Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27103

222 (2021) 81–91
May

Surface spreading of the brine discharge from the seawater reverse osmosis plants: Hamma Water Desalination plant in Algeria

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Received 4 August 2020; Accepted 6 February 2021

ABSTRACT

In a contrasting background of declining renewable water resources and increasing demand for drinking water, recourse to seawater desalination appears an attractive alternative to explore. The main role of a seawater desalination plant is therefore to ensure drinking water that meets sanitary norms while causing the least harm to the marine environment. The Hamma Water Desalination (HWD) plant in Algeria has attracted our attention as it drains 500,000 m^3/d of seawater on which 300,000 m^3/d is being discharged as brine into the shallow water of the Algiers bay at ~8 m water depth. The study deals with monitoring the plant's outfall surrounding area using the satellite images provided by Google Earth Pro software. The horizontal spreading on the water surface caused by the brine jet was tracked over time, and its behavior was analyzed using image processing at different marine conditions. This investigation thus provides a better understanding of the complex behavior of free surface spreading of brine discharges in shallow waters. In this regard, environmental conditions have a significant impact on the horizontal spreading on the water surface, which may affect the dilution process. Based on the satellite observations, this investigation suggests making changes to the design of the HWD plant outfall or replace it with a modern discharge system.

Keywords: Outfall; Brine discharge; Desalination; Satellite imagery

1. Introduction

Seawater desalination is bound to be an efficient way to provide drinking water to people living in regions with absolute water scarcity. However, this technique can lead to serious environmental problems [1–4], more especially in semi-closed seas like the Mediterranean and the Red Sea [5]. For example, it has been shown that *Posidonia oceanica* meadow living in the Mediterranean are affected by hypersaline discharges from reverse osmosis (RO) desalination plants [6]. A more recent study showed that the Mediterranean benthic heterotrophic bacteria were affected by seawater reverse osmosis (SWRO) discharges [7]. Impacts stated before could be reduced by implementing suitable mitigation measures, such as a good location of the plant and an optimal outfall design [8,9]. Indeed, particular attention must be paid to design the outfall since it is responsible to discharge the brine into the surrounding environment. Outfalls are classified according to their location (surface discharge, submerged discharge), their mixing feature (single port/multiport), and their effluent characteristics (positive or negative buoyant) [10,11]. They are designed to achieve maximal initial dilution according to the environmental regulations, set by regulatory agencies, inside the boundaries of the 'mixing zone' [12,13]. This zone is defined as a limited sacrificial area or volume within the coastal waters, characterized by slight impacts on

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marine life [14] and is usually limited to a region around the outfall where the initial dilution takes place [15].

Conceptually, the region where the initial dilution takes place is referred to as 'the near field' region. It is mainly influenced by the discharge parameters like the physical properties of the brine and the surrounding conditions [16]. The processes in the near field operate over small scales: distances of order tens of meters and times of order minutes [17]. The near field estimation can be achieved using computational methods such as length-scale [18–20], integral [21–24], and CFD models [25,26]. Away from the outfall discharge exit is located what is so-called 'the far field' region. In this conceptual area, the process operates within a time scale of hours to days and a length scale of tens meters to kilometers [17]. Further, large-scale motions such as buoyant spread processes and passive diffusion control the slow mixing and the plume trajectory [27].

Brine outfall design in shallow receiving waters is a major challenge. To our knowledge, there are only a few papers dedicated to the study of brine discharges in shallow coastal waters. Previously, Jiang et al. [28] assessed the effect of jet inclination in shallow water. Planar laser-induced fluorescence and particle image velocimetry methods were used to estimate the mixing characteristics in terms of water depth and densimetric Froude number. This investigation evaluated the surface impact on the dilution and provided information on inclined jets in shallow waters. In addition, Jiang and Law [29] derived semi-analytic solutions to design the multiport brine diffusers in shallow coastal waters. Abessi and Roberts [30] performed experiments in which nozzles were horizontally oriented between 30° and 60°. The spatial variations of tracer concentrations were calculated using the 3D laser-induced fluorescence. The three simulated scenarios flow image analysis (deep water, surface contact, and shallow water) showed a complex interaction with the free surface, especially for steep nozzle angles in shallow water. Therefore, the authors proposed recommendations for the design of outfalls in shallow waters. Angelidis et al. [31] dealt experimentally with the two-dimensional dense jets that emit vertically and impinge on the free surface. Results were used to derive an equation that correlates the initial Froude number and the characteristics of the jet.

SWRO plant designers strive to prevent the interaction between the brine jet and the water surface, but this cannot be avoided in some situations. This fact is encountered in the Hamma Water Desalination (HWD) plant (Algeria), which discharges its brine into the coastal waters of Algiers bay. In this study, the discharge area of the HWD plant is monitored using the satellite images provided by Google Earth Pro software [32]. The investigation aims to better understand the free surface spreading of the brine discharging into shallow waters on a realistic scale. Accordingly, image processing and geometric tools will be used to extensively analyze the spreading behavior due to the HWD plant outfall system.

This paper combines two objectives: (1) the use for the first time, to our knowledge, of satellite imagery and processing tools to track and analyze the surface spreading of brine coming from seawater desalination plants. (2) The revelation of an uncommonly surface spreading of a dense effluent emanating from an operating SWRO plant, potentially harmful to the marine environment.

2. Plant description

The HWD plant is part of an ambitious program launched by the Algerian authorities consisting to implement a large number of mega-scale desalination plants along the Mediterranean coast, where most of the country's population (80%) and industry are concentrated [33]. In 2011, these desalination plants achieved a desalination capacity of 1,461,920 m^3/d, of which 61% were produced using the RO process [34].

