Modeling of the near-field distribution of pollutants from a coastal outfall subject to tidal currents

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Résumé:

On étudie la distribution des polluants émis par un émissaire marin soumis à de forts courants de marée. Le problème est résolu en utilisant un modèle k-ε. Les constantes utilisées dans la loi logarithmique pour le profil vertical de la vistesse dans la couche limite de fond (BBL) sont obtenues à partir de données expérimentales données par un profiler acoustique. La distribution spatiale et temporelle de la concentration des polluants dans le champ proche du diffuseur est obtenue en fonction de la vitesse du courant ambient et des caractéristiques de l'effluent industriel. On montre que même lorsque la densité de l'effluent est notablement plus faible que la densité du milieu récepteur, le panache de l'effluent est susceptible d'impacter le fond marin, créant ainsi un risque de pollution des sédiments de fond remobilisables.

Abstract :

Pollutant distribution from a coastal outfall is studied accounting for strong tidal currents. The problem is solved using k-ε model. The constants in the logarithmic law for vertical velocity profile in the BBL (bottom boundary layer) are obtained by processing experimental data from a current profiler. The near-field distribution of pollutant concentration at different distances from the diffuser are obtained for different times, in terms of ambient flow velocity and outfall discharge characteristics. It is shown that even in the case where the effluent density is substantially lower than the ambient sea density the plume can impact the sea bottom, creating a risk of pollution of removable bottom sediments.

Keywords : near-field distribution of pollutants, environmental risk analysis, tidal currents, bottom boundary layer

1 Introduction

Traditionally, the sea has been considered as the ultimate sink of most pollution, due to its huge volume and assimilating capacities, and the coastal waters, because of their intermediate position between deep seas and human activities, has been acting as a buffer zone. During the past years, the interest in environmental issues in general, and in the conservation of the water quality in coastal regions, in particular, has steadily increased. Here, we consider the nearfield dilution of an industrial effluent discharged by a large and deep water outfall. A typical, large discharge diffuser (for a flow of 5m3/s) may be a kilometer in length and located in 60m water depth at a distance of 5-10kms offshore. There might be several hundred discharge jets (typical diameter (4-10cm) spaced along the diffuser [1]. The present paper is aimed to understand the environmental risk of the discharged effluent to pollute the seafloor sediments, even in the case of a buoyant effluent (i.e., less dense than the receiving marine water). Indeed, these bottom sediments could accumulate the pollution during several months, and suddenly migrate in response to storm-driven currents for example. In addition, the movable bottom sediments can accumulate, due to alternate semi-diurnal tidal currents, below the diffuser and obstruct the interval between the pipe and the sea bottom.

Our study is mainly devoted to the distribution of pollutants in the bottom boundary layer (BBL) which may be defined as the layer adjacent to the seafloor in which the flow is affected by processes occurring at the boundary and in which strong gradients of physical, chemical, and biological properties may occur [2]. In thickness it extends to a height of a few metres above the seafloor. Numerous studies have been devoted to the BBL and sediment dynamics on the shoreface; e.g., see [3-7].

So the present work concerns the BBL dynamics in the nearfield of a multiport ocean outfall with submerged buoyant jets discharging in the vicinity of the water bottom into a flowing ambient subject to a strong semi-diurnal tidal effect (with a current speed up to 0.6m/s). It concerns the risk of pollution of sea bottom sediments by an industrial effluent emitted by an outfall, even in the case of buoyant effluent (i.e., effluent density < ambient sea density). So, special attention is devoted to the problem of interaction between the effluent plume and the sea bottom. The aim is to determine the conditions for a bottom attachment (Coanda attachment), in terms of ambient flow characteristics and discharge characteristics.

2 Presentation of the problem

2.1 Geometry and problem parameters

We consider a circular ocean multiport oufall with vertical discharge placed near the seafloor perpendicularly to the main direction of the ambient current as shown in Fig.1. The diffuser involves hundred discharge jets (with circular opening of diameter d=5cm) spaced every 5m along the pipe.

