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ORIGINAL PAPER

Numerical modeling of brine disposal from Gaza central seawater desalination plant

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Abstract Gaza central seawater desalination plant is a promising solution to alleviate the problem of water crisis in the Gaza Strip. The plant in the short term, phase (I), will desalinate seawater for potable uses with a capacity of 55 million cubic meters per year, while in the long term, phase (II), the plant capacity will be doubled to 110 million cubic meters per year of freshwater. As a product from the reverse osmosis process, a huge amount of brine with salinity reaches to 75,000 mg/L will be redirected to seawater; nearly 12,200 m^3/h of brine will be rejected from phase (I) while in the long term, a brine flow rate of 24,400 m^3/h will be disposed from phase (II). In order to minimize the negative impacts of the rejected brine on the marine environment, it is urgent to modeling numerically the impact of the discharged brine through various disposal systems to define the most environmental system. Various scenarios were defined and simulated using CORMIX model to study the efficiencies of onshore surface open channel, offshore submerged single port as well as offshore submerged multiport outfalls taking salinity variations as an indicator. Sensitivity analysis was conducted to identify the most influencing input parameters on the simulation results as well as to evaluate the optimal environmental disposal system which can mitigate the adverse impacts of brine on the marine ecosystem as much as possible in the worst seawater conditions. The simulation results showed that the discharge via surface open channel is not environmentally feasible where the seawater salinity rose by more than 2000 mg/L at RMZ. The single-port scenario can meet the regulations at RMZ but the standard at GMZ was not met, where the rejected brine from phase (I) through single port at 1500 m offshore raises the seawater salinity at GMZ by more than 600 mg/L. The staged multiport outfall, capped by 24 ports, achieves acceptable brine dilution at seawater depth of about 7.5 m, and in the worst ambient conditions in the case of phase (II) in operation, the brine's excess salinity was 536, 497, and 379 mg/L above the salinity of seawater at RMZ, GMZ, and ROI, respectively.

Keywords Gaza strip · Desalination · CORMIX · Surface · Submerged · Sensitivity analysis

Introduction

Water is one of the vital commodities that sustains and nurtures our life on earth and can be easily obtained from our surrounding (Ang et al. 2015). Its availability enhances the quality of life and the economy of a community (El-Sadek 2010). However, water is an abundant natural resource that covers three quarters of the earth's surface, but only about 3 % of all water sources is potable (Karagiannis and Soldatos 2008). Several factors such as overuse of water, pollution of water resources, improper management of water, climate change, and population growth have led to a water scarcity crisis (Ang et al. 2015). In the twenty-first century, water scarcity crisis has emerged as one of the most pressing problems (Mehta 2006); water stress in some form threats nearly 80 % of the human population, and about 65 % of continental discharge feeds habitats that face moderate to high biodiversity threats (Vörösmarty et al. 2010). The Middle East and

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This article is part of the topical collection on *Water Resources in Arid Areas*

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North Africa are home to about 6.3 % of the world's population, and it holds only 1.4 % of the world renewable freshwater (Roudi-Fahimi et al. 2002). Fifteen years ago, more than 18 countries around the world were classified as water scarce (their freshwater resources are below 1000 m^3 per capita per year), and the majority of these countries are in the Middle East and North Africa (Bremere et al. 2001). Decreasing freshwater supplies and increasing pollution have become crucial problems that seriously affect a large population of people and the environment (Jacobson et al. 2010). To alleviate this problem, wastewater must be treated before being discharged, and new freshwater sources must be identified, through desalinating seawater or brackish water, especially for some areas where seawater is readily available but freshwater sources are limited (Zhang and He 2013). Desalination of seawater has been considered as one of the most promising techniques for supplying freshwater in the regions suffering water scarcity (Oh et al. 2009). It has been gaining popularity as a feasible option for potable water production, as available water sources are gradually depleting due to water scarcity as well as quality deterioration (Wilf and Bartels 2005). Seawater reverse osmosis is the most important desalination technology, but one of the main challenges that face that technology is compromised by brine disposal challenges, while these methods reduce total dissolved solid levels to produce potable water, large volumes of brine are redirected to the coastal waters (Palomar et al. 2012a; Morillo et al. 2014). Brine from desalination process is normally discharged directly into the sea, forming a very dense plume of water that spreads out over the sea floor following the steepest gradients and affecting the benthic communities encountered along the way; the impact of brine discharges on the marine ecosystem increasingly needs further attention and study, particularly in relation to seagrass (Sánchez-Lizaso et al. 2008; Portillo et al. 2013). The potential harm of brine on the environment yields from either its higher than normal salinity of ambient, or due to pollutants that otherwise would not be present in the receiving waterbody. These include chlorine and other biocides, heavy metals, antiscalants, coagulants, and cleaning chemicals (Miri and Chouikhi 2005; Lattemann and Höpner 2008; Ladewing and Asquith 2012). As environmental controls become more costly to implement and the penalties of judgment errors become more severe, environmental quality management requires more efficient management tools based on greater knowledge of the environmental phenomena to be managed (Jirka and Akar 1991). Recently, with the rapid increase in computer power, it seems that the physical models are getting too expensive. Thus, it is not surprising to note the shifting of numerical simulation from academic to practical applications. Numerical modeling is 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 (Palomar et al. 2012a, b). The numerical modeling 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, and 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 (Al-Sanea et al. 2014). The near-field region is located in the vicinity of the discharge point and it is affected by turbulent jet mixing, which depends critically on discharge parameters, brine physical properties, and environmental physical properties; numerically, this mixing area extends from the effluent's point of release to its interaction with a physical boundary (e.g., seafloor, sea surface), and flow and mixing characteristics of the near field region are dominated by small scales (Portillo et al. 2013). 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 seafloor and mixing is only affected by the physical processes of advection and diffusion, flow and mixing characteristics are dominated by large scales, and the brine dilution ratio is very small and depends on ambient conditions and density differences (Palomar et al. 2012a; Portillo et al. 2013).

Characteristics of Gaza coastal area

The Gaza Strip (Fig. 1) is 42 km long, between 6 and 12 km wide, and covers an area of 365 km^2. The Gaza Strip is one of the most densely populated areas in the world (Aufleger and Mett 2011). Based on the estimations of the Palestinian Central Bureau of Statistics (PCBS) for the year 2015, the population of Gaza Strip was 1.82 million inhabitants (PCBS 2015).

The Gaza Strip is located in the south-eastern of the Mediterranean, in the transitional zone between the arid desert climate of the Sinai Peninsula and the semi humid Mediterranean climate along the coast. The average daily mean temperature in the Gaza Strip ranges between 25.8 °C in summer and 13.4 °C in winter. The hottest month is August with an average temperature of 25 to 28 °C, and the coldest month is January with average temperature of 12 to 14 °C (CMWU 2012). The winter is the rainy season, which stretches from October up to March. The average rainfall rate over the Gaza Strip is about 317 mm per year (CMWU 2011). The daily relative humidity fluctuates between 65 and 60 % in the daytime and 85 and 80 % at night in the summer and

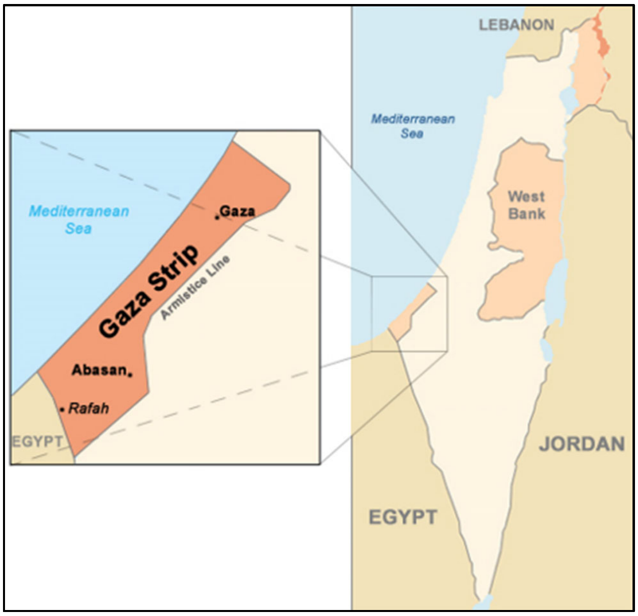


Fig. 1 Location of study area

winter, respectively (MEnA 2001). In summer, sea breeze blows all day and land breeze blows at night, and wind speed reaches its maximum value at noon period and decrease during night. During the winter, most of the wind blow from the Southwest and the average wind speed is 4.2 m/s. In summer, strong winds blow regularly at certain hours, and the daily average wind speed is 3.9 m/s and come from the Northwest direction. Storms have been observed in winter with a maximum hourly wind speed of 18 m/s (CMWU 2012). 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 (Perlin and Kit 1999). The estimations indicate that the net annual alongshore sediment transport on the beaches of Gaza is about 190,000 m^3 (Abualtayef et al. 2013). 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 Gaza the 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 (MEnA 2001). In contrast, the development of coastal structures along the coastline of Gaza act as barriers to the alongshore sediment transport and have led to the host of problems such as increased erosion, siltation, loss of coastal resources and the destruction of the fragile marine habitats. For instance, the existence of Gaza fishing harbor has 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 downdrift side of the harbor, the shoreline was retreating and beaches erode at an annual rate of −14,000 m^2 (Abualtayef et al. 2012). Furthermore, the building and roads adjacent to the shoreline are facing a stability problem and it is expected to have a serious erosion problem in the coming few years (Abualtayef et al. 2012, 2013). 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 (Abualtayef et al. 2014). The microbiological analysis campaigns along the Gaza Strip coast revealed that seawater, beach sand, and fishes were parasitically contaminated (Afifi et al. 2000; Elmanaema et al. 2004; Hilles et al. 2013; Abualtayef et al. 2014).