Currently, 11 desalination plants are operating in Algeria for a cumulative capacity of 2.1 million m^3/d [35]. Among them, the HWD plant produces 200,000 m^3/d of drinking water using the RO process and supplies a quarter of the water need in the Algerian capital. The HWD plant is situated in the Hussein Dey district, the commune of Belouizdad. It is close to Algiers port and to the Hamma Power Station. According to its designers, the plant location and the chosen process were assumed appropriate [36]. Plant additional details are shown in Table 1.

The HWD plant is located at the following GPS coordinates: latitude 36° 45′ 6.26″ N, longitude 3° 4′ 45.34″ E. The satellite image dated 2 February 2007 provides an overview of the plant under construction showing its main components such as the pre-treatment and post-treatment facilities, the RO modules shed, and the intake and outfall pipes (Fig. 1). Although the literature relating to this plant is not abundant, the references [36–39] provide valuable details on the process of the plant and its outfall system.

Table 1
Details of the HWD plant [37]

Builders	OCIA/Orascom Construction Industries, 03 bis, rue Raoul Payen, Hydra 16035, Algiers, Algeria (Construction) OCIA/Orascom Construction Industries, 03 bis, rue Raoul Payen, Hydra 16035, Algiers, Algeria & BESIX LLC, Headquarters, Avenue des Communautés 100, 1200 Woluwe-Saint-Lambert, Belgium (Studies and supply of equipment)
Operators	GE Infrastructure Water Process Technologies Algeria "GEIWPTA"
Components	9 modules of 25,100 m^3/d per production unit, including 8 in production and 1 on standby
Operation start	April 2008
Investment cost	$257 Million

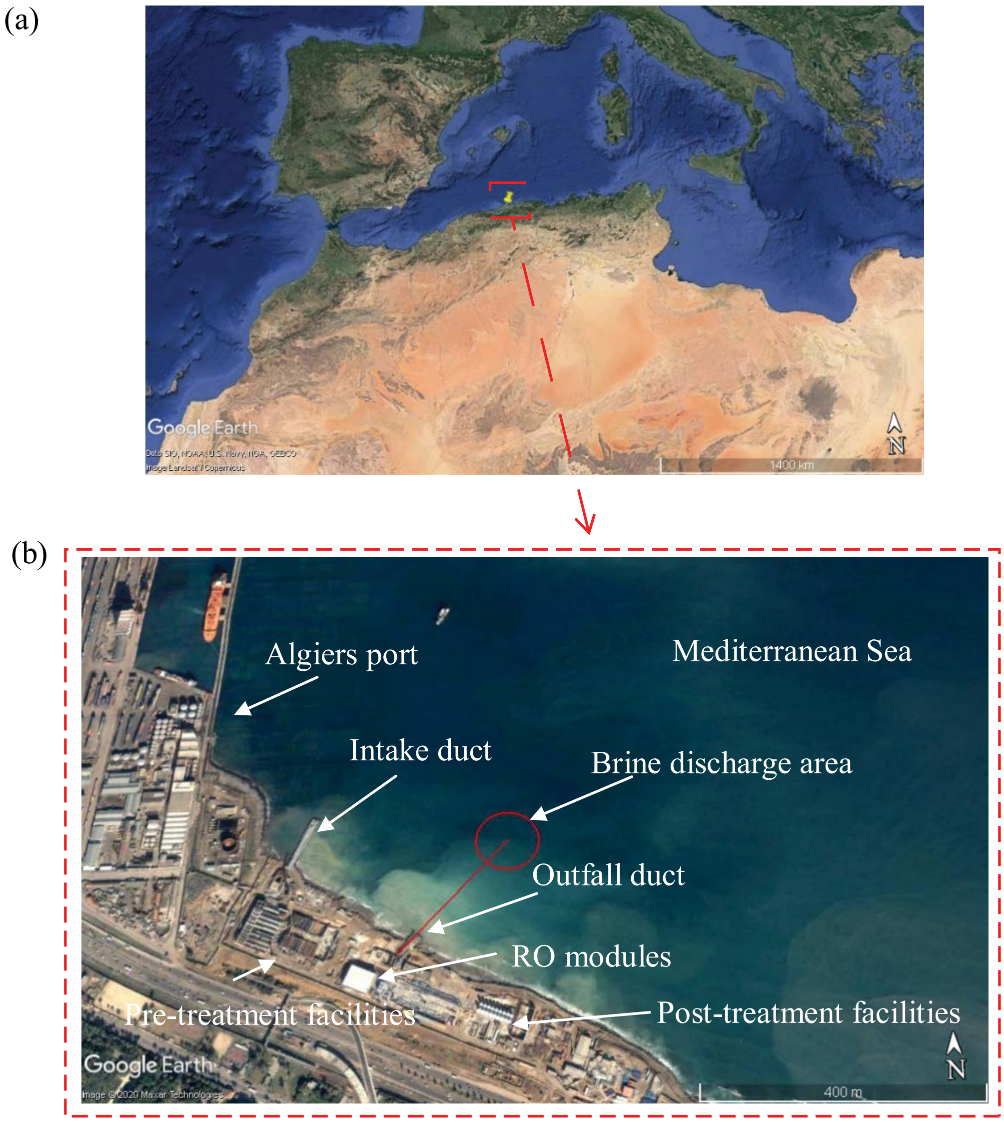


Fig. 1. Location of the HWD plant: (a) image was taken at 3,017 km altitude and (b) image taken at 1.18 km altitude.