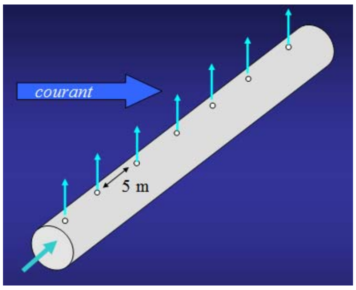


FIG. 1 – Schematic description of the multiport ocean outfall (the current direction being parallel to the mean shoreline and perpendicular to the diffuser; the discharge jets from circular ports are vertical)

We consider two main configurations, when the interval under the diffuser (which is surelevated from the seafloor of 0.5m) is empty or filled by removable bottom sediments. The first case corresponds to the “nominal” configuration (Fig.2), the second one would simulate the risk of sediment accumulation under the diffuser due to alternate semi-diurnal tidal currents (the pipe behaving as a barrier).

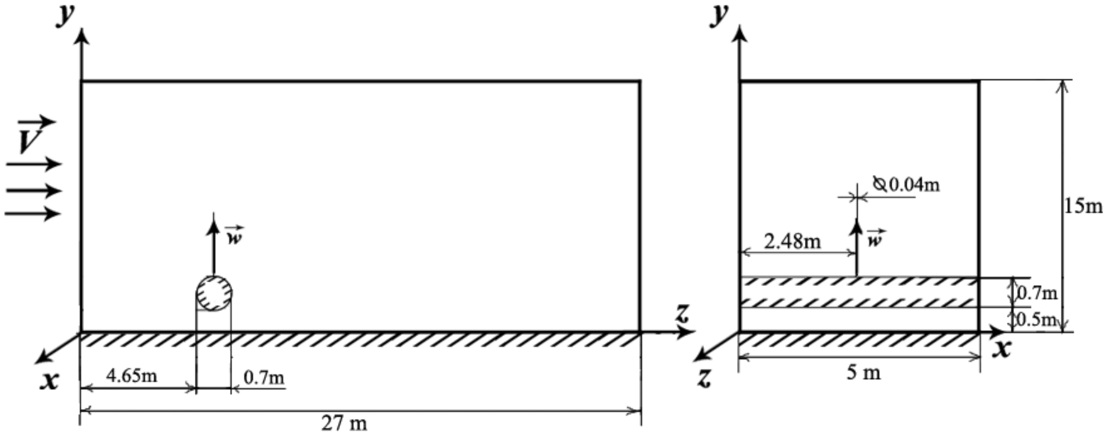


FIG. 2 – Schematic representation of the problem and coordinates: (a) view perpendicular to the diffuser; (b) transversal view (along the diffuser)

We undertake the numerical simulation of the pollution of coastal waters from a point source (Fig.2) which corresponds to one port (circular opening with a diameter of *d*) of the ocean outfall diffuser. The diffuser pipe has a circular section of diameter *D* at the height *L* from the sea bottom. We consider a buoyant effluent which is discharged vertically at an average velocity w. The velocity of the ambient current is denoted $\vec{V}$.

Environmental characteristics: density of sea water $\rho_a \approx 1024\ kg/m^3$, ambient temperature $T_a = 24^o C$, Current speed (perpendicular to the diffuser) $V = 0.1 \div 0.6\ m/s$, ambient water dynamic viscosity $\mu_a = 9.55 \cdot 10^{-4} Pa \cdot s$. Effluent characteristics: density at diffuser $\rho_e \approx 1004\ kg/m^3$, effluent temperature $T_e = 40^o C$, mean discharge speed , $w = 1.35\ m/s$, dynamic viscosity, $\mu_e = 9.55 \cdot 10^{-4} Pa \cdot s$.

2.2 Modeling of the 3D BBL dynamics

To get a realistic near-field distribution of pollutants a 3-D approach is needed. In addition, as the multiport diffuser is placed near the seafloor (i.e., in the sea bottom boundary layer), it is important to analyze the effect of the ambient BBL dynamics. For that purpose, we consider two types of vertical profile for the ambient current $V(y)$: (a) constant in y (i.e., without BBL effect), and (b) a logarithmic profile of ambient velocity; the constants are extracted from experimental data obtained from ADCP data (Acoustic Doppler Current Profiler) .

