Interpreting and modelling field data for wastewater dispersion into sea trough dimensional analysis

Mirella Di Giovanni [1], Salvatore Nicosia [2], Enrico Napoli [3], Gaspare Viviani [4], Giuseppe Ciraolo [5]

Keywords

On-shore discharge, wastewater discharge, pollutant dispersion, dimensional analysis.

Introduction

This paper deals with the mathematical and experimental characterization of a coastal urban wastewater discharge in the South Tyrrhenian Sea, namely the *Golfo di Palermo*, western Sicily (Italy).

The Gulf morphology strongly influences pollutants dispersion in the sea water, as an uninterrupted circle of mountains shields it from the winds blowing from W-SW sectors; currents and waves are therefore driven in a pattern which in several occasions severely reduces the self-depurative capacity of seawater.

In particular, the stretch of water lying before the central part of the capital town receives the wastewater originating from about 200 000 inhabitants. The sewage is currently still discharged on-shore without any prior treatment by a free-surface outfall called "Porta Felice".

This outfall discharge has crucial importance in the coastal water quality and in any environmental preservation plan. For this reason, the Municipality is implementing a plan featuring an intercepting main sewer and some pumping stations to connect the sewerage system of these areas to the main wastewater treatment plant.

At the moment, no mitigation measure has been applied yet and the quality of the Gulf is still largely affected by wastewater discharges.

Part of the plan was the characterization of the seawater in the Gulf; to this aim, in August and November, 2005, the *Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali (DIIAA), Università di Palermo,* carried out two survey campaigns, each two days long, in which the most important seawater quality features were investigated.

The survey campaigns

In order to study the quality of seawater in the Gulf, the survey campaigns were planned after preliminary considerations, such as the recognition of the most critical zones in the urban coast, arising from both direct inspections and a historical analysis of the sewerage system of the city.

The cruises were based on 25 measuring stations making up an array distributed in the stretch of water in front of the city (about 1 km^2 wide).

One of them was positioned far away from the coast with its sources of pollution, in order to obtain a *blank* sample to which it was possible to relate all measures.

[1] Mirella Di Giovanni, Ms, B.Sc., Research fellow, Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali (DIIAA), Università di Palermo, Viale delle Scienze, Ed. 8, 90128 Palermo, Italia – mirydigiovanni@hotmail.com – www.idra.unipa.it

[2] Salvatore Nicosia, Mr, Prof. Eng., Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali (DIIAA), Università di Palermo – nicosia@idra.unipa.it – www.idra.unipa.it

[3] Enrico Napoli, Mr, Prof. Eng., Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali (DIIAA), Università di Palermo – enrico@idra.unipa.it - www.idra.unipa.it

[4] Gaspare Viviani, Mr, Prof. Eng., Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali (DIIAA), Università di Palermo – gviv@idra.unipa.it - www.idra.unipa.it

[5] Giuseppe Ciraolo, Mr, Dr. Eng., Dipartimento di Ingegneria Idraulica ed Applicazioni Ambientali (DIIAA), Università di Palermo – www.idra.unipa.it

Figure 1 shows the distribution of the measuring stations.

Figure 1: the distribution of the measuring stations (Porta Felice outfall is circled in yellow).

The figure 1 shows the sea area of the surveys, distinguishing between stations in which only chemical-physical parameters were investigated *in situ* (marked with "M", *Misura* - Measure), and other stations in which, furthermore, was also taken a sample for laboratory analysis (points marked with "CM", where C stands for *Campionamento* - Sampling).

A multi-parametric probe was used to measure temperature, dissolved oxygen (DO), conductivity, salinity, turbidity, redox potential both at surface (50 cm below mean sea level) and at 2 meters depth.

In 14 stations out of 25 a water sample was also taken for each depth intended for laboratory analyses, regarding both the most important faecal bacteria (like total coliforms, faecal coliforms, *Escherichia coli*) and the nutrients (phosphorus and nitrogen).

The figure 2 below summarizes the parameters investigated, making a distinction between "M" and "CM" stations, as just defined.

Obviously, there was the necessity to organize the great amount of information given by the monitoring campaigns, and also to represent the collected data in a readily comprehensible way. To this aim the software Surfer® [1] was applied and then it was possible to generate a set of maps representing the distribution of each parameter at each depth, in the stretch of water investigated during each cruise.

