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Simulation study of the interaction between brine discharge and catchment water of a desalination plant in Tenes, Algeria under various hydrodynamic conditions

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ABSTRACT

The objective of this paper was to examine the interaction between brine discharge and catchment water of a desalination plant in Tenes Algeria using a modelling study under various hydrodynamic conditions. Simulations were performed with a CORMIX code for different scenarios related to the variations of natural conditions such as meteorological as well as the speed and direction of wind and current. To better exploit the results of the simulations and for a good visibility of the propagation of the brine discharge in the marine environment, three velocity cases were plotted (favorable, intermediate, and unfavorable), the planes of the plume in space (x, y) on QGIS3.16 .18, considering the position of the water intake point. A considerable increase in salinity, which sometimes exceeded 42 g/L, was noted in the catchment supply water at the desalination plant due to insufficient dilution of the brine plume. According to the simulation results obtained under the worst conditions. It was suggested to increase the distance between the capture point and the discharge point from 290 m to at least 500 m, by shifting the coordinates of the current capture point west. Based on simulations the dilution results were very promising with the excess concentration dropping from 6 to 1.8 g/L at the catchment point. Modifications to the system were recommended to improve its efficiency, even under unfavorable conditions.

Keywords: Desalination; Algeria; Tenes; Brine; Impacts; Environment; Diffuser; sea; Cormix; GIS

1. Introduction

Seawater desalination is a major source of freshwater for many parts of the world [1]. The most common environmental impact associated with desalination plants is the high concentration brine discharge. Recent advances in desalination technologies have significantly minimized the environmental impacts associated with desalination and reduced the consumption cost [2]. Effluent discharge processes play an extensive role, particularly for coastal settings, in impacting the environment. Brine disposal has adverse impacts on the coastal and marine environments,

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in modification of the salt and heat content of the ocean. Furthermore, countries bordering the Arabian Gulf are heavily reliant on seawater desalination for their freshwater supply and contribute to 33% of the global desalination capacity [1]. However, the reject brine can have up to twice the salinity of seawater and, unless highly diluted, can significantly impact the marine environment. Depending on the process, brine may also contain other contaminants such as anti-fouling and anti-scaling agents, which can be harmful to marine organisms. There is also the need to comply with local environmental regulations. Environmental modeling has become an important tool for projects, environmental management, and studies, due to the complexity of these environments [3]. With this tool, it is possible to integrate many variables and processes to obtain a dynamic model of those systems and evaluate present and future conditions.

Amitouche et al. [4] in a case study from Algeria in northwest Africa, reported that there was a significant increase in salinity, which sometimes exceeded 40 g/L, in the intake waters of a desalination station located in Tipaza State. An interaction was suspected between the discharge and the intake waters due to insufficient dilution of the brine plume coming out of the desalination plant. The authors diagnosed this problem by simulating several dispersion scenarios of release into the marine environment using the Cornell Mixing Expert System (CORMIX) code. They concluded that both wind and current played an important role in the development of the plume and therefore the dilution of the brine. In a related study [2] focused on the environmental impacts associated with brine and thermal discharge arising from seawater desalination plants at Yanbu, Saudi Arabia, on the southeastern coast of the Red Sea. The impacts associated with recirculation patterns and dispersions were investigated with a calibrated three-dimensional numerical model Delft3d. The authors concluded that a well-mixed environment caused more rapid dispersion. The present offshore outfall and further offshore locations were far enough to ensure quick dispersion. The environmental impact assessment and the process of identification and characterization could help improve strategies for better planning and management of the technological solutions related to desalination.

Noori et al. [5] studied the salinity and pH dilution pattern of discharged brine of the Konarak desalination plant into the Chabahar bay in Iran, their relation on coastal environment, and type of its brine discharge. They concluded that the type of brine disposal was a direct surface discharge of negatively buoyant flow in the coastal environment of the bay. The brine discharge mechanism was a shore-attached surface jet, which was most likely influenced by crossflow defection, dynamic shoreline interaction, and to a lesser extent by bottom attachment factors. Laboratory simulations using actual brine and seawater and satellite pictures supported the findings of the dilution pattern. In a similar study Pereira et al. [3] presented outcomes from brine discharge modeling in the water quality of the coast of Fortaleza in Brazil, using Visual Plumes to evaluate near-field dilution and SisBaHiA (Environmental Hydrodynamic Base System) software to generate a hydrodynamic model and evaluate far-field dilution. Hydrodynamic models, forced by wind and tide, were coupled with a wave propagation model, and then used in a Lagrangian transport model, which was fed by the outcomes of the near-field model. From the results generated, it was identified that the installation of a proposed desalination plant in Fortaleza would not compromise water quality and was consistent with the results reported in the literature, regarding the reduced impact caused by the disposal of this type of concentrate.

Confined plunging jets were investigated by Shrivastava et al. [1] as potential outfalls for the discharge of desalination brine. Compared to offshore submerged outfalls that rely on momentum to induce mixing, plunging jets released above the water surface utilize both momentum and negative buoyancy. Plunging jets also introduce air into the water column, which can reduce the possibility of hypoxic zones. Results showed that dilution decreased as the depth of the downcomer was increased. However, it was shown that confined plunging jets can be designed with a short downcomer to provide higher dilution than unconfined jets.

There are more than 16,000 desalination plants in the world producing in excess of 95 million m^3 of desalinated water and 142 million m^3 of brine discharge every day [6,7]. The Mediterranean region has 48% of the world's fresh water production capacity [6,8,9] with reverse osmosis (RO) being the most widely employed due to its energy efficiency and low cost of freshwater production [8,10]. Algeria, for example, has 11 large operational desalination plants spread over a coastline of 1,200 Km (Fig. 1), with a total capacity of 2.1 million m^3 of desalinated water and a discharge exceeding 2.4 million m^3/d [11].

Brine discharges from RO plants are characterized by salt concentrations between 40 and 90 g/L, and may contain chemicals from water pre-treatment, and from membrane cleaning which will affect the marine environment [10,12]. There are currently several conventional methods in the management of desalination brine: surface water discharge (i.e., direct discharge into the sea), sewer disposal, deep-well injection, land application and evaporation ponds. Another newer technique is zero liquid discharge (ZLD), which aims to reduce the volume of discharge to near zero and to recover valuable minerals from the brine to help reduce costs.

