UNEP Seawater Desalination in the Mediterranean: Assessment and Guidelines (2003)—Model Permit and Ambient Standards. UNEP standards are considered appropriate to the brine dispersion modeling and to establish potential permit levels. UNEP regulations on the discharge of liquid waste into the marine environment characterize that the salinity of the discharged brine should not elevate the ambient salinity by more than 10% at the edge of 100 m diameter regulatory mixing zone (RMZ) centered at the disposal point [53].

6. Effects of brine on the marine ecosystems

The produced brine from the RO seawater desalination plants is classified under the category of negatively buoyant effluents. Commonly, the brine is discharged directly into the sea, forming a very saline and very dense plume of water that diffuses along the benthos and harming the benthic ecosystems [23–25,54,55]. The scope of negative impacts of brine discharges on the marine environments depends on the hydrographical and biological abilities of that marine ecosystems to dilute these discharges as well as depends on the physical and chemical properties of these discharges [13]. The constitutes of brine contain pollutants that are not found in the nature like heavy metals, biocides, and other chemicals. Beside the high salinity of brine, these pollutants have the potential harmful to destroy the marine habitats and to inhibit significantly the variety of ecosystems [23,25]. The biological distribution of marine organisms is fundamentally controlled by salinity. However, most marine species can adapt deviations in salinity beyond the optimal salinity to tolerate salinities reach up to 45 practical salinity unit (psu) but the continuous exposure to high salinity for long periods could reduce the diversity of marine habitats [17,56,57]. The continuous disposal of brine into the marine ecosystem forms a very turbid plume of brine that prevents arrival of the solar radiation to the benthic plankton species. As a result, the continuity of photosynthesis process is inhibited and the variety of marine habitats are reduced as well [55]. Chlorine is the most commonly chemical additive used in the RO seawater desalination process to prevent fouling. The toxicity of chlorine is achieved at low concentrations. Typical dosage of 2 mg/l of chlorine is injected through the desalination cycle. Besides chlorine, traces of iron, nickel, chromium and molybdenum could be detected in the RO brines but the concentrations remain non-critical [17]. The U.S. Environmental Protection Agency (U.S. EPA) defines the water quality criteria in the framework of chronic Criterion Continuous Concentration (CCC) and acute Criterion Maximum Concentration (CMC), where for chlorine in saltwater the CCC and CMC are 7.5 and 13 µg/l, respectively [58]. The U.S. EPA recommends criteria of 2 µg/l for salmonid fish and 10 µg/l for other freshwater and marine organisms in order to protect sensitive aquatic life from the chronic effects of chlorine [59]. However, in 1985, freshwater 48 or 96 h LC_{50}s total residual chlorine (TRC) are reported to range from 17 µg/l for Daphnia (zooplankters) to 710 µg/l for stickleback. Salmonids are the most sensitive fish family with a mean LC_{50} of 77 µg/l, but two minnow species were actually the most sensitive fish with LC_{50}s of 40 and 45 µg/l. In saltwater, LC_{50}s for chlorine produced oxidants (CPO) range from 25 µg/l for eastern oyster to 1,418 µg/l for a mixture of two shore crab species. Mortality from chorine is rapid, nearly half occurring in the first 12 h of acute tests [60]. For marine life, according to the Canadian Water Quality Guidelines for the Protection of Aquatic Life (1999), a guideline of 0.5 µg/l chlorine-produced oxidants is recommended for the protection of marine life. Fig. 5 demonstrates the toxic concentrations of chlorine that is lethal to 50% of the tested species (LC_{50}) for a number of marine species [61].

The ambient salinity of the Mediterranean Sea is characterized as moderate with salinity reaches between 37 and 38 psu. The biological sensitivity tests for the Mediterranean seagrass *Posidonia oceanica* meadows reveal that the tolerance ambient salinity limit should be less than 40 psu [54]. The recommendations of the U.S. EPA state that salinity variations from natural levels should not exceed 4 units from natural variation in areas permanently occupied by food and habitat forming plants when natural salinity is between 13.5 and 35 psu [71].

7. Case study: Environmental impact assessment of brine disposal from the regional STLV seawater desalination plant of Dier Al-Balah

The regional STLV seawater desalination plant of Deir Al-Balah is one of three proposed STLV seawater desalination plants that provide the water sector of the Gaza Strip by 13 million m^3/y of freshwater. Currently, the regional STLV seawater desalination plant of Deir Al-Balah provides the water sector by 2.2 million m^3 of freshwater [47]. However, it is planned to upgrade the plant to reach a yearly production capacity of 7.3 million m^3 of potable water [31,47]. Nevertheless, one of the main challenges that face the STLV plant is compromised by brine disposal challenges where large volume of brine, about 55% of the treated water, is redirected to the coastal waters. The disposed brine from desalination process into the sea, forms a very dense plume, with a density of 1056.16 kg/m^3, of hypersaline water, with a salinity of 75,000 mg/l, that spreads out over the sea floor and affecting the benthic marine communities. In endeavor to control the negative impacts of liquid waste disposal, numerical modelling became a good prediction tool in the predesign and design stages due to the low cost of the experiments, and the ability to characterize brine behavior into the sea and predict its impact on water quality standards, considering effluent properties, discharge system features and ambient conditions [21,28]. The numerical modelling of brine discharge depends on several physical phenomena occurring during brine discharge into water bodies, e.g. the sea. Dispersion, diffusion, convection, and buoyancy are the main ones, the discharge process can be divided into two different regions; the near field and the far field depending on the relative magnitude of the involved physical phenomena [72]. For negatively buoyant discharges, where the effluent's jet trends to sink toward the seabed due to its high density regarding to the ambient density, the end of the near field is considered to be the point at which the turbulence collapses, the point where the brine jet hits the seabed, the far field region begins and the brine jet is now named brine plume, the far field plume forms a gravity driven current moving along the sea floor