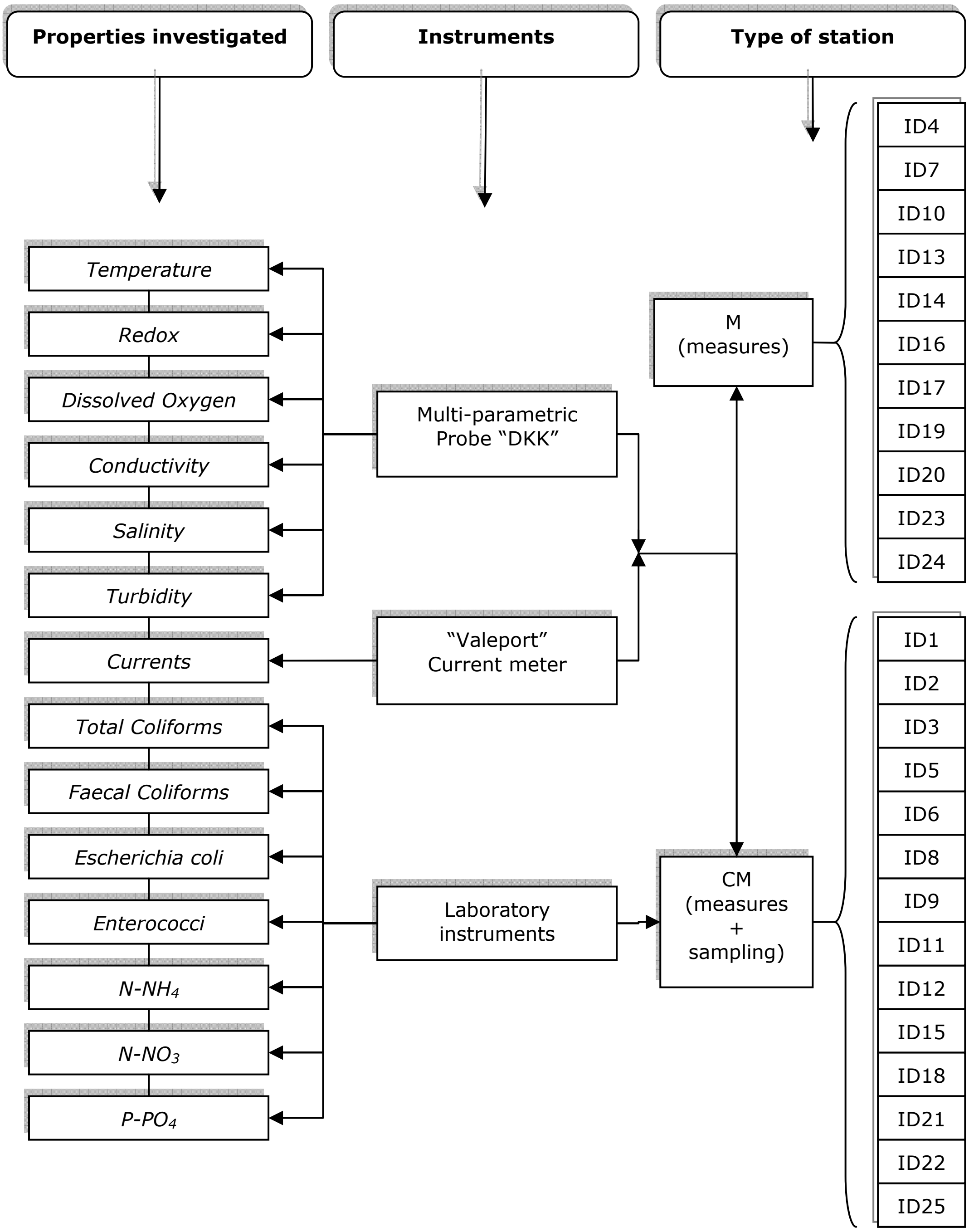


Figure 2: Field campaign flow chart

As an example, the following pictures show the map obtained plotting biological and physical data collected in the autumn survey, such as Faecal Coliforms (figure 3) and Salinity (figure 4).
From the great amount of information given by the monitoring campaigns, the Authors decided to focus their attention herein on the autumnal session and to analyze the dispersion of pollutants only in the sheet of water nearby the "Porta Felice" sewer discharge.