Surface water discharge (i.e., "jet direct to sea") remains the most widely used method in the world for coastal plants, as it can be utilized for all desalination capacities. It is cost-effective for large and medium discharge flows [12–14] assessed the damage exerted by desalination plants on the marine environment. They suggested effective management approaches to attack the problem. The desalination plants in Algeria discharge their brines directly into the Mediterranean Sea through submarine outfalls equipped with a diffuser with a single or a multi-port The dispersion, dilution efficiency and plume shape of the discharges was assessed by Hosseini et al. [13] based on two scenarios. The first assumes almost fixed conditions in time: discharge characteristics (flow, salinity, density), bathymetric and geomorphological characteristics of the site (slope, depth, bottom roughness...) and characteristics of the discharge system (diameter, number of ports, angles). The second category is variable conditions in the time: hydrodynamic characteristics (waves, current, tide, wind...) which vary according to the season. This implies that the mixing (dilution) of the brine can be insufficient during certain periods of the year (calm weather for example) on the one hand, and on the other hand the direction of the plume varies in time according to the direction of the wind and the current [15,16]. The discharge system must always be efficient and ensure good dispersion (i.e., permissible dilution) even under unfavorable hydrodynamic conditions.

At the Tenes desalination plant (Fig. 1) a flow of greater than 250,000 m^3/d was discharged directly into the sea through a submarine outfall equipped with a multi-port system of 6 double alternative diffusers [4,17–19] have monitored the dispersion and dilution rate in the marine environment in the discharge area.

The objective of this paper was to examine the interaction between brine discharge and catchment water of a desalination plant in Tenes Algeria using a modelling study under various hydrodynamic conditions. Simulations were performed with a CORMIX code for different scenarios related to the variations of natural conditions such as meteorological as well as the speed and direction of wind and current. Modifications to this system were then recommended to improve its efficiency, even under unfavorable conditions.

2. Materials and methods

A hyper-saline discharge diffuser (Fig. 2) was assessed at the Tenes desalination plant in Algeria in Northwest Africa. Its behavior was investigated in relation to climatic

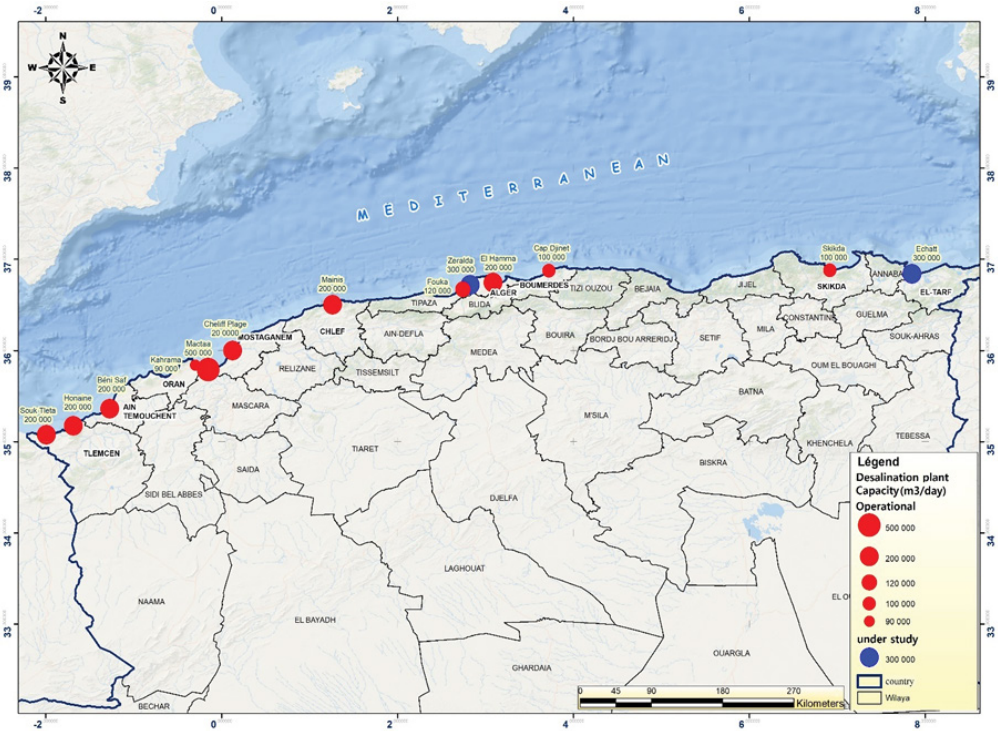

Fig. 1. Distribution of seawater desalination plants in Algeria.

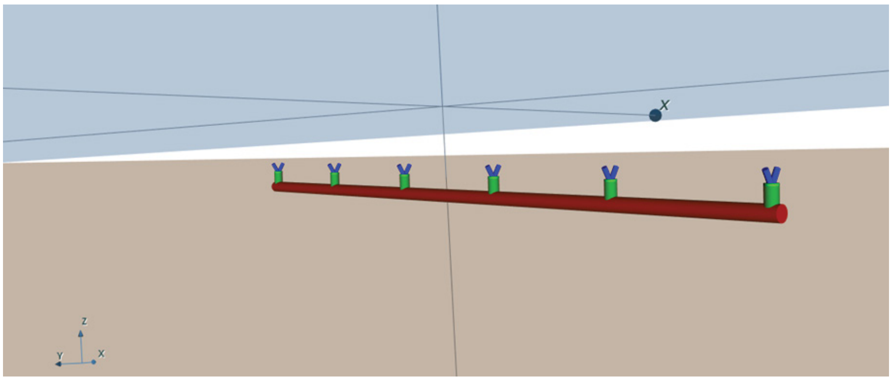

Fig. 2. Tenes plant diffuser (multi-port outfall of 6 alternative double diffusers) - 3D image on CORMIX 11.0.

variations through multiple simulations using a specialized model named “CORMIX”.

2.1. CORMIX model

For larger rivers, lakes and the marine environment, modeling using CORMIX (Cornell Mixing Expert System) software is the most widely used in studies and practical applications in the field of brine discharges from desalination plants into the marine environment [20,21]. The use of this software assumes possession of previous information about the hydrodynamics prevailing in the study area to know the longitudinal evolution of the effluent plume in time and space.

The Cormix program code adapted to model brine waste discharges, was capable of predicting plume dispersion, mixing and trajectory. It has been widely used in the field [22–34].

2.2. Simulation parameters

A set of parameters (Table 1, Fig. 3) common to all scenarios, representing the data and characteristics of the Tenes seawater desalination plant, was established to allow for comparison.

Catch point location: $X_{\text{UTM}} = 341{,}214$ m; $Y_{\text{UTM}} = 4{,}041{,}905$ m; The catch was at 8.0 m depth and its alignment is shown in Fig. 4. Fig. 5 represents the bathymetry of the study zone. Brine discharge location: $X_{\text{UTM}} = 341{,}365$ m; $Y_{\text{UTM}} = 4{,}041{,}611$ m; the depth was 4.5 m, the discharge was placed at 0.75 m from the bottom of the sea at 60º from the horizontal (Fig. 5), the vertical angle (discharge angle) was θ = 60°. The positions of the outfall and the catchment point are shown in Fig. 4. The seawater catchment pipes are shown in Fig. 6.

