Mixing study of the Ras-Laffan desalination plant outfall in Qatar coastal waters, methodology

Abolghasem Pilechi*, Abdolmajid Mohammadian**, Colin D. Rennie***, Hazim Qiblawey****, Ioan Nistor*****

*Ph.D. Candidate, Department of Civil Engineering, University of Ottawa. 161 Louis Pasteur, Ottawa, Ontario, K1N 6N5, Canada.
Email: apile073@uottawa.ca

**Associate Professor, Director of Water Resources Laboratory, Department of Civil Engineering, University of Ottawa. 161 Louis Pasteur, Ottawa, Ontario, K1N 6N5, Canada.
Email: majid.mohammadian@uottawa.ca

*** Professor, Department of Civil Engineering, University of Ottawa. 161 Louis Pasteur, Ottawa, Ontario, K1N 6N5, Canada.
Email: colin.rennie@uottawa.ca

**** Associate Professor, Department of Chemical Engineering, Qatar University. P.O. Box 2713, Doha, Qatar.
Email: hazim@qu.edu.qa

***** Associate Professor, Department of Civil Engineering, University of Ottawa. 161 Louis Pasteur, Ottawa, Ontario, K1N 6N5, Canada.
Email: inistor@uottawa.ca

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Abstract

An extensive field survey was conducted to study the near-field and far-field mixing patterns of the Ras Laffan Industrial City surface outfall in Qatar. A coupled field remote-sensing method was proposed to study the mixing process of thermal plumes. The thermal infrared satellite photos were calibrated versus the measured temperature data with CTD. The effect of tidal currents and waves on the plume dynamics was investigated. The entrainment coefficient as a result of jet mixing and buoyant spreading was also estimated separately. The calibrated satellite photos show that the proposed method can be used in investigating the dynamics of thermal plumes.

1. INTRODUCTION

Surface outfalls are the most common outfall system due to their simplicity, low construction cost and high discharge capacity. They have been historically used as the outfall system for industrial compounds, especially for cooling effluents. The rivers discharging into the seas and oceans are also analogous to the surface jets, with different densities to those of the receiving waters. Due to the popularity of the surface outfalls as well as the high rates of population growth and industrialization, much research has been conducted in the last few decades on the mixing patterns of surface outfalls. These studies can be generally categorized as experimental, field and numerical studies. Some of them were focused on investigating different parameters such as outfall geometry, discharge condition, ambient water
condition and wind effects on the mixing, and to develop empirical equations or numerical method to predict the plume dynamics under different conditions (Lal and Rajaratnam 1977, Luketina and Imberger 1987, Whitney and Garvine 2005, Hetland and MacDonald 2007, Atkinson 1993, Akar and Jirka 1995). Other studies were more dedicated to the general classification of effluent plumes (Nekouee et al. 2013, Saeedi et al. 2012). Mixing processes are generally investigated in the near field or far field. “Near field” is defined as the region in which the mixing is controlled by the initial discharge momentum and buoyancy flux as well as the outfall geometry. The effluent mixing in the far field is mainly caused by the ambient flow advection and diffusion. This is also known as passive diffusion, and its mixing process is controlled by the turbulence characteristics of the ambient flow (Jirka et al., 1991). The near field and far field mixing processes are different with respect to the length and time scales. The length scale addresses the largest possible eddy size that causes mixing. These eddies are sources of momentum, mass and energy transfer in and out of a control volume. For example, the transverse eddies that rotate horizontally about a vertical axis cause lateral mixing in a river (Gualtieri, 2009). The rate of turbulent diffusion in a turbulent flow is determined by the largest eddies, which also encompasses eddies with different sizes and intensities.

The effluent outflows generally have a different velocity and density from the receiving water. Therefore, the effluent is named a jet in the case of a momentum driving force, or plume when it is driven as a result of buoyancy. Effluents are generally called jet-plumes in the literature if they are influenced by both momentum and buoyancy effects.

The surface jet flows can be divided into three principle regions, as the Zone of Flow Establishment (ZFE), the near field and the far field (Lin et al., 1977). The ZFE is the region closest to the outfall. The effluent has uniform velocity and temperature profiles at the discharge location. The difference between the jet velocity in the ZFE and the ambient water produce shear, and consequently turbulence around the jet. The ambient water entrains the ZFE and decreases the width of this region with increased distance from the outfall. The extent of the ZFE is defined as being from the outfall location to the point that the jet centerline velocity or temperature starts to decay from the discharge value. The length of the ZFE for temperature is less than for velocity due to the higher turbulent diffusion coefficient (Lin et al., 1977).