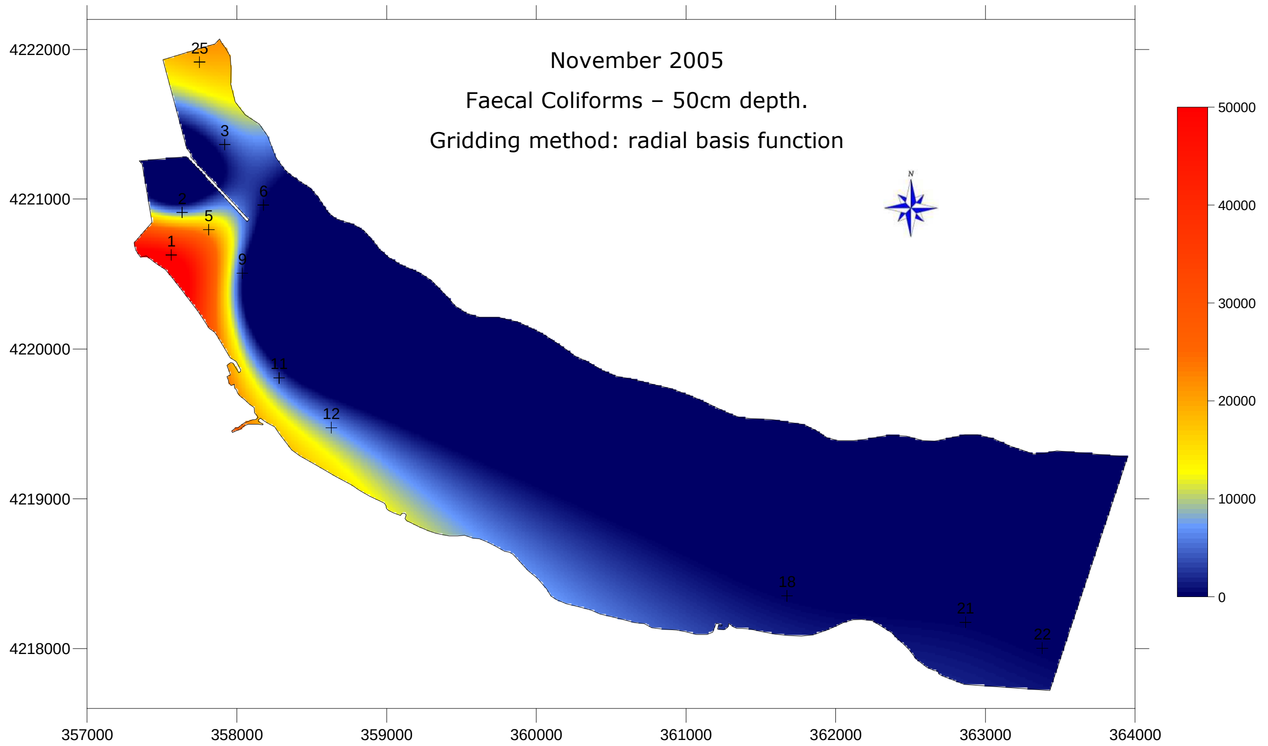


Figure 3: the distribution of Faecal Coliforms in the sheet of water investigated.

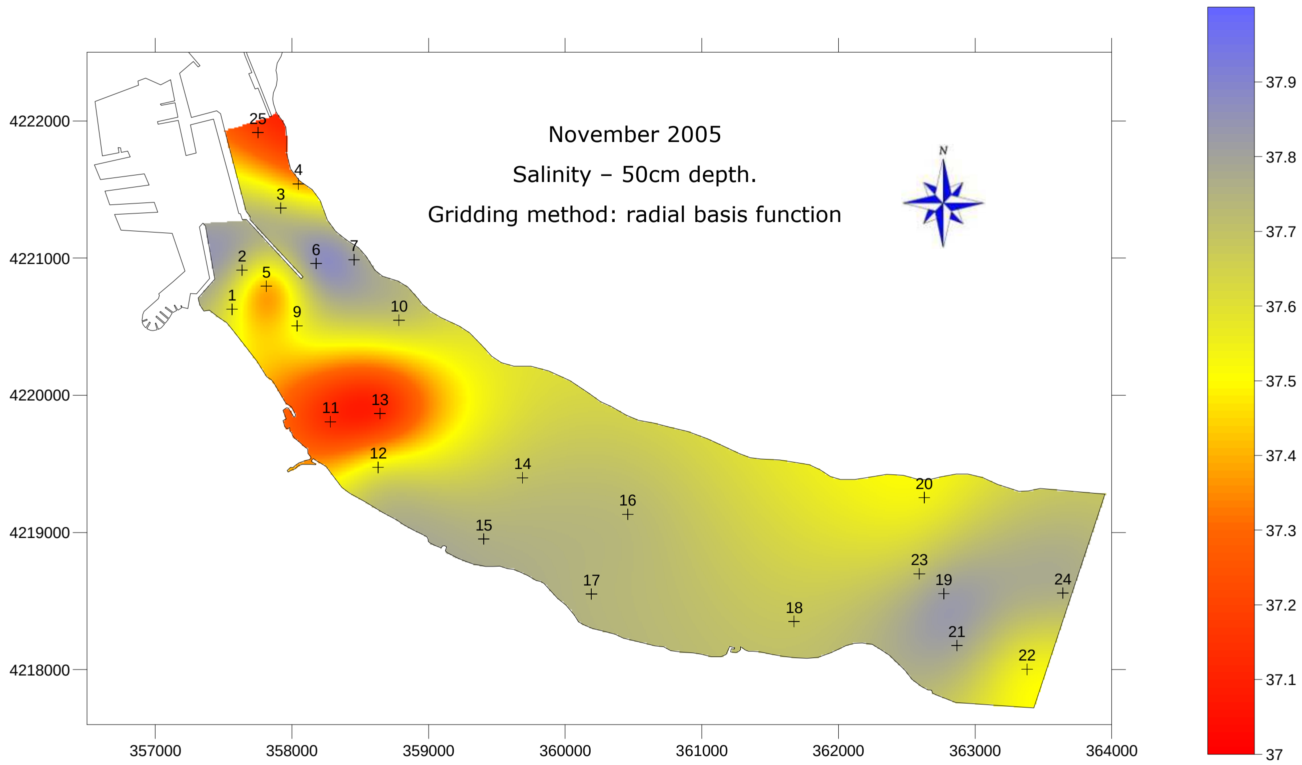


Figure 4: the distribution of Salinity in the sheet of water investigated.

The behaviour of wastewaters discharged into sea

It is well known that the wastewater discharged into the sea at its issue can hydraulically behave like a "plume" or a "jet" with different implications on the mixing process contributing to pollutants dispersion.

Briefly, by definition [2] a *simple jet* moves into the marine environment thanks to the initial value of its momentum at the outfall only. A *simple plume*, instead, has no initial momentum, but moves into the sea due to its tendency to buoyancy (caused by a density difference between the water discharged and the surrounding water).

In an unrestricted environment at a certain distance from the outfall a jet eventually turns into a plume; the place where it happens depends on some features characterizing the discharge.