The main components of the HWD plant and its desalination process are presented in Fig. 2. The plant is supplied with water from the Mediterranean Sea, which has a salinity between 34 and 37 g/L and a temperature between 15°C and 27°C. The seawater is drawn through two 550 m intake pipes (bottom depth at the site ~13 m) to a pre-treatment system. Here, coagulants are added to help remove suspended solids. After flocculation and sedimentation, the water passes through a double media filter and then into a clear well. The water is then pumped through 5-micron cartridges and distributed to nine trains of single-pass reverse osmosis membranes (8 on/1 standby). Each train has a high-pressure pump, a booster pump, and pressure exchangers. The pure water undergoes a post-treatment process before delivery to the city's water distribution system. The brine is discharged from the pressure exchanger units at 0.7 bar to be transferred to the sea via a submerged marine outfall.

About 300,000 m^3/d of brine comprising reject water and wastewater from cleaning processes overflows by gravity through a single reinforced concrete outfall pipe and discharges at ~8 m in depth via an exit nozzle (single port, without a diffuser). Under the effect of pressure, the jet of concentrate leaves the nozzle and then descends to the seabed by gravity. According to current designs, the angle of the nozzle is approximately 60° to the horizontal [10,11]. The length of the brine outfall pipeline is roughly 258 m and measures 1.6 m in inner diameter.

The salinity of the brine is largely a result of the plant recovery rate, which in turn depends on the salinity of the original seawater and process configuration [1,29]. The HWD plant was designed to work at a membrane recovery rate of 40%–44.5%, while the salt concentration of the brine is supposed to be about twice as high as the concentration of the intake seawater. Whereas, the temperature of the concentrate is similar to the temperature of the seawater. Thereby, the concentrate discharged by the plant is considered denser than the ambient seawater and negatively buoyant.

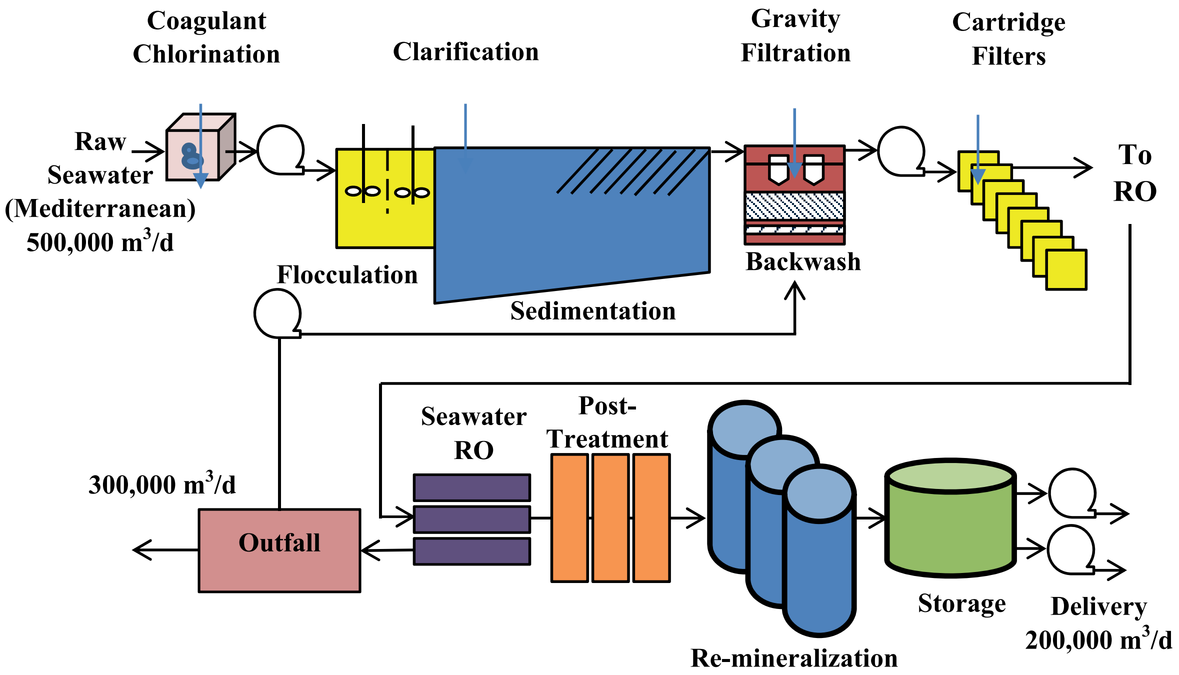


Fig. 2. Schematic representation of the HWD plant [37].

The brine is discharged not far from the port area, characterized by the following environmental conditions [40]. The difference between the low and the high tides for the entire Algerian maritime area is ~0.30 m but is insignificant in the port area. The sea height varies with the wind direction, reaching at most 75–80 cm. The main marine currents in the Algerian maritime zone are those that cross the Strait of Gibraltar to the east (typically 1/4–3/4 knots), while lateral currents moving west are generally low in the Algiers port sector. Most waves do not reach 0.5 m in height and usually come from the north to the northeast. Winds from the west, the northwest, and the northeast are the most common winds, and they can reach up to 20 m/s in winter.

3. Methodology

Monitoring of the HWD plant discharge area is performed with Google Earth Pro software [32], which maps the Earth and provides high-resolution satellite images. This investigation technique allows tracking over time of the seawater surface behavior in the area of interest and detects any interaction between the brine jet and the free surface. Thus, measurement tools implemented in this software are used to estimate the geometric characteristics of the brine plume that impinges on the water surface. The free image manipulation program GIMP [41] is also used to improve and handle satellite images, allowing a better interpretation of the surface spreading of the plume.