The next region is the near field, also known as the Zone of Established Flow (ZEF), in which the mixing is affected by the initial volume, momentum and buoyancy fluxes. Velocity, salinity or temperature all have self-similar Gaussian shape profiles in this region. In some studies, the extent of the near-field region is defined as the point where the jet center-line velocity excess is dissipated, but the density still differs in the plume region from the ambient environment (Lin et al., 1977). The momentum difference between the jet region and the ambient water in the near field generates shear, and consequently turbulence, which is the main mixing mechanism within the initial portion of the near field. The buoyancy-derived forces as a result of the density gradient also enhance the mixing process. The buoyant mixing mechanism is more significant when farther from the high-momentum region in the vicinity of the outfall.

Surface outfall flow regimes are generally classified as free jets, shoreline-attached jets, wall jets, and upstream intruding plume (Jones 1996, 2007). Nekouee et al. (2013) further improved the classification scheme by considering the wind effect on the plume shape in surface outfalls with large aspect ratios. Abessi et al. (2012) also added the classification criteria for negative buoyant surface outfalls.

Two transition zones can be defined in surface buoyant jets (Jirka, 2007). The first transition occurs within the zone of flow establishment, where the relative uniform velocity distribution is transformed to a sheared jet-like Gaussian-shaped profile. The entrainment mechanism within this region is due to the stream-wise or azimuthal shear (Jirka, 2004). As the jet gets farther from the source, it is weakened due to the momentum diffusion (Jirka, 1981), and the
second transition zone begins. This is the region in which jet-like behavior transitions to plume-like behavior, and vertical entrainment is inhibited and buoyancy-spreading dominates the mixing process. In short, the jet-like behavior transitions to plume-like behavior. This will result in a sharp-edged vertical profile which eventually causes a density-front formation and a uniform shape in the lateral direction. The entrainment mechanisms in this region are summarized by Akar and Jirka (1994) as buoyant damping of vertical entrainment, frontal entrainment, and interfacial entrainment at the plume base.

The near-field outfall behaviour can be addressed by the discharge properties such as the discharge velocity \( U_0 \), discharge channel width \( b_0 \), depth \( h_0 \), channel cross-sectional area \( a_0 = b_0 h_0 \), discharge density \( \rho_0 \) and discharge angle relative to the channel direction \( \sigma_0 \). In a general designation, these parameters are defined as the initial volume flux \( Q_0 = U_0 a_0 \), momentum flux \( M_0 = U_0^2 a_0 \) and buoyancy flux \( J_0 = U_0 g \Delta \rho_0' a_0 \). The initial buoyancy acceleration, \( g_0 = \left( \Delta \rho_0 / \rho \right) g \), is calculated from the initial density difference \( \Delta \rho_0 = \rho_a - \rho_0 \), where \( \rho_a \) is the average ambient density and \( g \) is gravity. Ambient water velocity \( u_a \), depth \( H \) and distance along jet trajectory are other ambient property parameters which affect the near-field flow regime and mixing pattern.

In order to simplify the above-mentioned parameters in the mixing process, some length scales are defined using dimensional analysis in order to represent the dynamic discharge quantities and the outfall interaction with the ambient water (Jones et al., 2007). The discharge length scale \( L_Q \) defines the extent of the zone of flow establishment where the flow characteristics are greatly influenced by channel geometry:

\[
L_Q = \frac{Q_0}{M_0^{1/2}} \quad (1)
\]

This parameter is used to define the extension of the zone of flow establishment, which is generally small and insignificant on the overall flow pattern. It is also measured against the jet to plume length scale (introduced in the following) to determine the upstream intrusion.

