IMPACT OF SUSPENDED SEDIMENT PROPAGATION AFTER THE HYPOTHETICAL FAILURE OF TAILINGS DAMS IN THE DOCE RIVER BASIN

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ABSTRACT – The collapse of tailings dams has caused severe socio and environmental consequences in Brazil. The last two major accidents (Fundão and Brumadinho Dams) alarmed the Brazilian authorities about the need of improvement on safety, contingency and remediation procedures. Based on the sediment transport measurements along the Doce River after the Fundão Dam collapse, the one-dimensional advection-dispersion equation with settling was developed, presenting satisfactory results for the propagation of the tailings along 570 km of the Doce River, including the effects of hydropower reservoirs. Further, it was validated in Paraopeba River, after the Brumadinho Dam collapse. This procedure is now applied to assess the potential impact of the hypothetical collapse of 51 tailings dams in the Doce River basin. The analysis quantifies the population that would be affected by severe water supply interruptions in the towns along the rivers. The simulation results show that tailings dams located in the Piracicaba basin, a Doce River sub-basin, have the highest potential to adversely impact the water supply of the downstream towns due to the tailings dams' features as volume stored and proximity with populated towns. Ultimately, the collapse of the four dams in this sub-basin could shut down the water supply for approximately 1.000.000 people.

Palavras-Chave – Barragens de rejeitos, Rio Doce, Transporte de sedimentos em suspensão

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1 - INTRODUCTION

Tailings dams collapse have been occurring in Brazil with undesirable consequences for society and for the mining industry sector. The disaster in Mariana in 2015, which caused the death of 19 people and an extended socio-environmental damage along the Doce River, was considered the worst environmental disaster ever occurred in the country (Marta-Almeida et al. 2016; Carmo et al. 2017). In terms of life loss, the Brumadinho dam failure was by far the most fatal accident, resulting in 270 life losses (Palu and Julien 2019b). Despite the relevance of this topic and recent advances in research about tailings dam failures, publications with concerns about the transport of the impounded material in natural channels after this kind of event are rare. Moreover, one should note that in some accidents the pollutant dispersion can extend the damage for hundreds of kilometers, as the case of Fundão Dam in Doce River and Baia Borsa and Baia Mare in Romania (Palu and Julien 2019a).

In general, after a tailings dam failure or spill, the magnitude of high sediment concentration and its consequences downstream, as contamination and interruption in water supply are unknown. Also, there is no knowledge about how many people one tailings dam can impact. Thus, the main objective of this paper is to simulate the hypothetical rupture of other tailings dams in the Doce River basin in order to map and classify the dams in terms of potential population impacted by water supply interruption.

2 - EVALUATION OF SUSPENDED SEDIMENT TRANSPORT AFTER A TALINGS DAM FAILURE

2.1 - Estimate of Spilled Volume after a Tailings Dam Failure

A simple and practical approach to estimate the spilled volume after the dam break is still to correlate the flood with dam parameters, as dam height and stored volume for instance (Lucia, Duncan, and Seed 1981; Rico, Benito, and Díez-Herrero 2008; Larrauri and Lall 2018). Rico et al., (2008) attained a reasonable agreement after correlating the tailings storage volume and the spilled volume using data from 21 accidents around the world. According to the authors, the relationship between the waste outflow volume V_F (which includes tailings and water) and the impoundment volume V is equal to:

$$V_F = 0{,}354V^{1{,}01} \quad (1)$$

Another equation given by Rico et al., (2008) is the flood peak discharge as the product of the dam height H (m) and the spilled volume V_F(10^6m^3).

$$Q_{peak} = 325(HV_F)^{0{,}42} \quad (2)$$

2.2 - Modeling the Propagation of Tailings along the River

An example of expressive river contamination is the case of Fundão Dam in 2015. The analysis and processing of collected data presented by Palu and Julien, (2019a), showed that the transport of suspended tailings along the whole extension of the Doce River was properly modeled using the concept of continuity applied over the suspended sediment, which is given by the one-dimensional advection-dispersion equation with settling. This model was further validated in Paraopeba River simulations after the Brumadinho Dam collapse (Salles and Saliba 2020). Thus, the continuity equation is given by:

$$\frac{\partial C}{\partial t} + U\frac{\partial C}{\partial x} = K_d\frac{\partial^2 C}{\partial x^2} - kC \tag{3}$$