Mixing processes take place in two different zones. Near the outfall, the behaviour of jets and plumes is controlled only by the initial conditions such as velocity and geometric features; farther away, environmental parameters such as currents prevail and eventually predominate.

Let the physical quantities playing a role in jet dynamics be the following five:

- A, the cross-sectional area of the jet;
- u, the time-averaged jet velocity in the axial direction;
- ρ, the density of the fluid discharged;
- q, volume per unit time or *volume flux* of the jet;
- m, the specific momentum flux.

A sixth quantity is purposely defined at this stage:

- β, the specific buoyancy flux.

It is well established then that the factors of major importance are linked together by the following relationships:

A) for the mass flux of the jet, which is the mass of fluid passing a jet cross section per unit time:

$$\rho q = \int_A \rho u \cdot dA \qquad [M \cdot T^{-1}] \qquad (1)$$

B) for the momentum flux, which is the amount of momentum passing a jet cross section per unit time:

$$\rho m = \int_A \rho u^2 \cdot dA \qquad [M \cdot L \cdot T^{-2}] \qquad (2)$$

C) for the buoyancy flux, that is the buoyant or submerged weight of the fluid passing through a cross section per unit time:

$$\rho\beta = \int_A g \cdot \Delta\rho \cdot u \cdot dA \qquad [M \cdot L \cdot T^{-3}] \qquad (3)$$

It has been demonstrated [2, 3] that the initial values of:

- specific mass flux, called also "volume flux" q ("Q", $[L^3T^{-1}]$);
- specific momentum flux, m ("M", $[L^4T^{-2}]$); and
- specific buoyancy flux, β ("B", $[L^4T^{-3}]$)

completely govern the dilution of round turbulent buoyant jets.

These are therefore called the *primary variables;* please note that they are written in capital letters.

A name like *issue* or *source variable* would probably have been not less appropriate than that; however in this paper the customary name will be maintained.

It is possible to deduce almost all of the properties of turbulent jets that are of importance to engineers by simple dimensional arguments involving the just defined variables, combined with empirical data.

A simple jet is perfectly characterized by the so-called *characteristic length scale* defined as

$$l_Q = \frac{Q}{\sqrt{M}} \qquad \frac{\left[L^3 \cdot T^{-1}\right]}{\left[L^4 \cdot T^{-2}\right]^{1/2}} = [L] \qquad (4)$$

The characteristic length scale appears - or can be put in evidence - in most of the relevant hydrodynamical parameters. As an example, it can be noticed that a physical quantity of universal interest like the jet mean axial velocity, u_m [2, *cit.*] depends on Q, M, and the ratio of the distance from the outfall (z) to the characteristic length scale (Eq. 5).

$$u_m \cdot \frac{Q}{M} = f\left(\frac{z}{l_Q}\right) \quad [L] \qquad (5)$$

This implicit relation can be drawn from dimensional analysis. In fact, regarding as relevant the 4 variables:

- axis velocity u_m;
- volume flux Q;
- specific momentum flux M;
- length scale l_Q,

it is possible to combine them in order to obtain 3 dimensionless groups, namely:

$$\Pi_1 = \frac{l_Q^{\;2}}{Q} \cdot u_m ; \quad \Pi_2 = \frac{l_Q^{\;2}}{Q^2} \cdot M ; \quad \text{and} \quad \Pi_3 = \frac{z}{l_Q}. \qquad (6)$$

These dimensionless groups can be then joined together to finally obtain just the equation 5 above.
The same procedure could be applied with the aim to find a relation for the volume flux at any distance along the trajectory or the mean concentration of a substance of interest *(tracer).*
Coming to the case of a simple plume, the procedure just explained can equally be applied, provided that the typical length scale is re-defined herein as:

$$l_M = \frac{M^{3/4}}{\sqrt{B}} \qquad (7)$$

Using this definition, the jet mean axial velocity cannot but depend on specific buoyancy flux, as well as on the distance from outfall and the viscosity.

$$u_m \cdot \sqrt[3]{\frac{z}{B}} = f\left(\frac{\sqrt[3]{z^2 \cdot B}}{\upsilon}\right) \qquad (8)$$

The results of the preceding demonstrations are summarized in the following table 1.

Parameter	m. u.	Analytical solutions for simple jets	Analytical solutions for simple plumes
u_m	$\left[L \cdot T^{-1}\right]$	$u_m \cdot \frac{Q}{M} = 7 \cdot \frac{l_Q}{z}$	$w_m = 4{,}7 \cdot \sqrt[3]{\frac{B}{z}}$
C_m	$\left[M \cdot L^{-3}\right]$	$\frac{C_m}{C_0} = 5{,}64 \cdot \frac{l_Q}{z}$	$\frac{C_m}{Y} = \frac{9{,}1}{B^{1/3} \cdot z^{5/3}}$
q	$\left[L^3 \cdot T^{-1}\right]$	$\frac{q}{Q} = 0{,}25 \cdot \frac{z}{l_Q}$	$q = 0{,}15 \cdot B^{1/3} \cdot z^{5/3}$

Table 1: analytical solutions for simple jets and plumes

In order to simulate the sewage dilution in seawater, it is therefore possible to calibrate and apply an analytical model based

