# PERFORMANCE OF AN INTEGRAL TYPE MODEL APPLIED TO OCEAN OUTFALLS

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ABSTRACT
Using numerical models for simulation of plume behavior and optimization of outfall characteristic results in saving in time and expenses compared to using laboratory studies. In this study, four ocean outfalls (Gosport and Bridport in the United Kingdom; Charlestown, Rhode Island New York in the U.S.A and Broward outfall in Florida) were numerically simulated. The minimum dilutions obtained from laboratory and field observations were compared with those of an integral type model called VISJET. In general, the results predicted by VISJET were relatively in good agreement with the obtained data. Furthermore, a non-dimensional parameter, $R_V$ which is the ratio of ambient current velocity to the discharge velocity, was defined for classification the plume behavior and its dilution. In the weak ambient current regime where $R_V$ <1, the initial dilution increases slowly with increasing the $R_V$ while for strong ambient current regime where $R_V$ >1 the dilution increase more rapidly.

**KEYWORDS: multi port diffuser, near field dilution, numerical simulation, Visjet,**

## INTRODUCTION

Ocean outfalls are commonly used for the propose of rapidly reducing the magnitude of effluent concentrations in the coastal areas. Wastewater can be discharged through single port or multi port diffusers. Using submerged multi port diffusers is an efficient method to reduce the adverse impacts of ocean disposal and results in much higher initial dilution. The behavior of plume trajectory and its dilution are commonly studied with physical models or field observation, since the behavior of discharged flow in the ambient water is complex and exact simulation for optimization and prediction of plume dilution is difficult.

In the presence of computer technology, simulation of discharged flow and their corresponding parameter results in saving in time and expenses compared to using laboratory experiments. Three types of numerical models are presently available to simulate the prediction of discharged flow characteristics. Three dimensional finite element or finite difference models used the system of equations that require large computational time. This group of models uses complex equations, which govern the dynamics of discharged flow and need extensive calibration and verification. Therefore, a lot of time and effort are required to simulate a real case with this type of models.

Initial dilution obtained from laboratory experiments and field observations have been extensively verified and compared with the second type of numerical models, which is called length scale model (Tsanis & Valeo, 1994; Valeo & Tsanis, 1996 and Zaker et al., 2001). Length scale models use dimensionless parameters to classify the flow regime and predict the initial dilution. Consequently, in some cases the results of length scale models over/under shoots the measured dilution. The last group of models is called integral type model. Integral type models are based on ordinary differential equations. VISJET is one of the integral type models and was developed by Lee et al. (2000).The propose of this study was to evaluate the performance of VISJET model in simulating field observation and laboratory experiment.

## THEORY AND BACKGROUND

Wastewater discharged in the ambient water is characterized by three classes of parameters: nature of the outfall, discharged flow characteristics and environmental factors (Fischer et al., 1979). Plume behavior and dilution are characterized by kinematics mass, momentum and buoyancy fluxes, respectively.

$$Q = u_\circ p D^2 /4 \tag{1}$$

$$M = Q.u_\circ \tag{2}$$

$$B = Q.g^{'} = Q.[(r_a - r_\circ)/r_a].g \tag{3}$$

Where *d* is port diameter, $u_\circ, r_\circ$ are jet discharge velocity and density, respectively. $r_a$ Is the ambient density and *g* is gravitational acceleration (Fischer et al., 1979). Dimensional analysis of the above parameters, in unstratified condition flow, leads to two length scales definitions (Jirka and Doneker, 1991).

$$L_Q = \frac{Q_\circ}{M_\circ^{1/2}} \tag{4}$$

$$L_M = \frac{M_\circ^{3/4}}{B_\circ^{1/2}} \tag{5}$$

$L_Q$ is the discharge (geometric) length scale and $L_M$ is the jet/plume transition length scale. When Z is smaller than $L_Q$ the behavior of the plume is unpredictable. For $Z>L_Q$, jet geometry is not important and flow behavior is governed by

$M_{\circ}$ and $B_{\circ}$, while Z>$L_M$ the buoyancy becomes more effective and the plume is plume like. When Z<$L_M$ the initial jet momentum becomes more important than the initial buoyancy momentum and the flow is jet like.

In the presence of ambient current, a non-dimensional parameter is defined as the ratio of the ambient current velocity to the discharged velocity:

$$R_V = \frac{u_a.H}{u_{\circ}.D} \tag{6}$$

Where $u_a$ and H are the ambient current velocity and depth of discharge, respectively.