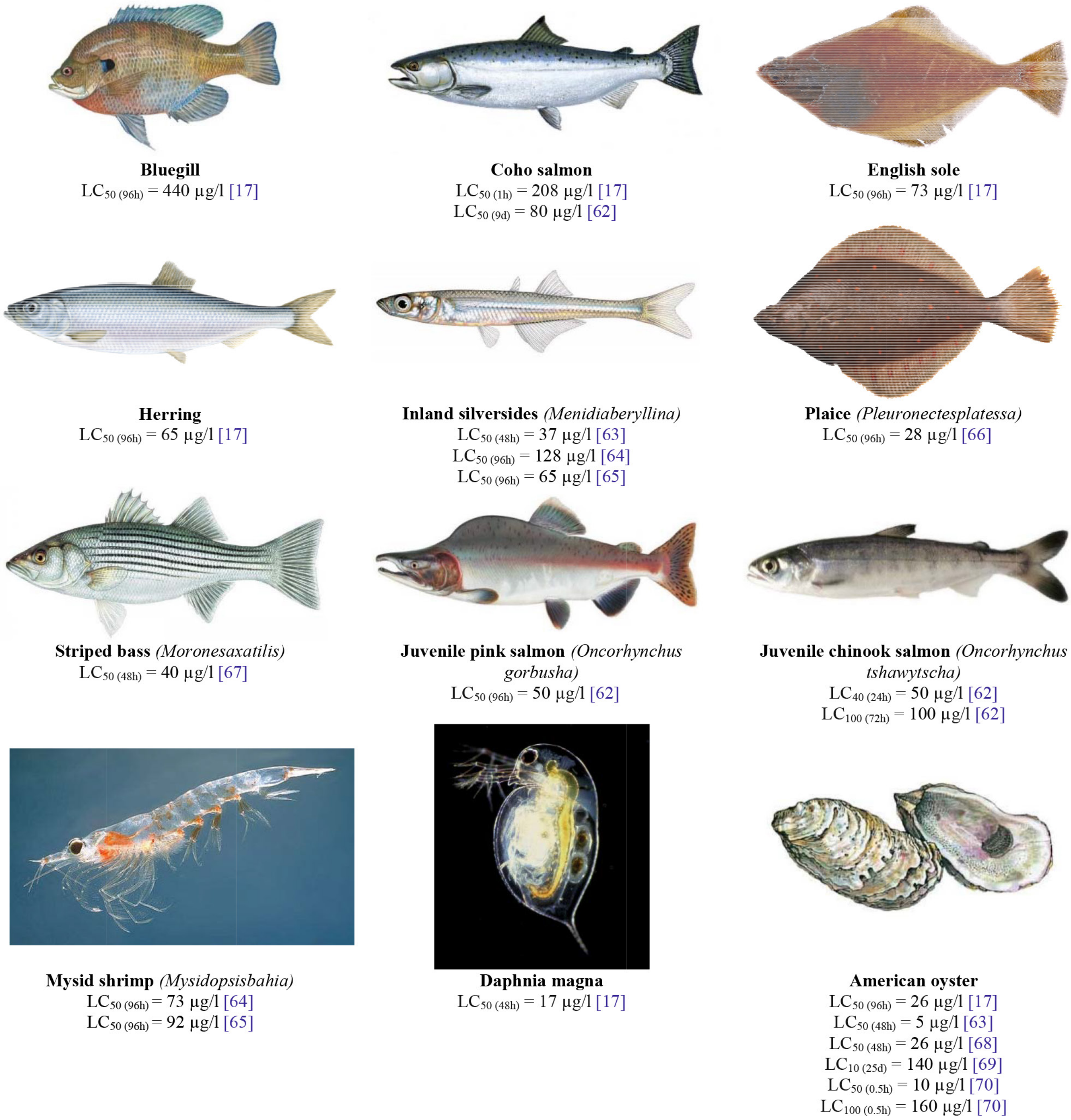

Fig. 5. Chlorine toxicity levels for a range of marine species.

and mixing is only affected by the physical processes of advection and diffusion, flow and mixing characteristics are dominated by large scales, the brine dilution ratio is very small and depends on ambient conditions and density differences [24,72]. In the Gaza Strip, in order to minimize the negative impacts of the rejected brine from the large-scale regional GCDP on the marine environment, the impact of the discharged brine through various disposal systems was numerically simulated to define the most environmental system that could serve the plant in its short-term and long-term operation capacities. The study states that a staged multi port outfall, capped by 24 ports, can achieve acceptable brine dilution at seawater depth of about 7.5 m [45].

