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NUMERICAL SIMULATION OF SUSPENDED SEDIMENT TRANSPORT AND DISPERSAL FROM EVROS RIVER INTO THE NORTH AEGEAN SEA, BY THE MECHANISM OF TURBIDITY CURRENTS

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EXTENDED ABSTRACT

The suspended sediment concentration in a river, usually reaches maximum values in the case of floods. This fact, results in river density larger than the sea or lake density, considering the river as a mixture of water with suspended sediment. Therefore, when the river discharges in a water basin, it plunges underneath the free water surface and continuous to flow along the bottom, forming a hyperpycnal plume, also known as a turbidity current. Such complex flows, are usually formed at river mouths in the ocean, lakes and reservoirs and are capable of travelling long distances, transporting, eroding and depositing considerable amounts of suspended sediment.

The main aim of the current paper is the use of computational fluid dynamics methods (CFD), offered by the commercial CFD code Fluent, in order to simulate the dynamic behaviour, structure and flow characteristics of turbidity currents that are potentially formed in Evros River mouth. More specifically, a previously tested and verified, 3d numerical model is applied at Evros River discharge into the North Aegean Sea, for the simulation of suspended sediment transport and dispersal, in the case of a flood discharge where the river suspended sediment concentration is high enough, in order for a turbidity current to be formed. The numerical model used, solves the Reynolds-averaged Navier-Stokes equations, accordingly modified for their application in multiphase flows. Closure of turbulent stress terms is achieved with the application of the dispersed option of the RNG (Renormalization-group) k-ε turbulence model.

In order to investigate more clearly, the effect of the bottom topography and the Coriolis force, the inflow discharge from Evros River is assumed to be constant, while the potential effects of other parallel to the shore and subsurface currents are not taken into account.

The simulation results indicate, that during the inflow of the fresh water – suspended sediment mixture from Evros River into the saline water of the North Aegean Sea, a turbidity current is formed, plunging to the bottom of the receiving basin. It is found that the travel and dispersal of the proposed turbidity current, is highly influenced from the bottom topography, as well as from the Coriolis force. Moreover, a characteristic differentiation in the response of the different suspended sediment types in the flow field is observed.

Key words: Turbidity currents, suspended sediment transport, Coriolis force, river mouth, Evros River, North Aegean Sea

1. INTRODUCTION

In the case of floods, the suspended sediment concentration in a river considerably increases. This fact has as a result a subsequent increase in the river's density. Hence, when the river discharges in a water basin, the fresh water – suspended sediment mixture of the river, plunges to the bottom of the receiving basin, forming a hyperpycnal plume, or else a turbidity current. Such flows are usually formed at river outflows in the sea, lakes or reservoirs and are capable of travelling for long distances, transporting, eroding and depositing large amounts of suspended sediment particles [1, 2].

Turbidity currents are very difficult to be observed in the field. This is due to their rare and unexpected nature, as they are usually formed during extreme flood events [3, 4]. Scaled laboratory experiments constitute an alternative and widely used method, for studying the dynamic, erosional and depositional characteristics of turbidity currents [5, 6]. Finally, the third and most promising way for studying turbidity currents, is their simulation with the use of suitable numerical models [7-10].

The main aim of the present paper is the use of Computational Fluid Dynamics (CFD) methods that are offered by the commercial software Fluent, for the numerical simulation of the dynamic behavior and the main flow characteristics of turbidity currents, which are potentially formed at Evros river mouth. More specifically, a 3D numerical model is applied at Evros river mouth, in order to simulate the river's suspended sediment transport and dispersal into the North Aegean Sea, in the case of a flood discharge, where the suspended sediment concentration of the river water is considerably high, in order for a turbidity current to be formed. It should be mentioned that the effects of the bed morphology and the Coriolis force are taken into account, during the numerical simulation. The numerical model that is used in the present paper solves the Reynolds-averaged Navier-Stokes equations, accordingly modified for their application in multiphase flows, such as turbidity current flows. Closure of the turbulent stress terms is achieved through the RNG (Renormalization-group) version of the k-ε turbulence model. The numerical model used, is tested against laboratory experiments, in the paper of Georgoulas et al. [11].

2. DESCRIPTION OF THE NUMERICAL SIMULATION

The flow examined in the present paper, is a flood discharge of Evros River that is based in existing flood data. It is treated numerically as a multiphase flow, with saline water (North Aegean Sea) being the primary phase and fresh water and suspended sediment particles (Evros River) being the secondary phases. For the present numerical application, two separate phases of suspended sediment particles are assumed. The first consists of fine sand particles of 0.235 mm diameter and the second consists of very fine sand particles of 0.069mm diameter.