3. Results and discussion

The required effluent dilution rate was calculated and corresponded to $S = 36$, based on a 5% increase in tolerated salinity [30]. The salinity of the discharge was equal to 72 g/L and had to be diluted more than 36 times, so that the plume that was generated did not exceed the tolerated 38.5 g/L, when mixed with sea water.

3.1. Diagnosis of behavior of diffuser in receiving environment

The behavior of the diffuser was examined for three pairs of speeds, a first pair represented an unfavorable case, a second represented an intermediate case and the last represented a favorable case (Table 2).

$$C = \frac{C_0 + nC_1}{n} \tag{1}$$

Table 1
Characteristics of the Tenes desalination plant [35]

Effluent characteristics	
Maximum discharge flow	2.93 m^3/s
Salinity	72 g/L
Increase of salinity	31.5
Density (19.5°C)	1,055.05 kg/m^3
Characteristics of the receiving environment	
Salinity	38 g/L
Density (19.5°C)	1,026.81 kg/m^3
Wind speed	2–8 m/s
Current speed	0.02–0.4 m/s
Diffuser characteristics	
Distance from the coast	150 m
Depth of the first diffuser port	4 m
Depth of the last diffuser port	5 m
Length of the diffuser section	40 m
Number of ports	12
Diffuser height	0.75 m
Distance between ports of the diffuser	8 m
Port diameter	0.28 m
Jet speed	3.96 m/s
Discharge angle	60°

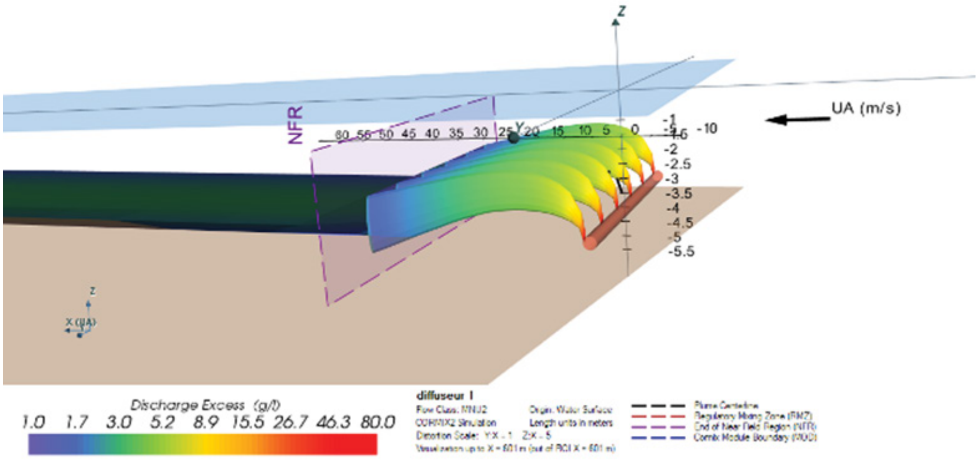

Fig. 3. 3D image of brine discharge on CORMIX 11.0.

Fig. 4. Google Earth image.

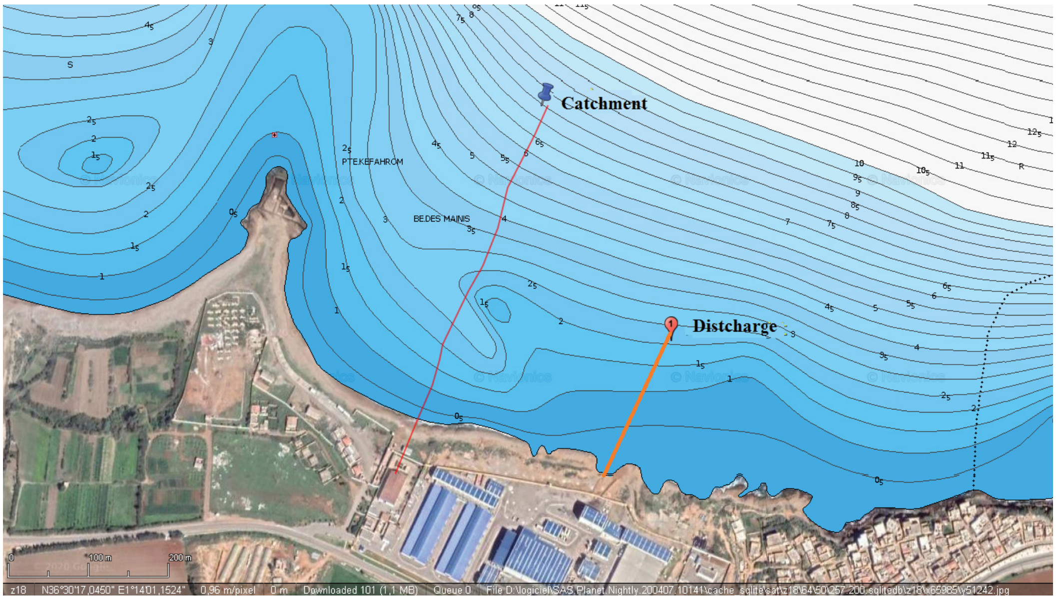

Fig. 5. Depth contour map on SAS Planet.

where n: Dilution, C: Concentration tolerated, C_0: effluent concentration, C_1: ambient concentration.

Figs. 7 and 8 represent the different dilutions and concentrations for the three pairs of water current and wind speeds. For the first and second cases, the dilution became constant after 20.90 and 23.40 respectively, and the required dilution rate would never be reached. The discharged brine would always have a salinity. This is not impermissible for the environment [36]. For the third case, the dilution continued to increase but the required dilution rate would also never be reached.

From these results, it could be concluded that the current water outfall from the Tenes desalination plant was not performing well, because it did not ensure a good dilution of the brine under all possible environmental conditions. Therefore, the negative impact on the environment would be high. Modifications or even alternatives of the diffuser needed to be applied. To test the possible interaction between the catchment water and the brine discharge water, several scenarios were simulated.