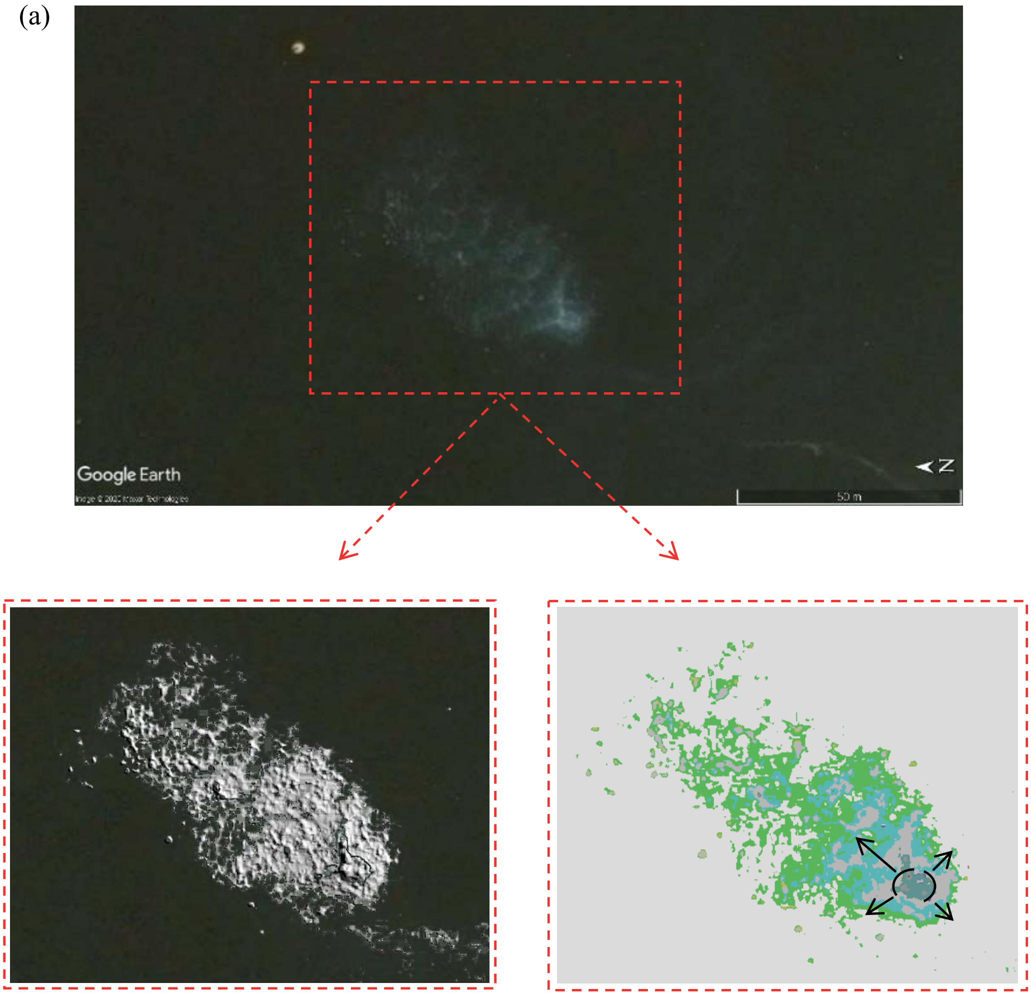
Using the tools mentioned above, the methodology followed in this work could be described in two main stages: The first phase of the investigation consists of collecting the satellite images corresponding to the plant site. The chronology of the satellite images allows us to follow the changes on the site during the different stages of the project (before, during, and after the construction). As stated before, particular attention is paid to the marine area where the plant discharges its brine. The second phase of the investigation includes an in-depth analysis of the collected satellite images focusing first on the near field region, and then the far-field using image processing tools. Thus, satellite images undergo image treatments such as relief and posterization effects to detect the boundaries of the plume and its behavior. This process is repeated for each of the satellite images to track the changes in the free surface spreading over time and to obtain useful information on its behavior under different environmental conditions.

4. Results and discussion

As mentioned in Fig. 1, the outfall pipe route and its discharging area are detected using the geometric tools available on Google Earth Pro software. The water surface activity surrounding the outfall exit is discussed in the following sections.

4.1. General observations

The analysis method of the surface spreading of the plume is fairly illustrated in Fig. 3. The original satellite image, dated 03 August 2017 at 168 m above sea level at coordinates (36°45′13.66″ N, 3°4′52.30″ E) is shown in Fig. 3a. Intense activity is observed on the water surface where the discharge nozzle is located. The satellite image shows a boiling formation on the water surface, which is resulting from a centerline impingement regime [28,29]. Namely, the jet centerline impacts the water surface causing major surface disturbances and can also be defined as a shallow water condition [30]. Indeed, this surface



(b)

(c)

Fig. 3. The analysis method of the surface spreading of the plume: (a) original satellite image, (b) with a relief effect, and (c) with a posterization effect.

interaction is probably due to one or the combination of the following factors: the high brine jet momentum coming from the outfall nozzle (high Froude number), the high steep nozzle angle, and the water shallow depth. The treatment of the original image with a relief effect (Fig. 3b) allows a better detection of the boundaries of the free surface spreading and gives more details about its roughness. After applying a posterization effect (Fig. 3c), it is possible to identify precisely where the brine jet impacts the water surface, defined as the initial plume stage [28] as well as the caused wave propagation. Indeed, depending on the disturbance, the color changes, e.g., the initial plume stage has a dark contour that decreases as it moves away from it. These observations help us to understand the surface propagation of the plume during a calm sea, which spreads mostly downstream (northeast direction), even upstream, and on the sides, as shown on lab-scale experiments [30].