The integral type models consist of ordinary differential equations derived from the cross sectional integration of jet from properties such as mass, momentum and buoyancy fluxes. These models perform well for simple flows with no shoreline interaction or attachment. They are just able to simulate flow characteristics near the source (Lee and Chung 1990). The general simulation of a jet/plume in a weak cross flow, with the jet axis making an angle of with the cross flow was shown in Figure 1.

The ambient current in the plane of the jet cross section is then $u_a \sin\psi_K$. The general formulation can be expressed:

$$\Delta M = E_S \frac{(\pi - \varphi_K)}{\pi} + (E_P + E_C + E_W)\sin\varphi_K \tag{7}$$

Where $\varphi_K$ is a "separation angle", $\Delta M$ is the increase in mass of the plume element at each step. $E_S$ is the shear entrainment at each time step, can be expressed:

$$E_S = 2\pi\alpha_S b_k h_k \Delta U \Delta t \tag{8}$$

$$\alpha_S = \sqrt{2}(0.057 + 0.554\sin\phi_K / F_l^2)(\frac{2V_K}{\Delta U + V_K}) \tag{9}$$

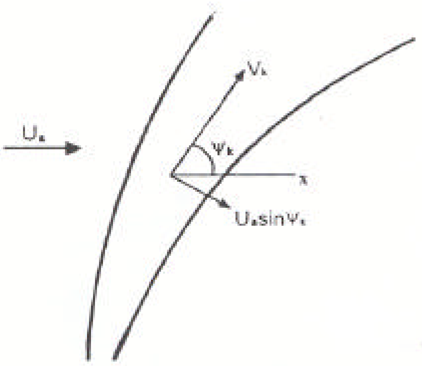


***Figure 1:*** *Schematic diagram of jet trajectory traced out by Lagrangian plume elements (after Lee and Chung 1990).*

Where $V_K$ is the jet velocity, $\Delta U = \left|V_K - u_a \cos\varphi_K \cos\theta_K\right|$ is the relative jet velocity in the direction of the jet axis, and $b_K, h_K$ are the radius and thickness of the plume element. $\alpha_S$ and $F_l$ are the entrainment coefficient and local jet densimetric Froude number, respectively. $E_P$ is the cylinder term, $E_W$ is a correction term due to the increase in plume width and $E_C$ is a correction term due to plume curvature (Lee and Chung, 1990).VISJET is one of the integral type model developed for analysis and prediction of dilution and its corresponding parameters into stagnant or not stagnant water. In addition, this model is windows-based flow visualization developed by Lee et al. (2000). VISJET adopts top-hat concentration profiles, for comparison with centerline concentration obtained from field measurement data, the dilution results are adjusted by factor of 1.7 (Lee and Chung, 1990).

## PHYSICAL MODEL AND FIELD CHARACTERISTICS

Three ocean outfall measurements and a physical model study were selected to evaluate the performance of VISJET in presence of ambient current. Gosport, Brid port Outfalls in the United Kingdom (Lee and Neville Jones, 1987) and Broward outfall in State of Florida (Proni et al., 1994) are single port outfalls. The New England Power Company's number 1 nuclear generation station proposed for Charlestown, Rhode Island (Valeo and Tsanis, 1996) has submerged multi port diffuser and was modeled with a physical model.

Wastewater samples in Gosport outfall were measured between 15.2m to 15.9m depth, diameter of each port is 0.91 m and the ambient current velocity is between 0.11 to 0.81 $ms^{-1}$. Also the angle between a port and seabed is20.

Depths of measurement in the Bridport outfall were between 6.1 to 8.2m and wastewater is horizontally discharged. Diameter of a port is 0.38m and the ambient current velocity varies between 0.1 to 0.29 $ms^{-1}$ (Lee and Neville Jones, 1987).

Broward outfall measurement is a part of Southeast Florida Outfalls Experiment II (SEFLOE II). Domestic sewage whose density is approximately0.998 $gcm^{-3}$ is discharged after secondary treatment in to ambient water. Wastewater is discharged through a single port, extending approximately 2130m offshore in a diameter of 1.37m. The average effluent discharge rate is 1.90$m^3s^{-1}$ and the depth of discharge is 32.5m. Effluent is discharged horizontally and in some cases study stratification affected the plum behavior.