Water crisis in 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 underlying groundwater that is grossly contaminated, and at present yields, almost no flow of acceptable quality for domestic use (PWA 2011). At its present rate of deterioration, over 95 % of the underlying 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 (PWA 2014). Desalination of water through reverse osmosis has become the most realistic option to meet the rapidly growing water demand in the Gaza Strip (Ghabayen et al. 2004). Currently, in the Gaza Strip, six large brackish water and one seawater reverse osmosis desalination plants providing 4 % of the total water demand of the Gaza population owned and operated by the Palestinian Water Authority (PWA) and different municipalities. In addition, there are many small desalination units owned and operated by private investors for commercial purposes (Baalousha 2006; Mogheir et al. 2013). One of the major options for the remedy of water shortages in the Gaza Strip and the protection of its coastal aquifer from either depletion and becoming saline is the utilization of desalination technology for seawater in that region (Assaf 2001). In response to this worsening water crisis, the comparative study of water supply options for the Gaza Strip (CSO-G) led by international consultants and validated by consultations with the main stakeholders in the Palestinian water sector has become the Government of Palestine's strategic framework for addressing the critical issues in the water sector of Gaza. CSO-G highlights that a large-scale regional seawater desalination facility is the priority project to protect the groundwater adequately from totally failing (PWA 2015a). The urgency for the desalination facility for Gaza has increased with the rising level of humanitarian crisis in Gaza related to inadequate water resources with related impacts on human health (UfM 2011). The Palestinian water law PWL (2002, 2014), which recommended to establish the PWA, states that "Every person has the right to obtain his needs of suitable quality drinking water for utilization and water service providers shall take the necessary measures to ensure this right and prepare the plans required for the development of services in this regard." The lack of drinking water in the Gaza Strip made desalination a national goal to enhance the quality of life in this region. Hence, standing at its responsibilities, it is not surprising to report that the PWA reviewed various desalination technologies as membrane processes and thermal evaporation and distillation processes for seawater treatment as a new water resource since several years (El Sheikh et al. 2003). The earlier studies suggested that the regional reverse osmosis seawater desalination plant in Gaza should have a maximum capacity of 55 million cubic meter per year (Ismail 2003). Its first stage capacity is about 120,000 m^3/day by the year 2008, and an additional of 30,000 m^3/day by the year 2016 in order to maintain a freshwater balance in the coastal aquifer and to fill the water demand for different uses in a sustainable manner (Ghabayen et al. 2004). Due to the political conditions in Palestine, these dates were postponed. However, strategic analysis since that time concluded that this was an underestimate. Extract estimations indicate that in 2025, at least 100 million cubic meters per year of desalinated flows will be required in Gaza. In the face of potential climate change, this conclusion appears to be inescapable (PWA 2011).

Description of Gaza central seawater desalination plant

In the Gaza Strip, it became clear that the main trend to overcome the problem of water crisis is to exploit the advances in the desalination technologies to treat seawater to the potable uses. The reverse osmosis Gaza central seawater desalination plant (GCDP) was set up as a strategic solution to alleviate Gaza growing demand for freshwater. In the short term, the production capacity of GCDP shall be 150,000 m^3/day (55 Mm^3/year) 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/day (110 Mm^3/year). The site of GCDP (Fig. 2) is located on the Mediterranean beach of the middle area of Gaza Strip.

Fig. 2 Location of GCDP

An area of land equivalent to 80,000 m^2 has been allocated by PWA to build GCDP, the area will be sufficient to build the first phase, and also to include allow the construction of a dedicated power plant or some other infrastructure relevant for selected power supply options (Ufm 2011; PWA 2015a). The desalination plant needs nearly 25 MW of installed power. About 10 % of this power can be generated by photovoltaic cells (peak load) as a source for renewable energy on site, and additional renewable energy sources could be secured from offsite interventions. The PWA recommends grid connection with additional energy supplies from neighboring countries or expanding Gaza Power Generation Plant capacity. In addition to 100 % back up onsite reciprocating duel fuel fired engines that can be operated in the future on gas supplies (PWA 2015a). The seawater intake system consists of three submerged pipes manufactured from high-density polyethylene (HDPE) material with a diameter of 1600 mm which extends to 875 m offshore at about 10 m seawater depth. The maximum proposed capacity of the seawater intake system for GCDP is 18,900 m^3/h for each phase (total of phase (II) is 37,800 m^3/h), the recovery ratio is 35.5 %, and thus, the remaining flow rate of 12,200 m^3/h (total 24,400 m^3/h) could be brine. The hypersaline water from GCDP will be discharged into the sea through an outfall pipeline. The land surface features in the coastal zone of GCDP can be described as flat with an average slope of 1:100; elevations vary from sea level up to 4 m above mean sea level (MSL). The coastal zone is covered by finer sediments (i.e., sand and silt). However, the coastal profile does not only consist of sand, but also consist of erosion-resistant formations of rock and kurkar, which protrude in parts of the seabed, the beach, and in sea cliffs (MEnA 2001). The nearest residential areas to the proposed desalination plant site are Deir Al Balah refugee camp and the city center, located approximately 2 km to the north and 3.5 km to the north east from the plant site, respectively. The community uses the beach for recreation; the beachfront area to the west of the desalination plant site is open and is used for fishing-related activities. There are no major industries in the area, and the main significance feature situated near the GCDP site is Deir Al Balah seawater desalination plant, which is situated approximately 4 km to the north of the site.