7.1. Characteristics of Gaza coastal area

The coastal area of the Gaza Strip extends along 42 km of the south-eastern coast of the Mediterranean Sea from Rafah in the south to the governorate of north Gaza in the north. The coastline of the Gaza Strip was formed over 15 thousand years ago by the deposits coming from the Nile originated in the first place from the mountains of Africa;

therefore, two main factors have created the beach of Gaza: the availability of sand and the motion of waves [73]. The estimations indicate that the net annual alongshore sediment transport on the beaches of Gaza is about 190,000 m^3 [74]. The coastal profile of the Gaza Strip consists of sand, and erosion-resistant formations of rock and kurkar protrude, on the seabed, on the beach, and in the cliffs. The marine environment of the Gaza Strip contains about 201 fish species which are distributed at a depth between 20 and 200 m. The majority of the species are bony fishes 163 species consisting 81% of the fish population; moreover, the presence of cartilaginous fishes such as sharks, rays, and other forms is 19% of the observed fish fauna. The fish distribute in different types of habitats; the most important habitat for bony fishes in the Gaza Strip is the rocky substrate, while the majority of cartilaginous fishes use the soft bottoms, muddy, and sandy substrates [75]. The coastline of the Gaza Strip forms an important economic source for the Palestinians in the Gaza Strip, where the Palestinian fishing sector participates in supporting the Palestinian national product by employing large numbers of fishermen, estimated by about 3600 fishermen and about 500 persons engaged in fishing related professions, fish mechanics, electricians, boatmen, fishing equipment traders, etc. Additionally, the coastal area of the Gaza Strip supports the Palestinian food security through the provision of animal protein from fish, where the fishing quantity for the year of 2015 is reached about 3,251 tons [76]. Many types of Mediterranean fish are caught in the seawater of the Gaza Strip. Commonly, the fish of Sardine (Clupeidae), Red mullet (Mullus), Pakala (Merluccius hubbsi), Jaraa (Micropogonias), Danese (Sparus aurata), Bory (Mugil cephalus), Blue crab juveniles (Callinectus sapidus) and Shrimp (Caridea) are caught in the coastal waters of Mediterranean Sea of Gaza Strip as highlighted in Fig. 6.

The constructed coastal structures along the coastline of Gaza act as barriers to the sediment transport which increase the problems of erosion, siltation, loss of coastal resources and the destruction of the fragile marine habitats. For instance, the existence of Gaza fishing harbor has

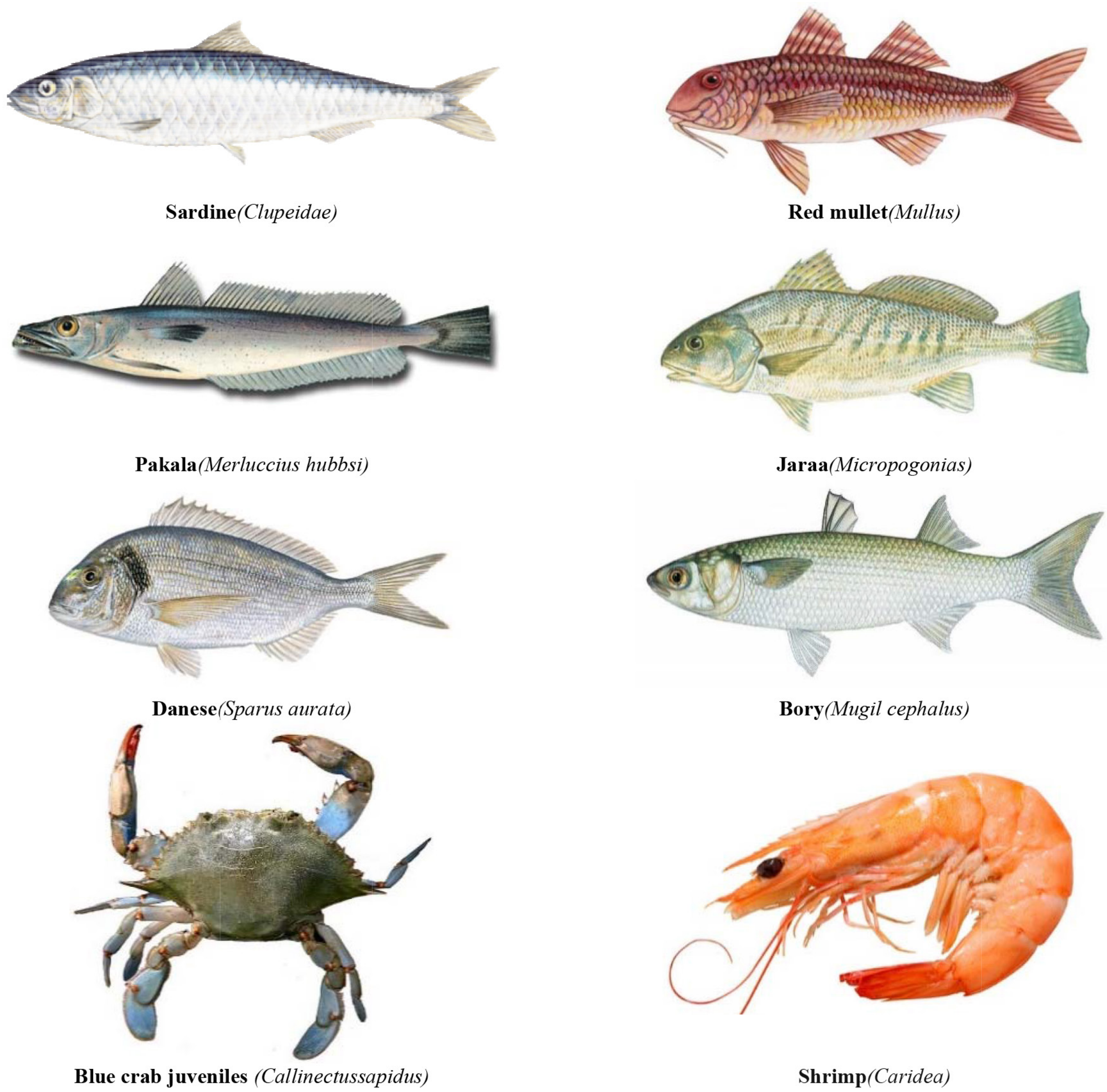

Fig. 6. Commonly found fish in the Gaza Strip seawater.