The relative importance of the initial momentum and buoyancy flux is measured with the jet to plume length scale \( L_M \):

\[
L_M = \frac{M_0^{3/4}}{J_0^{1/2}} \quad (2)
\]

This length scale shows the extension of the region where the jet-mixing process is overtaken by buoyancy-induced lateral mixing. This length scale is independent from the ambient water properties and defines the balance between unsteady jet-mixing and buoyant lateral spreading mechanism. The jet to cross flow length scale defines the relative significance of the initial momentum to the ambient cross flow as:

\[
L_m = \frac{M_0^{1/2}}{u_a} \quad (3)
\]

where \( u_a \) is the ambient current velocity. This length scale shows where the flow changes from a weakly deflected regime to a strongly deflected regime. The ratio of the initial buoyancy flux to the ambient cross flow is defined with the plume to cross flow length scale \( L_b \):

\[
L_b = \frac{J_0}{u_a^3} \quad (4)
\]
As previously mentioned, the upstream intruding plume is one of the main surface outfall categories defined by Jones (1996, 2007). The $L_0$ length scale is used to determine the extent of upstream spreading.

The near-field mixing models can be categorized as jet integral models, numerical models and length scale models (Jones et al., 1996). The length scale models use experimental or field-measured data to develop an empirical expression to predict the average dilution rate, shape and trajectory of the jet/plume. The length scale models are based on the empirical expression of the plume parameters and are derived from laboratory studies (Roberts et al., 1989a, 1989b, 1989c).

A group of studies have used detailed measured data and theoretical and statistical analysis to develop formulas for predicting the mixing under different initial discharge and ambient conditions. Jirka et al. (1996) combined different research in this regard and developed the CORMIX model. This model is based on the flow classification which is most appropriate for a given outfall’s properties, and uses formulas from other experimental studies in predicting the dilution in similar cases.

The jet diffusion theory governing equations are based on the conservation relationships for mass, momentum and energy (Abraham, 1972). However for a turbulent flow, the number of unknowns is more than the system of equations can resolve, which leads to the closure problem. This is the main idea behind using the entrainment concept in the governing equations to obtain a closed system of equations. In one of the earliest studies, Morton et al. (1956) employed the entrainment rate in an integral model to study the mixing of a simple plume in a stratified environment. The idea of jet integral models dates back to the 1960s and 1970s. Morton et al. (1956) and Townsend (1966) are two of the earliest studies in which the entrainment constant concept has been used in modeling the turbulence-mixing. Jet integral models are based on solving the ordinary differential equations and are derived by integrating the jet properties like momentum, buoyancy and mass fluxes across a section (Jirka et al., 1981). These models consider the influence of different turbulence sources by the empirical entrainment coefficients in the conservation of mass, buoyancy and momentum fluxes. Integral models apply the effect of different mixing sources such as wind, turbulent mixing, buoyancy, and interfacial and drag forces as entrainment coefficient in the simplified governing equations. Shirazi and Davis (1974), Jones et al. (1996) and Jirka et al. (2004, 2006 and 2007) are some examples of the integral models developed for modeling outfall-mixing. The entrainment rate is introduced to represent different phenomena which are expected to affect the mixing rate, such as turbulence, waves, wind stress, etc. (Akar & Jirka, 1995; Jirka, 2007). The concept of entrainment can be expressed as:

$$V_e = E_s U_m$$  

(4)

where $V_e$ is the entrainment velocity at the plume edges, $U_m$ is the plume centerline velocity and $E_s$ is the entrainment coefficient and is derived using experimental or field data. The entrainment is assumed to be perpendicular to the jet trajectory. This equation is valid only for low-velocity ambient flow conditions (Lin et al., 1977). The spreading coefficient is another parameter which represents the rate of change in the plume width along the jet trajectory. This parameter can be used instead of the entrainment velocity to achieve a closed system of equations. This parameter has a concept similar to that of the entrainment velocity. Jirka et al. (1975) and Stolzenbach and Harleman (1971) showed that there is a linear relationship between entrainment velocity and spreading coefficient. For a heated surface discharge, the entrainment process is generally divided into lateral entrainment (Hoopes et al., 1968) and vertical entrainment (Stolzenbach & Harleman, 1971). The spreading coefficient and entrainment velocity are yielded by solving the continuity and momentum equations. The solution is based on the hydrostatic pressure distribution assumption, and the...
buoyancy forces produced by the density gradient are balanced with the hydrodynamic drag forces. The total spreading process in either the horizontal or vertical direction can be split into buoyant and non-buoyant components. The non-buoyant component is zero at the jet axis and increases linearly to the jet boundaries.

