Hydrodynamic and morphodynamic impacts of a flood discharge tunnel in the Tagus estuary

Modelling the local effects

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Abstract: Floods are a common occurrence in Lisbon, in particular in the lower areas such as Alcântara and Chelas. The recent worsening of these floods, associated to climate change and increasing population, impose a need to develop solutions that reduce the impacts, the causes or the frequency of flooding. One such measure, as outlined in the General Drainage Plan for Lisbon 2016 - 2030 (*Plano Geral de Drenagem de Lisboa 2016 - 2030* or PGDL) is the construction of a rainwater drainage tunnel to collect excessive or flooding rain water and discharge it in the Tagus river's estuary. This system is designed to drain emergency water loads that the standard drainage system currently in place is not able to handle. Using a numerical modelling software (MOHID), this tunnel's discharge was simulated, with the goal of predicting potential hydrodynamic (changes to the velocity field and modulus and dispersion of a generic conservative pollutant) and morphodynamic (changes to the estuary's bathymetry, sediment dispersion) impacts on the Tagus river's estuary. The simulated results suggest that hydrodynamic impacts are both localized and temporary, as the effects are very small or negligible after 2 hours from the end of the discharge episode, whereas during the discharge, the approximate maximum radius of the affected area is 1150 meters. As for the morphodynamic impacts, the effects of the discharge are residual throughout the simulation, since the discharge depth is not sufficient enough to significantly affect the bottom. Therefore, these impacts, as simulated, are considered to have a low significance in the general context of the PGDL.

Keywords: modelling, hydrodynamic, morphodynamic, impacts, sediments, floods

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Introduction

Lisbon has a history record of several flooding events. According to *DISASTER - GIS database on hydro-geomorphological disasters in Portugal*, there are 411 documented occurences of floods in the Lisbon metropolitan area for the period extending from 1865 to 2010. According to this source, this district accounts for 25.3% of all flooding events with damaging effects in the aforementioned period in all of Portugal.

The most recent relevant flooding event in Lisbon occurred in 2014, when several locations throughout Lisbon city were under intense rainfall to the point where many buildings, vehicles and other infrastructure where heavily damaged; indeed, according to Lisbon Municipality's flood risk vulnerability map, many areas within the city are subject to a high risk of flooding, with many more being subject to a medium risk (Figure 1).

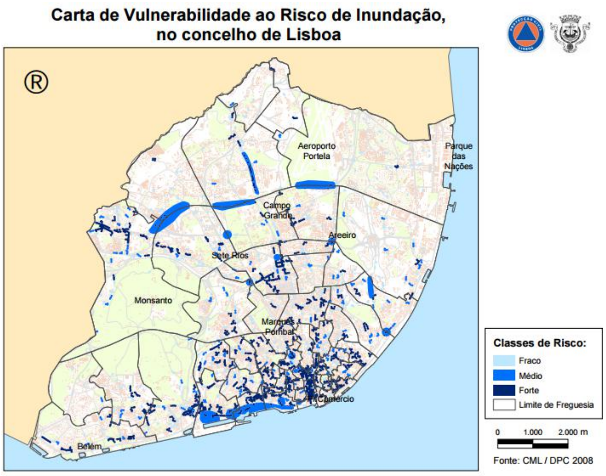

Figure 1 - Lisbon Municipality's flood risk vulnerability map.

The location under study is the Tagus river's estuary. It marks the transition between the Tagus river and the Atlantic ocean, and therefore it is affected by both bodies of water's dynamics. Its size is about 320 km^2, its width varies between 2 and 15 km, its average depth is 10.6 m and it is approximately 80 km long (Fernandes 2005). Its upper limit is located near Muge. According to Rodrigues (2015), the tidal influence is extremely important in the estuary dynamics: the tidal prism is around 600×10^6 m^3 while the river flow per tidal cycle is 8.2×10^6 m^3, and there is a 4000 ha difference in submerged area between high and low tides. The main source of fresh water is the Tagus river with an average water flow of around 600 m^3/s, but there is a considerable monthly and seasonal variability. The general location of the Tagus river's estuary in displayed in Figure 2.

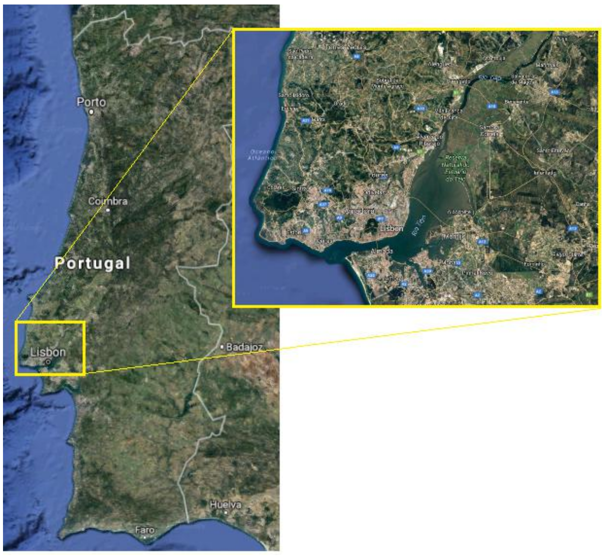

Figure 2 - Satellite photograph of the Tagus estuary.