locally disturbed the coastal erosion and sedimentation pattern and resulting in sand erosion problems. Due to this, the shoreline was advanced south of the Gaza fishing harbor, where the wave-induced littoral transport was halted by southern breakwater and the annual beach growth rate was 15,900 m^2. On the down drift side of the harbor, the shoreline was retreating and beaches erode at an annual rate of –14,000 m^2 [74,77]. Besides, the continuous discharge of untreated or partially treated wastewater along the shoreline forms the main source of pollution in the coastal zone of Gaza. The pollution presents a major health risk for swimmers and marine life [78]. The microbiological analysis campaigns along the Gaza Strip coast revealed that seawater, beach sand, and fishes were parasitically contaminated [78–82].

7.2. Model setup

Cornell Mixing Zone Expert System CORMIX v.9.0 was applied in this study to analyze, predict, and design the outfall mixing zones resulting from a continuous point source of brine into seawater. The system of CORMIX computes the plume characteristics in the mixing zone within which the fluid motion, turbulent field and saline dispersion are dominated by the discharge properties such as the mass flux and buoyancy flux of outfall jet [83]. The hydrodynamic flow classification schemes in the CORMIX system use the length scale concepts, as a measure of the influence of each potential mixing process due to momentum and buoyancy fluxes of the discharge relation to boundary interactions, in order to predict steady state mixing zone characteristics and plume dynamics such as free jets, shoreline attached jets, wall jets and upstream intruding plumes [84].

7.3. Oceanographic data

The oceanographic conditions of the receiving water body play a significant role in the dispersion of brine. Table 2 addresses the seasonal characteristics of seawater near the plant's site.

Tidal currents in the Eastern Mediterranean are in general relatively weak. The currents in most cases have low speeds of about 0.10 m/s which decreases towards the shore, and the vertical distribution is almost uniform [88]. Typically, in the coast of Eastern Mediterranean, the observed mean currents are directed northward most of the time and the mean current velocities are between 0.05–0.10 m/s [89]. Tidal (astronomic) range of the coast of Eastern Mediterranean varies between 0.4 m during spring tides, and 0.15 m during neap tides [88]. In Palestine, the lowest astronomical tide (LAT) can reach in the worst case –0.35 m below mean sea level (MSL) [75]. The surveying data for the coastal area in the front of Deir Al-Balah seawater desalination plant address that the average MSL seabed slope is about 1 in 25 for a distance between 0–50 m offshore and 1 in 90 for distances between 50–1000 m offshore [90].

Table 2
Seasonal characteristics of the seawater

Season/Parameter	Winter	Spring	Summer	Autumn
Temperature (°C) [85]	17.16	20.25	27.18	23.40
Salinity (ppt) [85]	38.90	38.99	39.21	39.27
Density (kg/m^3)	1028.27	1027.47	1025.48	1026.74
Wind (m/s) [86]	1.01	1.33	1.21	0.83
Current (m/s) [87]	0.17	0.11	0.12	0.10

7.4. Environmental standards and regulations

This study employs the environmental standards and regulations of the UNEP *Seawater Desalination in the Mediterranean: Assessment and Guidelines (2003)* – Model Permit and Ambient Standards, to simulate the brine dispersion and to establish potential permit levels. UNEP regulations on the discharge of liquid waste into the marine environment characterize that the salinity of the discharged brine should not elevate the ambient salinity by more than 10% at the edge of 100 m diameter regulatory mixing zone (RMZ) centered at the disposal point [53]. Hence, in this study, UNEP standards specify that the salinity excess at RMZ should not be more than 3.89 ppt. However, many researchers reported that the impact of brine on marine species can be observed at absolute salinity of 40 ppt [54,91]. As the coast of Gaza Strip suffers from many pollutants, the concern of this study is to provide a design configuration for brine disposal system that can achieve a dilution with an excess salinity of less than 0.5 ppt above ambient at RMZ.

7.5. Brine disposal options

Ocean outfalls are classified into onshore surface discharges or offshore submerged discharges [13]. Onshore surface discharges may cause adversely shoreline impacts by causing high concentrations accumulating in the nearshore region due to the limited mixing characteristics of these discharges [13,49,92,93]. Therefore, it is recommended to apply modern efficient mixing devices, which overcome the limitations of the traditional surface onshore discharges. Such single or multi port submerged diffuser systems are characterized by their flexible location and their high mixing rates [13,49,92,94]. In this study, a parametric sensitivity analysis on the seasonal variation in the characteristics of the receiving water body and on the design configurations was conducted to evaluate the effect of the various input parameters on the simulated results. The discharged brine from STLV through eight offshore submerged disposal systems was modelled to compare the mixing behavior and efficiency of these outfalls and to determine the optimal outfall structure. The design discharging velocity via these outfalls is 4 m/s to maintain the discharging Froude and Reynold numbers of more than 10 and 4,000, respectively [95–97]. The orientation of the outfall can have a significant effect on the mixing process within the boundary of RMZ. For example, in the case of single port, a strong near field mixing can be controlled when the flow is maintained in a cross-flow discharge (in the direction perpendicular to the ambient current) or in an in-flow discharge (in the ambient current direction), however a counter-flow discharge in the opposite direction of the ambient current velocity should be avoided [98]. Fig. 7