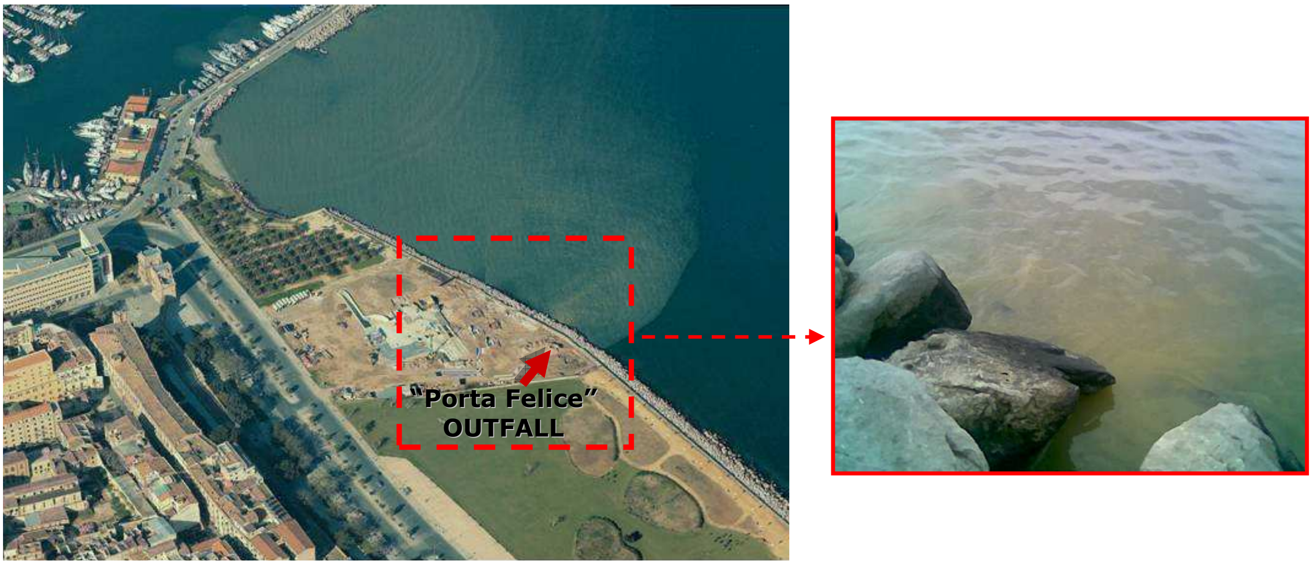
a) on dimensional analysis and on the definition of the discharge behaviour and local environment parameters, and
b) on the discharge geometrical factors.

This is the classical theory of diffusion of jets and plumes in the receiving water body.
It must be added that the relationships applied herein are the ones demonstrated for round jets.

Outfall configuration and discharge data

With the aim of predicting the dilution of the wastewater discharged into the seawater, the Authors decided to apply the classical theory of jets and plumes at the free-surface outfall called "Porta Felice" (see figure 1 above).

This outfall, as shown in figure 5 (a) and (b), discharges on-shore the wastewater originating from 200 000 inhabitants. The area is relevant for touristic and residential activities and it is located at the mouth of the most important commercial harbour of Western Sicily. Such conditions increase the importance of this study in view of the expected benefits of the pollution mitigation measures planned by the Municipality.



(a) (b)

Figure 5: aerial view of the study area with the indication of the outfall (a) and details nearby the outfall (b)

First of all, the outfall was characterized by drawing the geometric information needed. It has square cross-section 2,20 meters wide and the bottom elevation is 1.80 m below m.s.l. (figure 6).

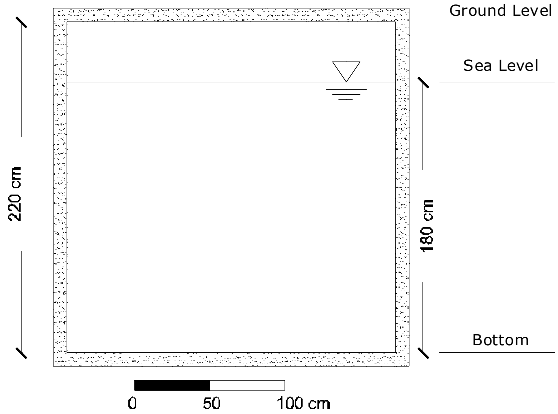


Figure 6: outfall geometric features

Since the outfall this paper is dealing with has a shape other than circular, the Authors needed to fit classical relations to the specific case resorting to the so-called "equivalent diameter *ED*" defined as

$$ED = 4 \cdot HR \quad (9)$$

where *HR* is the hydraulic radius of the square cross-section.

Unfortunately no flow gauge was available on the site, thus average sewage rate of flow was deduced from served people (200 000 inhabitants) and pro-capita drinking water volumes supplied (about 400 litres/(capita*day)), resulting in 1,55 m^3/s of wastewater discharged in the sea by the outfall.

The prediction of wastewater dilution into marine environment

The application of the classical theory of diffusion of jets and plumes requires, first of all, the calculation of the above mentioned "primary variables" (i.e. the initial values of volume flux, specific momentum flux and specific buoyancy flux), using the above recalled relations (eq. 1 to 3).

The values of these primary variables allow to state whether the fluid discharged behaves initially like a plume or a jet. In this case study, the initial value of momentum was very low, so it was possible to define the discharge as a simple plume.