Surface interaction and visual impact of the jet on the water surface indicate the efficiency of the mixing process in the near field region, that is, less contact means a better dilution of the concentrate [30]. For that, the brine jet coming from the nozzle and interacting with the water surface is followed with great interest. Fig. 4 shows some examples of plan views taken during a calm sea and after applying a relief effect. The plume expands and tapers in length and width, and thus, the area, perimeter, and roughness vary. These changes could be attributed to several factors, such as the flow disruption of the concentrate and its chemical components, and/or to seasonal variations of seawater (surface temperature, salinity, etc.).

Other examples of satellite images taken in the near field region during a rough sea condition are shown in Fig. 5. The case of short-wavelength waves coming from the northeast is shown in Fig. 5a, while Fig. 5b shows the case of long-wavelength waves coming from the north. In both cases, the surface interaction between the jet and the water surface is hardly visible even after an image treatment. The high roughness of the seawater is probably greater than the one caused by the brine jet, which significantly reduces the surface interaction. Such observations reflect

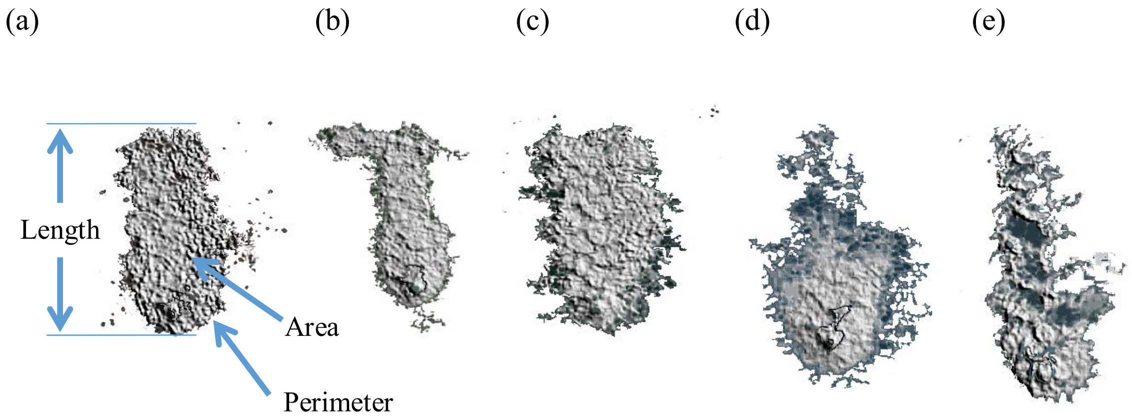
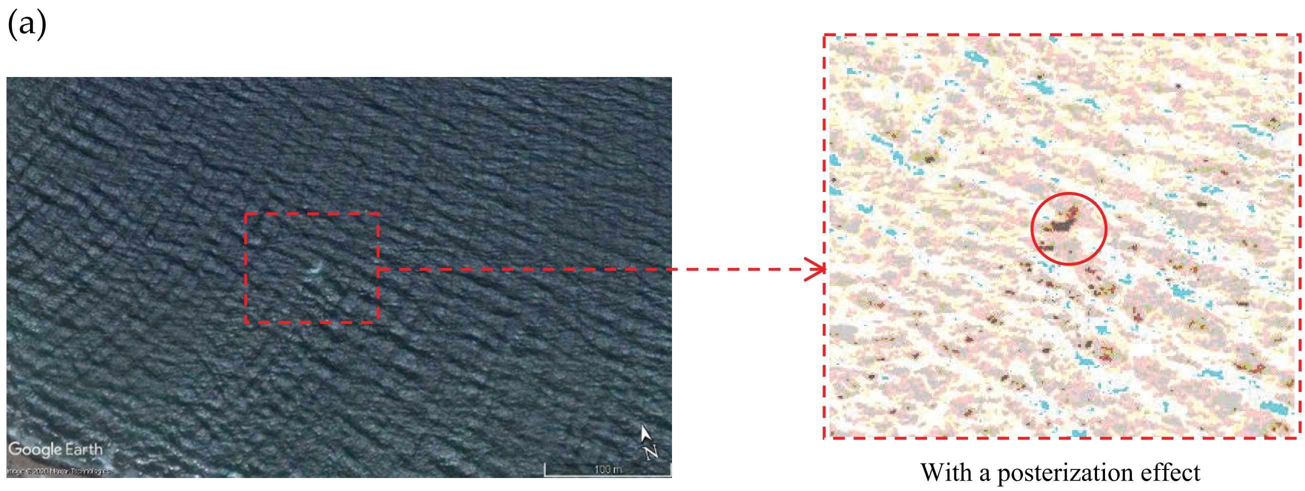
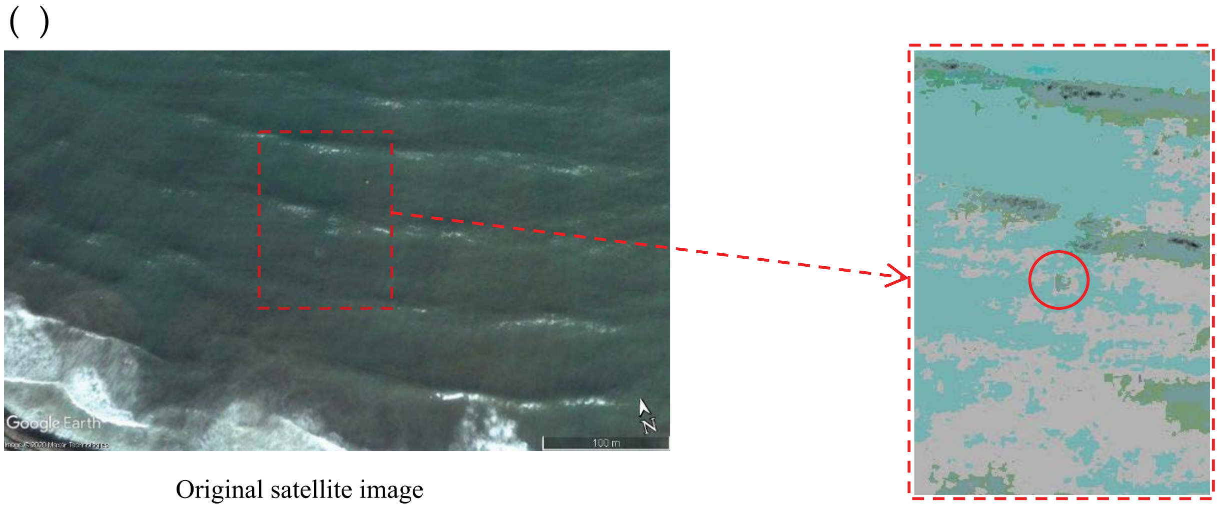