Within the PGDL report, one of the proposed measures is the construction of a flood discharge tunnel, whose impacts on the estuary are the object of this study. This tunnel is about 5 km long, originating roughly in the Monsanto area and discharging in the Sta. Apolónia area. It has slopes ranging from 0.5% to 0.7% (according to the PGDL report). At the discharge site, the tunnel has a width of 38.8 m and a height of 2.5 m, and the bottom of the tunnel's mouth lies at a depth of 1.56 m. The tunnel is predicted to be able to handle runoff in excess of 160 m3/s. A figure of the general outline of the tunnel is shown in Figure 3.

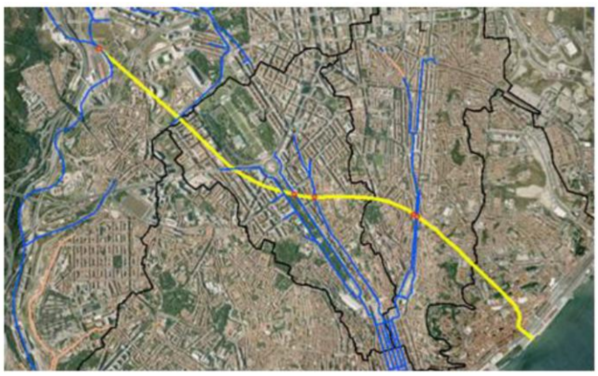

Figure 3 - General outline of the discharge tunnel, in yellow. (PGDL, 2015).

Methodology

In order to study two levels of spatial detail, two models were developed for both the hydrodynamic and morphodynamic studies: the "main" model and the "nested" model. The "main" model uses larger grid cells and time step and refers to a larger area, whereas the "nested" model has a smaller time step, grid cells and area. The smaller ("nested") model is nested in the bigger ("main") model, so as to have the bigger model provide frontier conditions for the smaller one.

Over the areas of both models, a grid was laid out. This grid's resolution is 25x25 m^2 for the "main" model and 5x5m^2 for the "nested" model, and to better suit the location under study, a 30º rotation was applied. The grid itself is 180 cells long and 64 cells wide for the "main" model and 135 cells long and 60 cells wide for the "nested" model. Afterwards, two bathymetry files were created using these grids, the definition of Lisbon's coastline (via a file supplied by MARETEC) and the bathymetric points on the Tagus estuary (also supplied by MARETEC), with the resulting bathymetric files shown below, in Figures 4 and 5.

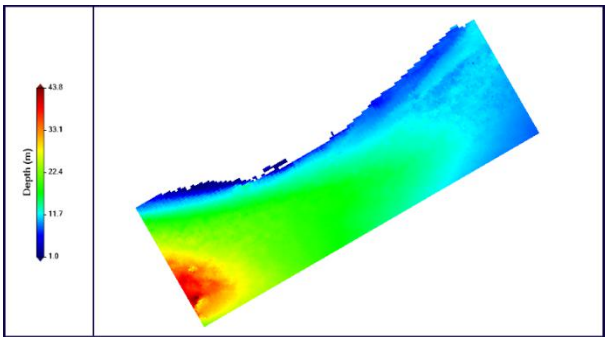

Figure 4 - "main" model bathymetry.

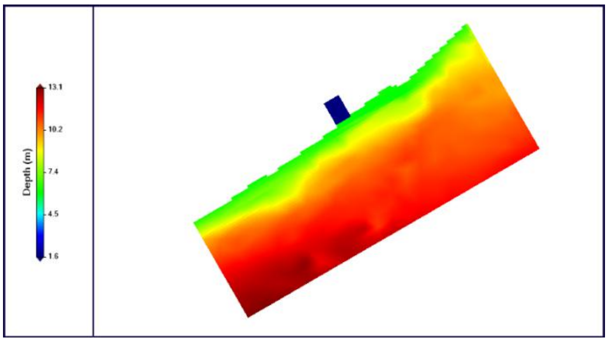

Figure 5 - "nested" model bathymetry.

The models were set to simulate a 12-hour period with a computational time step of 1.5 seconds for the "main" model and 0.25 seconds for the "nested" model. The simulated discharge was set to 160m^3/s and the discharged load was defined as being water with a generic property set to 1 000 000 (non-dimensional), no sediments, and no other properties. The discharge was set to begin immediately after the first hour of the run and set to stop at eleven hours after the run begun. The discharge was set to occur at the coordinates 9.1243 W, 38.7116 N, in the cell with grid coordinates I=48, J=97 of the "main" model and grid coordinates I=59, J=70 and I=59, J=76 of the "nested" model.