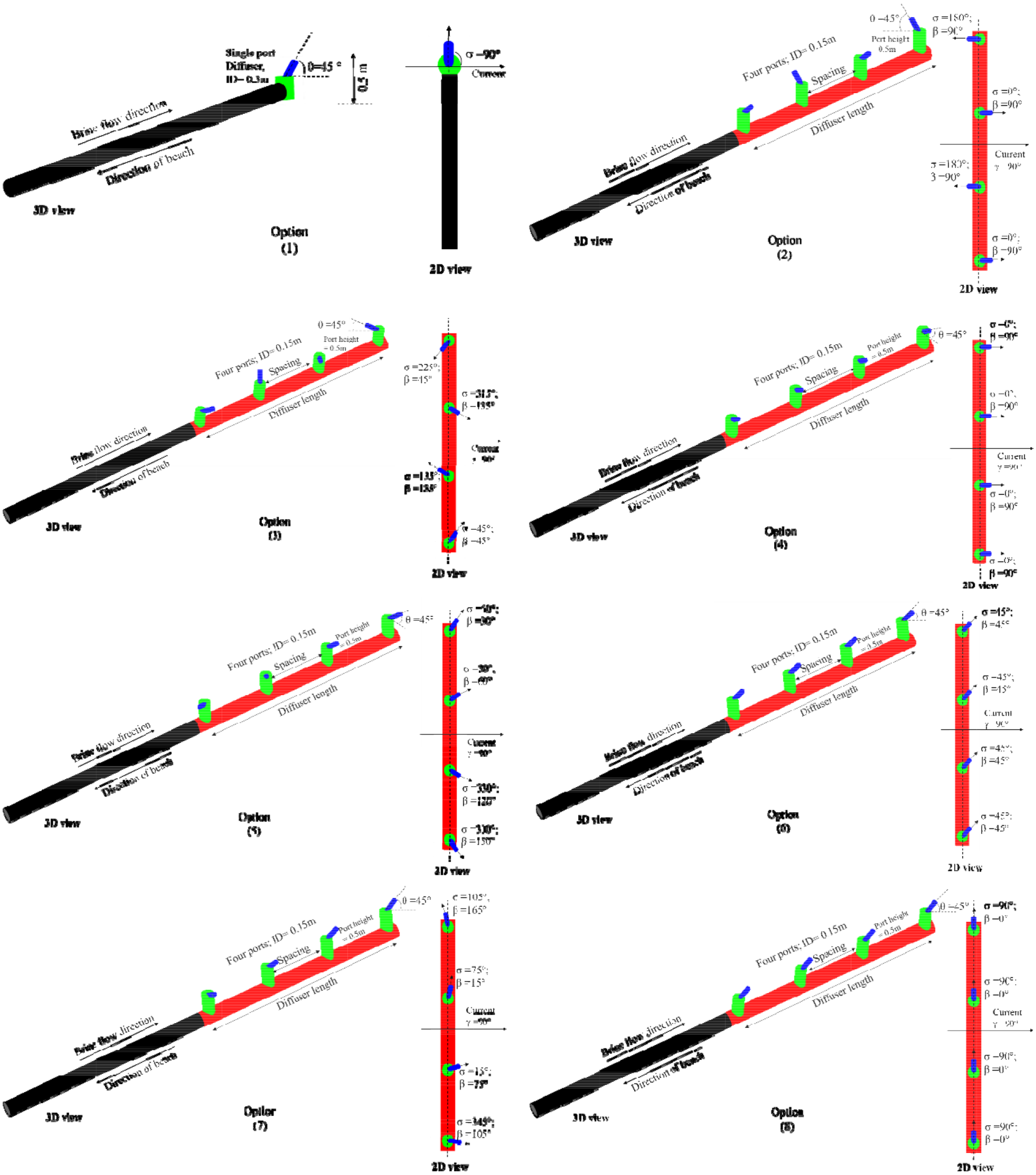

Fig. 7. CorSpy views for each of the eight involved options [84].

addresses the configurational characteristics for each of the eight involved options in this study.

- **Single port outfall:** this type of disposal systems demonstrates the discharge at single point as shown in option (1).
- **Alternating multiport diffuser:** these diffusers impart no net horizontal momentum flux [84]. The configuration for the alternating diffuser was represented by the same-direction nozzle diffuser ports of option (2). Furthermore, option (3) is a fanned-out nozzle diffuser ports design.
- **Unidirectional multiport diffuser:** these diffusers impart net horizontal and, in some cases, vertical momentum flux to diffuser line [84]. The design for this diffuser was highlighted by four options.

Options (4) and (6) demonstrate same-direction nozzle diffuser ports. While, options (5) and (7) are fanned-out nozzle diffuser ports.

- **Staged multiport diffuser:** these diffusers produce net horizontal momentum flux parallel to diffuser line [84]. Option (8) illustrates the same configuration for the same-direction and the fanned-out staged nozzle diffuser ports.

The simulation results in terms of achieving the disposal regulation of brine at RMZ over the four annual seasons show that the brine plume has better dilution rate over the four annual seasons in the case of MSL than in the case of LAT. The simulation results for the disposed brine from the regional STLV plant via single port outfall, option (1), shown in Fig. 8, demonstrates that in the case of MSL the standard can be met at an offshore disposal distance of greater than 350 m. However, in the case of LAT the brine should be discharged at more than about 400 m offshore.