We consider the pollutant transport in the three-dimensional stationary nonisothermal turbulent flow of viscous incompressible fluid. Numerical modeling is conducted with the help of commercial software package Fluent 6.3.26, by using the following options: $k-\varepsilon$ model for turbulent flows, species transport model for admixture distribution.

The boundary conditions are: on the seafloor and on the pipe surface $\vec{v} = 0, T = T_a, \partial c/\partial n = 0$; at the entrance of computational domain $(z = 0)$ $v_x = 0, v_y = 0, v_z = V, T = T_a, c = c_0$; at the pipe exit (port) $v_x = 0, v_y = w, v_z = 0, T = T_e, c = c_e$; on the remaining boundaries $\partial v_x/\partial n = 0, \partial v_y/\partial n = 0, \partial v_z/\partial n = 0,$ $\partial T/\partial n = 0, \partial c/\partial n = 0$

3. Nominal configuration (surelevated pipe); stationary case

First, let us examine the nominal configuration (surelevated pipe; fig.2), in the stationary case (the speed of the ambient flow being time-independent), and study the admixture distribution in the two following cases: (1) the ambient current is assumed to be constant along the vertical coordinate y ; (b) it depends on y according to a logarithmic law (BBL formulation):

$$V(y) = a + b\ \ln(y) \qquad (1)$$

where *a* and *b* are constants obtained from experimental data.

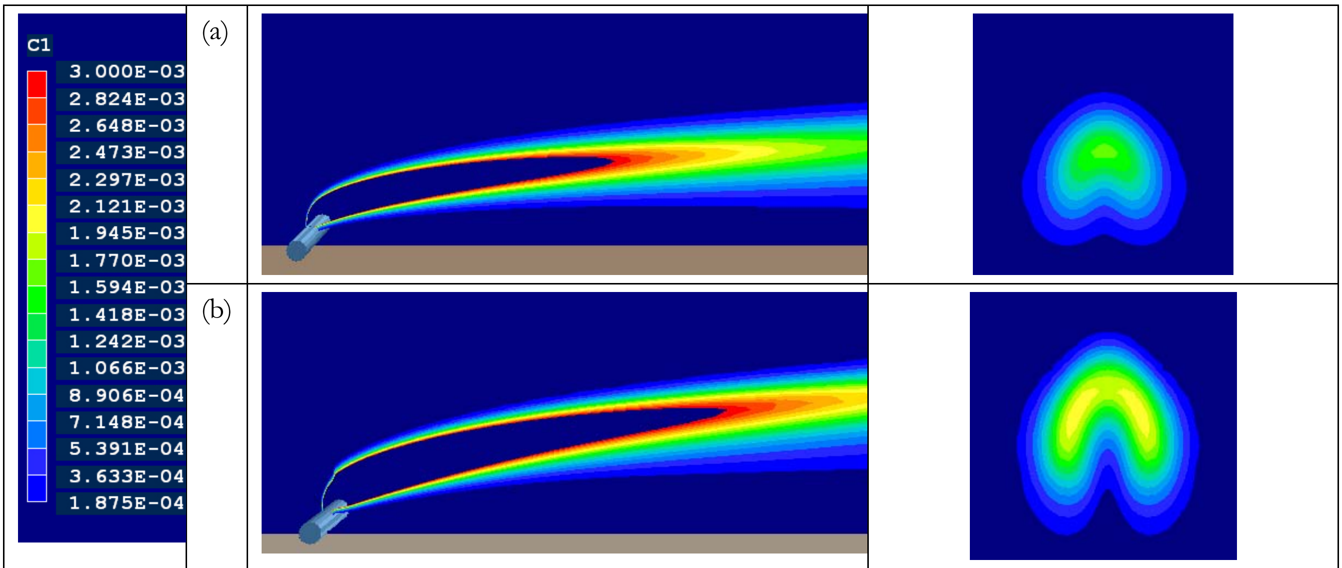
To analyze the role of BBL formulation, we will compare the results of numerical simulation with constant ambient velocity to the results obtained with a logarithmic profile (eq. 1) normalized according to the following rule: at the height 1.2 m. from the seafloor (which corresponds to the height of the discharge exit) the value of both velocity profiles coincides (i.e., $V_2(1.2) = a\ln(1.2) + b = V_1$).