The locations for the time series were chosen based on dispersion in the domain, meaning that the methodology adopted for selection the locations was to set one location to each corner of the model and one to the midway point between those locations, then one at the mouth of the discharge tunnel, and one at the centre of the domain. The locations for the time series are shown on Figures 6 and 7, and their exact coordinates are detailed in Table 1.

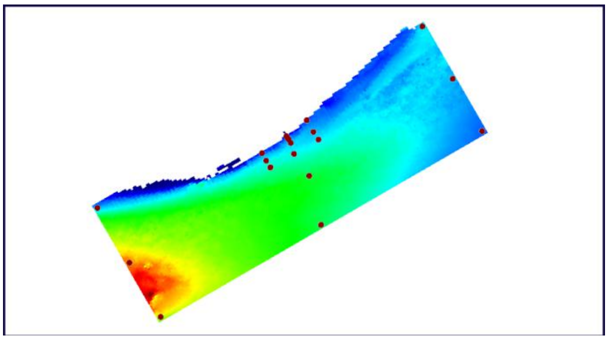

Figure 6 - Time series locations for the "main" model, in dark red.

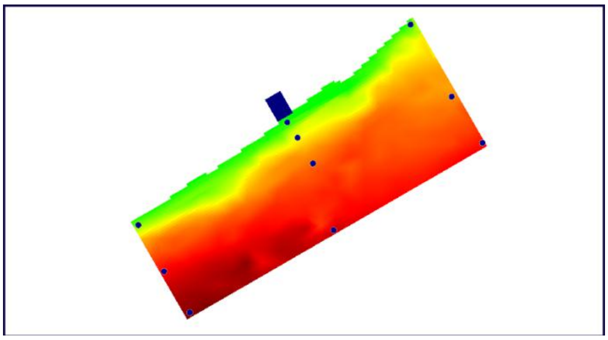

Figure 7 - Time series locations for the "nested" model, in dark blue.

Table 1 - ID, locations and coordinates for the time series' locations.

ID	Location	Latitude	Longitude
A	Top-left of "main" model	38.7028 N	9.1466 W
B	Centre-left of "main" model	38.6963 N	9.1428 W
C	Bottom-left of "main" model	38.6899 N	9.1391 W
D	Centre-bottom of "main" model	38.7008 N	9.1201 W
E	Bottom-right of "main" model	38.7119 N	9.1010 W
F	Centre-right of "main" model	38.7181 N	9.1045 W
G	Top-right of "main" model	38.7243 N	9.1081 W
H	Mouth of the discharge tunnel - "main" model	38.7110 N	9.1240 W
I	Centre of the domain - "main" model	38.7066 N	9.1215 W
J	Top-left of "nested" model	38.7093 N	9.1271 W
K	Centre-left of "nested" model	38.7084 N	9.1266 W
L	Bottom-left of "nested" model	38.7076 N	9.1261 W
M	Centre-bottom of "nested" model	38.7092 N	9.1233 W
N	Bottom-right of "nested" model	38.7109 N	9.1204 W
O	Centre-right of "nested" model	38.7118 N	9.1210 W
P	Top-right of "nested" model	38.7132 N	9.1218 W
Q	Mouth of the discharge tunnel - "nested" model	38.7113 N	9.1242 W
R	Centre of the domain - "nested" model	38.7105 N	9.1237 W

The model assimilates boundary conditions in its open borders, as well as tide and general hydrodynamic conditions, from a previous simulation of the entire Tagus estuary. This way, the border conditions are set according to this previous simulation of the Tagus estuary, in which there is no discharge tunnel, and therefore reflect the estuary “as is”, in its current state.

The modelled domain is divided vertically in two subdomains, both with σ (sigma) coordinates. Sigma coordinates adapt to bathymetry and change in accordance to the water column. Thicknesses are defined as a percentage of the water column. The first domain has 10 layers, each with 10% of the total domain height, and is the domain adjacent to the bottom. The second domain has 5 layers, each measuring 20% of the total domain height, and is located above the other domain, adjacent to the surface. This was done so that the compensation due to rising or falling water level (because of the tide) would affect only the top domain. The output times for all desired results were set at 10 minutes.

For the hydrodynamics and water properties, the computed variables were the water level, velocity, and a generic property. For the sediment module, developed by Franz et al. (2017), the desired results were those regarding different sand classes, cohesive sediments, and bathymetry evolution. The water column was set as having no sand, but 30 mg/L of cohesive sediments, uniformly distributed along the water column. The sediment column or settled layer was defined as having no cohesive sediment, but having sand. The sand classes were defined as shown in Table 2:

Table 2 - Sand classes, with d_{50} being the median diameter of each class, considered to be the representative diameter of each class.

