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SEDIMENT RESUSPENSION ASSOCIATED TO DENSITY CURRENTS. APPLICATION TO FLIX RESERVOIR (SPAIN)

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Summary. In 25th December 2001, a mercury dumping affected Flix reservoir (Tarragona, Spain) causing the death of several thousand of fish and polluting water supply of some important cities of the area. As none of the set out hypothesis explained satisfactorily the event, the possibility that a density current due to temperature difference could have resuspended contaminated reservoir bed sediment was studied. In this article, results of the analysis are shown, explaining the numerical model used and showing that the amount of mercury set into movement in this way is coherent with mercury concentrations measured in water after the incident.

1 INTRODUCTION

On Christmas day in December 2001 several thousands of dead fishes appeared in Ebro River, in Flix reservoir area. Consequently, water analysis was carried out and mercury levels higher than normal were detected. Fish bodies were analyzed concluding that mercury poisoning had caused animals death. This incident also affected water supply of important cities like Tarragona.

The happening caused a heavy discussion between public opinion in which several institutions, inside and outside of the political ambit, proposed different theories about the causes that could have provoked the contamination. These were the following:

- Point dumping of pollutant by the nearby chemical industry.
- Death due to unusually low temperatures.
- Death due to thermal shock at the outlet of the refrigeration circuit in the Ascó nuclear power station.
- Resuspension of contaminated sediment of the reservoir's bottom as a consequence of a sudden change in atmospheric pressure.
- Sudden change in water pH.

In Table 1, aspects that question the likeliness of these explanations as a global interpretation of the incident, are discussed schematically:

Hypothesis 1: - Total amount of mercury (about 400kg) is too large to come from a point dumping. - Mercury can't disperse alone all over the reservoir. - No escape neither accumulation of dead fishes close to the factory were detected.
Hypothesis 2: - Affected fishes come from northern Europe and are adapted to low temperatures. Hypothesis 3: - Reservoir animals are used to the temperature change in that area. Hypothesis 4: - No sudden pressure change is observed in meteorological registers of those days. - Atmospheric pressure change doesn't seem a powerful enough mechanism to raise sediment form reservoir's bottom.
Hypothesis 5: - In any case, it seems a secondary fact that could have influence, but not the main reason of the problem.

Table 1. Hypothesis proposed to explain fish death

As none of these theories answers the question in a completely satisfactory way, another thesis was developed trying to take into account the following points:

- Large a amount of mercury.
- Uniform distribution of the contaminant over a wide area of the reservoir.
- Extraordinarily low temperatures.
- Existence of different kind of pollutants in reservoir bottom sediment.
- Possible change in water pH.

According to this, and principally due to the fourth of the exposed points, a mechanism able to resuspend sediment from the reservoir bottom that was also coherent with Flix boundary conditions was looked for. A density current is proposed to be such a mechanism, so this phenomenon is explained in the next section.

On the other hand, *in situ* observations by eyewitnesses encourage to think about the existence of a density current. Apparently, in spite of being clear days without rainfall or extraordinary flows, an unusual turbulence could be observed in water, with a colour that indicated relatively high concentration of sediment.

2 DENSITY CURRENTS

2.1 Theoretical frame

Density currents are a natural phenomenon that can be observed in lakes and reservoirs which causes that a coming flow penetrates in a differentiated way in the reservoir, usually due to a density difference between the incoming flow and the water in the environment. This

variation can be caused by a difference in sediment concentration, salinity or temperature. Therefore, it is possible that the denser water falls to the bottom, slips along it and may be able to resuspend the sediment becoming a turbidity current.
The following are the conservation equations which describe this phenomenon (Parker et al., 1986).

$$\frac{\partial h}{\partial t}+\frac{\partial Uh}{\partial x}=e_w U \qquad (1)$$

$$\frac{\partial Ch}{\partial t}+\frac{\partial UCh}{\partial x}=W_s\left(E_s-r_0 C\right) \qquad (2)$$

$$\frac{\partial Uh}{\partial t}+\frac{\partial U^2 h}{\partial x}=RgChS-\frac{1}{2}Rg\frac{\partial Ch^2}{\partial x}-u_*^2 \qquad (3)$$

$$\frac{\partial Kh}{\partial t}+\frac{\partial UKh}{\partial x}=u_*^2 U+\frac{1}{2}U^3 e_w-\varepsilon_0 h-RgW_s Ch-\frac{1}{2}RgChUe_w-\frac{1}{2}RghW_s\left(E_s-r_0 C\right) \qquad (4)$$

In these equations, h is water depth; U, C and K are respectively velocity, sediment concentration and turbulent kinetic energy, averaged over height; e_w, water entrainment coefficient (Pratson et al. 2001); W_s, sediment fall velocity (Pratson et al. 2001); E_s, dimensionless erosion coefficient; r_0, ratio between sediment concentration close to the bottom and the averaged value C; S, local slope; u_*, friction velocity (Parker, 1986); R. relative sediment density; ε_0, energy dissipation coefficient due to viscosity (Launder & Spalding, 1972).