Where C is the sediment concentration, U is the cross-sectional averaged flow velocity, K_d is the longitudinal dispersion coefficient and k is the settling rate or rate of sediment deposition. This equation can be solved numerically using a finite-difference approach through the Crank Nicolson scheme (Chapra 2008).

$$\begin{aligned} -C_{j-1}^{n+1}\left(\frac{C_{as}}{4} + \frac{C_{ds}}{2}\right)_j^n + C_j^{n+1}\left(1 + C_{ds} + \frac{k\Delta t}{2}\right)_j^n + C_{j+1}^{n+1}\left(\frac{C_{as}}{4} - \frac{C_{ds}}{2}\right)_j^n \\ = C_{j-1}^{n}\left(\frac{C_{as}}{4} + \frac{C_{ds}}{2}\right)_j^n + C_j^{n}\left(1 - C_{ds} - \frac{k\Delta t}{2}\right)_j^n - C_{j+1}^{n}\left(\frac{C_{as}}{4} - \frac{C_{ds}}{2}\right)_j^n \end{aligned} \tag{4}$$

Where C_j^n refers to the suspended sediment concentration at the cross section j and in the time level n in the computational grid. In addition, C_{as} is the Courant number and C_{ds} is the diffusive Courant number, given by:

$$C_{as} = U\frac{\Delta t}{\Delta x}\ , C_{ds} = K_d\frac{\Delta t}{\Delta x^2} \tag{5}$$

Where Δx is the distance between each cross section and Δt is the time step. The observed concentration along the Doce River showed that the longitudinal dispersion coefficient K_d ranged from 30 to 120 m^2/s, which are in agreement with data from 50 rivers in USA and New Zealand (Palu and Julien 2019a). Moreover, among the existent empirical expressions for the calculation of this coefficient, the equation developed by Kashefipour and Falconer (2002) presented the best agreement with both, the literature and the Doce River data (Palu 2019).This equation is function of hydraulic parameters as shear velocity u_*, flow depth h, and flow velocity U:

$$K_d = 10{,}612(U/u_*)hU \quad (6)$$

Moreover, the shear velocity can be calculated as:

$$u_* = \sqrt{gR_hS_f} \quad (7)$$

In addition, the sediment settling rate k can be calculated by:

$$k = \frac{\omega_i}{h} \quad (8)$$

where ω_i is the fall velocity for the sediment fraction i, which is given by:

$$\omega = \frac{8\upsilon_m}{d_s}[(1 + 0{,}0139d_*^3)^{0,5} - 1] \quad (9)$$

where υ_m is the kinematic viscosity of a mixture, d_s is the particle diameter and d_* is the dimensionless particle diameter, written as:

$$d_* = d_s\left[\frac{(G-1)g}{\upsilon_m^2}\right]^{1/3} \quad (10)$$

Where the specific gravity G is the ratio between the specific weight of a solid particle and the specific weight of fluid at a standard reference temperature. At a reference temperature of 4ºC, the specific gravity of quartz particle is equal to 2,65. According to the data analysis, along the whole extension of the Doce River the sediment settling could be related with the particle size from 1,1 to 2 μm, which corresponds approximately to $\sim d_{15}$ (1,5 μm) of the fine sediment stored at the Fundão Dam. As the tailings propagated along the Doce River, they crossed four hydropower reservoirs: Candonga Dam, Baguari Dam, Aimorés Dam and Mascarenhas Dam. The observed data showed that the decay of sediment concentration due to settling in a reservoir can be modeled by the expressions given by Julien (2010):

$$C_i = C_{oi}e^{-kt} \quad (11)$$

Where C_i and C_{oi} are the downstream and the upstream concentration respectively, t is the time elapsed for the suspended sediment cross the reservoir and the settling rate k, given by Equation (8) considering the flow depth and flow velocity in the reservoir.