Fig. 4. Plan views of the free surface spreading obtained after an image treatment: (a) 21 July 2016, (b) 21 August 2016, (c) 6 September 2016, (d) 30 January 2017, and (e) 7 March 2017.



Original satellite image

With a posterization effect



Original satellite image

With a posterization effect

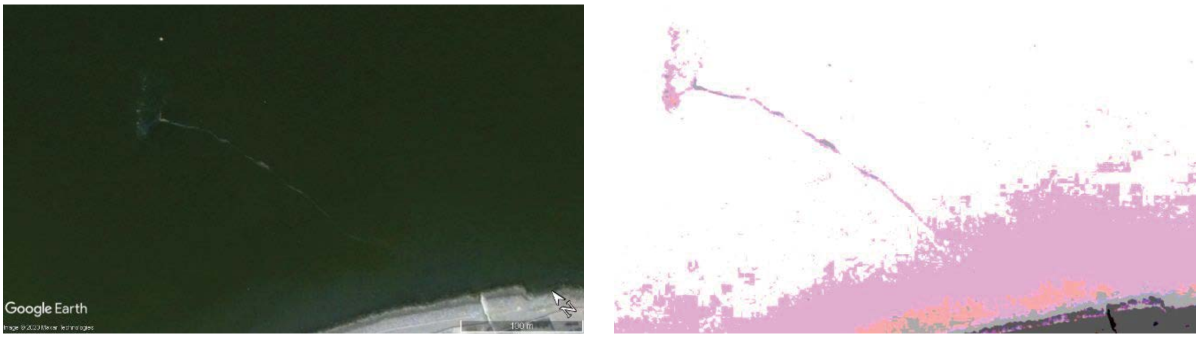
Fig. 5. Satellite images showing the surface spreading of the plume during rough sea conditions: (a) 22 June 2016 and (b) 11 January 2017.

the positive role of a rough sea in increasing dispersion and mixing [42].

Satellite images of the surrounding area of the disposal system highlight certain surface phenomena that derive from the brine plume. Fig. 6 shows that a part of the plume detached and was passively transported a hundred meters in the south direction to reach the shore. This is probably a sedimentation phenomenon or suspended solids used in the process and mixed with the brine (biocides, antiscalants, inhibitors, and others) [1]. The floating layer, clearly visible after applying an image treatment is drained to the shore mainly through the surface circulation responsible for contaminants transport within the Mediterranean Sea [8].

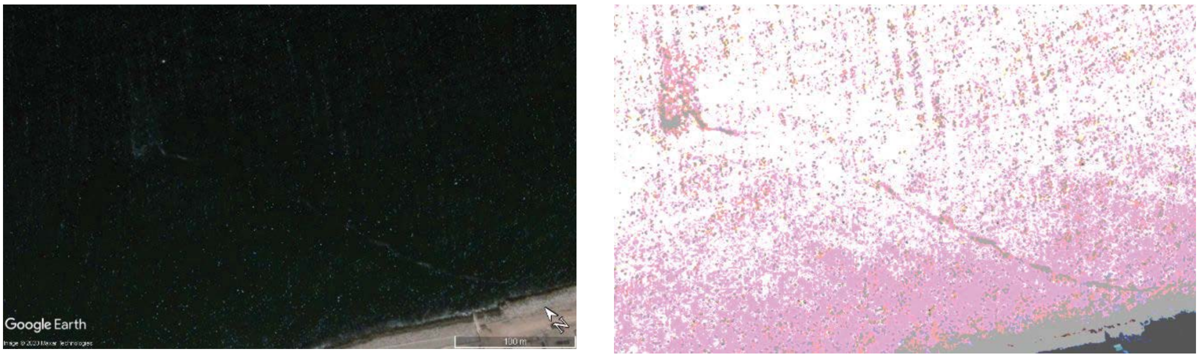
Observations reported above could be explained largely by the fact that the project promoters did not use the Environmental Design Optimization. Indeed, this technique

(a)



Original satellite image With a posterization effect

(b)



Original satellite image With a posterization effect

(c)

Original satellite image With a posterization effect

Fig. 6. Satellite images showing the surface spreading of the plume extending to the shore: (a) 11 April 2017, (b) 22 May 2018, and (c) 1 September 2018.