Jirka (2007) developed an integral jet model to predict the near field of surface outfalls. He generally categorized the complex processes as pure jet mixing, buoyant entrainment damping and collapse motions, lateral density front formations, a propensity for internal hydraulic jump discontinuities, Coanda attachment processes, low pressure shoreline interaction and recirculation effects, heat buoyancy loss, and wind-induced mixing. The developed integral jet model was based on the implemented principles by Jirka et al. (2004, 2006) for single-port jets. He considered the contribution of each of these mechanisms separately in the entrainment coefficient $E$ in the buoyant surface jet and applied each of them using equations for estimating entrainment from other experimental or theoretical studies (Parker et al., 1987; Akar & Jirka, 1994).

The mixing characteristics of buoyant coastal outflows have been investigated in different theoretical (Luketina & Imberger, 1989, Hetland & MacDonald, 2007), experimental (Lal & Rajaratnam, 1977) and field (Luketina & Imberger, 1987) studies. McCorquodale (2007) provided a comprehensive review of the theoretical, experimental, numerical, and field research on storm water discharges with jet-plume surface outflows and their interactions with flow in rivers and coastal waters. The specific feature of the coastal mixing studies is the mixing sources such as tidal currents, waves and wind, which affect the dynamics and the mixing pattern of the plume. The wind’s influence on coastal mixing can be considered by looking at wind-generated waves or wind-driven currents.

In surface wall-jet discharges in shallow water, the investigated case in this study, jet entrainment, is restricted by the presence of solid side walls and bed. The jet is initially attached to the bed in the region close to the outfall. This is the region where the inertial forces dominate and is referred as the turbulent core (Safaei, 1979). Linear spreading is observed within this region as the result of momentum exchange between the jet and the ambient water. This mechanism is also known as jet mixing. Flowing over a mild-slope bed, the jet reaches the maximum depth ($h_{max}$) and then detaches from the bed. From this point, turbulence and entrainment lessen greatly; buoyancy spreading controls the mixing after this point and the plume thickness starts to lessen to the point of uniform transverse distribution.

Recent advancements in remote sensing technology have greatly enhanced the popularity of employing remote sensing approaches in mixing studies, especially in regions where conducting a field survey is not possible due to access difficulties (Chin et al., 1997; Marmorino et al., 2010; Lathrop et al., 1990; da Silva et al., 2001; Abuhabaya et al., 2011). In this study, a coupled field remote-sensing method was proposed to study the mixing process of thermal plumes. The proposed method was used in studying the mixing pattern of the Ras Laffan Industrial City (RLIC) outfall in Qatar.

Qatar is a developing country with an extended coastline of 563 km, and supplies most of its needed water from desalination plants. The water pollution associated with industrial activities has always been a concern for Qatari environmental authorities. Understanding the mixing pattern at RLIC, the biggest industrial complex in Qatar, in addition to evaluating the current environmental situation, can greatly help in developing environmental protection plans. Ras Laffan Industrial City is the largest industrial complex in Qatar, and uses water from the sea for the purpose of cooling petrochemical, gas and fuel refineries in the industrial city. Part of the heated water from the plants is transferred to the Ras Laffan desalination plant. Desalination plants usually use seawater and discharge their hypersaline outfalls back into the sea. The Ras Laffan desalination plant uses a Multi Stage Flash (MSF) process. The
MSF desalination effluent is normally neutral or positively buoyant, which causes the plume to rise. In the Ras Laffan complex, the effluent from the desalination plant is mixed with the cooling water which comes from other plants before being discharged into the sea. The effluent salinity of the desalination plant is expected to be 10% higher than the seawater, and as this effluent is mixed with the aforementioned cooling water before being discharged into the port, the final effluent density is lower than that of the receiving water.

![Figure 1: Ras Laffan Industrial City Port. Adapted photo from Google Earth](image)