The advantage of using multi port systems other than single port systems comes from their capabilities to achieve the required dilution rate at lesser offshore distance than the needed distance by single port systems, thus, this can lead to optimizing the costs of construction, operation and maintenance. The sensitivity analysis for the demonstrated multi port outfalls under options (2–8) shows that beside the fluctuation in the seawater level between MSL and LAT, the main player in enhancing or inhibiting the plume dilution rate is the velocity of ambient. Increasing the ambient speed have a positive impact on the dilution rate and this was observed in winter, while the decrease in the seawater current can negatively affect the dilution rate, this inhibiting in the plume dilution was noted in autumn. Accordingly, the condition of low seawater current speed is the critical ambient situation for the multi port system, where the shifting of flow class from turbulent flow to stable flow may probably occur in the cases of semi stagnant ambient conditions. Therefore, the assessment of near field stability is a key aspect of effluent dilution analysis. Near field stability reflects the amount of local recirculation and re-entrainment of already mixed water back into the buoyant jet region. Stable discharge conditions are associated with weak momentum and deep water and are also sometimes called deep water conditions. Unstable discharge conditions have localized recirculation patterns and are also called shallow water conditions. If the buoyancy of the effluent flow is weak or its momentum is very high, unstable recirculation phenomena can occur in the discharge vicinity, this local recirculation leads to re-entrainment of already mixed water back into the buoyant jet region [84]. In this context, the required diffuser length for each of the involved multi port options to meet the disposal standard of 0.5 ppt at RMZ in the case of worst ambient condition in autumn at LAT can be addressed in Fig. 9. In general, all the involved multi port port options can meet the regulation standard at RMZ, but the demonstrated results in Fig. 9 show that option (7) is the optimal multi port outfall. The discharged brine through option (7) can meet the required standard at RMZ with shorter diffuser lengths than other options. However, the unidirectional multi port of option (7) can meet the RMZ standard at 100 m offshore by capping a diffuser length of about 51 m but to make sure that the momentum flux and thus the local recirculation and re-entrainment is the dominant a diffuser length of 30 m (spacing 10 m) for option (7) can be found well to dilute the discharged brine from the regional STLV during the unpredictable worst ambient conditions. Thus, the offshore distance at which the brine should be disposed is about 200 m at 3.67 m MSL (3.32 LAT).

The parametric sensitivity of the variation in the ambient conditions due to the seasonal fluctuations in the seawater properties shows that the chosen multi port outfall, option (7), can meet the RMZ standard over the four annual seasons as shown in Fig. 10.

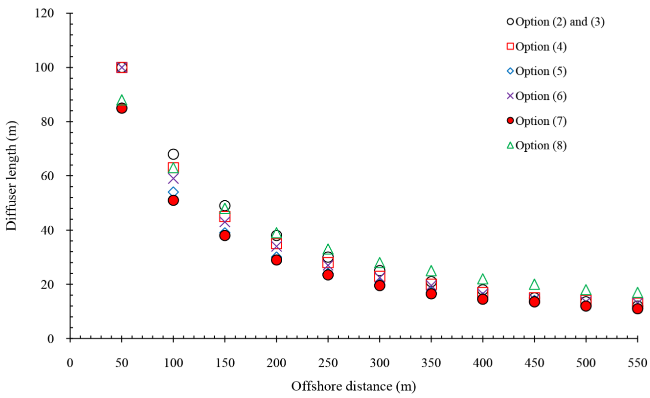

Fig. 9. Diffuser length as a function of offshore distance at RMZ.

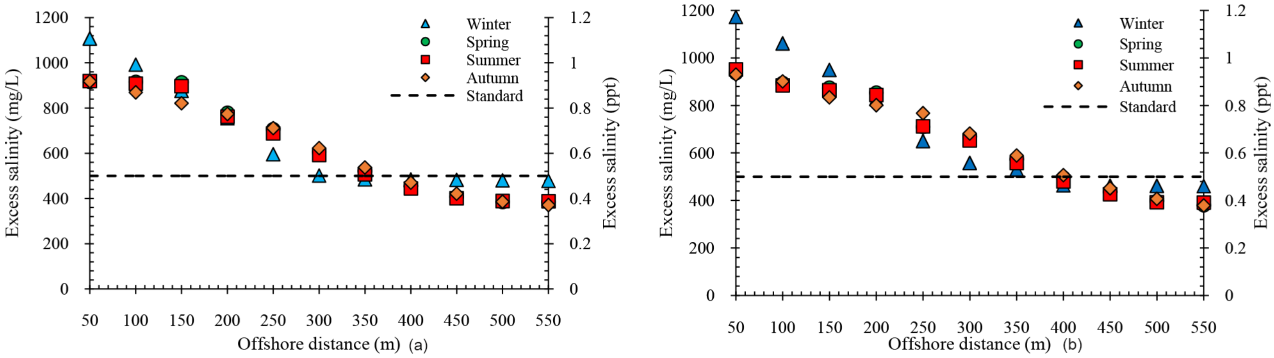

Fig. 8. Simulation results at RMZ for option (1): (a) MSL; (b) LAT.