Environmental standards and regulations

Adopted environmental standards and regulatory aspects in the forms of national laws or transnational agreements are important to control and restrict adverse environmental impacts of liquid waste disposals into coastal waters. These may regulate the brine discharge management, set up discharge limits or impose environmental standards, and conditions mandatory for receiving operating permits (Bleninger and Jirka 2010). In 1975, and in the context of the need to protect and improve the quality of Mediterranean environment with a view to the optimal utilization of its potentialities, 16 Mediterranean countries in collaboration with the European Community adopted the Mediterranean Action Plan (MAP). The MAP demonstrated the deep concern about the alarming state of the environment in the Mediterranean, due to the deliberate or unintentional neglect which has aggravated environmental pollution in this important part of the world. The plan considers the availability of framework convention and related protocols to be particularly necessary and urgent to provide a legal basis for the international cooperation to protect the marine environment in the Mediterranean. Accordingly, the objectives of the MAP were to assist the Mediterranean countries to assess and control marine pollution, to formulate their national environment policies, to improve the ability of governments to identify better options for alternative patterns of development, and to optimize the choices for allocation of resources by supporting the countries with the needed training and technical assistance activities designed to enable all countries of the region to undertake the marine protections activities (MAP 1975). Furthermore, Barcelona convention for the protection of the Mediterranean Sea against pollution (1976), its original amendment (1995), and the amended convention that was recorded as convention for the protection of the marine environment and the coastal region of the Mediterranean (2004) aim to reduce pollution in the Mediterranean Sea from land-based sources and protect and improve the marine environment in the area by taking all appropriate measures to prevent, abate, and combat pollution of the Mediterranean Sea area caused by discharges from, rivers, coastal establishments, outfalls, or emanating from any other land-based sources. Likewise, appropriate measurements should be taken to protect and preserve biological diversity, rare or fragile ecosystems, as well as species of wild fauna and flora which are rare, depleted, threatened, or endangered and their habitats, in the area to which this convention applies (the Barcelona conventions 1976, 1995, 2004). In Palestine, the Palestinian National Authority (PNA) legislates and regulates the activities and projects concern water and coastal zones in order to enhance the protection of the environment against all forms and types of pollution, protection of public health and welfare, encouragement of sustainable development of vital resources in a manner that preserves the rights of future generations, and protection of biodiversity and environmentally sensitive areas, as well as the improvement of the environmentally harmed areas. In this respect, regarding the activities in the marine environment, the Palestinian environmental law (PEL 1999) forbids to perform any action which may cause pollution of seawater in a manner that contradicts with the standards, directives or conditions prescribed for the purposes of marine environment protection against pollution. Therefore, the PEL (1999) authorized the environmental quality affairs (EQA), in coordination with the competent agencies, to specify the necessary environmental conditions required for the establishment of any coastal or offshore buildings or facilities. EQA shall prescribe rules and regulations for the prevention of pollution and preservation and control of the marine environment, against what is generated by the different activities that occur in the free economic zone, continental drifting or the sea bottom which are all subject to the jurisdiction of Palestine. As well, the PEL (1999) prevents any action, which may affect the natural track of the beach, or adjust it inside or far from the sea unless an environmental approval is obtained from the EQA. Without contravention of the provisions of the PEL, the PWL (2002, 2014) gives the rights to the PWA to participate in preparing special guidelines for the environmental impact assessment for any activity relating to water resources which include the sea. Unfortunately, until now, there are no clear standards that relate to the regulations and criteria for discharging liquid effluents into the marine environment in Palestine. In Israel, the construction and installation of desalination plants require applying suitable environmental solutions for protecting and preserving the marine and coastal environment from ruin or deterioration. The Israeli environmental requirements permit the discharge of brine to the sea only in the case of applying the best available technology (BAT) for a better dispersion and dilution. Accordingly, the design criteria for the marine outfalls specify that the minimum outfall length should be 300 m offshore and to avoid the damage to the coastal area, as much as possible, the outfall should extend to a water depth of 30 m or to a distance of one nautical mile. Moreover, the outfall should be terminated by a diffuser. In case of desalination brine, heavier than seawater, the outfall diffuser should be at least 2 m above the seabed for a better dilution (Safrai and Zask 2008). Generally, with respect to the worldwide desalination activities, the regulatory situation is very diverse and unclear. No common standards exist as each country has its own water regulations which are more or less publicly accessible. Most regulations are abstract and do not apply specifically to desalination plants, but to industrial effluents in general (Bleninger and Jirka 2010). The current attempts to regulate the disposal behaviors into the receiving waterbodies focus on defining plant specific mixing zones at the point of discharge. These zones take into account the capacity of the receiving water to dilute the effluent and limit aquatic degradation spatially and temporally (Alameddine and El-Fadel 2007). There are many potential regulations related to mixing zones, but there are no specific regulations on mixing zones particular to brine discharges in Palestine, nor any specific standards that could be directly applied from other countries or plants. 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. However, UNEP standards are considered appropriate to the brine dispersion modeling and to establish potential permit levels for GCDP, but unfortunately, these standards do not allocate explicitly the boundary dimensions of the regulatory mixing zone (RMZ). The mixing zone should encompass the near-field processes, defined as those influenced hydrodynamically by the discharge itself. These processes typically occur within a few tens of meters from the discharge. In Oman, the boundary of RMZ is characterized by 300 m from the discharge point (sultanate of Oman 2005). However, in the Gold Coast of Australia, the RMZ is limited by 120 m downstream from the disposal point (GCD Alliance 2006). In this paper, to be strict, the mixing zone was specified to extend 100 m from the discharge structure in all directions and over the whole water column. In this regard, it is recommended an incremental salinity limit at the mixing zone boundary of no more than 5 % of that occurring naturally in the waters around the discharge (Jenkins et al. 2012). In this study, the features of mixing zones can be characterized to the following criteria: Water quality standard (WQS) of salinity of 2 ppt above ambient should be achieved at the edge RMZ of 100 m downstream, WQS of salinity of 0.5 ppt above ambient should be met at the edge of guideline mixing zone (GMZ) of 200 m downstream to maintain the quality of feed water, and the region of interest (ROI) is 4000 m to demonstrate the propagation of the brine's plume along the coast of Deir Al Balah city.

Collection of oceanographic data

The oceanographic conditions of the receiving waterbody play a significant role in the dispersion of brine. Hence, coastal data for seawater temperature, salinity, ocean current speed and direction, and wind speed were gathered from stations in the vicinity of GCDP.

Seawater temperature and salinity

The dataset for seawater temperature and salinity are summarized in Table 1**.** The raw hourly dataset was retrieved from Ashkelon station which is located at 31.63358° N 34.4928° E to the north of the plant's site.

The average seawater temperature and salinity are 24.17 °C and 39.23 ppt, respectively. Figure 3a, b demonstrates a time series for the annual variation in the seawater temperature and salinity.

The mixing process of brine discharge into marine coastal waters is significantly influenced by the ambient density, which is controlled by the temperature and salinity of the seawater. The dataset demonstrate that the yearly average density of seawater is 1026.40 kg/m^3. Actually, the characteristics of the produced brine are mainly related to the characteristics of feed water and hence, the brine properties change regarding to the change in the ambient temperature and salinity. In this study, the design brine salinity and density were taken equal to 75,000 mg/L (75 ppt) and 1056.16 kg/m^3, respectively. Thus, the brine excess salinity was taken equal to 36.56 ppt above ambient.

Wind speed data

The dataset for the monthly wind speed are demonstrated in Fig. 4, the raw hourly dataset were collected from Deir Al Balah metrological station which is located at 31.356744° N, 34.356744° E to the east of the plant's site.

The wind speed in the vicinity of GCDP varies between zero and 7.2 m/s, with an average speed of 1.3 m/s as shown in Table 2. Typically, the wind speeds can be categorized between breeze and light wind.

The probability distribution for the occurrence of wind at different speed can be illustrated in Fig. 5.

The histogram highlights that the most significantly speeds are approximately between zero and about 4 m/s.

Current speed data

Tidal currents in the Eastern Mediterranean are in general relatively weak. The currents in most case have low speeds

Table 1 Characteristics of seawater (IOLR 2015, 2016)

Parameter	Temperature	Salinity	Density
Unit	°C	ppt	kg/m^3
Minimum	16.46	38.44	1024.03
Average	24.17	39.23	1026.40
Maximum	31.41	39.59	1028.52
Variance	21.53	0.03	1.96
St. deviation	4.64	0.16	1.40

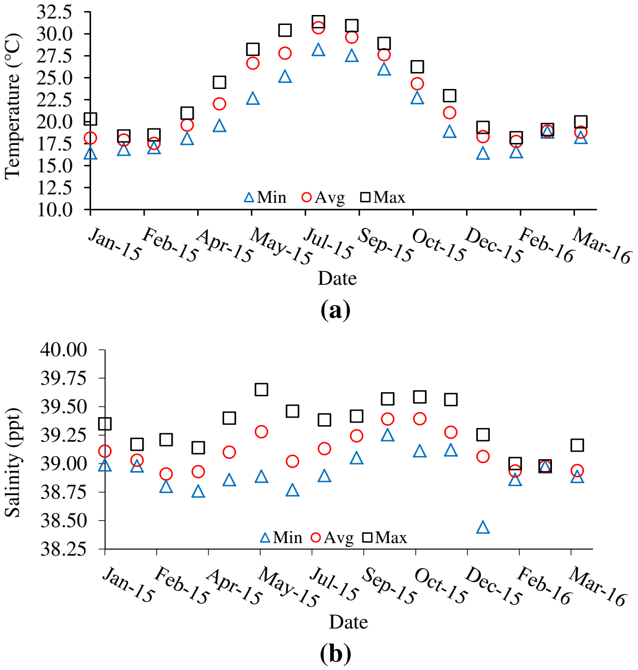


Fig. 3 Seawater **a** temperature; **b** salinity (IOLR 2015, 2016)

of about 0.10 m/s which decreases toward the shore, and the vertical distribution is almost uniform (Rosen 2001). Typically, in the coast of Eastern Mediterranean, the observed mean currents are directed northward and the mean current velocities are 0.05–0.10 m/s (Brenner 2003). The general circulation, due mainly to the geostrophic current and shelf waves, depicts the well-known anticlockwise circulation around the whole Levantine basin of Eastern Mediterranean (Brenner 2003; Menna et al. 2012). Almost, the Eastern Levantine basin is dominated by two recurrent anticyclonic eddies: the Cyprus Eddy and Shikmona Eddy (Menna et al. 2012). The Shikmona Eddy main anticyclonic lobe reaches a bin-averaged speed of 0.20 m/s, whereas the velocities of a secondary cyclonic lobe, south of the main eddy, are weaker less than 0.10 m/s. The along slope current flows off the Egypt, Palestine, and Lebanon coasts with mean speed of 0.15–0.20 m/s; its velocity increases in the Cyprus-Syria Passage and in the northern Levantine sector (Cilician and Antalya basins), with mean values exceeding 0.25 m/s (Menna et al. 2012). Real-field measurements for the ocean current speed were gathered from Ashkelon station for the years from 2012 to 2015. Figure 6 summarizes some of these data. The typical mean velocities are between 0.08 and 0.27 m/s.

Table 2 Statistical analysis of wind speed

Year	Min (m/s)	Avg (m/s)	Max (m/s)	Var $(m/s)^2$	St. dev (m/s)
2015–2016	0.00	1.30	7.20	1.47	1.21

The statistical analysis summarized in Table 3 shows that the current speed fluctuates between minimum and maximum values of zero and 1.08 m/s, respectively. The average mean current for the years from 2012 to 2015 can be assigned to 0.12 m/s.

The frequency distribution for the velocity of current speed can be highlighted in the histogram of Fig. 7. The histogram highlights that the most significantly speeds are between zero and about 0.35 m/s.