Tab. 1. Correspondence between constant and logarithmic speed of ambient current

$V_1 = const$, *m/s*	$V_2(y) = a + b\ \ln(y)$, *m/s*
0.05	$V_2(y) = 0.048 + 0.014\ \ln(y)$
0.15	$V_2(y) = 0.144 + 0.033\ \ln(y)$
0.25	$V_2(y) = 0.241 + 0.014\ \ln(y)$
0.35	$V_2(y) = 0.340 + 0.062\ \ln(y)$

3.1. Numerical results

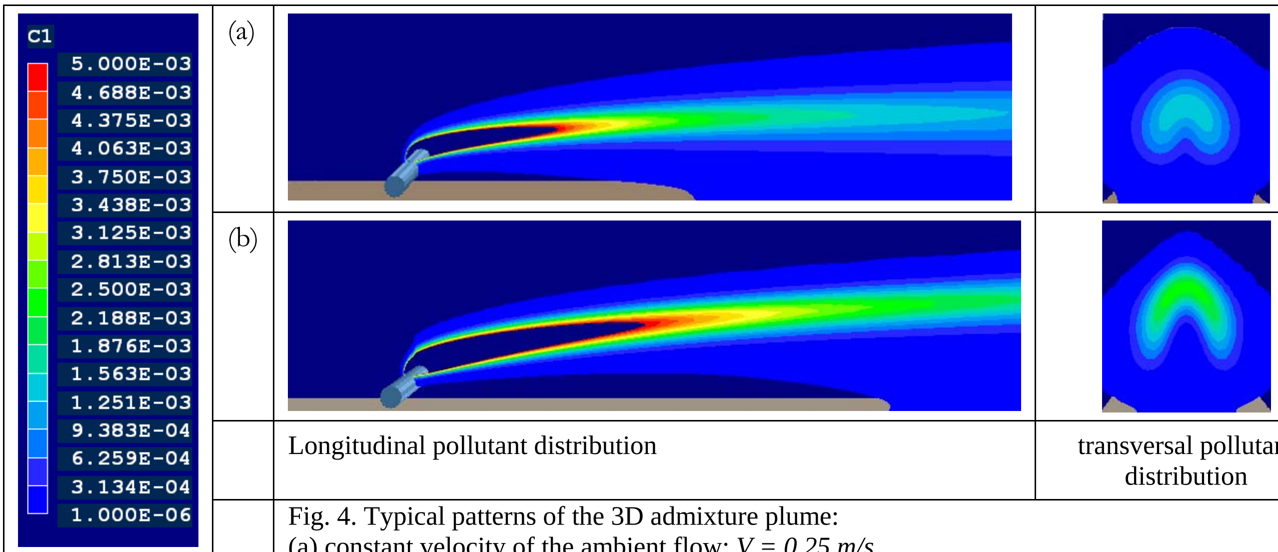
The effect of BBL formulation is analyzed for two values of current speed: *V = 0.15 m/s* and *V = 0.25 m/s*. Figs. 3 and 4 show the patterns of the propagation of admixture for the two types of vertical profile of the ambient velocity: (a) constant in y, (b) logarithmic in y.



Longitudinal pollutant distribution

transversal pollutant distribution

Fig. 3. Typical patterns of the 3D admixture plume:
(a) constant velocity of the ambient flow : *V = 0.15 m/s*
(b) logarithmic BBL profile $V(y) = 0.144 + 0.033\ln(y),\ m/s$



Longitudinal pollutant distribution

transversal pollutant distribution

Fig. 4. Typical patterns of the 3D admixture plume:
(a) constant velocity of the ambient flow: *V = 0.25 m/s*
(b) logarithmic BBL profile $V(y) = 0.241 + 0.014\ln(y),\ m/s$

In both cases our results recover the classical horse-shoe structure of a turbulent round jet deviated by a transverse flow (see for ex., Sherif & Pletcher, 1998).