RLIC has a surface outfall located at 25° 53.480’ North (latitude) and 51° 34.483’ East (longitude), discharging into the sea at about 222 m³/s. The outfall is located inside the Ras Laffan port, and therefore the generated plume is a confined jet. The water level in the port varies during the tidal cycle; however, due to the low tidal current velocity in the port, the ambient water can be considered as stagnant. The very high discharge value and shallow depth at the outfall generate a wall-jet-like flow regime at the outfall which is discharged into a stagnant ambient. In contrast to the buoyancy forces which intend to detach the jet from the bottom, high momentum close to the outfall enhances vertical mixing and thickens the plume in the near field of the jet. As the discharge has a higher temperature than the ambient water, it is expected that the effluent detaches from the bed while getting away from the outfall and buoyancy-induced mixing, which decreases the plume thickness and widen it overcomes. The detachment location distance from the outfall can be estimated from different equations, such as Atkinson’s (1993). There are two main flow regimes expected to be observed in this case. The first is a horizontal and vertical jet like mixing growth of the jet in the near, and the second is a decrease in the plume thickness as a result of buoyancy-induced spreading. After the detachment point, the buoyant spreading dominates and the turbulence lessens greatly.

In the current study, the near field and far field of the RLIC effluent plume were surveyed in an extensive field campaign using an acoustic Doppler current profiler (aDcp) and Conductivity-Temperature-Depth (CTD) probe. The collected data from the field campaigns as well as measured data from 3 environmental buoys out of the port were used in calibrating the LandSat7 thermal infrared photos.

The innovative aspect of this study is in combining a remote-sensing approach and a field measurement technique to study the near-field mixing process. The current study is also distinctive for the size of the investigated outfall. The investigated outfall in this study has an aspect ratio (the ratio of width to depth) of about 300, which makes it unique compared to similar previous studies such as Nekouee et al. (2013) a=16 and Pritchard and Huntley (2002, 2006) a=40.
The real-time measurements used in this study allowed for on-the-fly optimization of the survey path to best characterize the effluent plume.

2. METHODOLOGY

Field survey

Extensive field measurements at the RLIC outfall were conducted on March 19 and 24 and May 15, 17, 18 and 19, 2014. The near-field and far-field temperature and salinity of the RLIC effluent plume were surveyed from a boat moving both across and along the plume using an a Conductivity, Temperature Depth (CTD) instrument. The collected data from the field campaigns as well as data from 3 environmental buoys outside the port were used in calibrating the LandSat7 TIR photos (discussed in the remote sensing section). The hydrodynamics parameters (water velocity and depth) were also measured, using an acoustic Doppler current profiler (aDcp).

The CTD used in the present study was a Seabird SBE19-Plus Conductivity-Temperature-Depth (CTD) probe. This CTD can detect temperatures ranging from -5 C to 40 C with a resolution of 0.005 C. Temperature data were recorded with a sampling frequency of 4 Hz. CTD data were collected at one elevation in the water. The vertical temperature profiles were also measured by stationary measurements at the edges and middle of the surveyed transects. The CTD was mounted on the boat by a winch, which also allowed moving the CTD up and down in the water for vertical profile measurements.

The outfall hydrodynamics were measured using a Teledyne RiverRay acoustic Doppler current profiler (aDcp). The aDcp measured water velocities and depths at a 1 Hz sampling frequency, using bottom-tracking for the boat velocity reference. The CTD and aDcp data were collected simultaneously and synchronized by means of Global Positioning System (GPS) position and time-stamp data that were integrated into the data streams collected by both the CTD and the aDcp. An S320 Global Differential Positioning System (GPS) manufactured by Hemisphere was used on the boat to locate the measurement locations. Position data were collected at 10 Hz, and were integrated into the CTD and aDcp data sets for correct positioning and synchronization of the CTD and aDcp data. The measurements were conducted continuously while moving away from the outfall in a zig-zag pattern.

Remote sensing

Due to the high spatial resolution and free availability of data as well as the high extent of coverage, thermal infrared (TIR) photos have been previously used in different water surface temperature studies (Kishino et al. 2000, Donlon et al. 2002, Kumar et al. 2003, Kay et al. 2005; Becker and Daw 2005, Lamaro et al. 2012).

The thermal infrared (TIR) band (Band 6) LandSat7 photos from USGS were used in the remote-sensing approach for this study. LandSat7 images have eight spectral bands. The wavelength of Band 6 is 10.40-12.50 micrometers and provides 30-meter resolution for products processed after 2010. TIR images are available in low-gain band (B6L) and high-gain band (B6H). Following Chande et al. 2009 and Lamaro et al. 2012, the low-gain band was used in this study due to its greater range and lower saturation. Water surface temperature at-satellite can be estimated from TIR images using the available relationship in the LandSat7 handbook. However, the calculated values from these equations is at-satellite, which may differ from actual water surface temperatures depending on the effective climatic parameters such as cloud coverage, humidity, etc. The water surface temperature can be calculated using different methods like the Single Channel Generalized Method (SCGM) (Jiménez-Munóz and Sobrino, 2003) or Radiative Transfer Method
LaMaro et al. (2012) compared these two methods and found the SCGM method better than the RTM with respect to estimating rather small temperature differences.