Figs. 9 and 10 shows the simulation results of scenario N°1 (Table 3) plotted on QGIS 3.16.18. It was noticed that there appeared to be an interaction between the brine discharge water and the catchment of the plant, with an excess of salinity (i.e., concentration of +6 g/L at the catchment point). This meant that the position (i.e., geographical coordinates)

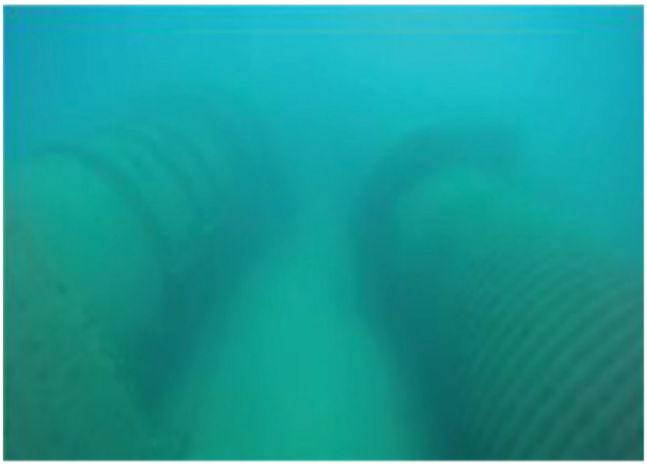

Fig. 6. Seawater catchment pipes from the Tenes desalination plant.

Table 2
Cases of environmental speeds studied

Type	Water current speed (m/s)	Wind speed (m/s)
Case 1: Unfavorable	0.065	3.5
Case 2: Intermediate	0.11	5
Case 3: Favorable	0.2	8

of the catchment point and that of the discharges were poorly located, or perhaps there was an improper dimensioning of the discharge diffuser. In addition, the brine discharge plume was converging and approaching the beach. There was a need to change urban discharges away from the coast and to choose the location of the discharge point more carefully to use the capacity of marine currents and other meteorological parameters to push the discharge away from sensitive zones and boost dilution [37].

The interaction between the discharge water and the catchment water can have a negative impact on the performance of a desalination plant. The conditions for the effective dilution of a volume of water with a concentration of 37 g/L are different from same volume of water with a concentration of 42 g/L.

3.2. Improvements and alternative configuration of the current diffuser

There were several key variables found in the dilution process.

3.2.1. Port diameter variation (discharge velocity)

For a discharge angle of 65°, a diffuser height of 0.75 m, at a depth of 4.5 m and an environmental current velocity of 0.065 m/s, Fig. 11 shows the dilutions for the 3 different diameters D_1 = 0.1 m (v = 31.08 m/s), D_2 = 0.15 m (v = 13.82 m/s), D_3 = 0.2 m (v = 7.7 m/s). It was noted that there was no improvement in dilution when the diameter of the ports was varied, (Fig. 11) the curves were superimposed on each other. This intervention on the diffuser was negative so another solution had to be found by changing parameters to improve dilution.

Table 3
Characteristics of scenario N°1

Diffuser length (m)	40 m
Current (m/s)	0.155
Wind (m/s)	6.5
Distance between ports (m)	8 m
Depth (m)	4.5
Distance from the shore (m)	150

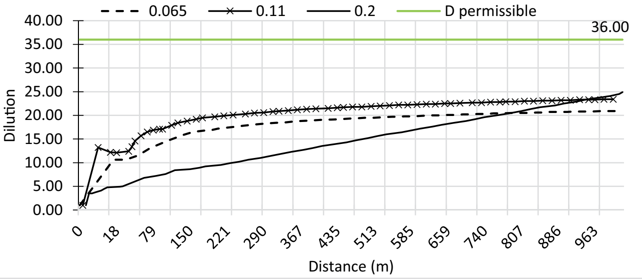

Fig. 7. Graphs of dilutions according to the different environmental velocity.

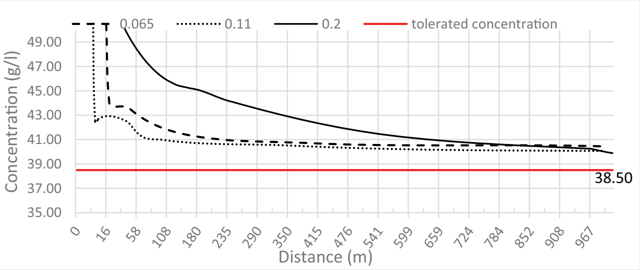

Fig. 8. Graphs of concertation according to the different environmental velocity.

3.2.2. Change in number of ports

In this scenario the dilution was examined and the possible interaction when modifying the diffuser design. To do this the number of ports was increased from 6 double ports to 15 double ports while keeping the same characteristics as the previous scenario (scenario N°3) (Table 4). It can be seen in Fig. 12 that the dilution was ensured from the first 100 m and there was also a slight interaction between the brine discharges and the catchment water whose excess concentration (salinity) at the catchment point was 0.7 g/L. This low salinity value did not influence the functioning of Seawater Desalination Plant (SDP). An improvement was visible compared to the initial state (+6 g/L) (Fig. 10). This intervention on the design of the submarine outfall had a positive influence on the operating performance and a negative influence on the cost of the diffuser. A 3D image of a 15-port dual alternative diffuser on CORMIX.11 is shown in Fig. 13.