3 - MODELING THE SUPENDED SEDIMENT PROPAGATION AFTER THE HYPOTHETICAL COLLAPSE OF TAILINGS DAMS IN THE DOCE RIVER BASIN

3.1 - Doce River Basin

The Doce River basin has a drainage area of 82.600 km^2, with most of the area located in the state of Minas Gerais (86%), and the remaining in the State of Espírito Santo. The main river is the Doce River, comprising an extension of 570 km and flowing then to the Atlantic Ocean. There are 225 towns in the Doce River basin, which corresponds to a population of approximately 3.6 million inhabitants (ANA 2016b). The current study considers data of 51 tailings dams in the Doce River basin which are enrolled in the Dam Safety National Plan (ANM 2019). For all these dams available data are: location, geographic coordinates, type of ore stored, stored volume, dam height, dam type (upstream, downstream or centerline), risk category and associated potential damage, both classified as low, medium or high (ANM 2019).

3.2 - Model Description

The empirical expressions to estimate the spilled volume after a tailings dam collapse [Equations (1) to (2)] and the suspended sediment transport model previously developed after the Fundão Dam accident [Equations (3) to (11)] are now combined to simulate the hypothetical collapse of tailings dams and propagation of the sediment (tailings) along the Doce River basin. The goal is to quantify the impact of each dam in terms of the population affected by the interruption in water supply. After a hypothetical tailings dam failure, the resultant sediment pulse is propagated in the main tributaries using the solution of the advection-dispersion equation. Then, the operation limit of water treatment plants, estimated in 5,000 NTU (Chang and Liao 2012), is converted from turbidity through the relationship obtained along the Doce River measurements. Accordingly, the relationship between suspended sediment (SS) and the turbidity (NTU) was SS/NTU ≈ 0.5 (Palu and Julien 2019a), which results in a maximum concentration equal to 2,500 mg/l. Therefore, the towns located around the rivers where the sediment concentration is equal or exceeds 2,500 mg/l are considered affected, since the conventional water treatment is hindered. Figure 1 illustrates the processes simulated in the proposed model. One should note that the sediment is not considered toxic, since most of dams in Doce River basin store tailings similar as those in Fundão Dam.

The population affected by the water supply interruption was counted considering the geospatial data of the Brazilian Institute of Geography and Statistics (IBGE 2010), processed in Arc Map 10.1.

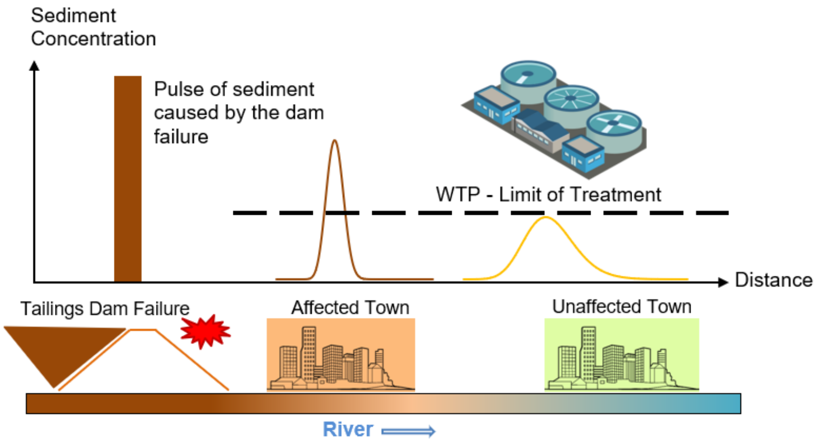

Figure 1 – Scheme of the sediment propagation after a hypothetical tailings dam failure

Considering that flood hydrograph after the dam break has a triangular shape, the time for the spill of the stored material can be approximate to:

$$t_{spill} = \frac{2V_F}{Q_{max}} \tag{12}$$

Then, substituting the empirical equations (1) and (2) into (12), one can obtain the time of spill t_{spill} in seconds:

$$t_{spill} = 3369{,}5\frac{V^{0{,}59}}{H^{0{,}42}} \tag{13}$$

Where V is the total impoundment volume in hm^3 and H is the height of the dam in m. In addition, to simulate the hypothetical failure of the tailings dams in the Doce River basin the following assumptions are taken into account:

1. The collapse of a tailings dam results in a pulse of sediment in the nearest stream, which time duration is function of the stored volume and the dam height, as given by Equation (13).
2. The concentration of the suspended sediment after the spill is adopted equal to 1,500,000 mg/l, which is equivalent to volumetric concentration of ≈46%, and corresponds to the maximum concentration estimated immediately downstream of Fundão Dam after the collapse (Palu 2019).
3. The propagation of the sediment pulse after the tailings dam collapse can be calculated through the one-dimensional advection-dispersion equation, i.e. Equation(3), which is the theoretical approach presented in the literature for the calculation of fine sediment propagation (Julien 2018) and validated with the measured data along the Doce River after the Fundão Dam collapse and with data in Paraopeba River after the Brumadinho Dam collapse (Salles and Saliba 2020).