2.2 Energy balance equation due to heat flux

Density difference needed to trigger a density current can be caused by different factors, as mentioned above. Circumstances that surrounded Flix incident, suggest that temperature difference between two water bodies could have been the cause in this case. Independently of the origin of the current, sediment resuspension can act as a feed-back mechanism as when colder water is moving along the bottom, sediment incorporation increases its density and therefore, difference between this and the one of the warmer water.

Relationship between water density and temperature is adjusted by parabolic regression, obtaining the following equation:

$$\rho=-0.064T^2+0.0416T+992{,}92 \qquad (5)$$

During the days of the incident, Catalonia was immersed in an extraordinarily cold weather, as is shown in the following table:

	Average temperature (ºC)	Minimum temperature (ºC)	Maximum temperature (ºC)
14.12.01	5.2	-0.2	9.1
15.12.01	-1.4	-3.1	0.3

16.12.01	0.1	-4.9	5.2
17.12.01	-4.7	-6.1	-2.7
18.12.01	-2.3	-5.4	0.3
19.12.01	0.1	-3.0	4.2
20.12.01	-0.1	-2.1	2.1
21.12.01	0.1	-1.4	2.8
22.12.01	-0.5	-1.9	2.5
23.12.01	-0.6	-2.0	1.2
24.12.01	0.9	-4.4	6.7
25.12.01	-3.6	-6.9	3.4
26.12.01	2.3	-6.3	10.7
27.12.01	6.9	-0.3	12.4
28.12.01	6.2	0.8	13.1
29.12.01	3.0	-1.1	10.8
30.12.01	7.3	1.0	13.6
31.12.01	7.1	3.0	11.1

Table 2. Temperature registration

According to these data, it could happen that after a sudden opening of Ribarroja reservoir floodgate, upstream from Flix, water could have got colder before arriving to the downstream reservoir of Flix, which would be at a higher temperature.

As the equations that described the phenomenon so far, did not take into account temperature, it was necessary to introduce a new balance equation related to heat flux. The expression proposed is the following:

$$\frac{\partial(\rho chT)}{\partial t}+\frac{\partial(\rho chTU)}{\partial x}=e_w U\rho_0 c_0 T_0+\rho_s c_s w_s\left(E_s-r_0 C\right)T^*+\left(k+\rho c v_T\right)\frac{\partial}{\partial x}\left[h\frac{\partial T}{\partial x}\right]+\varepsilon_0\rho h \tag{6}$$

In this equation, subscript “0” refers to environment water, “s” refers to sediment and magnitudes without subscript refer to density current itself. T* represents density temperature when $E_s - r_0 C$ is negative, whereas it refers to sediment when this term is positive. v_T is turbulent viscosity and k is water conductivity.

In the left side there are the local and convective variations of internal energy, ρchT, while in the right member there are the several terms that contribute to that variation, which are respectively:

- Water entrainment coming from the environment which is at a different temperature.
- Sediment entrainment coming from the bottom, which is at a different temperature.
- Heat diffusion, by conduction as well as turbulent viscosity.
- Heat dissipation related to viscosity

2.3 Applied methodology

The objective of the study was to carry out a numerical analysis of the phenomenon using a 1D model. The starting point was a previous program, BANG 1D (Pratson et al., 2001) used to solve the system formed by equations (1) to (4). To do so, equations as shown above, that is, in their eulerian form, are transformed into their lagrangian form developing local derivatives into total ones. In this way, the program sets a finite difference scheme that allows solving the system, obtaining its unknowns: height, velocity, sediment concentration and turbulent kinetic energy.

To study temperature evolution, equation (6) is also transformed into its lagrangian form and introduced in the program. In addition to that, several modifications were carried out mainly related to data output. The new version of the program was called BANG 1DT, and was used to obtain the results that are exposed in the following section. Computations carried out in this study did not consider the last two terms of the equation, as a more important influence of the other two was estimated. However, the implementation of the whole equation could be the aim of future investigations.

3 RESULTS

Next, main results obtained with BANG 1DT are shown. Before applying the model to Flix reservoir case, a qualitative study was carried out to analyze the influence of several variables in density current evolution, as initial speed, temperature difference, sediment concentration and slope.

3.1 Application to Flix reservoir situation

Therefore, Flix reservoir bathymetry is introduced in the model and density current behavior under different conditions of initial velocity, temperature and sediment concentration, is studied. Two different values of velocity were adopted (1,0 m/s and 3,0 m/s), and for each of them two different initial temperatures (4,0 ºC and 8,0 ºC). Then for each combination, three different initial sediment concentrations (0,0; 0,0002; 0,001 sediment volume/total volume) were tested. Next, eroding profiles for each pair of initial temperature and velocity are shown, and in each of them a comparison between the different values for initial sediment concentration (for initial velocity of 3,0 m/s, erosion is almost the same for the three initial sediment concentrations):