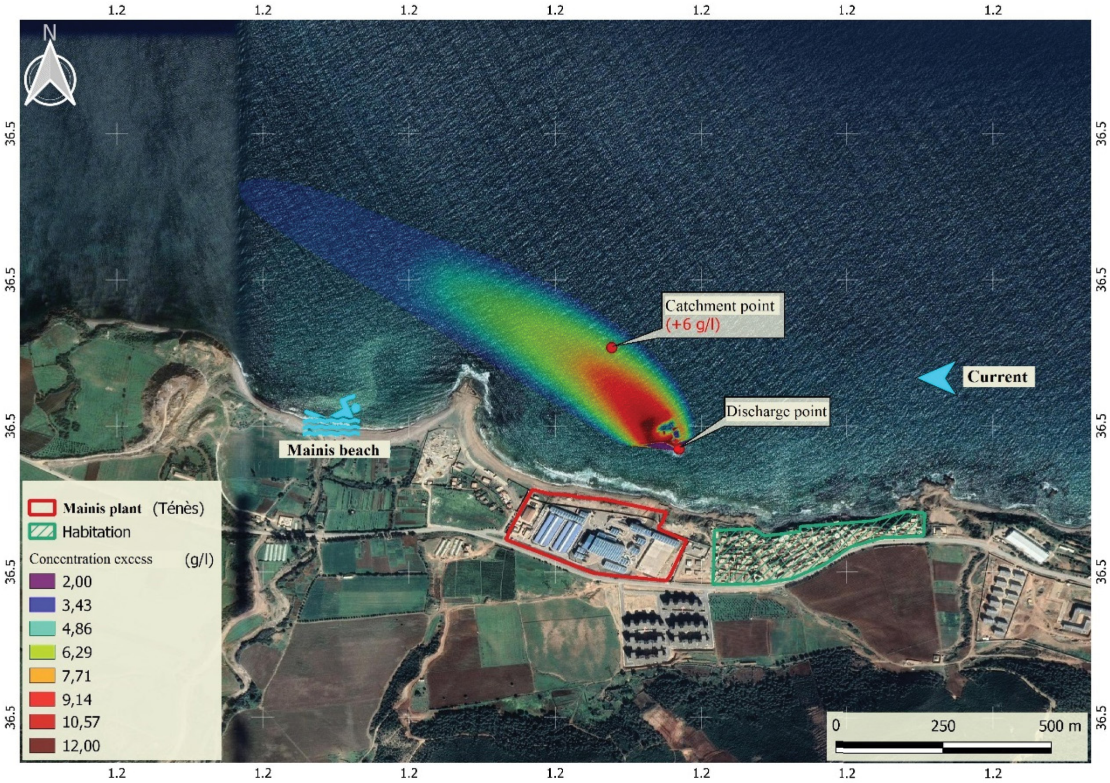

Fig. 9. Presentation of simulation results (CORMIX GT 11.0) of plume on QGis 3.16.18 (sub-layer: google earth).

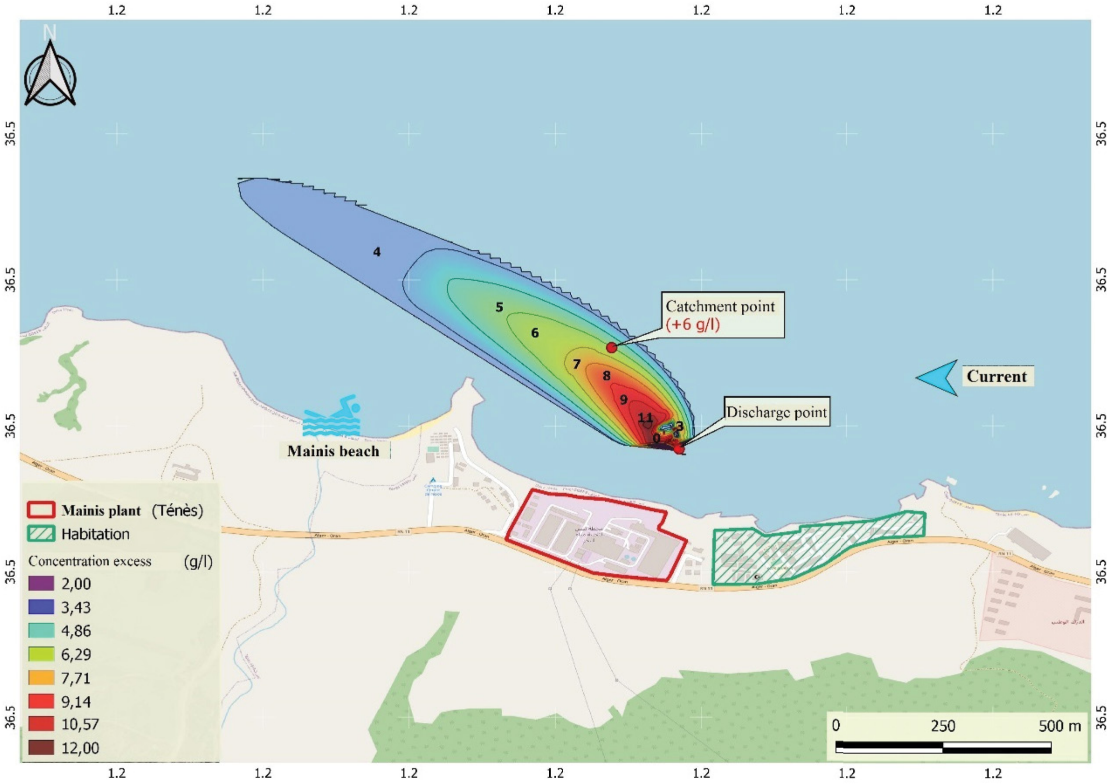

Fig. 10. Presentation of simulation results (CORMIX GT 11.0) of plume on QGis 3.16.18 (sub-layer: google map).

3.2.3. Variation of the distance between ports (diffuser length)

To evaluate the influence of the distance between the ports on the dilution, a simulation was realized (scenario N°2) on CORMIX 11.0 who's the variable was the distance between the ports while keeping the other characteristics constant (Table 5).

Fig. 14 illustrates the results obtained when the concentration decreased to 40.5 g/L (previously 41.94 g/L) after 300 m. The results obtained from this scenario showed that the increase in the distance between the ports from 8 to 20 m clearly affects the dilution, the latter increased from 18.3 to 27.8 after 300 m, the length of diffuser became 100 instead of 40 m which influenced the design cost. The improvement of the dilution was effective, but the admissible dilution had not yet been reached (Fig. 15).

3.2.4. Final improvement (length + diffuser depth)

After detecting the problem on the diffuser (insufficient distance between the ports), other interventions were applied on the diffuser while keeping an equilibrium on the cost / performance ratio (Table 6). The depth variation of the submarine outfall was varied from 4.5 to 6.2 m (as depth increased, dilution increased) [38]. The variation of port height to the marine bottom was changed from 0.75 to 2 m. This height affected the dilution rate (Figs. 16 and 17).

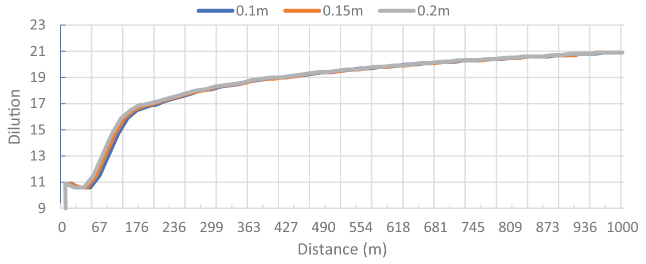

Fig. 11. Graphs of dilutions according to different port diameters.

The concentration decreased to 39.8 g/L (41.9 before) after 300 m and to 39.60 g/L after 500 m of distance covered (Fig. 16). This configuration gave successful results and improved the operation of the diffuser of the case study desalination station. This design was the most favorable.