The LandSat photos are taken every 8 days at 3:00 PM local time in the RLIC outfall region. Of the many archived TIR photos between 2013 and 2014, only the photos with zero cloud cover were used for the calibration. Due to the concurrency of one of the field survey date (May 15) to the satellite photo capturing, the measured data in the near field of the outfall in May 15 were used for calibrating the satellite photo. The images were calibrated using the buoy data and field-measured data (Fig. 2).

**Figure 2.** Raw LandSat7 on the left and Google Earth photo on the right. The red circles show the location of the environmental buoys mounted outside the port. The discrete points in the red rectangle represent the measured data from the May 15 survey.

The pixel value of May 15 measured points as well as the environmental buoys were extracted from the geo-referenced LandSat7 TIR photos for May 15 and all LandSat7 satellite photos with zero cloud coverage from 2013 until May 2014. The pixel values were then plotted against the measured temperature at the corresponding location.

**Figure 3:** Calibration Curve (the calibration curve was prepared using the measured data from the May 15 survey as well as environmental buoy data from 2013 until 2014 from the dates when the LandSat7 photos were taken)
3. RESULTS AND DISCUSSION

The entire path surveyed in May 2014 is shown in Fig. 2. Integrating the GPS position data with CTD data in real time allowed for measurement of the spatial distribution of temperature, which consequently helps in investigating the near-field mixing process of the outfall.

The field-measured data including salinity, temperature coordinates of the measured points were imported into ARCGIS and superimposed on the geo-referenced Google Earth images. The imported data were interpolated using the kriging method, and the spatial distribution of the effluent temperature was obtained for each survey date (Fig. 4).

![Figure 4: Measured temperature field from CTD.](image)

Figure 4: Measured temperature field from CTD. The vectors presented on each subplot show the 6-hour average wind speed and direction before the measurement times.

Due to the significance of the tidal currents on the coastal mixing process, the entire tidal cycle from the survey dates as well as the tidal range during the measurement times is provided on each temperature contour plot in Fig. (4). Using the linear equation obtained in the remote sensing section, the TIR LandSat7 photo was converted to a thermal image Fig. (5). As LandSat photos are taken every 8 days in the RLIC region, the presented images in Fig (5) are for the dates on which LandSat photos with zero cloud coverage were available. In order to consider the effect of wind on the plume dynamics, the six-hour averaged wind speed and direction before measurements as well as satellite photo capture times are presented by a scaled vector on the contour plots in Figs. (4) and (5).
As the surveys were conducted on successive dates in March and May, the discharge rate and temperature were close to the same for the other survey dates in each month. The main parameters which could have affected the plume dynamics were tidal and wind conditions.

The May 17 and 19 fieldworks are similar with respect to the surveyed region (far field) and tidal conditions. The near-field region was surveyed on May 15 and 18 in the same period of the tidal cycle. The May 18 data were the data collected closest to the outfall (jet-mixing region).

The March surveys were conducted during the same discharge and wind conditions. However, comparing the tidal conditions shows that the March 19 measurement was mostly carried out during the tidal flood. This has resulted in a more longitudinally-extended plume for March 19 with respect to March 24 (compare the locations of the 29.5 C contours, for instance). The tidal condition did not show a significant effect on the transverse shape of the plume. A complex flow regime observed in the March 19 temperature contours (close to the outfall) may be attributed to the merging of the separated discharge channel at the outfall and the bed shape in this region.

The May 15 and 18 surveys were conducted during the same tidal conditions. However, the cross-shore wind speed on May 15 was much lower than on May 18, which has resulted in elongation of the plume on May 18 (note the locations of the 36 C contour in both images). Comparing the temperature contours from the May 15 and May 18 plumes, it can be seen that on May 15, the plume detached from the side jetty at a shorter distance from the outfall. Also, comparing the contour shapes (36.5 C for example) at the end of the jet mixing zone, a higher buoyant-mixing rate is observed in the May 15 plume, which is attributed to the cross-shore wind effect. The May 17 and 19 plumes were surveyed during similar tidal conditions. However, the wind directions were almost opposite in these cases, and caused some inclination of the plume trajectory towards the southern jetty on May 19.