Class	d_{50} (mm)	ID
1	0.2	Very fine
2	0.6	Fine
3	1	Medium
4	1.4	Coarse
5	1.8	Very coarse

The sediment column was defined, for the whole domain, as being 2m in height. It was divided into 20 layers - the top 15 were set as empty (to be filled, in case of net aggradation) and the bottom 5 were considered to each be filled with a single sand class. Each layer was considered to have equal height to one another (considering the 2m height of the sediment column, that means each of the 5 filled layers tally 20% of the total height, or 0.4m each). This means that the top layer is 0.4m of exclusively very fine (class 1) sand, the second layer is 0.4m of exclusively fine (class 2) sand, and so on. Actual sediment distribution in the Tagus river's estuary was not used, as such data was not found, and as such this distribution must be considered a schematic or case study, and the results cannot be interpreted strictly as the real sediment distribution.

Results

The discharge's impact, when considering the velocity field, occurs mostly at the surface level, with velocity below surface being affected only by the tide rather than by the discharge (Figure 8). A clear wedge forms because of the influence of the discharge (Figure 9). The maximum area affected by the discharge has an approximate radius of 1150m (Figure 10). There is an apparent formation of internal waves, possibly as a result of the discharge (Figure 11). After the 12-hour simulated period (therefore, 1 hour after the end of the discharge), the discharge has no effect on the velocity modulus, as the only force affecting it is the tide (Figure 12).

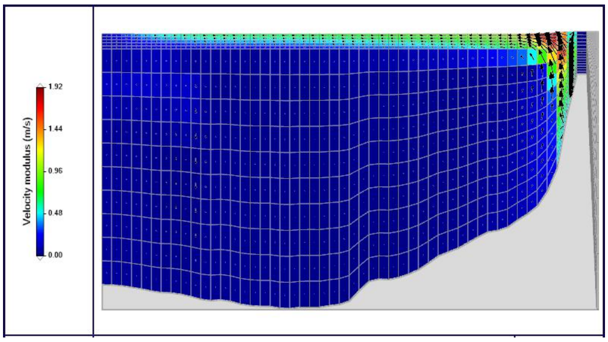

Figure 8 - Velocity modulus (m/s) and velocity field after 07h00m of simulation, "main" model, vertical cut.

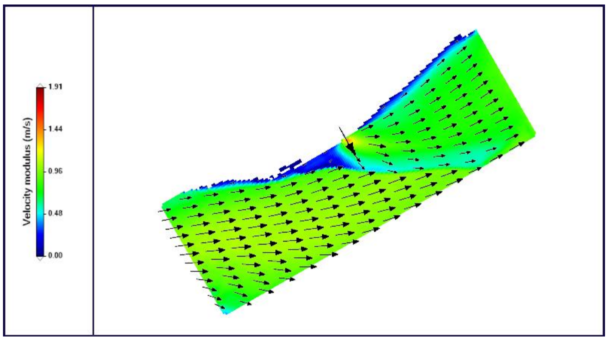

Figure 9 - Velocity modulus (m/s) and velocity field after 10h10m of simulation, "main" model, horizontal map.

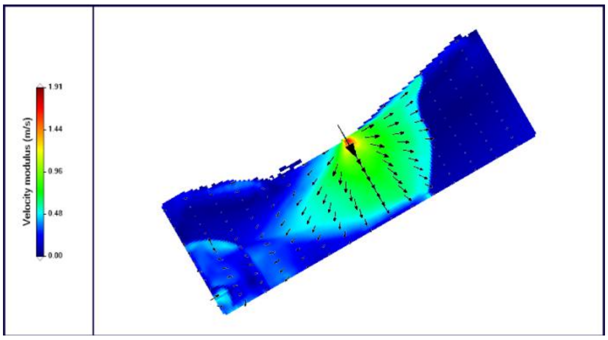

Figure 10 - Velocity modulus (m/s) and velocity field after 07h00m of simulation, "main" model, horizontal map.

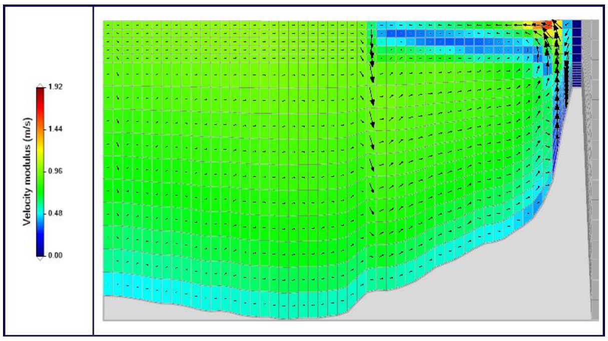

Figure 11 - Velocity modulus (m/s) and velocity field after 10h10m of simulation, "main" model, vertical cut.