3.3. Comparison between dilution in initial configuration and proposed configuration

To verify the behavior of the diffuser after the modifications were made, the dilution of the brine discharge was compared between the initial state and the final state (Table 7) This comparison was carried out under the same

Table 4
Characteristic of scenario N°4

Diffuser length (m)	96
Current (m/s)	0.05
Wind (m/s)	3
Distance between ports (m)	3.31
Depth (m)	4.5
Distance to shore	150
Diffuser height (m)	2
Ports number	15 double (30)

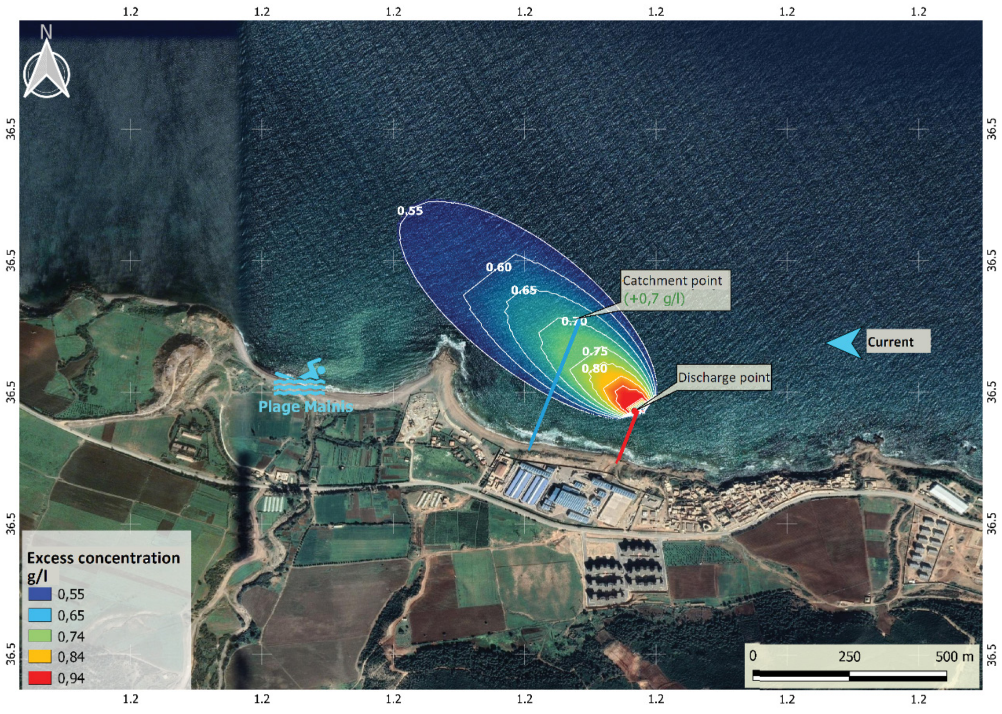

Fig. 12. Presentation of CORMIX GT 11 simulation results on QGis 3.16.8.

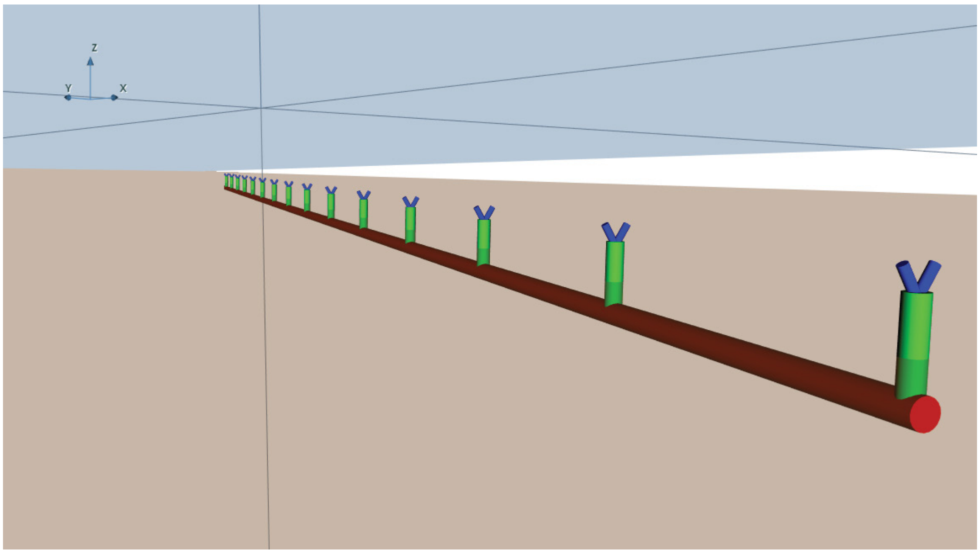

Fig. 13. 3D image of a 15-port dual alternative diffuser on CORMIX.11.

Table 5
Scenario N°2

Diffuser length (m)	100 (instead of 40 m)
Current (m/s)	0.065
Wind (m/s)	3.5
Distance between ports (m)	20 (instead of 8 m)
Depth (m)	4.5
Distance to shore	150

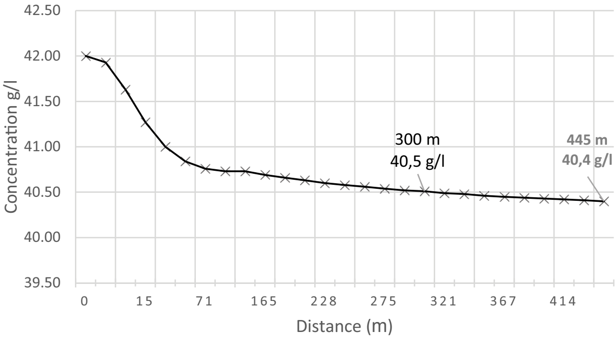

Fig. 14. Seawater saline concentration graphs when varying the distance between ports.

climatic conditions (i.e., wind speed and current). The increase in dilution was remarkable as seen in Fig. 18. The new configurations proposed gave better dilution results than before.

3.4. Offset of the discharge point

To limit the environmental impact of the brine discharges on the marine environment, the discharge point was moved away from the beach and environmentally sensitive areas. The location was chosen to maximize the dilution of the brine discharge into the marine ecosystem and to avoid a possible interaction between the discharge and the intake points (Table 8).

It was proposed to move the brine discharge point from position A to position B according to the coordinates quoted in Table 8 as shown in Fig. 19. This new position allowed for avoiding the influence of interaction between the discharge and the catchment water. Furthermore, the operation

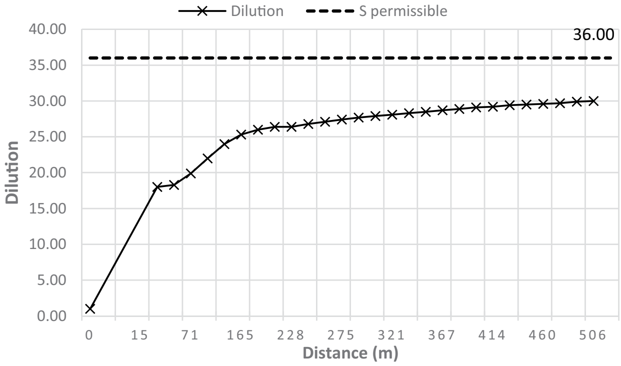

Fig. 15. Dilution graphs when varying the distance between ports.