The geometry used in the numerical simulation, has been extracted from a 3D digitized bottom relief model of the North Aegean Sea, which is illustrated in Figure 1 below. The region, denoted by number 1 in the digitized bottom relief model, is the wider region of Evros river mouth, while the hatched area in the sub-region denoted by number 2, is the part that was selected for the numerical simulation of the present paper. The triangular surfaces shown form the bottom relief of the North Aegean Sea basin. As it is shown in sub-region 2, only one of the two major outflows of Evros River is taken into consideration in the preset application.

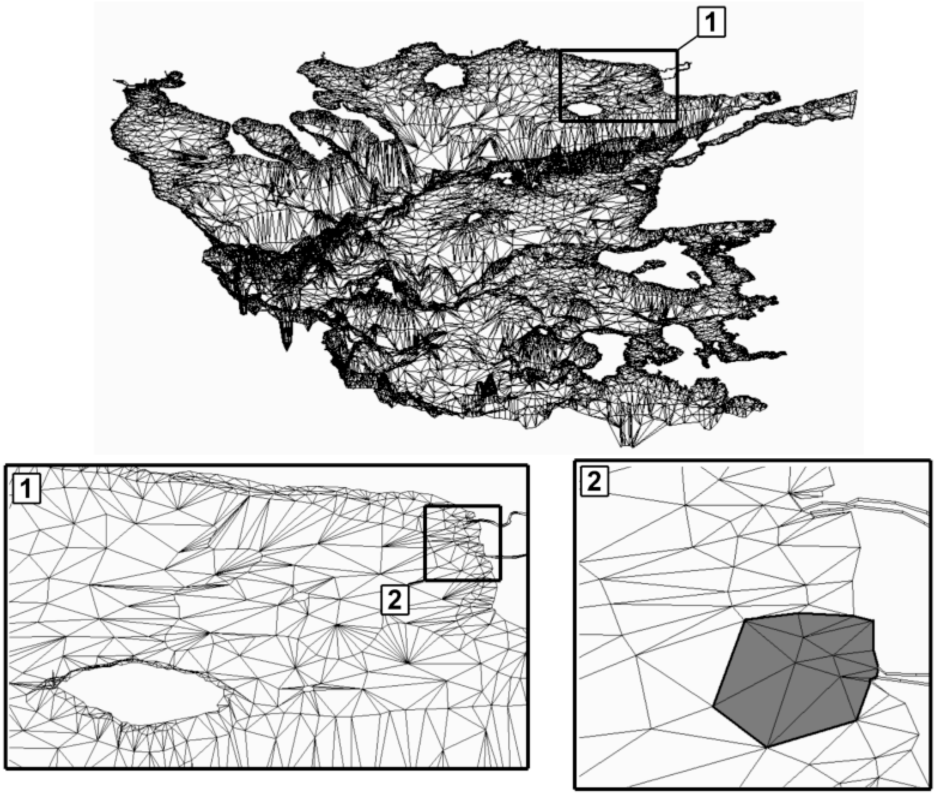

Figure 1: 3D digitized bottom relief model of the North Aegean Sea, region of Evros River Outflow (region 1) and region of numerical simulation (hatched region within Sub-region 2).

The resulting numerical geometry, the computational mesh and the boundary conditions that are used for the simulation of the present paper, are illustrated in Figure 2. The computational mesh consists of a total number of 56,720 hexahedral cells (Figure 2a). For the inflow (Figure 2b) a “velocity inlet” boundary condition is applied, where the inflow velocities and the volume fractions of the secondary phases of the flow are specified. For the shoreline east and west of Evros river outflow (Figure 2c), a “wall” boundary condition is applied. For the open sea boundary of the flow field (Figure 2d) a “pressure outlet” boundary condition is applied. For the bottom boundary a “wall” boundary condition is used (Figure 2e), while for the free water surface of the ambient sea water a “symmetry” boundary condition is used (Figure 2f). Thus, there are neither convective nor diffusive fluxes across the top surface. This type of free surface boundary condition has also been used by other researchers in literature [9, 10]. At this point, it should be mentioned that during the simulation, the entire flow field is rotated with respect to the Z-axis (vertical axis), with a rotational speed that corresponds to the rotational frequency (Coriolis parameter) of the North Aegean Sea region (latitude $\varphi = 40°N$), in order for the Coriolis force effect to be taken into account. The initial conditions applied for the simulation of the present paper, are summarized in Table 1.