Once defined the behaviour of the fluid discharged into the sea, under the assumption of Gaussian distribution of concentration across the plume axis, it was possible to calculate the value of the most important variables characterizing the plume, such as velocity, buoyancy and concentration of a tracer released within wastewater, aiming at predicting the dilution.

The Authors selected the variable "salinity" as indicator for calculation, firstly because it is a conservative tracer. Furthermore, this tracer has an immediately comprehensible physical meaning: a drop in its value in the analysed area cannot be but due to the discharge of fresh water into the marine environment, and – ultimately - to the wastewater outfall.

The Authors chose to estimate the dilution of the salinity nearby the "Porta Felice" outfall, in which some measuring stations were positioned, as the weighted average between the wastewater and the seawater entrained during the rise of the plume.

First of all, it was necessary to calculate the most important variables governing the plume motion into the surrounding environment, as explained previously. To calculate the value of those variables in points at any given distance *x* from plume axis *z* (see Figure 8), it is common to resort to the assumption of Gaussian distribution of tracer concentration across it:

$$C = C_m \cdot e^{-(x/b_T)^2} \qquad (10)$$

For a plume issuing from bottom ports, the seawater entrained during the rise is the areal integral of velocity over the cross section, as explained by Eq.1 above.

The plume we are dealing with, instead, originates from a surface port; reminding the features of the discharge, the general formulation is modified according to the following one:

$$q = H \cdot u_m \cdot \int_{-x_n}^{x_n} e^{-(x/b_u)^2} dx \qquad (11)$$

where:

the cross section *A* was substituted by the distance, *x,* and the depth of the sea body, *H;*

b_u is the spreading coefficient, typical of the Gaussian concentration distribution.

Empirical studies [2] suggest to use the relation

$$\frac{b_u}{z} \approx 0{,}107 \qquad (12)$$

The solution of the previous integral leads to the following equation:

$$q(z,x) = H(z,x) \cdot u_m(z) \cdot b_u(z) \cdot \sqrt{\pi} \cdot erf\left(\frac{x}{b_u(z)}\right) \qquad (13)$$

where the "error function" is involved.

After this passages, salinity can be calculated at each measure station as the weighted average between the wastewater and the seawater entrained during the rise of the plume:

$$S_{calc}(z,x) = S_{sea} \cdot \frac{q(z,x)}{q(z,x)+Q} \qquad (14)$$

The following scheme summarizes the method just explained (Figure 7).

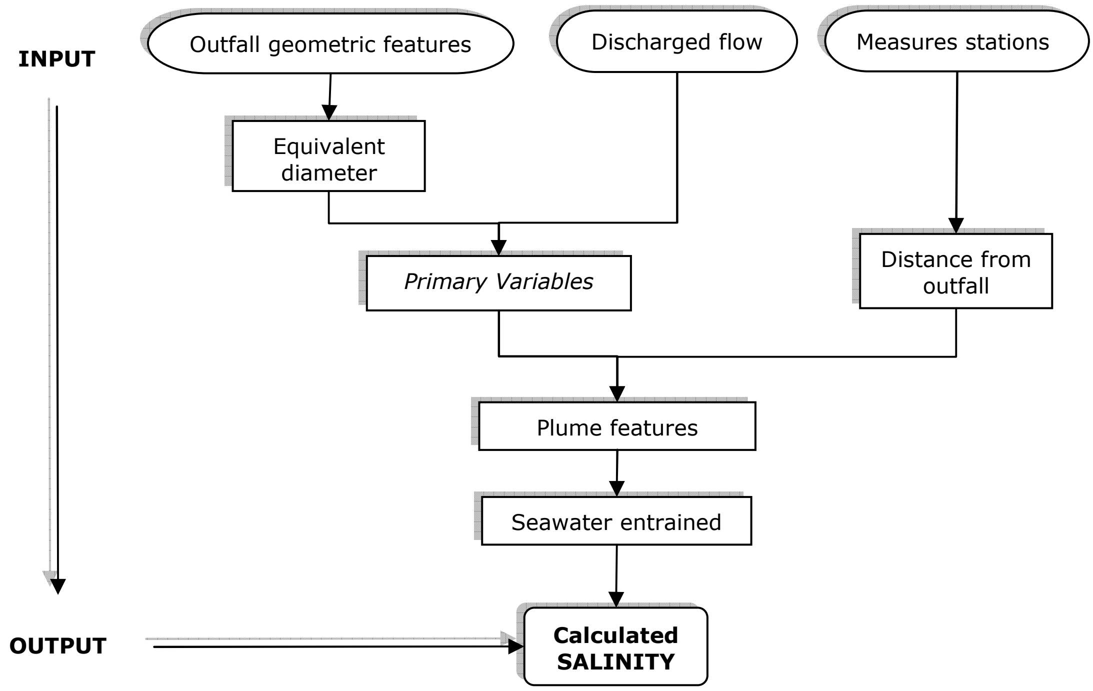


Figure 7: the procedure for calculating the value of salinity of the wastewater field in the marine environment

The following table 2 shows the results and it permits to make a comparison between measured and calculated values for the salinity in each measuring station involved in the study. The near figure 8 shows the planar distribution of the measuring stations in the stretch of water in front of "Porta Felice" outfall.