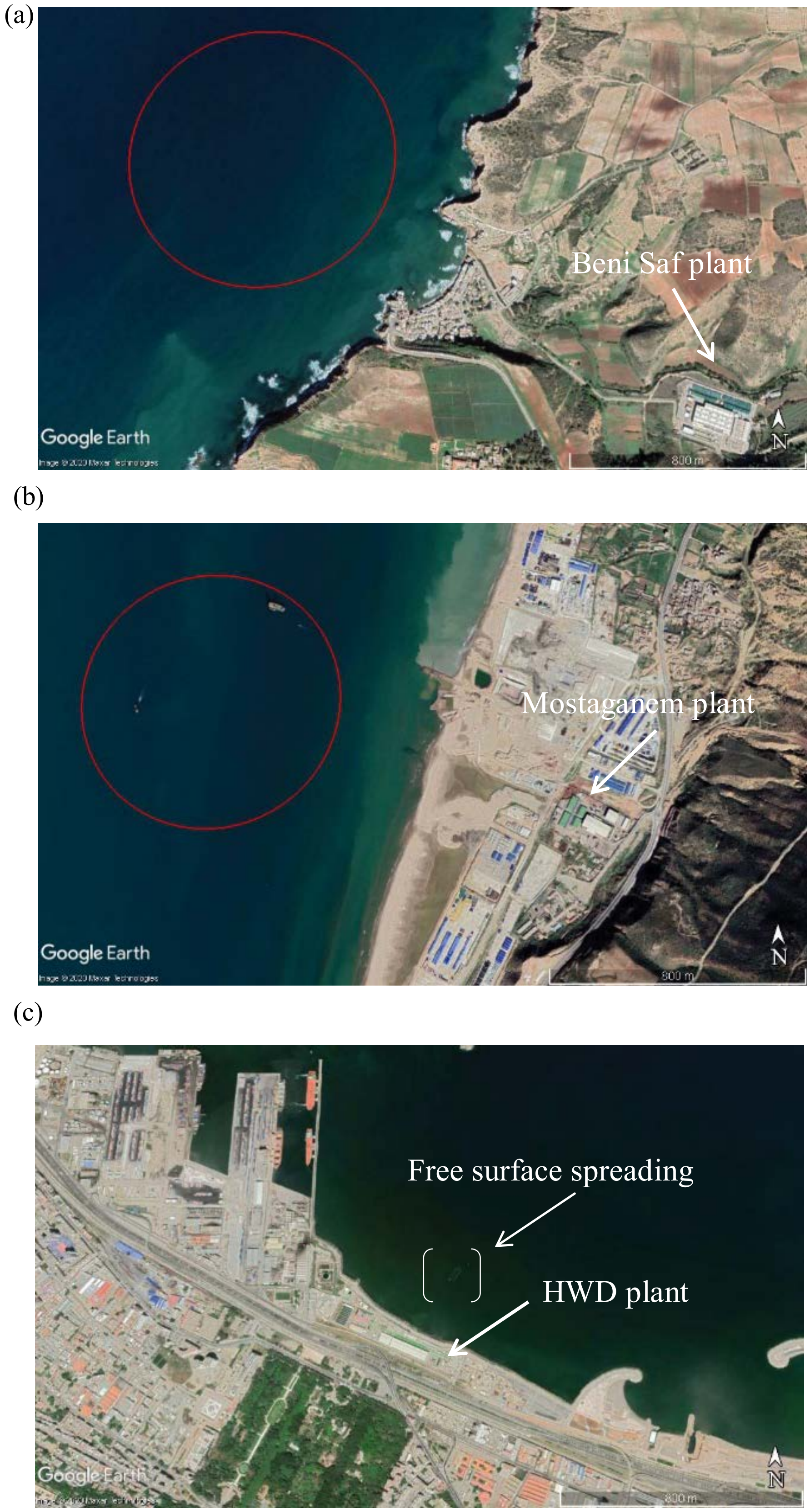


Fig. 7. Satellite images of some desalination plants operating in Algeria: (a) Beni Saf plant; 21 November 2018, (b) Mostaganem plant; 6 February 2018, and (c) HWD plant, 10 May 2019.

aims to design optimal outfall systems (length, position, arrangement) to limit the impact on the environment and reduce investment costs [36].

For a comparison purpose, the discharge areas of Beni Saf (35°21′39.24″N, 1°15′54.44″O) and Mostaganem (36°0′50.34″N, 0°7′40.25″E) plants were also monitored using satellite images. These plants have many common points with the HWD plant such as the desalination capacity (200,000 m^3/d), the process used (RO) and the bathymetry of the discharging site (~8 m). However, the characteristics of the disposal systems may vary. For example, the Beni Saf outfall discharges the brine through a nozzle, while the Mostaganem one is fitted with a diffuser containing 50 nozzles [42,43]. The observations did not identify any surface interaction between the brine jet and the water surface for Beni Saf and Mostaganem plants, which is not the case with the HWD plant (Fig. 7). This comparison is even more interesting if we focus only on Beni Saf and HWD plants that are equipped with the same type of outfall (single pipe, without a diffuser). It is worthy to note that the maximum excess salinity measured at the Beni Saf plant is 72% (brine detected up 1.5 km from the outfall). While it does not exceed 9% at the Mostaganem plant (brine detected up 200 m from the outfall) [42,43].