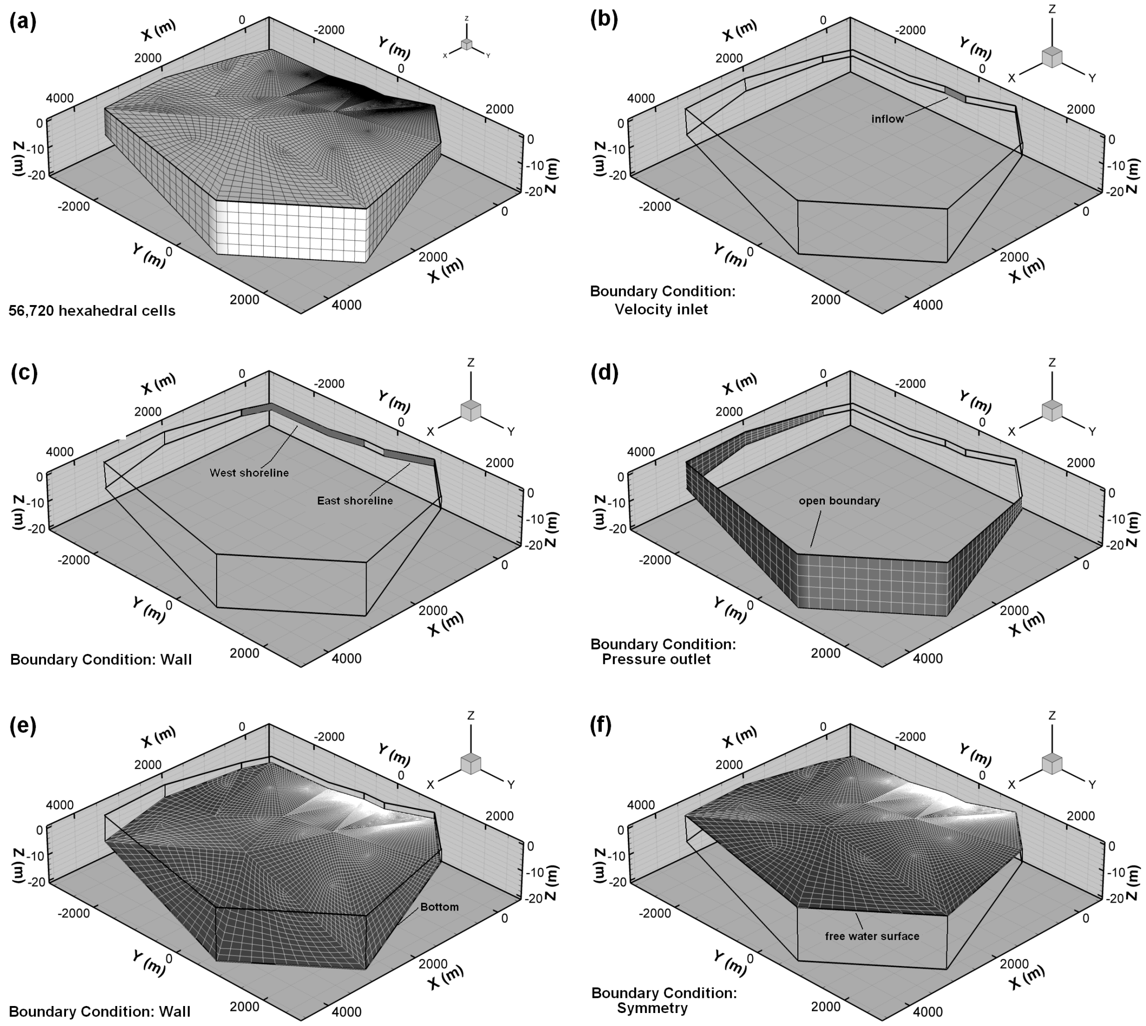

Figure 2: Numerical simulation geometry, computational mesh and boundary conditions.