Reasonably, the outfall design does not necessarily rely only on remote episodes of very high current speeds. It is also economical as it does not only follow minimum current speed ≃ 0, which is a stagnant and rarely occurring case (Maalouf et al. 2014). The simulation of stagnant conditions should usually be avoided. If zero or a very small value for ambient velocity or discharge is entered, CORMIX will label the ambient environment as stagnant. In this case, CORMIX will predict only the near field of the discharge, since steady-state far-field processes require a mean transport velocity. Although stagnant conditions often, but not necessarily always, represent the extreme limiting case for a dilution prediction, a real waterbody never is truly stagnant. Therefore, a more realistic assumption for natural water bodies would be to consider a small, but finite ambient cross-flow (Doneker and Jirka 2007). Hence, in this study, the stagnant ambient condition was considered at current speed of 0.05 m/s in designing the brine's outfall. The direction of current speed plays major role in allocating the ordination of outfall pipe, and the current rose shows that the dominant current direction is almost along the shoreline with 31° to north as shown in Fig. 8.

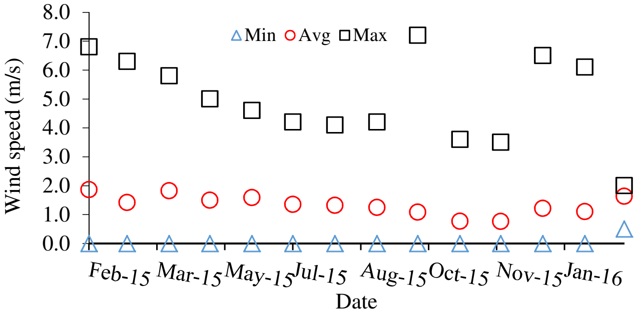


Fig. 4 Monthly variation in wind speed (MoA 2016)

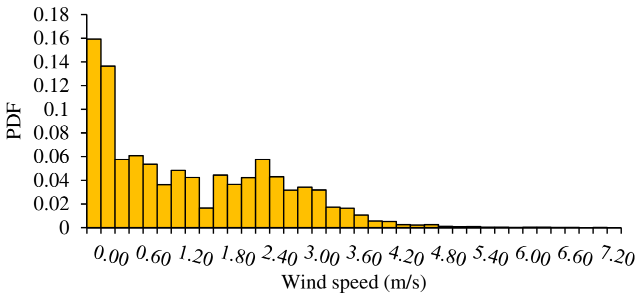


Fig. 5 Histogram of wind speed

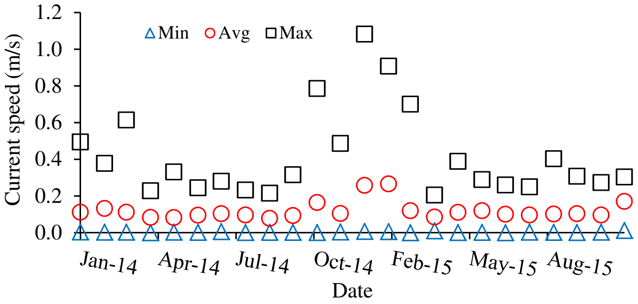


Fig. 6 Monthly variation in current speed (IOLR 2014, 2015)

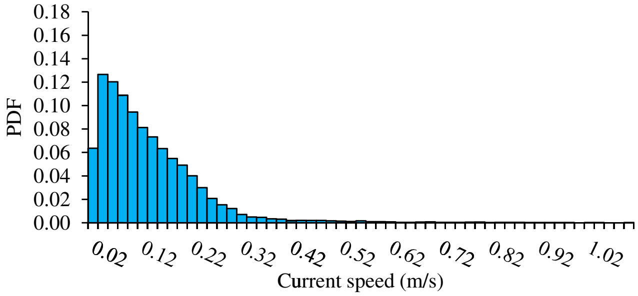


Fig. 7 Histogram of current speed

Thus, as the brine stream is released from the outfall, the ambient current strongly deflects the jet-like plume trajectory into the current direction, inducing higher dilution and the plume remains at the seabed due to its negative buoyancy.

Outfall design criteria

Systematically, the design criteria of brine's outfalls relate to the hydraulic characteristics of the flow through the parts of the disposal systems. Many researchers offered design criteria to guiding the configuration design of outfalls.

Onshore surface disposal

Surface disposal of effluent demonstrates the shoreline discharge via surface open channel. The slope of open channels mainly depends on the features of terrain and the type of soil. Robertson et al. (2013) stated that a slope of 0.3 % may be regarded as the minimum practical slope for construction. In this study, a slope of 3 % has been regarded as a maximum practical slope in order to be in the limits of the permissible maximum velocity of 6 m/s that can safely be adopted for concrete material channel (Subramanya 2009). However, CFR (2006) states that the maximum and minimum permissible velocities for the concrete open channels are 7.5 and 0.9 m/s, respectively.

Table 3 Statistical analysis of current (IOLR 2012, 2015)

Year	Min (m/s)	Avg (m/s)	Max (m/s)	Var $(m/s)^2$	St. dev (m/s)
2012	0.00	0.13	0.73	0.01	0.11
2013	0.00	0.13	0.49	0.01	0.08
2014	0.00	0.10	0.79	0.01	0.09
2015	0.00	0.14	1.08	0.02	0.14
2012–2015	0.00	0.12	1.08	0.01	0.10

Offshore submerged disposal

Multiport diffusers are the effective engineering devices installed at the modern marine outfalls for the steady discharge of effluent streams from the coastal seawater desalination plants seawater desalination. The diffuser section is equipped with a number of ports that disperse brine discharge into coastal waters within the mixing zone (Purnama 2011; Maalouf et al. 2014). Submerged outfalls equipped with a single port or a multiport diffuser system must be properly designed and adequately equipped with ports (nozzles). This may help avoid rapid plume sinking, improper mixing and stratification problems (Maalouf et al. 2014). To avoid intrusion of ambient seawater into the diffuser section and ascertain that all ports operate properly, the port densimetric Froude number F_r must be at least equal to 10 (recommended between 20 and 25) and the port Reynold number R_e must be greater than 4000 (Jirka 2008; Bleninger and Jirka 2008; Bleninger et al. 2010).

$$\mathbf{F_r} = \frac{\mathbf{Q_o}\left(\frac{4}{\pi}\right)}{\mathbf{D_o^{2.5}}\sqrt{|\mathbf{g_o'}|}} \tag{1}$$

$$\mathbf{R_e} = \frac{\mathbf{Q_o}\left(\frac{4}{\pi}\right)}{\nu \mathbf{D_o}} \tag{2}$$

The variable Q_o (m^3/s) is the effluent flow rate (leaving a diffuser port), D_o (m) is the port diameter, $g_o^{`}$ (m/s^2) is referred to as the buoyant acceleration at discharge, and ν (m^2/s) is the effluent kinematic viscosity. Hence, designing the port diameter is actually related to the discharge velocity from the port. Thus, an appropriate velocity must be chosen to reduce deposition, pipe scouring, and outfall plugging, as well as to avoid possible adverse conditions for sensitive fish populations. Jirka (2008), Bleninger and Jirka (2008), Bleninger et al. (2010) and Palomar et al. (2012a) recommended to use port discharge velocity values between 4 and 6 m/s to maximize water entrainment and dilution. However, Alameddine and El-Fadel (2007) stated that areas that translate into discharge velocities between 3 and 8 m/s are recommended. Regarding the port diameter, Jirka (2008) recommended port diameter

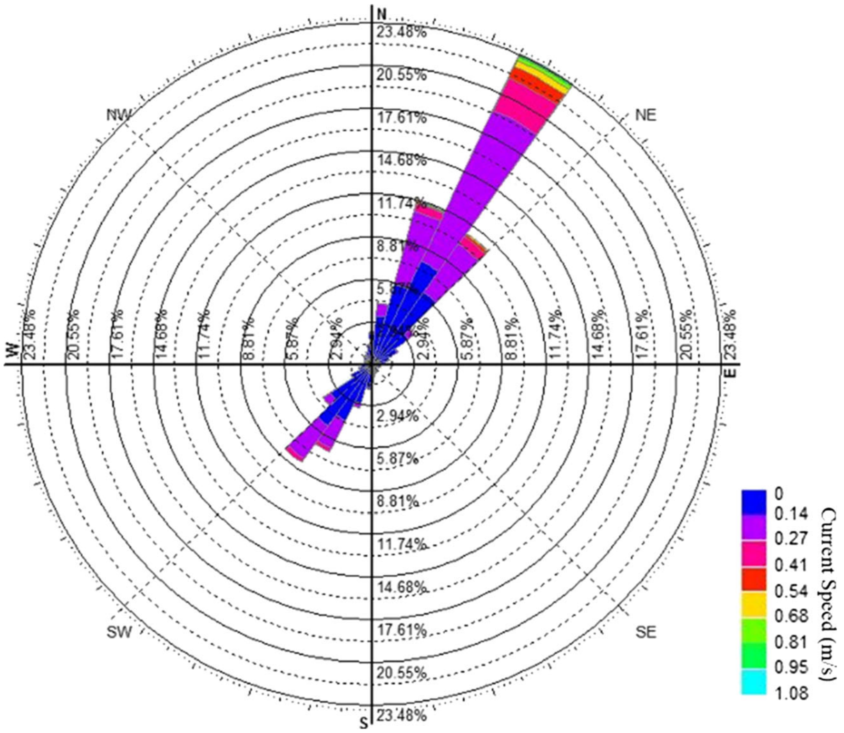


Fig. 8 Current rose (IOLR 2012–2015)