In fig.4, for a higher speed of ambient current (*V = 0.25 m/s)*, there is an evidence of bottom attachment. For the logarithmic profile formulation, the bottom attachment occurs at a slightly larger distance from the diffuser.

4. Configuration with deposit under the pipe (blockage)

The configuration examined above is idealized. In the real life, the bottom sediments can be accumulated under the pipe due to the alternate semi-diurnal tidal current, as the pipe constitutes a barrier to the bottom sediment transport. In this case let us introduce a new configuration with a rigid wall under the pipe (Fig. 5).

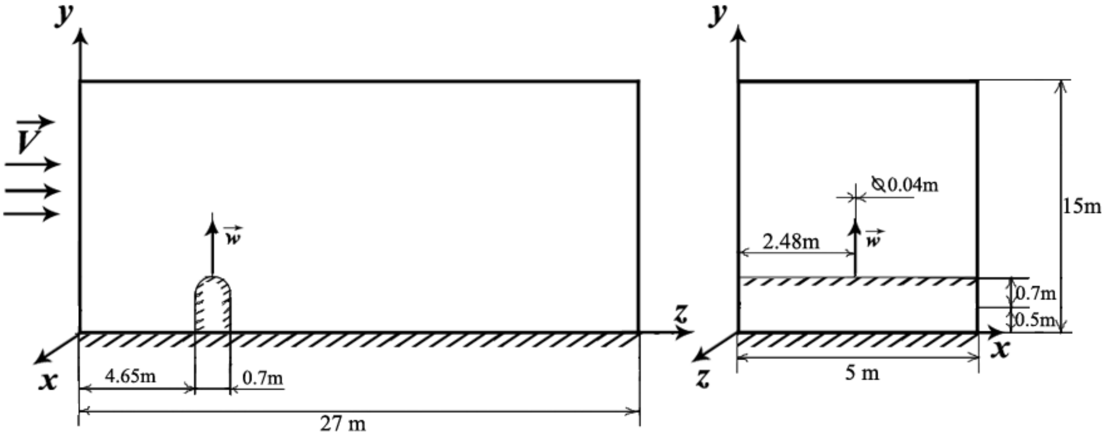
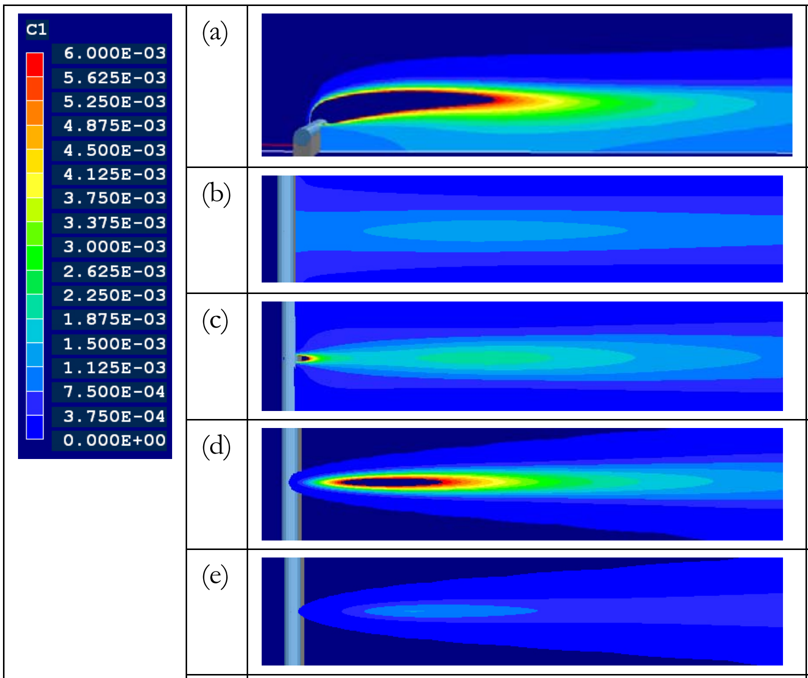


Fig. 5. Configuration with the deposit under the pipe

Let us analyze the effect of BBL in the configuration with blockage in the case of high enough velocity of the ambient current ($V = 0.25$ *m/s*) considered here above. We present the pollutant distributions at different distances above the seafloor obtained numerically with and without taking into account BBL (Figs.6 and 7).