Table 1: Numerical simulation initial conditions

Inflow discharge (m^3/sec)	4,555
Inflow velocity (m/sec)	4
Fine sand particle diameter (mm)	0.235
Very fine sand particle diameter (mm)	0.069
Fine sand concentration (vol%)	0.7%
Very fine sand concentration (vol%)	0.7%
Saline water density (kg/m^3)	1028,75
Fresh water density (kg/m^3)	998,2
Sand particle density (kg/m^3)	2,650
Latitude φ (°N)	40
Coriolis parameter f (Hz)	$9.35x10^{-5}$
Rotational period T (hr)	37.34
Rotational velocity (rpm)	0.000446

The numerical simulation was conducted with relatively simplified conditions, in order to investigate more clearly the effects of the bottom topography and the Coriolis force, in the results of the studied flow. Therefore, the inflow discharge from Evros River was assumed to be steady, and the potential effects of other parallel to the shore, subaqueous currents were not taken into consideration.

The value of the Evros river discharge that was indicatively used in the simulation (4,555 m^3/sec), corresponds in a big flood discharge of the proposed river. Since there are not any available data for the maximum sediment discharge at Evros River mouth, the initial suspended sediment concentration that was used for the numerical simulation, was estimated, taking into consideration the sediment discharge measurements, upstream of the river mouth, in the work of Gergov [12].

The initial condition for the ambient water was assumed to be constant for the entire flow field, with a salinity of 38.6 ppt and a temperature of 15.0 °C that correspond to a density value of 1028.75 (kg/m3). The width of Evros River at the inflow position into the North Aegean Sea was assumed to be 450 m, while the corresponding depth was assumed to be 2.5 m. The type of boundary condition used for the open sea boundary, allows the passive inflow or outflow of water, from every computational cell, according to the flow needs.

The time step for the calculations was 0.1 sec and total number of 144,000 time steps was simulated. This value corresponds to 4 hr of real flow. A high resolution computational mesh was constructed (56,720 computational cells), in order to achieve high accuracy in the results. Approximately 48 hours of computational time was needed, for the simulation of 1 hour of real flow, in a PC with a Linux operational system and an Intel P4 processor, at 3.00 GHz speed, with 3.00 GB of RAM memory.

3. NUMERICAL SIMULATION RESULTS

The 3D, time evolution of the root and dispersal of the suspended sediment - fresh water mixture that enters the flow field, is illustrated in Figure 3.

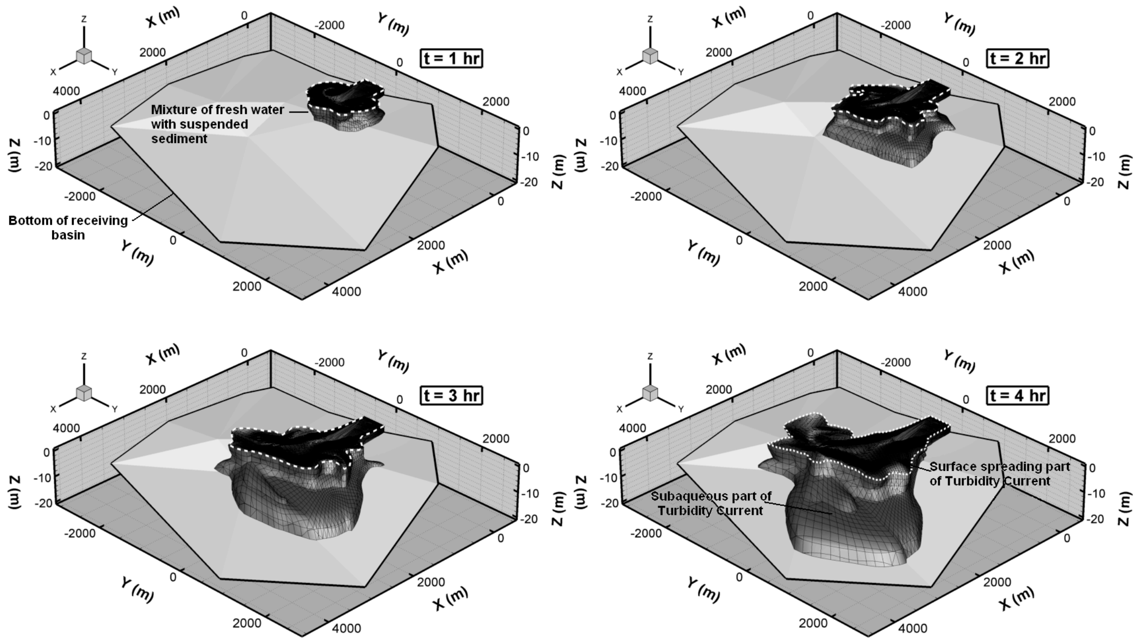

Figure 3: Time evolution of the root and dispersal of the suspended sediment – fresh water mixture that enters the flow field.