between 0.1 and 1 m, while Palomar and Losada (2011) stated that nozzle diameters should be larger than 0.2 m, to prevent clogging due to biofouling. In this context, to avoid brine jet interaction with the hypersaline spreading layer formed after the jet impacts the bottom, it is recommended that the port height be between 0.5 and 1.5 m above the seabed (Palomar et al. 2012a). Comprehensive laboratory experiments on multiport diffusers for dense effluents such as brine reported that the effect of port spacing is significant in shaping the phenomena of Coanda effect, whereas the port spacing was reduced, the rise height and other geometrical variables decreased and the dilutions also decreased. These were caused by Coanda effects and merging. The Coanda effect caused an under pressure on the interior jet surfaces which caused them to curve more sharply inwards. This shortened their trajectories, reducing the external surface area available for entrainment. Jet merging restricted entrainment of clear water to the inner surfaces and exacerbated the Coanda effect. Thus, to prevent reduction in dilution attributable to restricted entrainment, it is recommended to maintain adequate port spacing (Abessi and Roberts 2014):

$$\text{Spacing} > 2 \times \mathbf{D_o} \times \mathbf{F_r} \tag{3}$$

Due to the lateral merging and interactions of adjacent brine plumes, forming a dynamically equivalent two-dimensional plume as if the discharges are made from a two-dimensional slot diffuser and that the downstream plume behavior after merging is independent of the port arrangement (Al-Barwani and Purnama 2011). This study aims to design a disposal system which can accommodate the discharged brine from the short-term stage, phase (I), as well as from the full capacity stage, phase (II), of GCDP. Thus, based on the stated above design criteria, the appropriate single port diameter is 0.9 m where the discharging velocity is 5.33 m/s for phase (I) lifted to 10.66 m/s in phase (II); hence, the F_r is 10 and 21 for phase (I) and phase (II), respectively. The R_e is above 4000 for the two phases. In this regard, the appropriate multiport diffuser is compromised by 24 ports with a diameter of 0.25 m. The discharging velocity is 2.88 and 5.76 m/s, and F_r is 10.5 and 21 for phase (I) and phase (II), respectively. R_e is already above 4000 in the two cases, and the port height is 1 m above seabed.

Model setup

Cornell Mixing Zone Expert System CORMIX v.9.0 has been 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. 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 (Jones et al. 2007). Boundary interaction analysis on mixing processes, from laboratory and field experiments, provide a rigorous and robust expert knowledge base that distinguishes among these many complex flow patterns that may occur (Jirka 2004). This study focuses on simulating the dispersion of the brine plume in the marine environment by considering the brine effluent from phase (I) to phase (II) of GCDP taking the variation in salinity as an indicator. Three disposal scenarios were defined and simulated using the CORMIX model to compare the mixing behavior and efficiency and to determine the optimal structure of onshore surface open channel, offshore submerged single port, and offshore submerged multiport outfalls. Furthermore, parametric sensitivity analysis was conducted to evaluate the effect of the various outfalls design configurations and to characterize the effect of the continuous variations in the ambient properties on the simulation results. The regional bathymetric survey, conducted at the coast of GCDP, illustrates that the average seabed slope is about 1 in 90 (PWA 2015b). Sensitivity study for the effect of the change in the characteristics of seawater was addressed under seven cases as shown in Table 4. These cases demonstrate the variation in the parameters of ambient density, current speed, and wind speed. The base simulation case demonstrates the average combination of the three parameters. The simulations were conducted by varying one parameter at a time while holding the rest constant. The most significant parameters are ambient density and current velocity. The variation in wind speed does not affect the plume dilution rate; this finding was also reported by Alameddine and El-Fadel (2007). In general, CORMIX is a near-field, regulatory mixing zone model. Hence, wind is unimportant for near-field mixing. Wind can affect plume behavior in the far field. This paper concerns in modeling a negatively buoyant brine effluent; the negatively buoyant plume is well submerged where surface wind has little to no effect on mixing. In this context, for deeply submerged negatively buoyant plume that is sitting on the slopping bottom, wind is unlikely to have any effect on mixing. Wind effects are mostly significant for heated, positively buoyant effluent plumes that sit at or near the water surface. In such scenarios, wind effects could affect the surface plume buoyancy due to heat exchange and hence mixing. Furthermore, surface winds can generate wind currents that may have an effect in shaping the ambient velocity field near the surface (MixZon Inc 2016).

Table 4 Simulation cases

Simulation cases	Density (kg/m^3)	Current (m/s)	Wind (m/s)
Base simulation case	1026.40	0.12	1.3
Case (1)	1024.30	0.12	1.3
Case (2)	1028.52	0.12	1.3
Case (3)	1026.40	0.05	1.3
Case (4)	1026.40	0.35	1.3
Case (5)[a]	1026.40	0.12	0.0
Case (6)[a]	1026.40	0.12	7.2

[a] These cases were modeled only for onshore surface open channel scenario

Results analysis and discussion

Effluents of reverse osmosis desalination plants have a variety of physical properties and chemical constituents which can be harmful for the marine environment. Nowadays, modern large capacity seawater desalination plants discharge a concentrated brine effluent into coastal waters by means of submerged marine outfalls equipped with a single-port or a multiport diffuser system in the form of a negatively buoyant jet, which ensure a high dilution in order to minimize harmful impacts on the marine environment (Jirka 2008). The simulations for the efficiencies of diluting the disposed brine through different outfall configurations to a limit conforms to the environmental regulations in conjunction with sensitivity analysis for different ambient conditions and design configurations were run to three disposal scenarios covering the discharging process of brine through onshore and offshore outfalls. For any configuration to succeed, it is necessary to achieve the regulations at RMZ and GMZ in the case of phase (I) and in the case of phase (II), simultaneously.

Onshore surface open channel

Under this scenario, the process of brine disposal through many onshore surface open channels with different channel's widths and slopes at various disposal water depths were modeled over different ambient conditions for phase (I) and phase (II) of GCDP. The sensitivity analysis study, regarding the effect of channel's widths on the dilution process, covers widths between 0.5 to 6.5 m and channel's slopes between 0.3 and 3 %. The effect of the increasing in the ambient water depths at the disposal location was also studied. The produced brine in the Shoaiba seawater desalination plant in the Kingdom of Saudi Arabia is discharged through an open channel to sea by gravity at a discharge depth between 2.5 and 4 m (Le Roux 2010). Ashkelon desalination plant discharges the waste brine to the sea via surface open channel at water depth of 0.5 m (Einav and Lokiec 2003; Safrai and Zask 2008). In Oman, a surface open channel with a width of 4 m and a depth of 0.3 m is used to discharge brine from Al-Ghubrah Desalination Plant with a flow rate of 12 m^3/s at a discharge depth of 0.5 m (Purnama 2012). In this context, Kish Island (Iran) seawater desalination plant discharges the returned water (brine) of about 3 m^3/s through an open surface channel with 2 m width, 1.5 m depth, and 30 m length. The outfall of the disposed brine with a salinity of 1540 mg/l higher than the intake water concentration (36,800 mg/l) is positioned at water depth of 2.5 m (Vaselali and Vaselali 2009). Based on the foregoing, and in order to stay in the limits of the onshore disposal, this study provides simulations results for disposal water depths range from 1.5 to 5.5 m, in order to confirm the failure of using a surface disposal for the rejected brine from GCDP. Considering the effect of geometric design criteria, the simulation outputs at RMZ show that the increase in the channel's width, channel's slope, and the ambient water depth at the disposal point will enhance the dilution behavior of the disposal process. Form the view of ambient conditions, the increase in the ambient density inhibits the brine mixing process where the increase in the ambient density will oppose the sink of the brine plume; however, the increasing in the speed of ambient current leads to increase in the dilution of the brine plume. The variations in the ambient wind velocity do not demonstrate any significant change in the mixing process. Increasing the width of the channel coupled with reducing its depth is expected to increase the dilution process of the plume and enhance its ability to spread horizontally (Alameddine and El-Fadel 2007). Table 5 highlights a view of the simulations at RMZ for the disposed brine from phase (I) and phase (II) of GCDP through different surface open channels' widths at a slope of 3 % at a water depth of 5.5 m. The outcomes show a decreasing in dilution as a result of doubling the brine flow rate from phase (I) to phase (II). Generally, it is not environmentally to discharge the rejected brine from GCDP through an onshore surface open channel where this scenario fails to achieve the WQS at the boundary of RMZ.

The effect of change in the ambient density was demonstrated in case (1) and case (2), in comparison to the base simulation case, decreasing the ambient density will enhance the brine dilution. The increase in the current speed, case (4), can also improve the brine dilution. In contrast, there is no noticeable change in the dilution due to the variation in the wind speed.