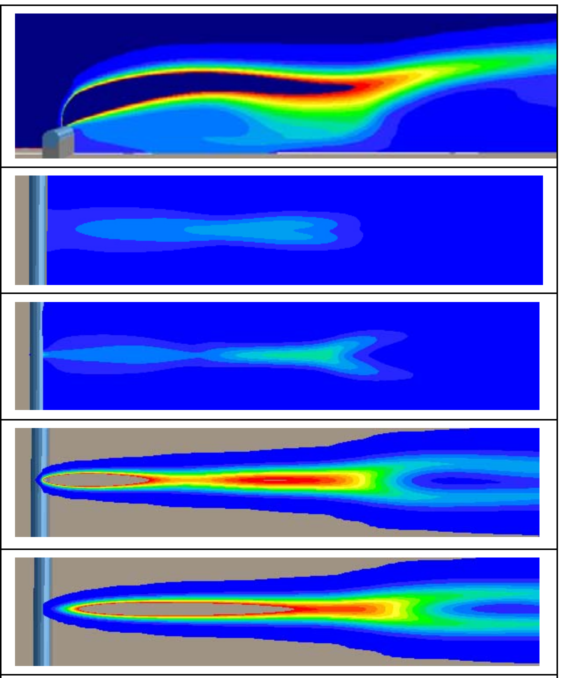


Fig.6. Longitudinal pollutant distribution for an ambient flow with constant velocity $V = 0.25$ *m/s.*: a) – vertical cross-section, b-e) – top view at different distances above the seafloor: (b) 0.5m; (c) 1.2m; (d) 2.5m; (e) 3m.

Fig.7. Longitudinal pollutant distribution for logarithmic profile $V(y) = 0.241 + 0.014\ln(y)$ m*/s:*
a) – vertical cross-section, b-e) – top view at different distances above the seafloor: (b) 0.5m; (c) 1.2m; (d) 2.5m; (e) 3m.

In the case of logarithmic profile, i.e. when we take into account BBL a spot of pollutant near the bottom is also of low enough concentration (as in the previous case) but differing from the previous case it occupies much smaller area. As one can see, pollutant is distributed to larger distances in horizontal direction and maximal values of pollutant concentration are observed at larger distances from the bottom which can be attributed to the formation of vortex just after the blockage (in the case of constant velocity such vortex also exists but it has lower intensity and occupies smaller area). This vortex shifts the pollutant plume upward.

5. Tidal effect

Preliminary study concerning the tidal effect has been also carried out, in the frame of the BBL formulation. In this case the ambient velocity was imposed in the form:

$$V(y,t) = -0.45\sin(0.202-0.042t/300)-0.065\ln(y)\,\sin(0.202-0.042t/300).$$

Both configurations, with and without blockage, have been analyzed. The results concerning the temporal evolution of pollutant concentration at the distance of 1.2 m above the seafloor are shown in Fig. 8 and 9, in both cases (without and with blockage, respectively).