4.2. Spatiotemporal analysis of the free surface spreading

The surface interaction between the brine jet and the water surface was monitored in terms of length, area, and perimeter from July 2016 to June 2017. Fig. 8 provides useful information on the efficiency of the mixing process during the year. The plots follow the same trend for the three monitored parameters. During the summer, the length, area, and perimeter of the free surface spreading reached the highest values, while the lowest values were recorded during the winter. As a result, the brine dilution is more efficient during the cold season than the hot season. These results depend strongly on the characteristics of the brine and the surrounding environment. Probably, the HWD plant reaches its maximum production during the summer, which results in more brine discharge. Indeed, due to the high demand for drinking water combined with low rainfall, low filling levels of dams, the desalination plant must operate at full capacity. Another plausible explanation concerns the seasonal fluctuation in salinity due to precipitation and evaporation variation, as well as changes in marine circulation and waves [44]. Meanwhile, the geometrical characteristics of the free surface spreading follow the same tendency as the annual sea surface temperature reported in the literature [45,46].

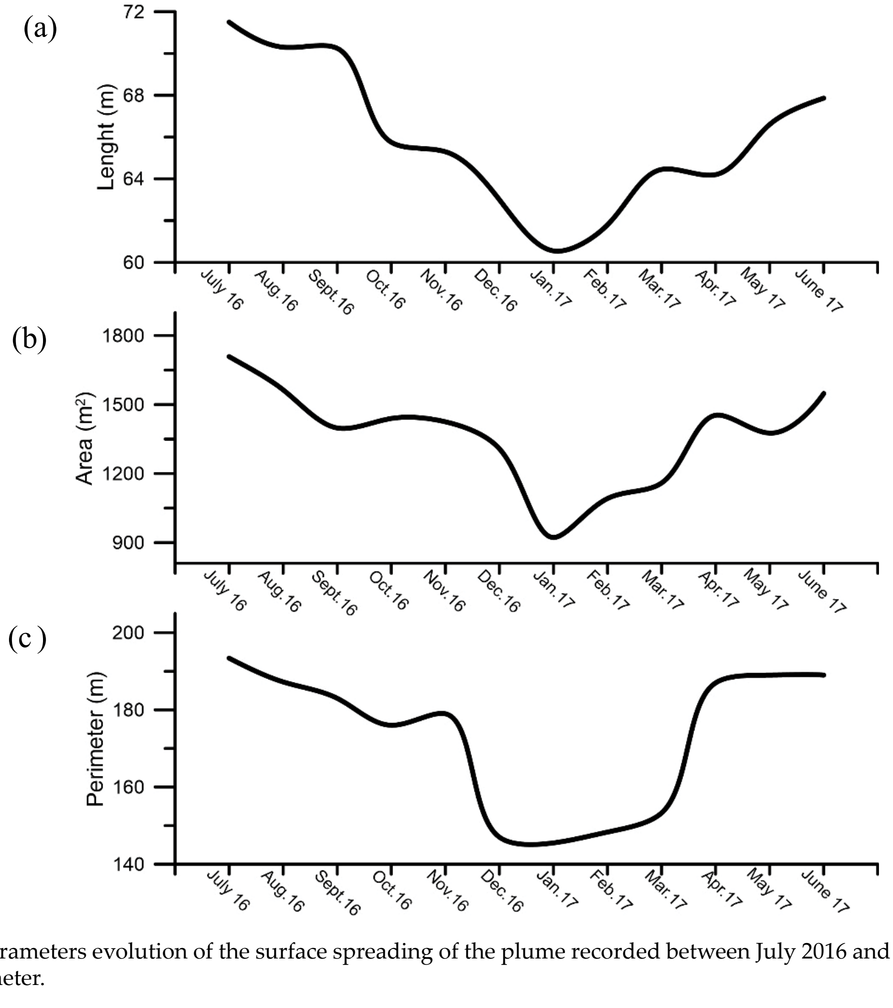


Fig. 8. Geometrical parameters evolution of the surface spreading of the plume recorded between July 2016 and June 2017: (a) length, (b) area, and (c) perimeter.

5. Conclusion

The outfall system of the Hamma Water Desalination plant in Algiers, Algeria, was monitored using satellite images provided by Google Earth Pro software. This study focused on the observation of the dense effluent discharged from the outfall nozzle that impinges on the water surface. The use of image processing has allowed us to analyze the interaction between the brine jet and the water surface in various marine scenarios. In this regard, the roughness of the free surface spreading is not uniform, where the disturbance is more prominent at the initial plume stage and decreases by spreading on the water surface. The behavior of the surface interaction and its shape are unpredictable and complex to define accurately since the spread over the water surface depends on environmental factors and the characteristics of the concentrate. Thus, the free surface spreading has a non-constant evolution during the seasons of the year, where it extends in the summer and retracts in the winter. This could be caused by the water volume fluctuations dealt with the HWD plant and/or the seasonal seawater characteristics variations.

Based on previous investigations carried out at a laboratory scale [30], in the field [42,43], and according to our observations, it could be concluded that the outfall of the HWD plant is not appropriate with the site location. Indeed, the surface interaction between the jet and the water surface is adverse for the brine dispersion. However, some suggestions are proposed to remedy this: (1) make changes in the design of the outfall by replacing the nozzle with a diffuser system [44,47] or by increasing the length of the outfall pipe [42]. (2) Study the impact of the plant on the environment and conduct a monitoring program to follow the brine discharge behavior [47]. (3) More globally, the authorities should revise the regulations concerning the seawater desalination sector (such as the choice of the site location, control the discharges, etc.).

The use of satellite images provided by Google Earth Pro software as the main investigation tool has shown many benefits, like the free use of satellite images, the availability of geometrical calculation tools, and chronological images. However, this approach has some disadvantages, mainly the need for an internet connection, the bad resolution of some images, and the lack of updated images. Besides, this detection technique does not provide more information on plume characteristics, such as salinity and temperature. So, the use of field investigations and numerical methods are highly recommended.

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