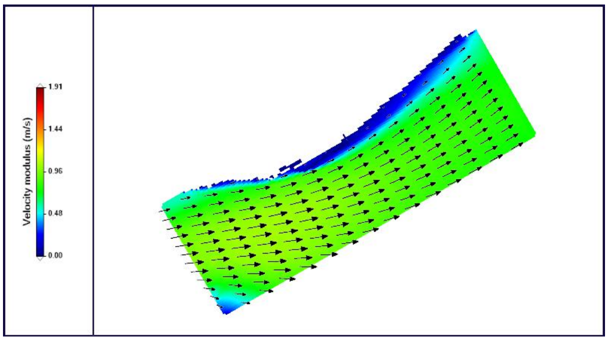

Figure 12 - Velocity modulus (m/s) and velocity field after 12h00m of simulation, "main" model, horizontal map.

The time series results reveal that the edges of the domain are mostly affected by tide, rather than by the discharge (Figure 13), with the higher velocities in these locations coinciding with ebb and flood tide and lower velocities coinciding with high and low tide.

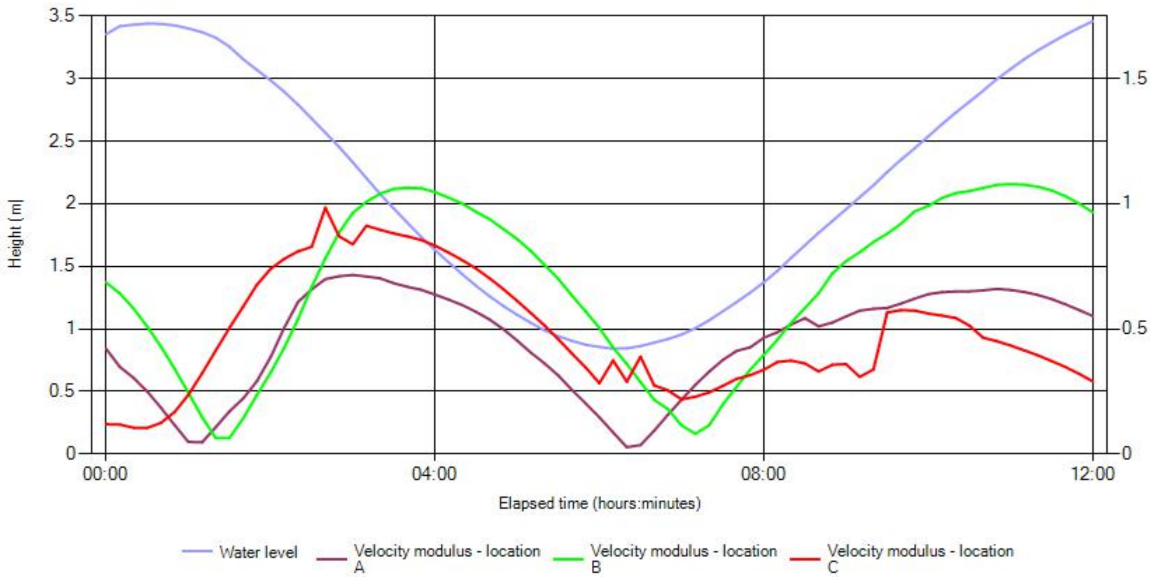

Figure 13 - Velocity modulus (m/s) and water level over time, "main" model, south-west domain border locations.

The "nested" model showed generally the same or similar results; in this domain, the time series results show the absolute highest velocity modulus of the simulation, of approximately 1.9

m/s, occurring near the discharge site (Figure 14).