ID Nr	Measured values	Calculated values
1	37,57	37,53
2	37,66	37,71
5	37,41	37,72
9	37,53	37,72

Table 2: comparison between measured and calculated values of salinity

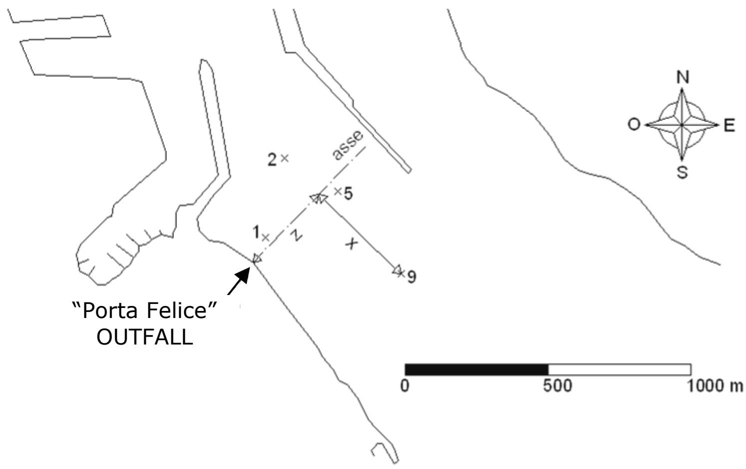


Figure 8: a planar view of the measuring stations which this study is based on

The previous Figure 4 illustrates the distribution of the salinity in the entire stretch of water investigated. Since the presence of the outfall manifestly does not involve the whole region, it appeared reasonable to focus the attention only on the seaboard next to the discharge. Moreover, in order to better check measured against estimated values, the Authors created a new map showing the distribution of the reckoned values of salinity. The maps were realized with the software Surfer®, using the same colour scale for each one (Figure 9). The large red areas visible to North and South – West from the outfall are respectively connected to the discharges inside the commercial harbour and to the estuary of Oreto river.

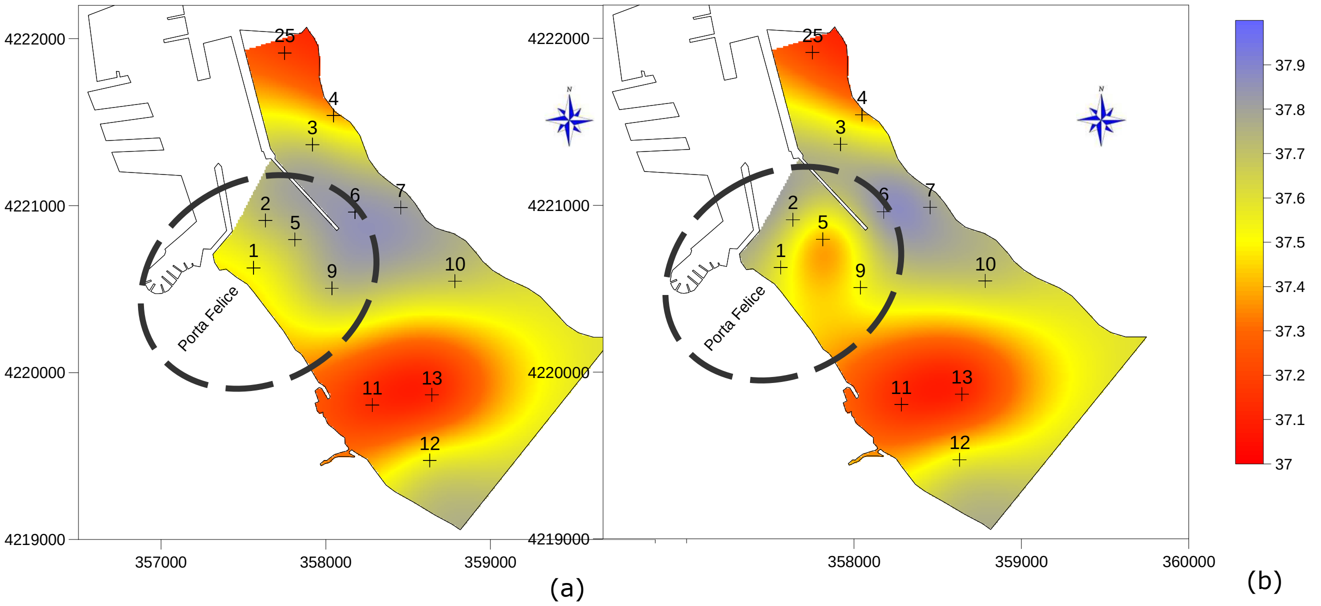


Figure 9: the maps showing the distribution of salinity in situ values (b) and calculated ones (a).

Some comments on the results

The previous maps allow to notice some differences between in situ values and calculated ones, just as the figures in table 2.

Looking at the measure station nearest to the outfall, called "ID1", a lower value of salinity was expected than one given by the model. Actually, measures have been taken at a smaller depth than in other measuring stations: in this case, the model provides an underestimated value of clean seawater entrained by the plume, and that turns into an expected value of dilution lower than the real.

The other way, the value measured in the point "ID2" was lower than the estimated one, because of the impossibility, in this simple model, to consider the presence of other contiguous sources of contamination, such as the near city harbour and the touristic harbour called "Cala". At the time of the survey, in fact, both the commercial and the touristic harbours were still final receptor for wastewaters.