4. The longitudinal dispersion coefficient K_d can be calculated through Equation (6).
5. The settling rate along the rivers is given by Equation (8) assuming a representative particle size is equal to 1,5 μm, which is the average particle size correspondent to the observed settling rate along the Doce River and corresponds approximately to d_{15} of the finer material stored at Fundão Dam. The water temperature was adopted to be equal to 25ºC.
6. As a simplification, the pulse propagates at a constant velocity of 1 m/s (one should consider that the fine sediment is carried by flow velocity rather than the floodwave celerity) with Manning's coefficient equal to 0,035, which is a common roughness value in rivers (Julien 2018).

The length and slope of the river reaches are obtained using the Doce River basin DEM data with spatial resolution of 10 m (Geonetwork 2007). The data was processed in Hydrology Tool (Spatial Analyst Tool) in ArcMap 10.1. This procedure allowed the measurement of length and slope of each stream, starting from the nearest creek going to the next tributary and finally to the Doce River. The finite difference method using the Crank Nicolson numerical scheme [Equation (4)] was used to solve the advection-dispersion with settling, the numerical simulation was implemented using Matlab R18. The grid analysis was carried out considering features similar of those observed in the Doce River, i.e., a high concentration sediment pulse propagated considering a flow velocity of 1 m/s and depth of 1m. After a grid analysis, the adopted mesh was equal to Δx = 250 m and Δt = 300 s since the improvement on the results was negligible with finer grids.

7. As observed in the Doce River, there will be hydropower reservoirs along the path of the contaminated waters. Thus, to consider the effect of the reservoirs over the suspended sediment propagation Equation (11) can be applied, which presented satisfactory results with the observed concentrations along the Doce River.
8. Flow velocity in every reservoir was adopted equal to 0,15 m/s and the representative particle size for the calculation of the settling rate equal to 7 μm. Those values are the average observed values in the Doce River reservoirs (Baguari, Aimorés and Mascarenhas) after the Fundão Dam collapse. Data of the hydropower reservoirs in the Doce River basin are presented in Palu (2019).

3.3 - Results

The numerical simulation result provides the classification of the tailings dams in the Doce River according to the potentially affected people by the interruption of water supply, as shown in Figure 2. The numerical model reproduced the propagation of the high sediment concentration along the rivers due to the hypothetical spilling caused by the collapse of each dam. After that, the maximum sediment concentration in the main river nearby the towns is compared with the water treatment limit. When the limit is exceeded the population is considered affected and counted.

According to the results, the region where the dams have the highest potential impact is the Piracicaba River sub-basin, with an area of 5.400 km². There are 31 dams in this sub-basin, which are prone to affect more people due to factors as: stored volume, proximity with populated towns and existence of only small hydropower reservoirs (reduced capacity to trap sediments). One should note that each dam in this basin can affect at least 500.000 people. Furthermore, in this basin there are four dams with potential to affect the water supply for a population between 750.000 to 1.000.000 people.