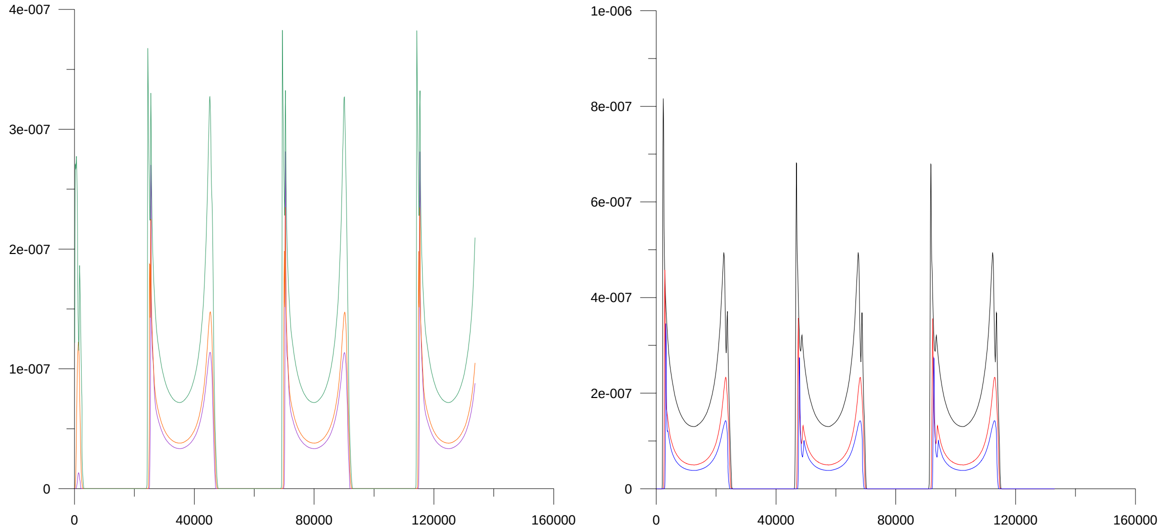


Fig.8. Temporal evolution of pollutant concentration in the case without blockage at the distance 1.2 meters from the bottom: a) in 10, 50 and 90 meters to the left of discharge port (green, orange and violet lines respectively); b) in 10, 50 and 90 meters to the right of discharge port (black, red and blue lines respectively)

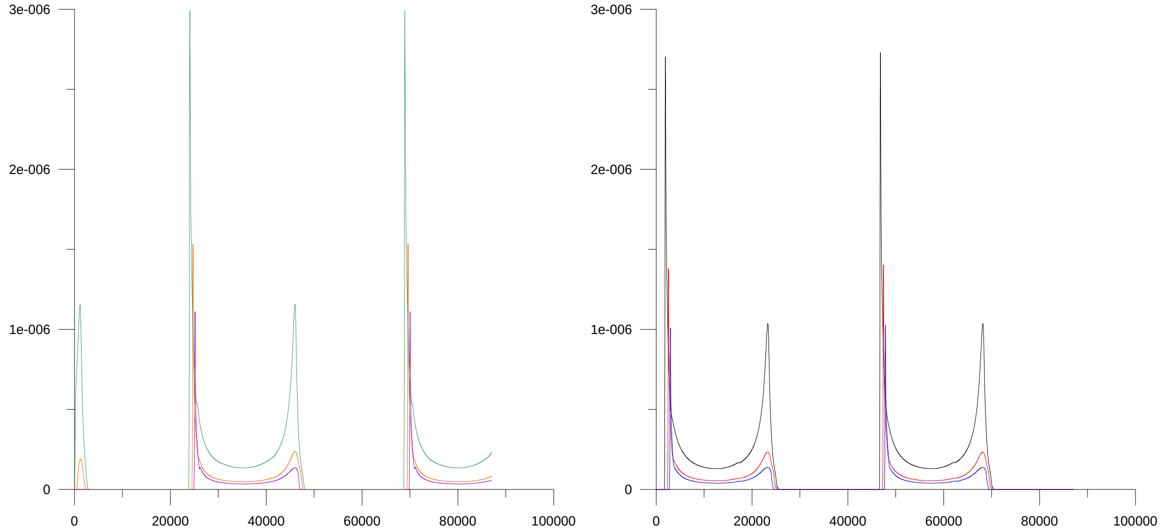


Fig.9. Temporal evolution of pollutant concentration in the case with blockage at the distance 1.2 m above the seafloor: a) in 10, 50 and 90 meters to the left of discharge port (green, orange and violet lines respectively); b) in 10, 50 and 90 meters to the right of discharge port (black, red and blue lines respectively)

6. Conclusion

In the case of buoyant effluent $\rho_e \approx 1004\ kg/m^3$) discharged vertically in sea water ($\rho_a \approx 1024\ kg/m^3$), we can predict a bottom attachment as soon as the current velocity is of the order of $V = 0.25\ m/s$. This attachment effect is increased in the case of blockage under the diffuser. The role of the BBL formulation has been discussed. Preliminary results for tidal effect are presented.

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