Table 6
Scenario N°3

	Initial	Proposed
Diffuser length (m)	40 m	100
Current (m/s)	0.065	0.065
Wind (m/s)	3.5	3.5
Distance between ports (m)	8 m	20
Depth (m)	4.5	6.28
Distance to shore (m)	150	200
Jet height from the bottom (m)	0.75 m	2 m

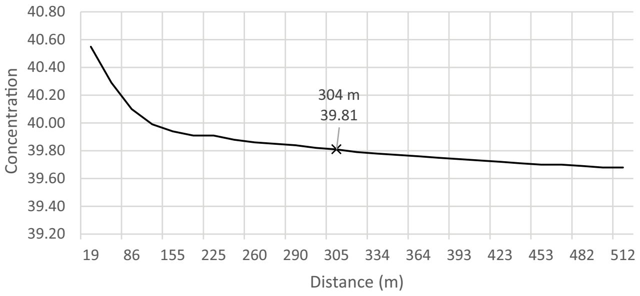

Fig. 16. Saline concentration in g/L when changing the height of the diffuser.

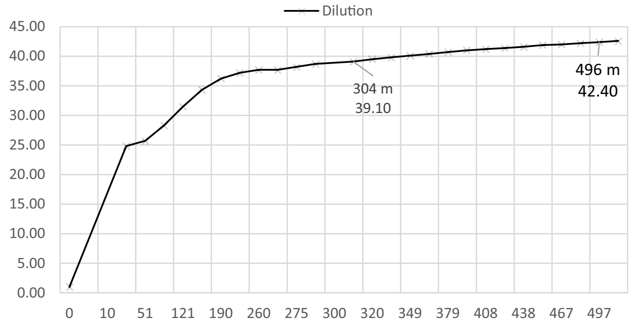

Fig. 17. Dilution graph when changing the height of the diffuser.

Table 7
Comparative table of the dilution between the initial and final state of the diffuser

Distance travelled	Dilution		Increase in rate
	Initial configuration	Proposed configuration	
100 m	14.7	28.3	92.5%
300 m	18.3	38.7	111.5%
500 m	19.5	42.2	116.4%
1000 m	20.9	46.1	120.6%

of the diffuser was also more effective due to an adequate depth, and the plume dispersion occurred far from the beach (Fig. 20).

Most of the scientific research and experimental and numerical studies on the dynamics of mixing zones have focused on the environmental impact of discharges and the behavior of the device (i.e., the submarine outfall), but few that have attempted to treat the case of the interaction between discharge and catchment waters. In the current investigation a simulation with the code Cormix was effectively employed in analyzing the discharge efficiency of the brine from a desalination plant in order to verify the dilution rate and follow the plume dispersion, taking into account the position of the catchment point. The rate of dilution and the dispersion of the plume were considered in the positioning of the catchment point.

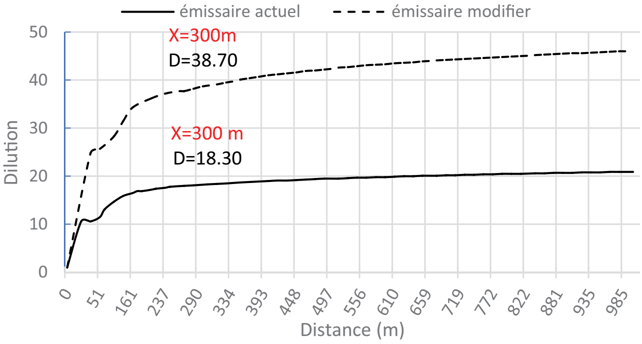

Fig. 18. Comparison between the initial dilution and the final dilution.

Table 8
Comparison between initial and proposed positions

	Initial state	Proposed state
Position (m)	X_{UTM}: 341354 Y_{UTM}: 4041608	X_{UTM}: 341931 Y_{UTM}: 4042114
Distance between discharge & catchment (m)	290	720
Discharge point depth (m)	4.5	19
Pipe length (m)	200	950
Distance au rivage	150	600

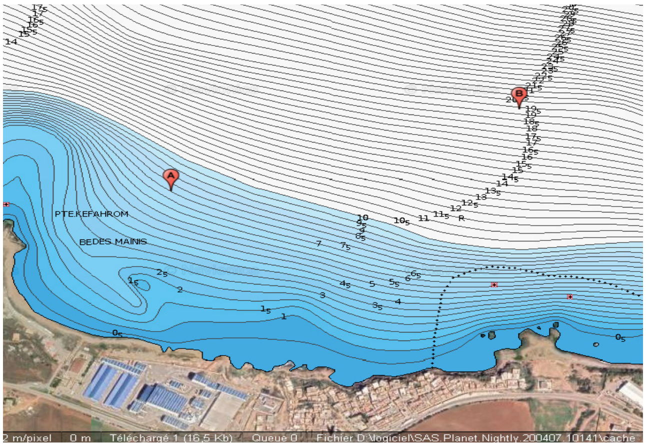

Fig. 19. Initial position A and final position B of catchment point on SAS Planet.

The behavior of the existing diffuser and the dilution obtained under the worst (i.e., unfavorable) meteorological conditions (i.e., current direction parallel to the direction of the catchment point from east to west) showed that there was an interaction between the discharge water and the catchment water whose plume touched the catchment point with a salt concentration of 44 g/L and exceeded the ambient salinity of 38 g/L with an excess of salinity of +6 g/L (Fig. 9). From this it was concluded that the current diffuser of the desalination plant at Tenes was badly dimensioned, and the localizations of the catchment point and that of rejection were not well studied. A diffuser with 12 nozzles was an expensive diffuser, (Ishita, et al., 2021) did not