The application of the classical theory of diffusion overestimated salinity at points "ID5" and "ID9", due both to their greater distance from the outfall and to the increased depth of seawater. Actually, low values of salinity were observed even at distance from the coast, indicating that the outfall influence area extends as far as 350 meters away from seaboard and even farther.

Apparently the measures were also affected by the marine currents, which the calculations cannot allow for.

Surface water circulation is represented in the following Figure 10; this map shows the strength and direction of currents measured with a Valeport current-meter.

Figure 10: a map showing the strength and direction of currents

It can be noticed that the direction of currents into the zone seems to create a sort of "short circuit": as a result, seawater moves in a clockwise direction. Values taken at the ID2 measure station seem to suggest that the current drives away the water coming from "la Cala" basin in S-E direction; furthermore, the influence of that basin on ID5 is emphasized by the currents measured in that station.

Concluding remarks

The study object of the present paper aimed at the prevision of the dilution of wastewater discharged on-shore into the sea trough the free-surface "Porta Felice" outfall, determining the value of salinity, chosen as indicator for reckoning, and then making a comparison between reckoned values and experimental data gathered with a survey campaign.

The previous paragraph already pointed out and explained the small differences between the salinity measured *in situ* and the calculated one.

The simple model applied herein foretold a plume considerable dilution effect not farther than the nearest 200 meters from the coast; instead, low values of salinity were actually observed with the instruments even at greater distance from the coast, indicating a weak influence area of the outfall extending itself as far as 350 meters away from seaboard.

Current maps showed how the differences between predicted dilution and experimental data are to be ascribed to the presence of other sources of contamination, such as the commercial and the touristic harbours of the city, in which nowadays some sewer discharges wastewater (see Figures 1 and 5a).

Due to its simple structure, the analytical model cannot deal with the presence of overlapping sources of contamination; on the other hand, a merit of the model stays in requiring a slight computational effort for the characterization of the stretch of water analyzed, even if it was necessary to complete mathematical considerations with empirical ones, such as superficial water circulation and direct inspections.

Acknowledgements
The Municipality *(Comune di Palermo, Ufficio per il Centro Storico)* encouraged planning of this research and provided financial support for its development. Its contribution is gratefully acknowledged.

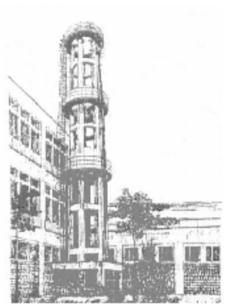
Mirella Di Giovanni was born in Palermo on 30th July, 1983. She initiated Engineering studies in 2002. She graduated "magna cum laude" in Environmental Engineering in 2006 at the University of Palermo (Italy). Her 3-years Degree dissertation regarded the analysis of the quality status of Palermo Gulf by measures both of currents and chemical-physical parameters. She is currently specializing in Environmental Engineering and the final 5-years dissertation is planned for November, 2008 with a thesis dealing with the environmental impact of a submerged wastewater treatment plant discharge.

Salvatore Nicosia was born in 1948; got a five-year Degree in Chemical Engineering with honours, Università di Palermo; now Associate Professor in Sanitary and Environmental Engineering and Scientific Director of the Laboratory of Sanitary Engineering within DIIAA. Key Qualifications: Analytical Control of Processes; Treatment of wastes from agricultural industry; WTE Systems; EI and LC Assessments.

Enrico Napoli was born in 1969; got his degree in Civil (Hydraulic) Engineering in 1993 and the PhD in Hydraulic Engineering in 1998. Currently Associate Professor in Hydraulics. Director of the Doctoral School of Hydraulic and Environmental Engineering at the University of Palermo. His research activity, partly joined with the research group leaded by Prof. J. Jozsa at the Budapest University of Technology and Economy, is mainly devoted to the numerical analysis of turbulent processes in natural waters. An apparatus for experimental studies on wind shear on shallow waters has also been set up.

Gaspare Viviani, born in 1953, is a Civil (Hydraulic) Engineer and a Full Professor in Hydraulic Infrastructures. His research work encompasses contaminated soils; diffusion in water and in atmosphere; non-point pollution in drainage systems; membrane treatment of wastewater. Participates in an international research group with the Governmental Agencies and the University of the Republic of Malta.

Giuseppe Ciraolo was born in 1969; is holder of a five-year Degree in Civil (Hydraulic) Engineering with honours, Università di Palermo, and a PhD. His research topics are: Remote Sensing; Hydrology; and shallow waters dynamics, with special regard to the interactions between breakwaves and submerged vegetation.



UNIVERSITA' DI PALERMO

DIPARTIMENTO DI
INGEGNERIA IDRAULICA ED
APPLICAZIONI AMBIENTALI

VIALE DELLE SCIENZE, ED. 8
I-90128 PALERMO, ITALIA

References

[1] Surfer® version 8.0, Copyright © 2002 Golden Software Inc., www.goldensoftware.com
[2] H.B. Fisher, E.J. List, R.C.Y. Koh, J. Imberger, N.H. Brooks: "Mixing in inland and coastal waters", Academic Press, New York, 1979.
[3] G. Abraham: "Jet diffusion in stagnant ambient fluid", Delft Hydraulics Laboratory, publication n°29, july 1963.