Thirty-six test cases were conducted in the New England Power Company's hydrothermal study. From these cases, fifteen cases with ambient current were chosen to calculate the ratio of $R_V$ and simulate with VISJET. For simplifying the geometric condition, average depth of diffuser start and diffuser end point was used as the discharged depth. The total effluent discharge rate is 54 $m^3s^{-1}$. Diameter of a port is 0.626m and the angle between each port and seabed is20, except in test 6 and 8 where $q = 10^{\circ}$. Orientation angle of ports relative to diffuser line, is 20, except in test 8 where $b = 10^{\circ}$. Alignment angle of diffuser line relative to ambient flow is 90. Temperature difference between ambient and effluent is 20.56 C (Valeo and Tsanis, 1996).

## RESULTS AND DISCUSSION

Dilution obtained from field measurements, physical model study and VISJET results are listed in Tables 1 to 4.

**Table 1: Field observations and predicted dilutions obtained by VISJET for Gosport outfall (Lee and Neville Jones, 1987).**

| Test Number | Volume Flux ($m^3s^{-1}$) | Depth of Discharge (m) | Current Velocity ($ms^{-1}$) | $L_M$ (m) | $R_V$ | Measured Dilution ($S_M$) | VISJET Predict Dilution ($S_V$) | ($S_V/S_M$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.273 | 15.92 | 0.3 | 0.771 | 12.49 | 71 | 76.1 | 1.07 |
| 2 | 0.299 | 15.47 | 0.69 | 0.844 | 25.5 | 153 | 196.4 | 1.28 |
| 3 | 0.266 | 15.47 | 0.83 | 0.751 | 34.41 | 183 | 270.1 | 1.476 |
| 4 | 0.292 | 15.29 | 0.77 | 0.824 | 28.75 | 141 | 222.3 | 1.576 |
| 5 | 0.266 | 15.29 | 0.67 | 0.751 | 27.46 | 109 | 207.6 | 1.9 |
| 6 | 0.28 | 15.38 | 0.75 | 0.791 | 29.48 | 181 | 227.2 | 1.255 |
| 7 | 0.273 | 15.2 | 0.34 | 0.771 | 13.52 | 30 | 83.9 | 2.8 |
| 8 | 0.273 | 15.47 | 0.11 | 0.771 | 4.45 | 14 | 18.4 | 1.31 |

**Table 2: Field observations and predicted dilutions obtained from VISJET for Bridport outfall (Lee and Neville Jones, 1987).**

| Test Number | Volume Flux ($m^3s^{-1}$) | Depth of Discharge, $H$ (m) | Current Velocity ($ms^{-1}$) | $L_M$ (m) | $R_V$ | Measured Dilution ($S_M$) | VISJET Predicted Dilution ($S_V$) | ($S_V/S_M$) |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.0408 | 7.6 | 0.11 | 0.427 | 6.11 | 41 | 27.3 | 0.666 |
| 2 | 0.0408 | 7.6 | 0.23 | 0.427 | 12.77 | 180 | 96.3 | 0.535 |
| 3 | 0.045 | 6.46 | 0.25 | 0.471 | 10.62 | 225 | 72 | 0.32 |
| 4 | 0.042 | 6.08 | 0.23 | 0.439 | 9.94 | 82 | 60.6 | 0.74 |
| 5 | 0.042 | 6.34 | 0.29 | 0.439 | 13.07 | 212 | 91.2 | 0.43 |
| 6 | 0.044 | 7.79 | 0.26 | 0.46 | 13.66 | 163 | 111.4 | 0.683 |
| 7 | 0.044 | 7.6 | 0.18 | 0.46 | 9.23 | 8.7 | 60.6 | 0.696 |
| 8 | 0.051 | 8.17 | 0.26 | 0.534 | 12.42 | 129 | 105.3 | 0.816 |
| 9 | 0.051 | 7.6 | 0.24 | 0.534 | 10.66 | 101 | 82.1 | 0.813 |