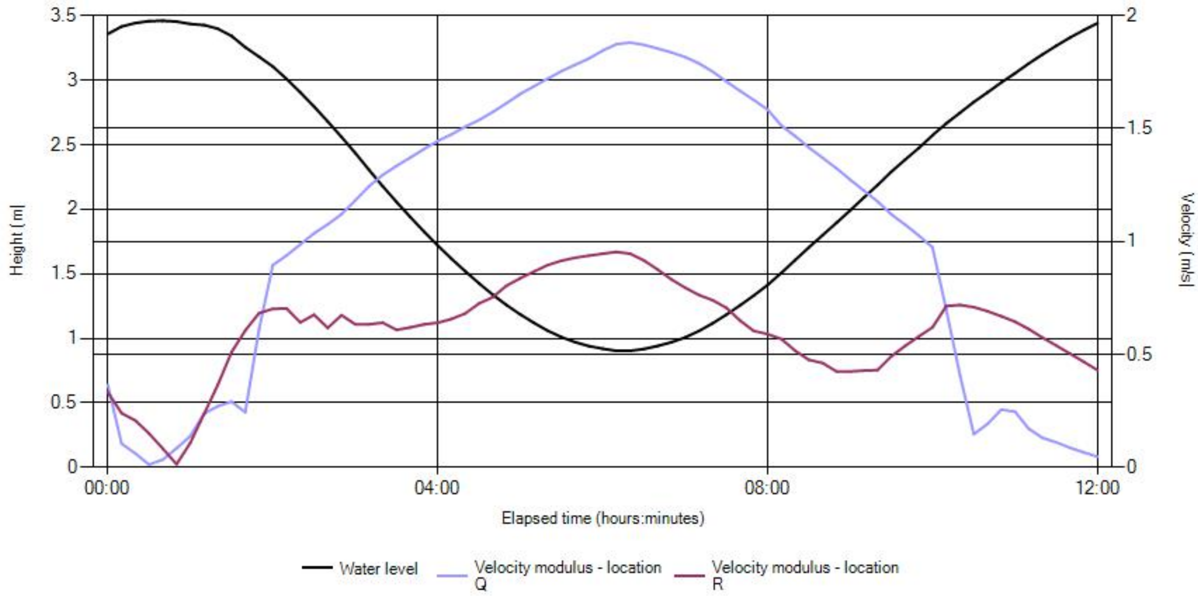

Figure 14 - Velocity modulus (m/s) and water level over time, "nested" model, centre of the domain and tunnel mouth locations.

The results for the concentration of the generic conservative property show that, while once again being mainly dispersed horizontally at the water surface, there is some vertical dispersion near the discharge location (Figure 15).

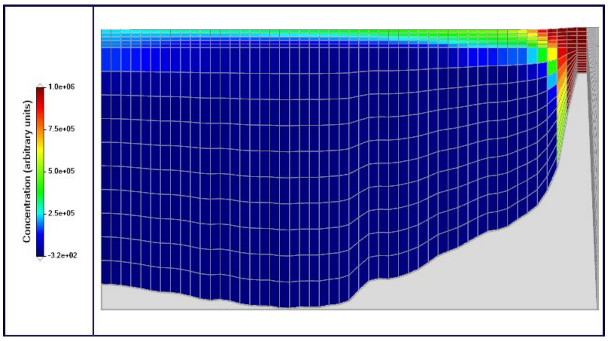

Figure 15 - Generic conservative property concentration after 07h30m of simulation, "main" model, vertical cut.

During the simulation, the highest extent of water surface area in which there is at least 50% of the concentration of this property compared to its concentration in the discharged water is within a 410m radius (Figure 16). At the end of the simulation, the highest concentration within the domain was 23% of the discharge water's concentration (Figure 17).

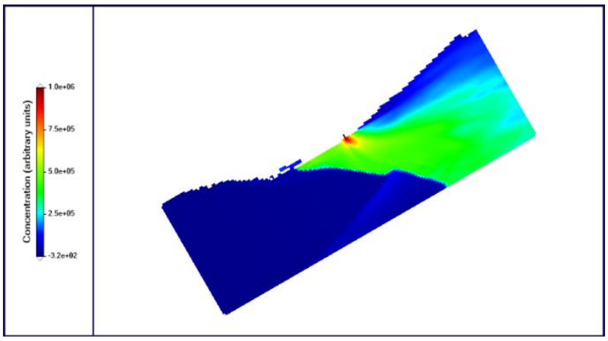

Figure 16 - Generic conservative property concentration after 09h30m of simulation, "main" model, horizontal map.

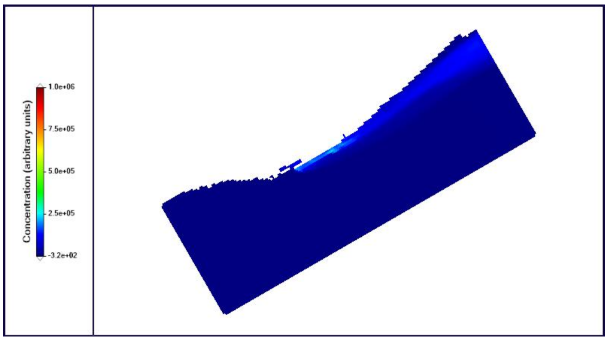

Figure 17 - Generic conservative property concentration after 12h00m of simulation, "main" model, horizontal map.

With regards to the "nested" model, the results were similar; in this smaller domain, at the end of the simulation, the highest concentration was 17.2% of the discharge water's concentration (Figure 18).

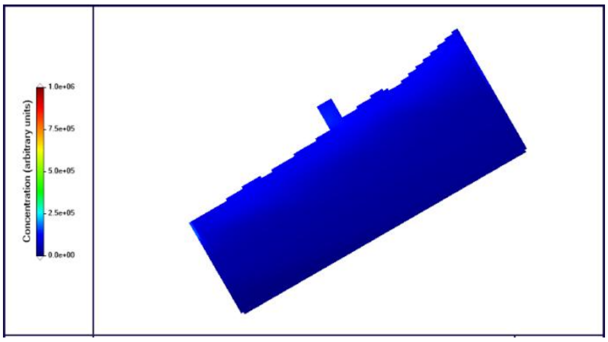

Figure 18 - Generic conservative property concentration after 12h00m of simulation, "nested" model, horizontal map.