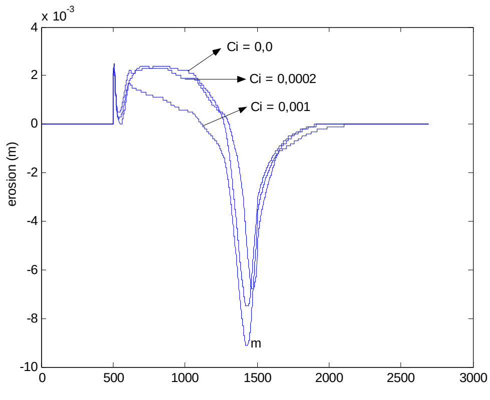

Figure 1. Erosion with initial temperature of 4,0ºC and velocity

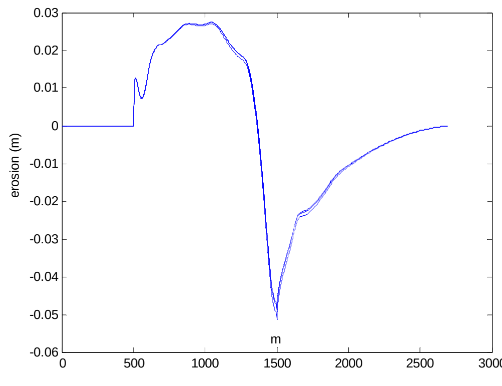

Figure 2. Erosion with initial temperature of 4,0ºC and velocity of 3,0 m/s

The influence of initial length of the density current over the erosion profile in Flix reservoir bathymetry was also studied. In the next figure there is a comparison between results for three different values of the initial length:

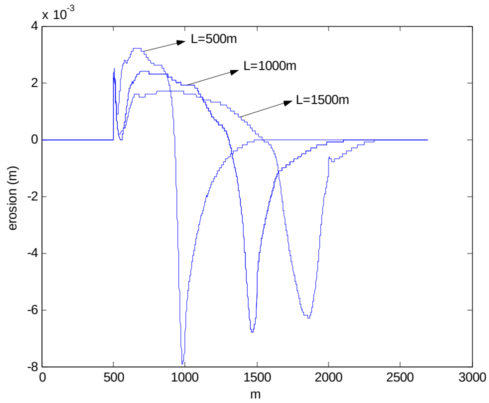

Figure 3. Erosion for different initial length

Concerning to total resuspended sediment volume, it increases with the initial length, although the highest local erosion is found for localized density currents.

Observation: due to the length of the available reservoir's bathymetry, the longest current introduced was of 2000 meters. However, it would be interesting to know the effect of the entrance of larger masses of cold water. Studies referred in this figure are useful just to obtain an idea about the qualitative behaviour of increasingly large density currents.

3.2 Contaminant mobilization

Starting from the shown erosion results, mobilized sediment volume can be estimated, multiplying the area of the previous graphics by the width of the current. No data about this point were available, so an estimated value of 30 meters was adopted, as this is the width of the most contaminated area. According to this, resuspended sediment volumes are the following:

Initial velocity (m/s)	Mobilized volume (m^3)
1,0	45
3,0	540

Table 3. Mobilized sedment volume

Figure 4 shows mercury concentrations (mg/kg) in Flix reservoir sediment:

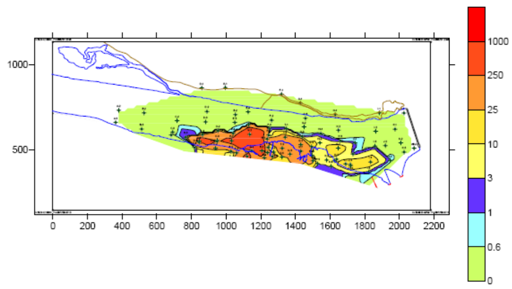

Figure 4. Mercury concentrations in Flix reservoir sediment

According to these data, an average value of 200 mg/kg can be adopted for the mercury concentration in the sediment affected by the current. Mobilized amounts of mercury for the previous cases are the following:

Initial velocity (m/s)	Mobilized mercury mass (kg)
1,0	23,85
3,0	286,2

Table 4. Resuspended mercury mass

These results are just estimation, and it is important to consider the possibility that a slower but longer and wider density current, may provoke similar sediment mobilization.

4 CONCLUSIONS

- A previous 1D model, BANG 1D (Pratson et al., 2001) has been modified to consider density currents due to temperature difference.
- An energy balance equation related to heat flux has been proposed.
- Initial current velocity is the most determinant parameter for sediment resuspension by a density current.
- When Flix bathymetry is applied, results show that the first part of the reservoir is eroded, while resuspended sediment is deposited in the second part of it. This areas depend on density current initial velocity.
- With a high velocity (3,0 m/s), eroded sediment volume is 540 m^3, which corresponds to a mobilized amount of mercury of about 300 kg which is similar to the number obtained starting from the concentrations found in the river.
- As initial density current length increases, the amount of mobilized sediment is larger.
- A density current could be the cause of sediment resuspension in Flix reservoir in 2001 event. Several signs indicate so: storms absence, low activity in hydroelectric stations, extraordinarily low temperatures during those days and the observation of high water turbidity by witnesses.
- Fishes death was the visual alarm, but mercury contamination of water supply net in Tarragona was the fact which caused the political immediate action about sediment removal.

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