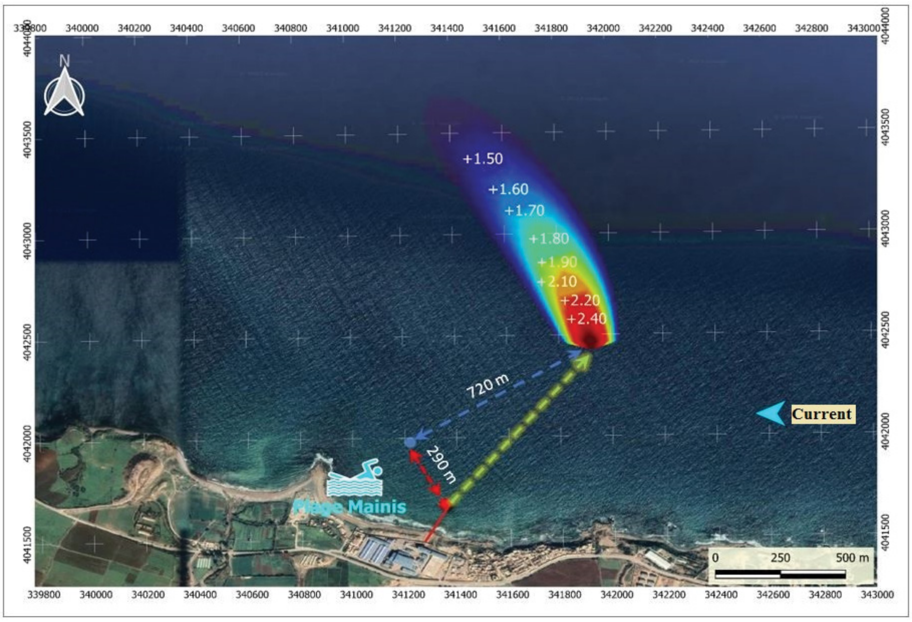

Fig. 20. Presentation of CORMIX 11.0 simulation results on QGIS 3.16.8.

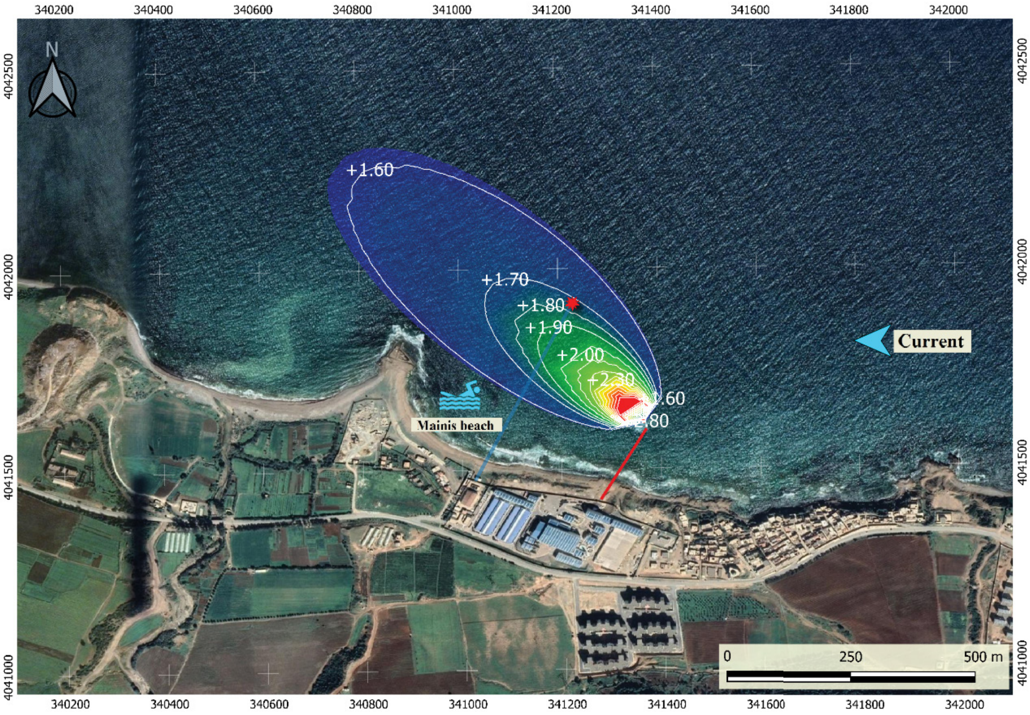

Fig. 21. Presentation of CORMIX GT 11 results on QGIS 3.16.18.

reflect the dilution results obtained. Furthermore, based on the current results and literature reports the designs and their influence on dilution such as distance between ports (Fig. 2) [38], diffuser depth and port height [39], were assessed to improve the performance of dilution and to avoid the possible interaction between the discharge and the capture.

The position of the capture point in relation to that of the discharge gave poor results (290 m) (Fig. 4). According to the simulation results obtained under the worst conditions (Figs. 9 and 10), it was suggested to increase this distance from 290 m to at least 500 m (Figs. 19 and 20), by shifting the coordinates of the current capture point (X_{UTM} = 341,088 m, Y_{UTM} = 4,042,047 m) west to X_{UTM} = 341,228 m and

Y_{UTM} = 4,041,913 m). To validate the proposed modifications to the parameters of the submarine outfall, a simulation was carried out. The dilution results were very promising with the excess concentration dropping from 6 g/L (Fig. 9) to 1.8 g/L (Fig. 21) at the catchment point.

The performance of a submarine outfall can be increased by increasing the port number and the distance between ports. These parameters have a direct relationship with the cost [40]. In addition, the maintenance of the distance between ports was a complicated and difficult operation. On the other hand, the climatic and meteorological conditions (i.e., water current and wind) are random and uncontrollable parameters, affecting the performance of the outfall. Previous studies have been reported on the initial dilution of brines with the seawater before their rejection in the marine environment, without submarine outfall being expensive and difficult to manage and with a safe and controlled dilution such as the Alicante and Javea desalination plants in Spain [41–44].

4. Conclusions

Scientific research and experimental and numerical studies on the dynamics of mixing zones have focused on the environmental impact of discharges and the behavior of the device (i.e., the submarine outfall), but few that have attempted to treat the case of the interaction between discharge and catchment waters. In the current investigation a simulation with the code Cormix was effectively employed in analyzing the discharge efficiency of the brine from a desalination plant. The behavior of the existing diffuser and the dilution obtained under the worst (i.e., unfavorable) meteorological conditions (i.e., current direction parallel to the direction of the catchment point from east to west) showed that there was an interaction between the discharge water and the catchment water whose plume touched the catchment point with a salt concentration of 44 g/L and exceeded the ambient salinity of 38 g/L with an excess of salinity of +6 g/L.

According to the simulation results obtained under the worst conditions. It was suggested to increase the distance between the capture point and the discharge point from 290 m to at least 500 m, by shifting the coordinates of the current capture point west. Based on simulations the dilution results were very promising with the excess concentration dropping from 6 to 1.8 g/L at the catchment point.

Avoiding direct discharge into the marine environment is the only solution to reduce the environmental impact. An initial dilution with sea water before discharge is a practical, economical, efficient, and sustainable solution. Management of the rejects of seawater desalination plants is expensive. It can be argued that there is a need to rethink the design of the desalination plants, even for the plants in service if necessary and if possible.

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