The morphodynamic results regard only the "nested" model. No bathymetry evolution occured, which may be explained by the fact that the discharge has almost no influence on the bottom.

The observed shear stress was at its overall highest during the ebb tide (during highest tidal velocity), as seen in Figure 19. There is a strong visual correlation with the sand that reaches the water surface, as seen in the sand classes results (Figure 25). It then abates during the rest of the simulation until it becomes almost negligible (Figure 20).

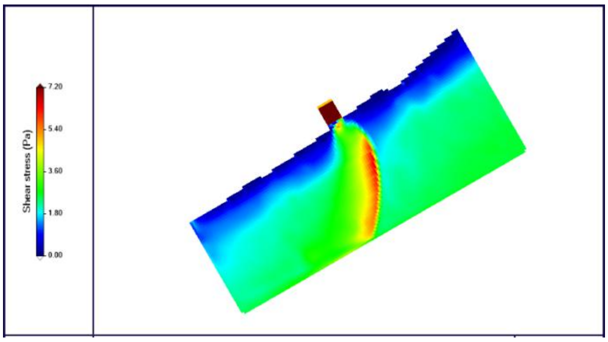

Figure 19 - Bottom shear stress aftert 03h40m of simulation, horizontal map.

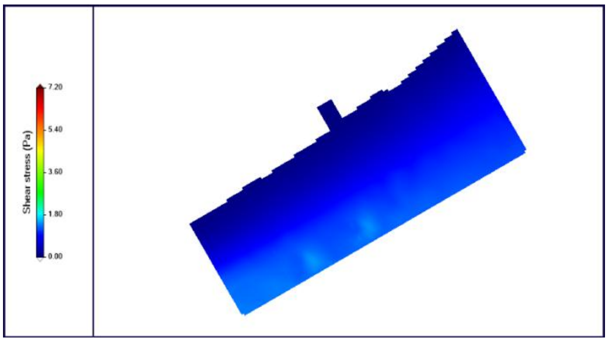

Figure 20 - Bottom shear stress after 12h00m of simulation, horizontal map.

In regards to cohesive sediments, a fluid mud layer (FML) initially forms over most of the domain, during high tide (Figure 21); then, it only exists near the coastline, during ebb tide (Figure 22), then once again over most of the domain during low tide (Figure 23); and almost immediately afterwards, it once again forms only near the coast (Figure 24).

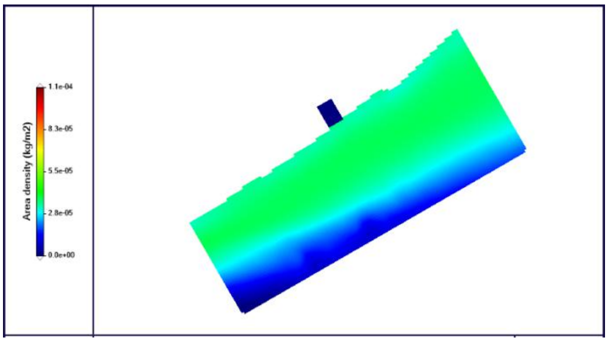

Figure 21 - Fluid mud layer after 00h40m of simulation.

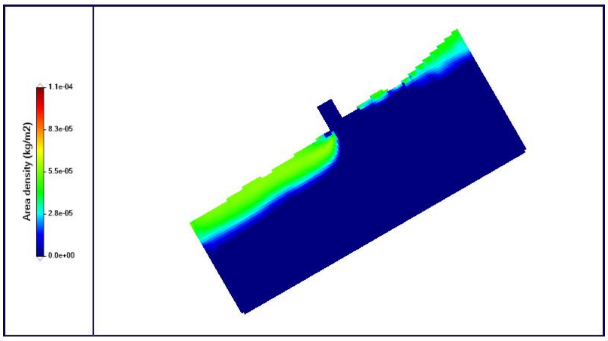

Figure 22 - Fluid mud layer after 06h00m of simulation.

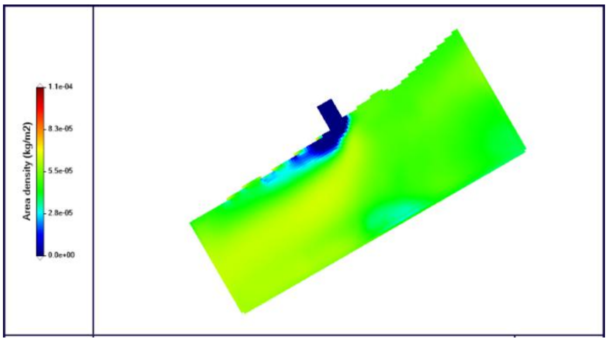

Figure 23 - Fluid mud layer after 06h40m of simulation.