Offshore submerged single port

This scenario demonstrates the disposal of brine through a submerged single port outfall. The designing of the outfall's port ordination plays a significant role in controlling the initial mixing behavior. In the CORMIX system, the single-port orientation is represented by two angles of discharge, the vertical angle (θ), and horizontal angle (σ). Hence, to optimize the near-field mixing due to the effluent discharge flow rate, the outfall discharge was pointed directly offshore toward the sloping seabed in a direction perpendicular to the ambient current (cross flow discharge). The trajectory of the negatively buoyant effluent plume is dramatically influenced by the vertical angle of discharge (θ) (Purnama et al. 2012). Thus, iterative sensitivity analysis was carried out to highlight the behavior of mixing at RMZ by varying the values of (θ) for the base simulation case in regard with change in the disposal offshore distance and flow rate of phase (I) and phase (II) , as shown in Fig. 9. In general, the effluent plume dilution values are identical for port's vertical angle of 0 up to 45°, slightly above 45°, the dilution suddenly drop and become constant up to 90°. Drop in the effluent dilution values, which

Table 5 Excess concentration (ppt) above ambient of the disposed brine via onshore surface open channel at RMZ

Channel's width (m)	Phase	Base case	Case (1)	Case (2)	Case (3)	Case (4)	Case (5)	Case (6)
1	I	3.32	3.30	3.37	3.59	2.71	3.32	3.32
	II	4.93	4.88	4.96	5.09	4.29	4.93	4.93
2	I	2.65	2.64	2.68	2.95	2.49	2.65	2.65
	II	4.07	4.03	4.10	4.32	3.42	4.07	4.07
3	I	2.30	2.29	2.32	2.57	2.35	2.30	2.30
	II	3.53	3.49	3.54	3.80	3.15	3.53	3.53
4	I	2.19	2.18	2.20	2.34	2.25	2.19	2.19
	II	3.14	3.11	3.16	3.45	3.00	3.14	3.14
5	I	NA*	NA*	NA*	NA*	NA*	NA*	NA*
	II	2.87	2.84	2.89	3.19	2.86	2.87	2.87
6	I	NA*	NA*	NA*	NA*	NA*	NA*	NA*
	II	NA*	NA*	NA*	NA*	NA*	NA*	NA*

*NA** CORMIX specifies that the aspect ratio (depth/width) of outlet discharge must be between 5 and 0.05, CORMIX does not allow extremely wide and shallow, or narrow and deep discharge channel cross section.

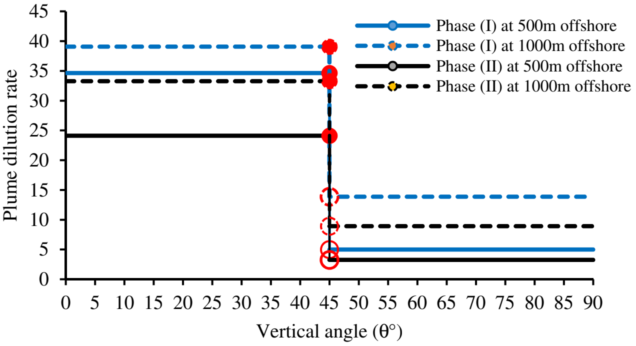


Fig. 9 Effluent dilution as a function of vertical angle within the RMZ

reflects the fact that mixing processes do not always behave in a consistent manner, occurred when a change in the angle θ resulted in a different CORMIX flow class. The flow class NH5 representing discharge with strong momentum flux for a shallow (near horizontal) negatively buoyant jet discharge controls the discharging behavior for angles between 0° and 45°. In contrast, a flow class NV5 demonstrating discharge with strong buoyancy for a steep (near vertical) discharge was marked for angles greater than 45° up to 90°. To maintain the port from the plugging and to enhance the mixing dilution, the practical range for the port's angle is between 30° and 75° (Christodoulou et al. 2015). Therefore, in order to lift the mouth of the nozzle above seabed as much as possible to minimize clogging, the most suitable and practical vertical angle (θ) to be used is 45°. Increasing the offshore distance reflects the increase in the water depth at the discharge point; thus, the increasing in the disposal offshore distance will enhance the dilution of brine plume. The volume of flow rate can significantly affect the dilution rate; therefore, it is not surprising to note the decrease in the dilution rate of brine's plume due to the increasing in the brine quantity from phase (I) to phase (II). This study considers locating the offshore disposal point for the single-port outfall from two views: the fist view is to achieve the regulatory standard at RMZ while the second view is to achieve the guideline standard at GMZ.

The success of the single-port outfall relates to meeting the two views for all of the simulated cases. The sensitivity of plume dilution to the variation in the seawater density for phase (I) and phase (II) shows that no significant effect on the plume dilution due to the change in the ambient density. Figure 10 demonstrates a comparison study for the variation in ambient density between the base simulation case and cases (1) and (2) for phase (I) at RMZ. Hence, in this study it can be concluded that the fluctuation in the seawater density between the minimum and the maximum value due to the change in the seawater temperature and salinity over the year has not a significant effect on the behavior of plume mixing. Afterwards, in this study, it is conservative to exploit the average seawater density in the simulations iterations.

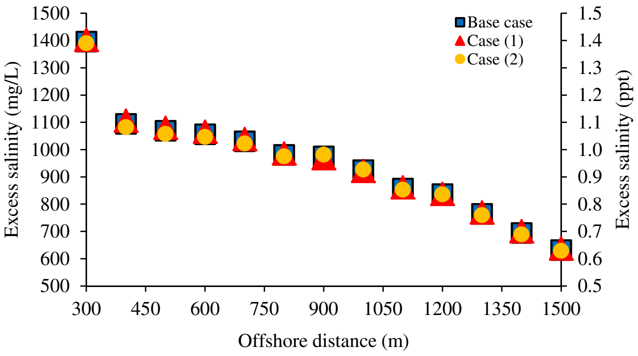


Fig. 10 Sensitivity of change in seawater density for phase (I) at RMZ

Significantly, the main ambient parameter that can dramatically affect the mixing process of brine is the current velocity (UA). In this regard, judging on the successful of the single port scenario, the sensitivity analysis for the current effect on the dilution of the disposed brine at the maximum practical offshore distance of 1500 m was investigated under the base simulation case, case (3) and case (4). Figure 11 demonstrates the effect of current speed (UA) on the downstream dilution of the disposed brine at 1500 m offshore (16.65 m seawater depth) for phase (I) and phase (II), respectively.

Generally, depending on the flow rate of the disposed brine, for single port, increasing the current can improve the plume dilution to some extent, while higher current velocities limit the shearing contact between the brine and the ambient body and, hence, decreases the dilution of the brine plume. There is

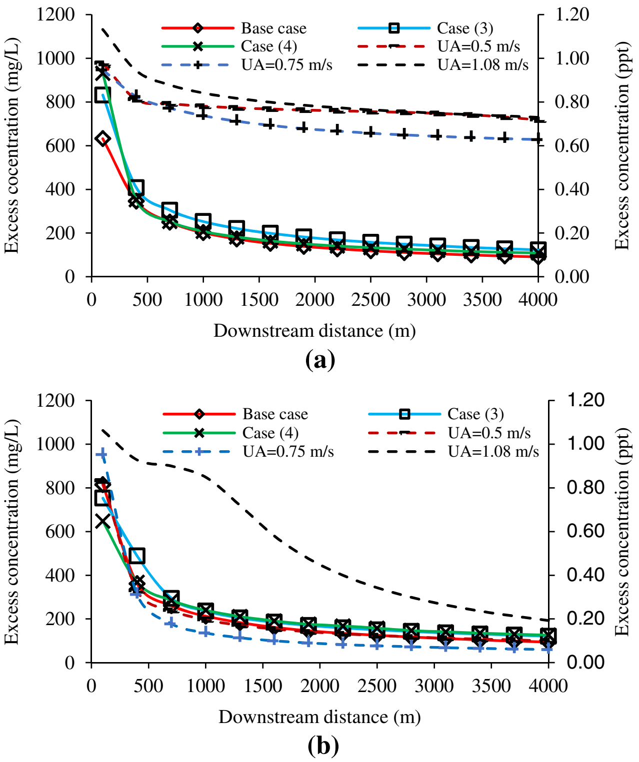


Fig. 11 Downstream stream excess concentration of the discharged brine at 1500 m offshore as function of current velocity for: **a** phase (I); **b** phase (II)

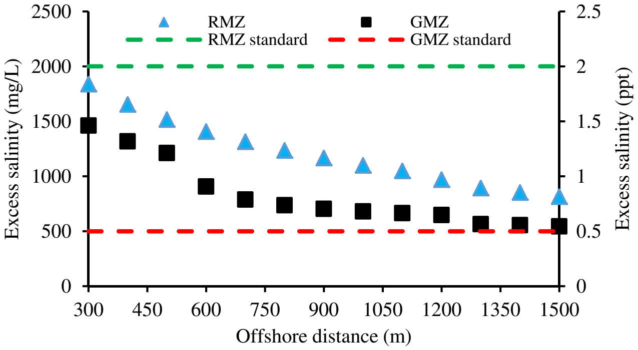


Fig. 12 Brine excess salinity at RMZ and GMZ for phase (II) at the base simulation case