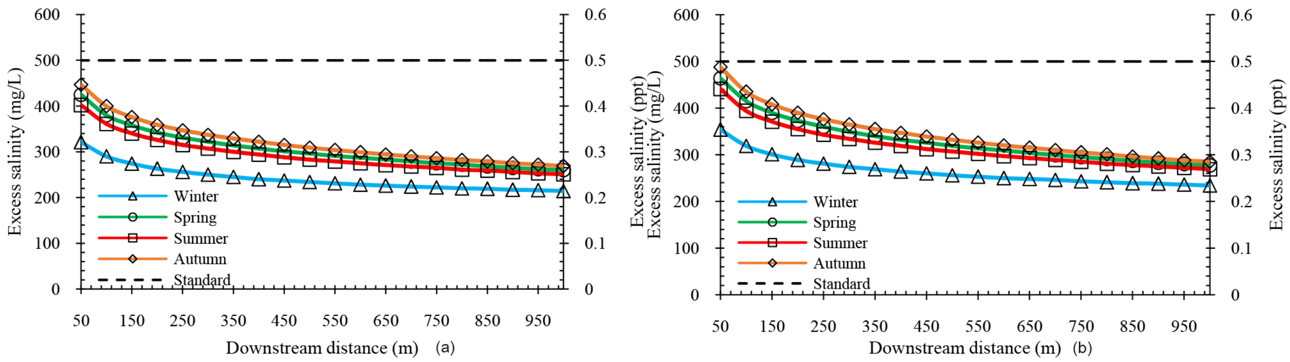

Fig. 10. Brine plume downstream dilution: (a) MSL; (b) LAT.

The downstream simulation results of excess salinity, shown in Fig. 10a, demonstrates the brine dilution at MSL for a distance reaches 1,000 m downstream from the discharge point, the results show good dilution rates over the four seasons, and the rates of brine excess salinity concentrations to the seasonal ambient salinity vary between 0.83–1.14% above the ambient salinity of seawater at RMZ, which are within the 10% limit of the UNEP guidelines and within the 1.27% limit of specified regulation standard of excess salinity of less than 0.5 ppt above ambient salinity. The worst dilution pattern was observed in autumn, due to the lower current velocity. Excess salinity of 269 mg/L (0.269 ppt) above the ambient level (39.27 ppt) has dispersed beyond 1,000 m. Similar results were found for excess salinity considered at LAT level (water depth 3.32 m) with lower dilution rates compared to at MSL. Excess salinity concentrations results, Fig.10b, were 0.91–1.25% above ambient during various seasons at RMZ. Mixing at short distances from the multi port diffuser is usually controlled by designing the diffuser alignment in respect to the direction of ambient current [92,94]. To maintain a strong initial mixing due to the effluent discharge flow rate, adopting a perpendicular alignment of the diffuser line with regard to the ambient velocity may be effective in optimizing near-field mixing [49]. Fig. 11 demonstrates the seasonal simulation results for several alignments of option (7) in the case of MSL and LAT. Generally, diffuser in parallel alignment (γ = 0°) respecting to the ambient current velocity is not advantageous for better mixing process.

The sensitivity analysis for the effect of diffuser alignment on the mixing process shows that the regulation standard can be met at alignment angles of greater than 73°, Fig. 11a, in the case of MSL, while in the case of LAT, Fig. 11b, the alignment angle should be at least equal to about 82°. The propagation of plume dispersions for the disposed brine through the selected outfall, option (7), are shown in Fig. 12 for the best dilution season of winter and for the worst dilution season of autumn in the case of MSL. Furthermore, the dispersion schemes in the case of LAT for the two seasons are demonstrated in Fig. 13.

In the case of reverse osmosis (RO) seawater desalination, the main concern is the increase in the normal salinity of seawater due to the discharge of raw brine where in the RO process there is no use for any type of heavy metals as well as the chemical additives are pre-treated before the disposal of brine. Hence, the dispersion of brine's plume shows that the excess salinity within a region extends from the shoreline and an offshore distance of 100 m is less than 300 mg/l, this such salinity has no detrimental effect on the recreational activities like swimming or fishing. But as a protective measure, swimming should be prohibited within an area of 200–300 m in the vicinity of the brine disposal point.

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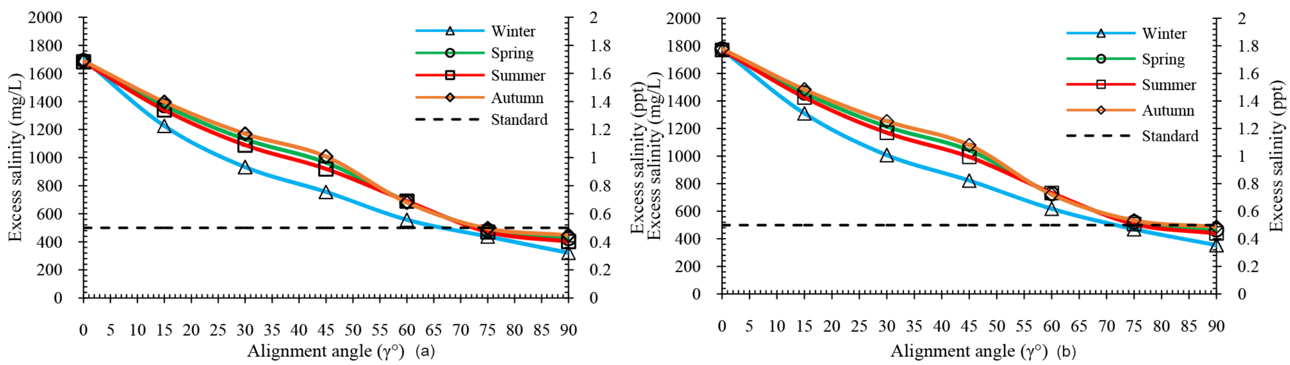

Fig. 11. Brine dilution as a function of alignment angle of diffuser within the RMZ: (a) MSL; (b) LAT.