**Table 3: Field observations and predicted dilutions obtained by VISJET for Broward outfall (Proni et al., 1994).**

| Test Number | Volume Flux ($m^3s^{-1}$) | Current Velocity ($ms^{-1}$) | $L_M$ (m) | $R_V$ | Density at Bottom $gcm^{-3}$ | Density at Top $gcm^{-3}$ | Measured Dilution ($S_M$) | VISJET Predicted Dilution ($S_V$) | ($S_V/S_M$) |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 1.84 | 0.345 | 2.74 | 6.55 | 1.0243 | 1.0243 | 56.8 | 128.5 | 2.26 |
| 2 | 1.63 | 0.161 | 2.41 | 3.44 | 1.0248 | 1.0248 | 33 | 30.39 | 0.92 |
| 3 | 2.12 | 0.089 | 3.13 | 1.47 | 1.0248 | 1.0248 | 14.8 | 17.06 | 1.15 |
| 4 | 1.46 | 0.094 | 2.15 | 2.25 | 1.0251 | 1.0245 | 31 | 20.46 | 0.66 |
| 5 | 1.87 | 0.084 | 2.79 | 1.56 | 1.0245 | 1.0241 | 25 | 17.32 | 0.69 |
| 6 | 1.61 | 0.166 | 2.39 | 3.58 | 1.0249 | 1.024 | 22.5 | 36.92 | 1.64 |
| 7 | 2.06 | 0.255 | 3.03 | 4.32 | 1.025 | 1.025 | 84 | 59.08 | 0.7 |
| 8 | 1.83 | 0.255 | 2.69 | 4.86 | 1.025 | 1.025 | 67.8 | 67.89 | 1.01 |
| 9 | 2.05 | 0.145 | 3.01 | 2.47 | 1.025 | 1.025 | 32 | 22.37 | 0.73 |
| 10 | 1.52 | 0.114 | 2.24 | 2.61 | 1.025 | 1.025 | 58.9 | 22.39 | 0.38 |

**Table 4: Results of Physical model study and predicted dilutions obtained by VISJET for Charlestown, Rhode Island (Valeo and Tsanis, 1996).**

| Test Number | Volume Flux ($m^3s^{-1}$) | Depth of Discharge (m) $H$ | Current Velocity ($ms^{-1}$) | $L_M$ (m) | $R_V$ | Measured Dilution ($S_M$) | VISJET Predicted Dilution ($S_V$) | ($S_V/S_M$) |
|---|---|---|---|---|---|---|---|---|
| 2 | 1.6875 | 10.52 | 0.015 | 16.54 | 0.046 | 8.22 | 8.5 | 1.03 |
| 3 | 1.6875 | 9.9 | 0.274 | 16.54 | 0.79 | 12.1 | 11.25 | 0.93 |
| 6 | 1.6875 | 9.9 | 0.015 | 16.54 | 0.0433 | 8.94 | 10.83 | 1.21 |
| 8 | 1.6875 | 9.9 | 0.015 | 16.54 | 0.0433 | 8.94 | 10.83 | 1.21 |
| 9 | 1.6875 | 10.67 | 0.015 | 16.54 | 0.0467 | 9.8 | 8.62 | 0.88 |
| 10 | 1.6875 | 13.41 | 0.015 | 16.54 | 0.0587 | 10.28 | 10.39 | 1.01 |
| 12 | 0.931 | 14.33 | 0.015 | 9.12 | 0.114 | 12.1 | 10.27 | 0.85 |
| 15 | 1.6875 | 11.74 | 0.015 | 16.54 | 0.05 | 10.28 | 9.29 | 0.9 |
| 16 | 1.6875 | 9.6 | 0.015 | 16.54 | 0.042 | 7.91 | 7.94 | 1.00 |
| 17 | 1.6875 | 10.36 | 0.015 | 16.54 | 0.0453 | 10.28 | 8.43 | 0.82 |
| 19 | 0.931 | 11.13 | 0.015 | 9.12 | 0.088 | 10.82 | 8.23 | 0.76 |
| 21 | 0.931 | 11.58 | 0.015 | 9.12 | 0.092 | 10.54 | 8.59 | 0.81 |
| 23 | 1.588 | 9.6 | 0.015 | 15.58 | 0.0447 | 8.22 | 7.82 | 0.95 |
| 25 | 1.928 | 9.6 | 0.015 | 18.9 | 0.0352 | 6.9 | 8.09 | 1.17 |
| 31 | 1.588 | 9.6 | 0.305 | 15.56 | 0.908 | 10.88 | 11.89 | 1.09 |

As shown in above Tables, comparison of the field observations, physical model study and simulation with VISJET model shows that the dilution predicted by VISJET is relatively in good agreement with laboratory and field data. Average prediction, standard deviation and maximum error of predicted dilutions are listed in Table 5.