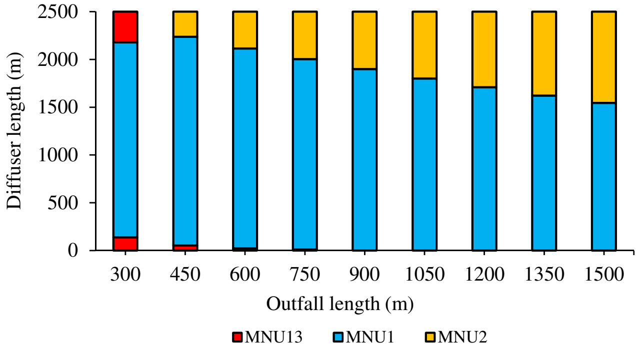


Fig. 14 Flow classification for option (*a*) in case (3) for phase (I)

better offshore transport of the mixed effluent during weak ambient current condition. Higher dilution rates are reached at the near field, due to the turbulence effects created by the shear layer because of the differences of velocity between the jet and the ambient body (Jirka 2008; Palomar and Losada 2011). Anyway, the investigation for the single port shows that this scenario can meet the standard at RMZ, but the standard of GMZ can be met within the offshore distance of 1500 m. Figure 12 highlights the excess concentrations of the disposed brine at different offshore locations for phase (II) at base simulation case (i.e., current speed of 0.12 m/s).

Offshore submerged multiport

Mitigating the environmental impact of brine disposal from GCDP into coastal water of Gaza Strip, as much as possible is the main priority of this paper. Since the disposal scenarios of brine via onshore surface open channel and offshore submerged single port failed to achieve the two conditions at RMZ and GMZ, the scenario to dispose the produced brine through an offshore submerged multiport forms a flexible scenario to meet the environmental constraints. This scenario interests in simulating and analyzing the design efficiency of three proposed multiport diffuser options. The first option is an alternating multiport diffuser (Fig. 13a) which imparts no net horizontal momentum flux. The second option is a unidirectional multiport diffuser (Fig. 13b) that imparts net horizontal momentum flux perpendicular to diffuser line, and the third option is a staged multiport diffuser (Fig. 13c) which produces net horizontal momentum flux parallel to diffuser line. Generally, any multiport disposal system consists of two sections: the outfall section and the diffuser section. In this study, a length of 300 m offshore was considered as the minimum length for the outfall of the multiport disposal system. The vertical angle (θ) of the port ordination was fixed at 45° for the three options, to maintain adequate turbulent mixing. The alignment of the diffuser line was setup perpendicularly to the current direction (i.e., perpendicular to shoreline). Each option contains 24 pots with a diameter of 0.25 m.

The parameters that can affect the plume dilution for the disposed brine through a multiport diffuser are the offshore disposal distance (i.e. outfall length) and the length of the diffuser section. The assessment of near field stability is a key aspect of effluent dilution analysis. It is especially important for understanding the behavior of the two dimensional plumes resulting from multiport diffusers. 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

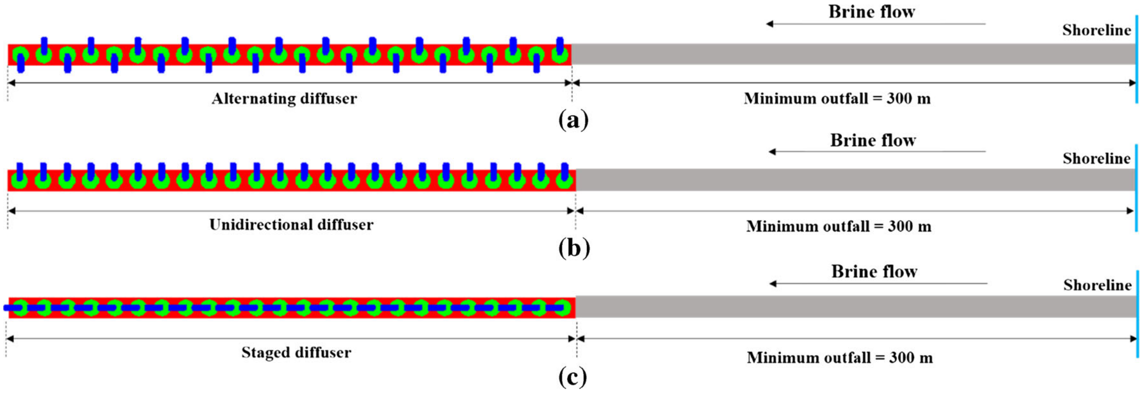


Fig. 13 Multiport outfall configurations: **a** alternating diffuser; **b** unidirectional diffuser; **c** staged diffuser

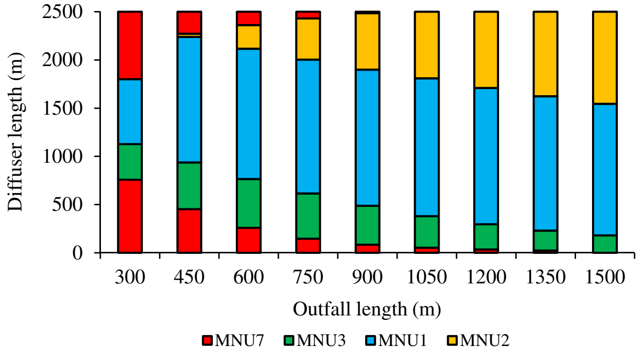


Fig. 15 Flow classification for option (*b*) in case (3) for phase (I)

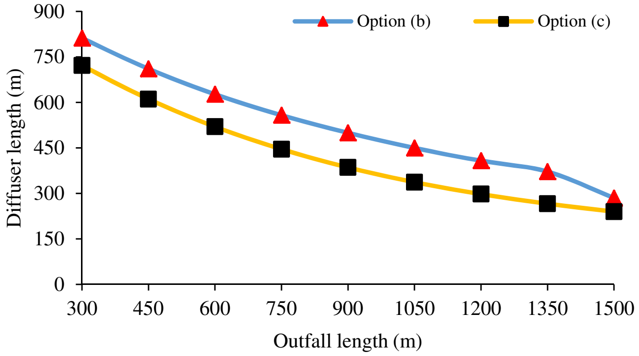


Fig. 17 Optimizing comparison between option (*b*) and (*c*) for phase (II) at case (3)

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. When a multiport diffuser represents a large source of momentum with a relatively weak buoyancy effect, such a diffuser will have an unstable near field with shallow water conditions (Doneker and Jirka 2007). Besides, the length of the diffuser, and hence spacing between ports, plays a significant role in influencing the phenomena of Coanda effect. The Coanda effect caused an under pressure on the interior jet surfaces which caused them to curve more sharply inwards; this shortened their trajectories, reducing the external surface area available for entrainment. Jet merging restricted entrainment of clear water to the inner surfaces and exacerbated the Coanda effect (Doneker and Jirka 2007; Abessi and Roberts 2014). In this regard, the critical simulation condition was noted in the case of stagnant ambient of case (3), i.e., current speed of 0.05 m/s, as well as in the case of phase (I) in operation of GCDP. The simulation outputs for phase (I) under case (3) demonstrates transitions in the flow classification as a result of change in the diffuser length between stable and unstable flows. Figure 14 demonstrates the relation between the length of the diffuser line and the flow classification at different outfall lengths for option (a). The column chart shows that the flow classification for the disposed brine from phase (I) under the demonstrated ambient conditions in case (3) via option (a) moves from unstable flow (MNU13), viz. the buoyancy of the effluent flow is weak or its momentum is very high, to stable flow (MNU1 and MNU2), viz. weak momentum flux or strong buoyancy, by elongating the diffuser of the outfall pipe. The unstable flow is significant at an outfall lengths between 300 and 600 m.

The practical diffuser length which can guarantee an unstable flow for the disposal process of brine is 137.5 m at an outfall of 300 m. This design gives excess salinity of 1.3 and 2.1 ppt above ambient for phase (I) and phase (II), respectively, at RMZ. Hence, option (a) is not feasible to be used for GCDP. In this context, the investigation (Fig. 15) study for disposing the brine quantity of phase (I) at the same ambient condition of case (3) through option (b) demonstrates the moving of the flow from unstable flow class (MNU7) to stable flow classes (MNU1, MNU2, and MNU3).

Figure 15 shows that the unstable class can be achieved at practical diffuser length between 758 and 144 m using outfall lengths between 300 and 750 m, respectively. In the same manner, Fig. 16 highlights the flow classification for phase (I) in operation of GCDP via option (c) under the calm ambient condition of case (3). The flow shifts between unstable (MNU10 and MNU11) and stable (MNU3, MNU1, and MNU2) classes.