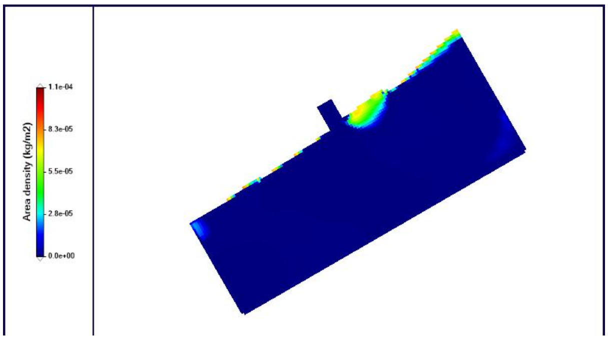

Figure 24 - Fluid mud layer after 07h40m of simulation.

Of the 5 defined sand classes in the sediment column, only the top class (class 1, very fine sand) was affected during the simulation. At one point, the eroded sand reached water surface level (Figure 25). However, throughout most of the simulation, it simply went through erosion and deposition cyclically (Figure 26).

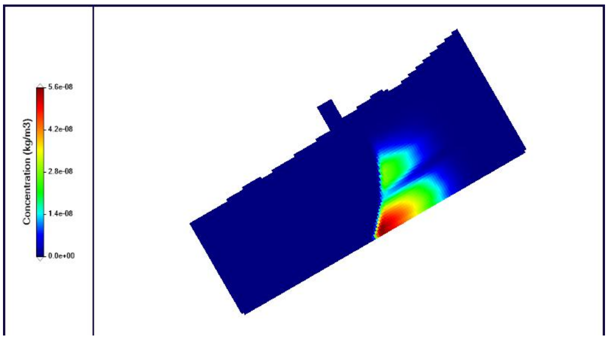

Figure 25 - Concentration of very fine (class 1) sand after 03h40m of simulation, horizontal map.

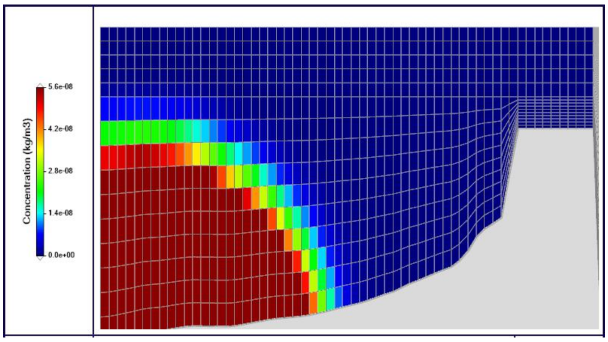

Figure 26 - Concentration of very fine (class 1) sand after 12h00m of simulation, vertical cut.

Conclusions

The effects of the tunnel's discharge on the velocity modulus were almost exclusively at the surface, with the sole exception of the apparent formation of internal waves. In terms of surface extension, the affected area was, at its highest extension, in an approximate radius of 1150m. After the 12 hours of the simulation, however, the tunnel's discharge does not affect the velocity modulus anywhere in either domain.

The results regarding the concentration of a generic conservative property show once again that the effect of the discharge is mostly horizontal, with the exception of the area very near (indeed, adjacent to) the discharge site. At the end of the simulation, within the "nested" domain, the highest remaining concentration is 17.2% of the concentration at the discharge, and only very near the coast, as anywhere else in this domain, the concentration is negligible.

In regards to shear stress, at its peak, it reached approximately 7 Pa in the zone directly ahead of the discharge site for approximately 2 hours; for the remaining simulation, it stayed nearly uniform in all of the domain, between 0 to 1.8 Pa.

The fluid mud layer forms, at two different moments, over almost the entire domain; however, throughout most of the simulation (for 9 hours and 30 minutes out of the 12 hour simulation), the fluid mud layer is only present next to the shoreline. At most, this fluid mud layer has an average surface density of approximately 60 mg/m^2.

The results for non-cohesive sediment (sand) show that only very fine (class 1) sand, with d_{50}=0.2 mm, was affected; this means that only the upper 0.4 m of the sediment column was impacted by the combined effect of the discharge and the tide, for the 12 hours duration. This sand actually reached the water surface for approximately 2 hours (during the discharge), whereas throughout the rest of the simulation it continually and cyclically eroded and deposited. All of these effects occurred away from the coast, near the south-eastern border of the domain. Displaced sand was not in enough quantity to affect the bathymetry.

The results suggest that most of the hydrodynamic and morphodynamic impacts that the discharge has on this part of the Tagus river's estuary are either localized, non-existent (or nearly non-existent) at the end of the 12 hour period, or both.

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