**Table 5: Average predicts dilution error, standard deviation and maximum error of VISJET model**

| Case study | Average predict dilution (%) error | Standard deviation (%) | Maximum error (%) |
|---|---|---|---|
| Gosport | +52 | 54.8 | +79.6 |
| BridPort | -36.6 | 17 | -68 |
| Broward | +1.4 | 55.6 | -62 |
| Charlestown | -2.6 | 14.5 | -31.4 |

Table 5 reveals that the predicted results for physical model study are better than those of field data. Also it is found that VISJET model is not able to predict plume dilution properly when the ratio of $R_V$ is high. In the strong ambient current (Gosport) the results of VISJET model are not as accurate as the weak ambient case. The ratio of $H/L_M$ implies that in the near jet regime, VISJET model performs better than in the plume regime. In addition, Table 5shows that the maximum error is more than ±70%. The reasons for this unacceptable prediction are not entirely clear, but may be due to occasional errors in the dye fluorescence measurements and weather conditions (Lee and Neville Jones, 1987). In Figure 2, measured dilution and dilution obtained from physical model study are plotted in log-log scale and indicates a linear relationship. Also as shown in Figure 3, simulation with VISJET model gives practically the same correlation.

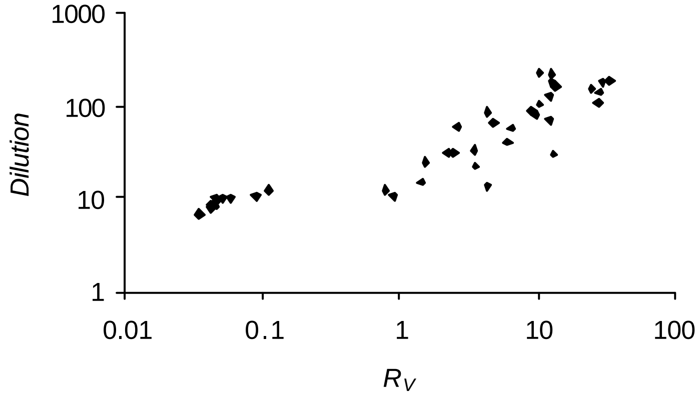


***Figure 2:*** *Measured initial dilution against $R_V$ which shows the two distinct regimes.*

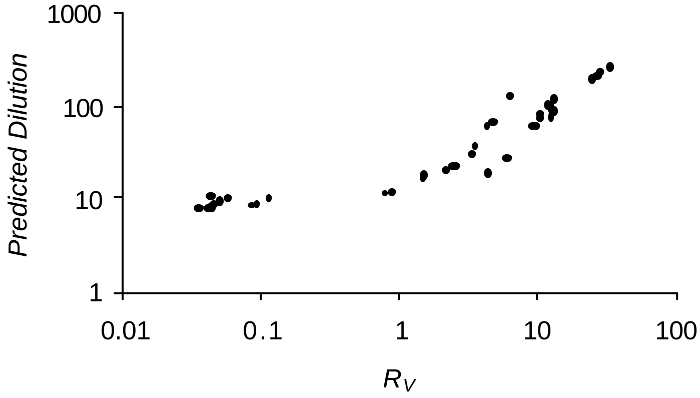


***Figure 3:*** *VISJET predict initial dilution against* $R_V$ *which shows the same correlation between dilution and* $R_V$.

Figure 2 and 3 show that, when $R_V$<1 measured and simulated dilution increase slowly with increasing the ratio of $R_V$. In this regime dilution increase with slop of 0.1 and 0.097 for laboratory observed and predicted dilutions, respectively. The regression coefficients are 0.65 and 0.728 for physical model study and simulated data. These regression coefficients imply that another relevant factor must be considered. The ratio of $H/L_M$ , is a suitable parameter since it controls when the flow behavior changes from jet to plume.

In the strong ambient current ($R_V$>1) dilution increases more rapidly with increasing $R_V$. In this regime dilution increases with slop of 0.542 and 0.587 for observed and predicted dilutions, respectively. The regression coefficients are 0.797 and 0.86 for field measured dilution and simulated data. Comparison of physical model, field measurement and model outputs were illustrated in Figure 4.