Practically, the question that arises is which is better than the other option (b) or option (c). Figure 17 demonstrates an optimizing for the diffuser lengths that can achieve the

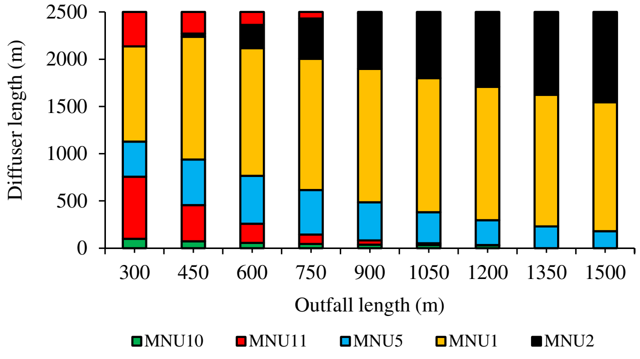


Fig. 16 Flow classification for option (*c*) in case (3) for phase (I)

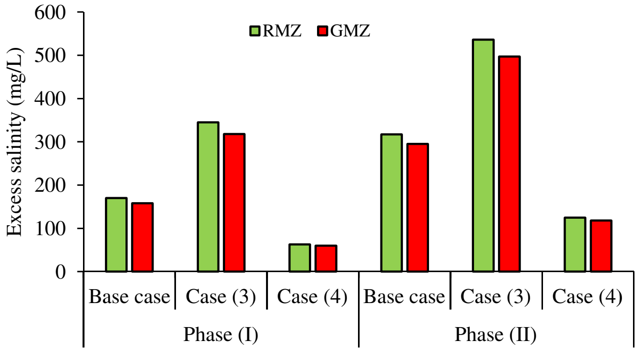
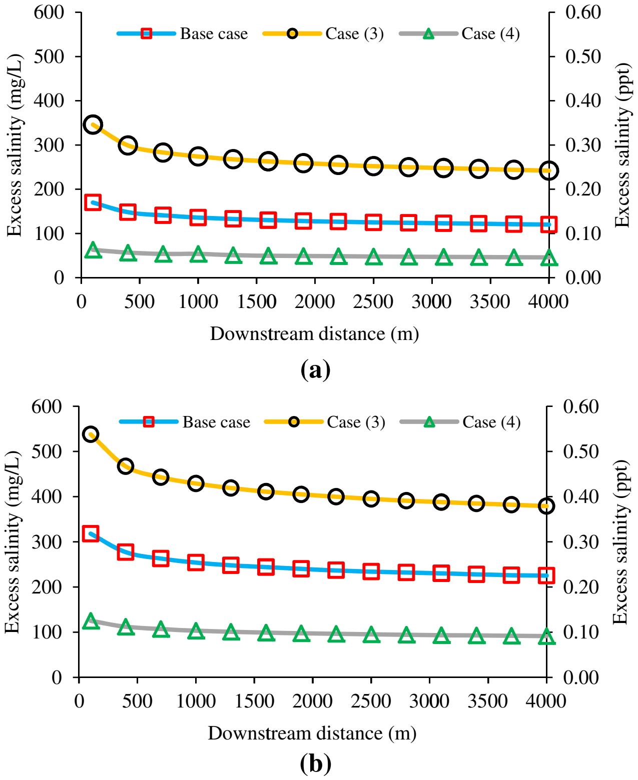


Fig. 18 Excess salinity at RMZ and GMZ



(a)

(b)

Fig. 19 Downstream excess salinity for: **a** phase (I); **b** phase (II)

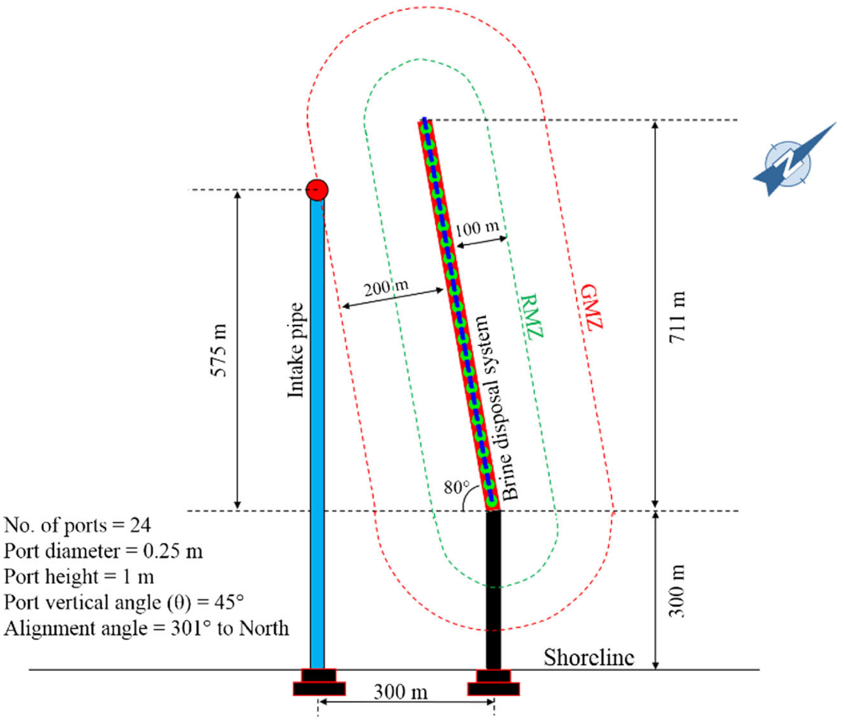
standard at GMZ for option (b) and (c) for the demonstrated seawater conditions by case (3), in the case of phase (II) in operation of GCDP.

The results of Fig. 17 highlight that option (c) is the most feasible one, for example, the outfall length of 300 m needs to be terminated by a diffuser length of 812 m in the case of option (b). In contrast, the needed diffuser length is 722 m in the case of option (c). Hence, it can be said that option (c) is the optimal one. Accordingly, and in order to guarantee an unstable discharge in the case of phase (I) in operation in the stagnant ambient condition, a staged multiport system, option (c), was chosen for GCDP, with outfall length of 300 m terminated with a diffuser length of 722 m. Figure 18 shows the excess salinity of the brine plume at RMZ and GMZ for phase (I) and phase (II) at the presented ambient conditions by the base simulation case, case (3) and case (4).

The outputs of Fig. 18 show that the current speed dramatically influences the dilution of the brine's plume, e.g., the excess salinity at RMZ for phase (II) at ambient speed of 0.05 m/s is 0.536 ppt, while increasing the current speed to 0.35 m/s will decrease the excess salinity to 0.125 ppt. In the worst case, the salinity of seawater at the end of ROI at the coast of Deir Al Balah seawater desalination plant will increase by about 0.7 % above ambient in the case of phase (I) in operation, while when the plant operates in its full capacity of phase (II), the excess salinity will be 1 % above ambient at ROI. Figure 19 highlights the downstream dilution of the brine plume for phase (I) and Phase (II).

Utterly, in contrast to stable flow where the brine plume tends to be attached the seabed due to the weak in the flow momentum flux, designing brine disposal system to ensure unstable (turbulent) flow is the concern of this study in order to optimize the dilution behavior in the mixing zone, where the unstable flow provides strong momentum flux in respect to the weak buoyancy effect (i.e., the flow can provide jetting

Fig. 20 Configuration design for GCDP brine disposal system



force to penetrate the waterbody and make projectile). Figure 20 presents the configuration design for the proposed brine disposal system for GCDP. This design can serve GCDP in the short-term operation, phase (I), as well as in the case of long-term operation of phase (II).

In this context, the design can ensure turbulent mixing of the discharged brine for the two phases in the case of weak ambient conditions (i.e., low current speed).

Conclusion

The reverse osmosis desalination plants account for the highest share in global seawater desalination capacity. The effluents of these plants have a variety of physical properties and chemical constituents which can be harmful for the marine environment. The disposal of the brine is one of the major environmental concerns associated with the desalination industry. In the Gaza Strip, desalination of seawater is the only feasible option to ease the consequences of water shortage and to remedy the deterioration in the underling aquifer. Nevertheless, the desalination of seawater should be conjugated with an environmental disposal of the produced brine into coastal water of the Gaza Strip. Simulations of the brine plume dispersion from GCDP in the Gaza Strip revealed the inadequacy of using surface discharge outfalls to discharge the produced brine. However, the standard at RMZ was met by using single-port diffuser, but the guideline set by this study (i.e., GMZ) to save the quality of feed seawater at the intake point was not met. Using multiport diffuser proved to be adequate to enhance dilution rates and limit the potential environmental impacts within the mixing zone. This study offers its design configuration to serve the disposal process of brine from GCDP in its short- and long-term capacities. The designed staged multiport diffuser, option (c), achieves the regulations at RMZ as well as saves the quality of the feed seawater at the intake point at GMZ. Finally, it is recommended to enhance the findings of this study by preparing a coupling interface linking pure near-field model with pure far-field model, bioassay studies for salinity and toxicity tolerance on the species commonly found in the discharge site of GCDP and species considered to be sensitive to environmental stress and to execute long-term field measurements to validate the presented results on large scale including local and regional features.

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