It is observed that a part of the suspended sediment – fresh water mixture, that enters the flow field, is spreading at the free water surface, while most of the mixture plunges underneath the free sea water surface, forming a turbidity current, which continuous to flow along the bottom. This subaqueous current, initially spreads out radically in all directions, with an irregular shape, due to the mixing of the current with the ambient fluid. After the second hour of flow, a major part of the turbidity current clearly deviates to the left of the main inflow axis, due to the general slope gradient of the bottom relief in this direction. However, it is obvious that a smaller part of the turbidity current deviates to the right of the main inflow axis, due to the effect of the Coriolis force, encountering even negative slope gradients. The effect of the Coriolis force is also evident in the part of the suspended sediment – fresh water mixture that is spreading in the free surface. The surface that is enclosed by the dashed line in Figure 3, constitutes the so called plunge region of the turbidity current. After this line the mixture plunges underneath the free water surface and continuous to flow along the bottom of the receiving basin.

In order to investigate the different concentration distributions, for the two separate suspended sediment phases, Figure 5 is plotted, which illustrates the corresponding volume fraction contours for each of these phases, in two (perpendicular to each other) vertical sections within the flow field, 4 hours (real flow time) after the start of the simulation. It is reminded that at the river inflow into the sea, the initial concentration values for the fine sand and the very fine sand phases are 0.7% by volume. The position of each of the proposed sections, within the flow field, is shown in Figure 4.

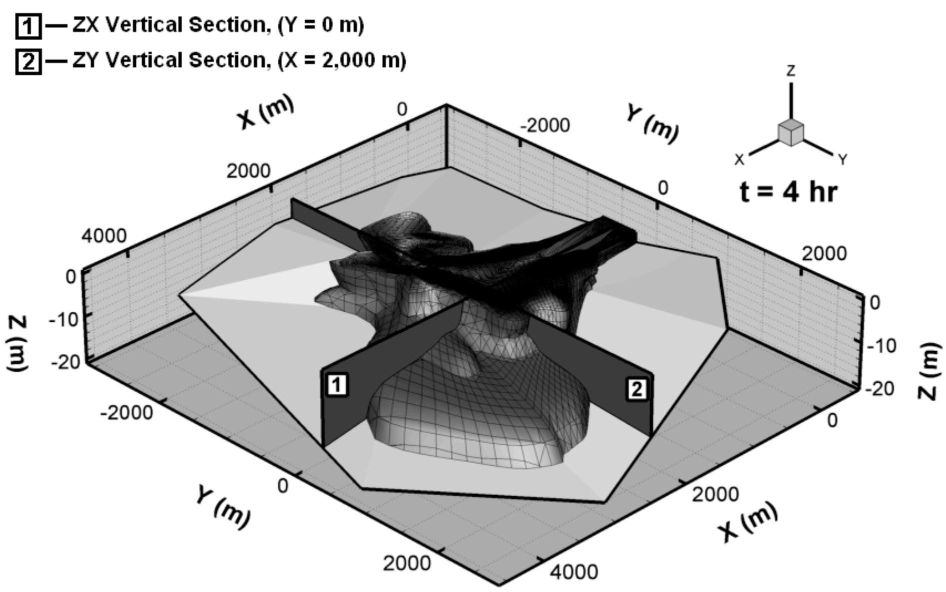

Figure 4: Position of vertical sections within the flow field (Flow time, t = 4hr).