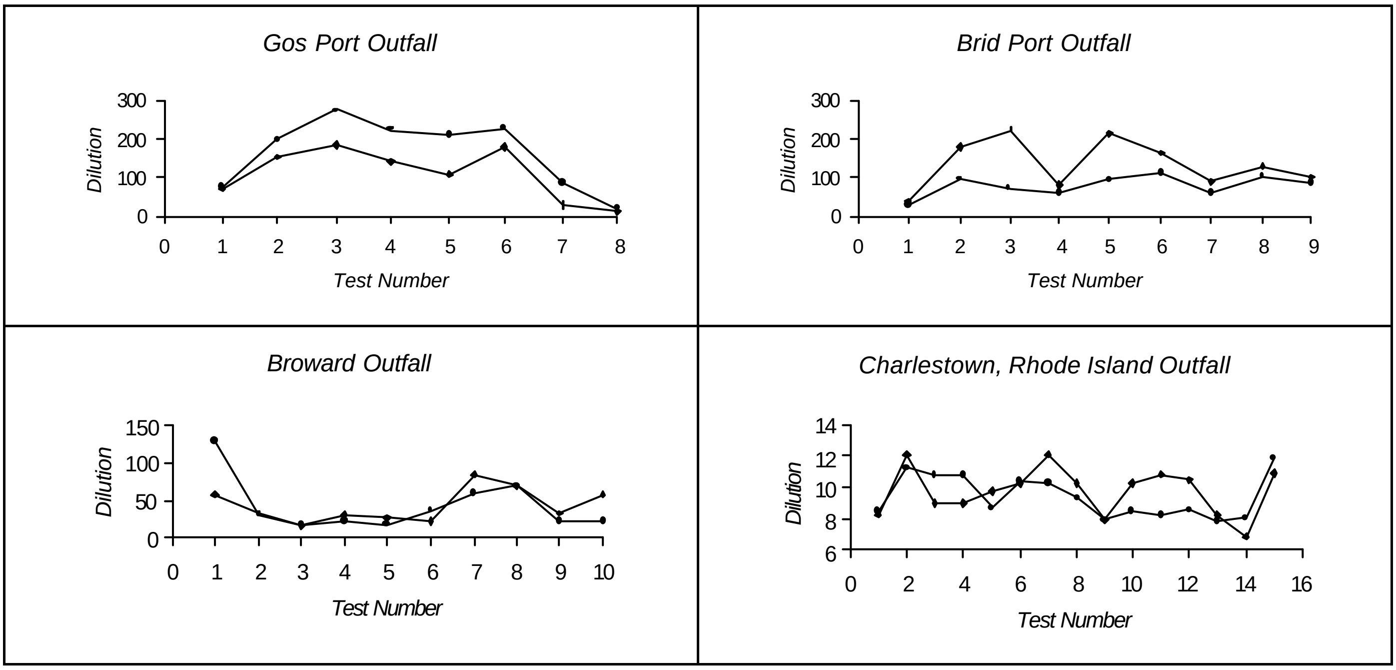
## SUMMARY AND CONCLUSIONS

Comparison of VISJET outputs versus field observation shows that in 74% of observed results the maximum error predicted by VISJET is less than ±50%. Considering to the ratio of $H/L_M$ implies that in the near jet regime VISJET model perform better than the plume regime. Comparison between the results of VISJET model and laboratory experiment indicates that in 80% of data the maximum error predicted by the model is less than ±20%. Hence, VISJET model is reliable in the weak ambient current condition ($R_V$<1 ) and it perform well when the hydrodynamic condition is near jet like. In the strong ambient current, the results of VISJET model are fairly in good agreement with the field measurements. The reason of a discrepancy between VISJET outputs and field measurements are not entirely clear, but may be due to occasional errors of sampling process and weather conditions. In conclusion, VISJET is a reliable model to simulate and predict dilution but, it has some limitation when used for the strong ambient current conditions that should be considered.

The following equation for the minimum initial dilution is obtained as a first estimate for initial dilution without simulation.

$$\log S_M = 0.1 \log R_V + 1.19 \qquad (R_V < 1) \tag{10}$$

$$\log S_M = 0.542 \log R_V + 1.27 \qquad (R_V > 1) \tag{11}$$


Gos Port Outfall

Brid Port Outfall

Broward Outfall

Charlestown, Rhode Island Outfall

***Figure 4:** Comparison of obtained dilution from laboratory and field measurement and predicted dilutions by VISJET; Diamonds ( ¨ ) are the experimental data, Circles ( ·) are the VISJET results.*

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