Fig. (5) presents some of the thermal photos obtained from the remote-sensing approach discussed in the current study. The satellite photos were all taken at 3PM local time for Doha, Qatar. However, the gradual shift in the tidal cycle has caused different tidal conditions in the presented contour plots. The highest tidal current occurs somewhere between the flood and ebb, and the current velocity is expected to have its minimum value at the highest and lowest tidal levels. The effect of the tidal current on the dynamics can be clearly seen in the plume trajectory in Figs. (5f, 5h and 5g). In spite of the low tidal current, discontinuity is observed in the jet trajectory in Figs. (5c and 5f). This discontinuity is attributed to wind-generated waves as the jet oscillates under wave interaction, which was also reported by Mori and Chang (2003). They reported that as the wave amplitude increases, the jet oscillation pattern changes from symmetric to asymmetric, and finally becomes discontinuous. Comparing Fig. (4c) and Fig. (5b) which are both for May 15, shows that the plume has been more longitudinally extended in the low tidal current conditions in Fig. (5b) and detaches from the jetty farther from the outfall. The effect of the offshore wind on elongating the plume is also observed in Fig. (5a)
Comparing all of the temperature contours in Figs. (4) and (5), it can be seen that the contour lines are generally more compact across the plume close to the outfall, which implies a higher transverse dispersion coefficient.

As mentioned above, the near-field mixing process can be categorized as jet-mixing (as a result of momentum exchange between the jet and the ambient water) and buoyancy-mixing (due to buoyancy-driven forces). Using the entrainment coefficient concept and the field-measured data in the current study, the mixing mechanisms were

Figure 5: Calibrated LandSat7 photos from 2013 until May 2014. The vectors presented on each subplot shows the 6-hour average wind speed and direction before the photo capture times.
investigated separately. The jet-mixing mainly occurs due to the high momentum exchange between the jet region and the ambient water close to the outfall. This will cause ambient water entrainment to the jet and consequently increases the jet discharge. Farther away from the outfall, the initial high momentum gradually diminishes due to bottom friction. Therefore, the rate remains constant at a specific distance from the outfall in the jet, and the buoyant spreading controls the mixing process. The cumulative discharge and temperature were extracted on several lines across the plume width (Fig. 4d) and plotted against the distance from the outfall location in Fig (5). Variation of the jet discharge with respect to the distance from the outfall shows the entrainment rate as a result of the jet-mixing process. Fig. (4a) shows that the initial discharge rate of the jet (222 m$^3$/s) has reached an approximate value of 420 m$^3$/s about 300 m from the outfall location, which implies an entrainment coefficient of 0.67 for the jet-mixing process. The discharge remained constant from this point, and buoyant spreading dominates the mixing process.

![Graph](image1.png)

Fig. (6) Shows the plume spreading with distance from the outfall. The linear growth in the plume width implies an entrainment rate of 0.78 for the buoyancy-mixing mechanism.

4. CONCLUSIONS

In order to investigate the near-field and far-field mixing patterns of surface outfalls, an extensive field study was conducted on the Ras Laffan Industrial City surface outfall in Qatar, with an aspect ratio of about 300. The spatial distribution of the thermal plume effluent and the jet velocity were mapped using data from CTD, aDcp and GPS. Using the field-measured data, entrainment coefficients of 0.67 and 0.78 were estimated for the jet mixing and the buoyant spreading processes respectively.

A coupled field remote-sensing method was proposed to study the mixing process of thermal plumes. The proposed method was tested in investigating the mixing pattern of the RLIC thermal effluent. The LandSat7 thermal infrared satellite photos were calibrated against the measured temperature data with CTD on May 15, 2014 as well as the available data from environmental buoys. The good agreement between the temperature contours provided from the field survey and the calibrated satellite photos showed that the proposed method can be used in studying the near-field and far-field mixing of the thermal plume as well as to investigate the effective parameters on the plume shape, such as dominant wind speed and direction. Using the field measured data and calibrated satellite photos, the effects of tidal currents and wind-generated waves have been found to be significant in the near-field and far-field fates of the plume.
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