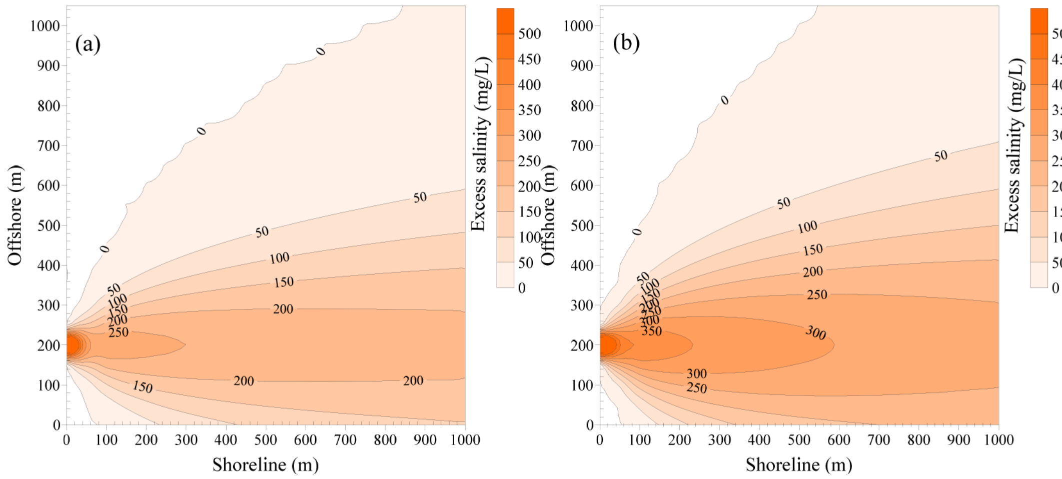

Fig. 12. Plume dispersion for MSL: (a) winter; (b) autumn.

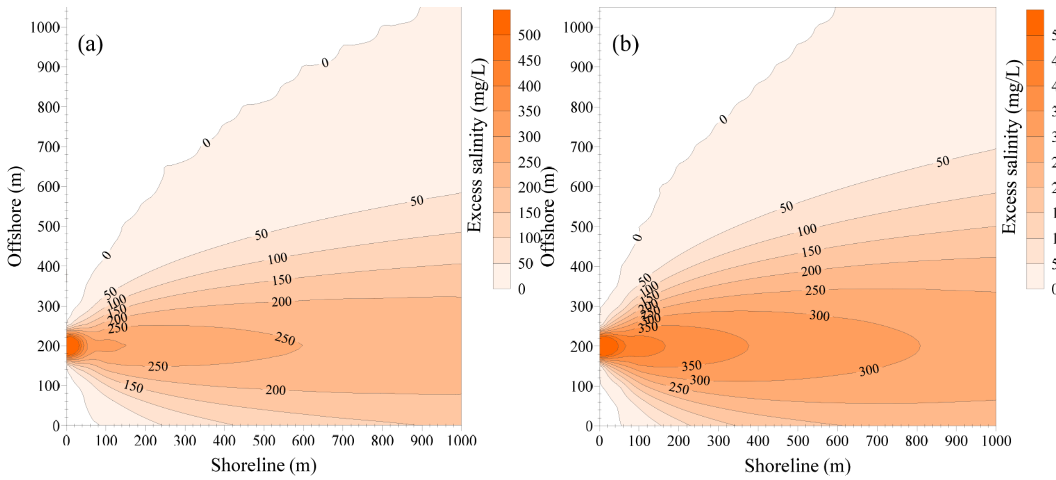

Fig. 13. Plume dispersion for LAT: (a) winter; (b) autumn.

thermore, the dispersion schemes in the case of LAT for the two seasons are demonstrated in Fig. 13.

In the case of reverse osmosis (RO) seawater desalination, the main concern is the increase in the normal salinity of seawater due to the discharge of raw brine where in the RO process there is no use for any type of heavy metals as well as the chemical additives are pre-treated before the disposal of brine. Hence, the dispersion of brine's plume shows that the excess salinity within a region extends from the shoreline and an offshore distance of 100 m is less than 300 mg/l, this such salinity has no detrimental effect on the recreational activities like swimming or fishing. But as a protective measure, swimming should be prohibited within an area of 200–300 m in the vicinity of the brine disposal point.

8. Conclusion and recommendations

The area of the Gaza Strip is classified as one of the most area that suffer from real and fatal water crisis where the available conventional water resources are overexploited and in a depletion state. Desalination of seawater became the most feasible and practical solution to mitigate the severity of water shortage in this area. The Palestinian Water Authority (PWA) put a strategic plan to construct number of seawater desalination plant. The regional STLV seawater desalination plant of Deir Al-Balah in parallel with the other two STLV desalination plants can mitigate the water shortages by providing the governorates of the Gaza Strip by 13 million m^3/y of freshwater. However, these plants produce huge amounts of hypersaline brine effluent that is usually re-discharged into seawater. The brine is a negatively buoyant in nature so it eventually sinks and gets attached to the seabed, and then spreads due to the bottom density current downslope, and affecting the marine ecosystem and other benthic organisms. Optimizing a brine disposal system is an urgent mitigation measure to minimize the negative impact on the environment. Modeling approach is an effective tool to preliminary analysis and design of an optimal outfall system and to assess and simulate the impacts of seawater desalination plant brine discharges from the outfall into the coastal waters. The simulation results for the disposed brine through several configurations of brine disposal systems demonstrate that providing a fanned-out unidirectional multiport diffuser can effectively dilute the discharged brine to less than 500 mg/l above the ambient salinity. This excess in salinity above the normal salinity of seawater meets the recommended best practice regulations for the disposal of liquid waste by UNEP.

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