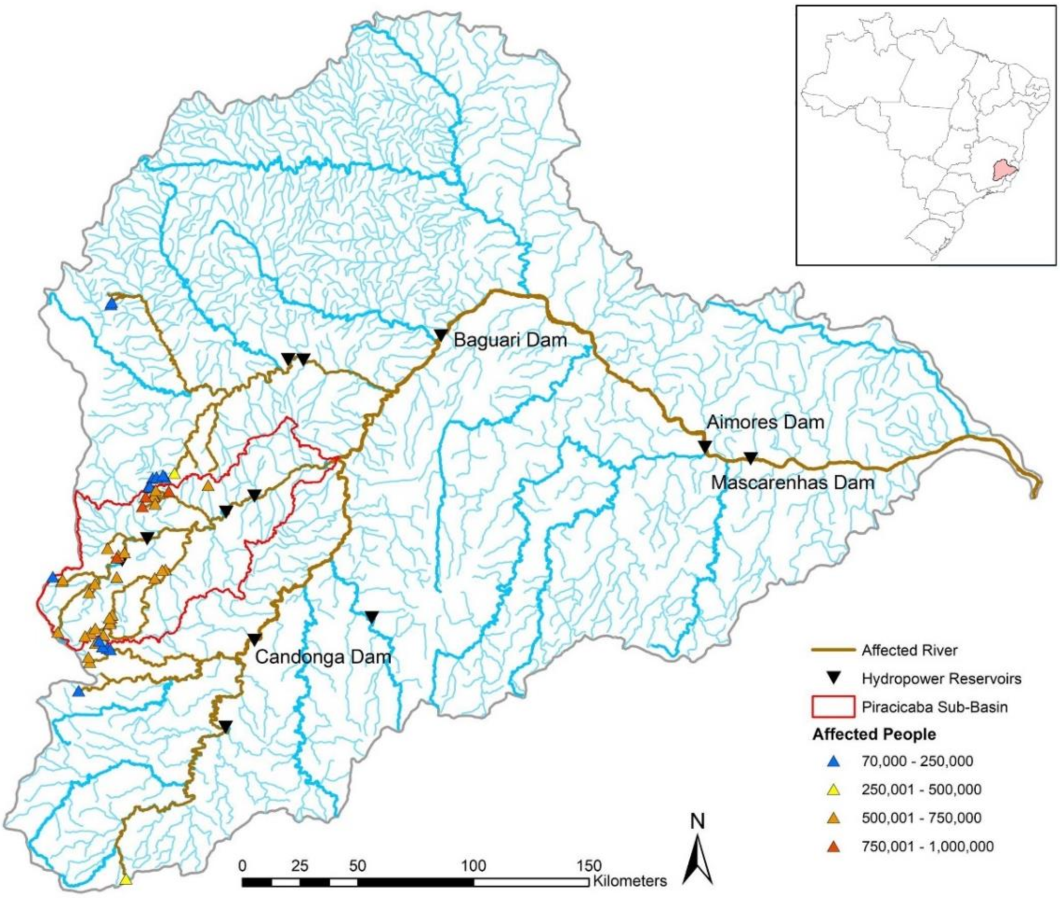

Figure 2 –Tailings dam classification according to the number of potentially affected people

The vulnerability of water supply systems in the towns in Piracicaba sub-basin and downstream is highly susceptible by the dam failures or spills. Thus, the provision of alternative sources of potable water, as ground water, the split of the water supply system in different rivers (in case the main river is contaminated) and pipelines communicating the water supply systems between the towns could be solutions to mitigate the impact of the tailings dam failures in the affected towns. In addition, the results herein obtained can be applied to compose the classification of the dams on a risk analysis, contribute to the management of water resources and contingency plans in this basin, especially in terms of water supply in affected communities.

4 - CONCLUSION

Recent advances in numerical modeling of tailings dam break enable the simulation of the hypothetical collapse of several tailings dams along the Doce River and its consequences downstream in terms of water supply interruption. The simulation herein presented considers that the failure of the dams would have caused a sediment pulse in the streams located immediately downstream. Propagation of the suspended sediment is calculated through the application of the advection-dispersion equation with settling, solved numerically using the finite difference method with Crank Nicolson scheme in the river reaches and the sediment settling equation in the reservoirs. The determination of the equation parameters is based on the observations on Doce River after the Fundão Dam collapse and validated in the Paraopeba River after the Brumadinho Dam accident. Simulation results show that the tailings dams located in the Piracicaba River sub-basin have the highest potential to disrupt the water supply of several cities along the Doce River. All the thirty-one dams located in this sub-basin have individually the potential to adversely impact at least half million people. Ultimately, the collapse each one of four specific dams in this sub-basin could affect almost one million people. Finally, the results obtained can contribute in a risk analysis and give support to the water resources managements and contingency plans in this basin, especially in terms of water supply in affected communities.

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