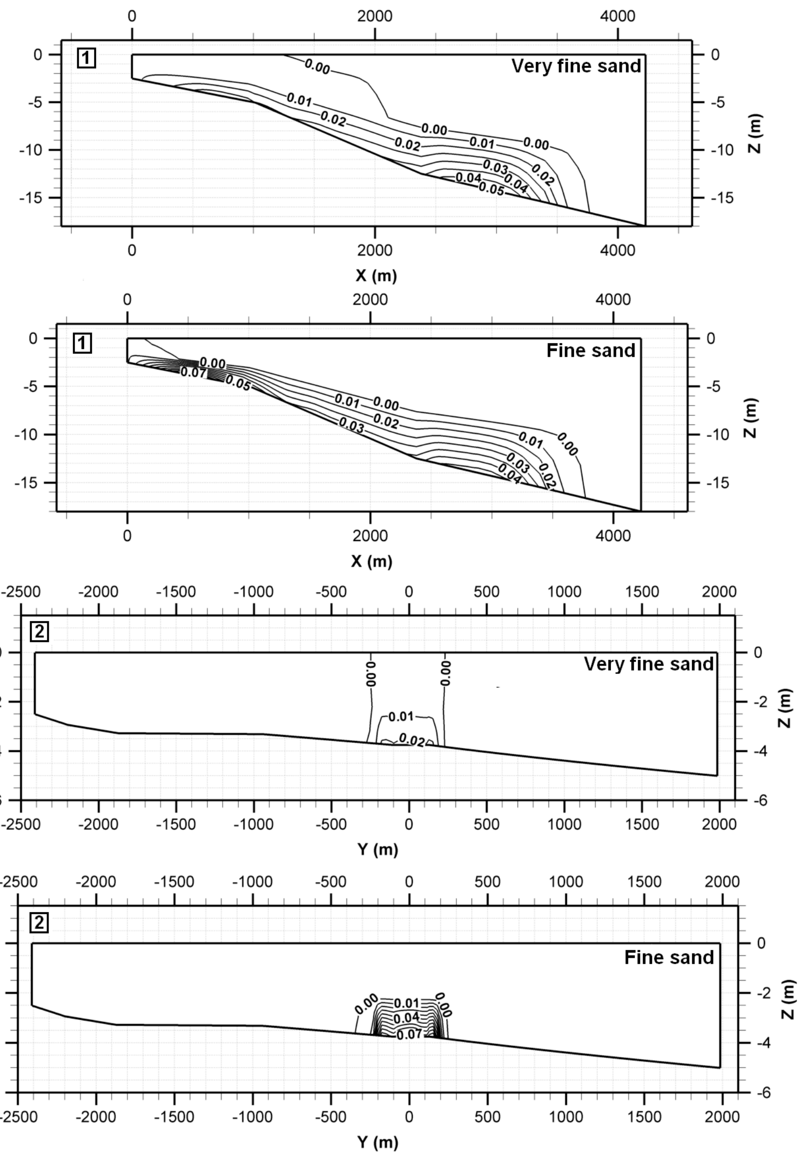

Figure 5: Volume fractions of fine sand and very fine sand phases in vertical sections 1 and 2 (Flow time, t = 4 hr).

As it is observed, both of the suspended sediment phases have similar concentration distributions, with increasing values from the interface with the ambient fluid to the bottom of the receiving basin. However, the top and more dilute concentration layer of the very fine sand phase (volume fraction values 0.00 to 0.01), occupies more height within the flow field, than in the case of the fine sand phase. This fact, is obviously due to the different settling velocities between the particles of the very fine sand and the fine sand. It is also evident that the part of the suspended sediment – fresh water mixture that spreads out along the free surface of the receiving basin, contains mainly fresh water and very fine sand particles. This can be seen in vertical section 1, where the plunge point of the very fine sand phase is traced in a considerably longer distance, from the inflow point (~1250 m), than in the case of the fine sand phase (~150 m).

4. CONCLUSIONS

At the present paper, a 3D numerical model is used, for the simulation of the suspended sediment transport and dispersal, from Evros River into the North Aegean Sea basin, in the case of a flood discharge, where the concentration of the suspended sediment particles that the river carries is high enough, in order for a turbidity current to be formed.

During the simulation, the real topography of the river mouth region as well as the effect of the Coriolis force, are taken into account. The calculations are performed with Fluent, a robust, commercial CFD solver. From the results it is concluded that for the assumed initial conditions, the inflow of the suspended sediment – fresh water mixture from Evros River into the North Aegean Sea Basin, forms a turbidity current, which plunges to the bottom of the receiving basin. The effects of the bottom topography as well as the Coriolis force, in the root and dispersal of the studied turbidity current, are highly evident. More specifically, a big part of the turbidity current deviates to the left of the main inflow axis, due to the general slope gradient of the bottom relief in this direction. Another, smaller part of the turbidity current deviates to the right of the main inflow axis, due to the Coriolis force effect, encountering even negative slope gradients. The different responses, of the different types of suspended sediment particles (fine sand and very fine sand) within the flow field, are also characteristic. In more detail, in the concentration distributions, the upper, more dilute layer of the very fine sand concentration occupies more height within the flow field, than in the case of the fine sand case. This fact is obviously due to the different settling velocities, between the particles of the very fine sand and the fine sand.

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