Assessment of Reservoir Sedimentation and Mitigation Measures: A Case Study of Palo Redondo Reservoir

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ABSTRACT

The accelerated sedimentation of the main Peruvian reservoirs has caused losses of the useful storage capacity that significantly affects the water allocation to the different users. This research aims to evaluate the sedimentation risk of Palo Redondo Reservoir of the Chavimochic hydraulic system, located in La Libertad region of Peru's northern, proposing alternatives to reduce its impacts. The reservoir was designed for a total capacity of 400 MCM, however, it is likely that in the future it has an accelerated sedimentation problem due to the high erosion of the Santa River Basin and because of its water uptake system whose sand trap has an efficiency less than 75%. The methodology includes the modeling for the prediction of stream flow and sediment yield in the Tablachaca sub-basin which is a critical drainage area of the Santa River Basin, using the soil and water assessment tool (SWAT). Likewise, it includes the modeling of sediment yield in the Palo Redondo small sub-basin using the kinematic runoff and erosion model (KINEROS). It could be activated during the occurrence of the El Niño phenomenon causing maximum discharges with high rates of sediment transport to the reservoir. The SWAT calibration results show a good model performance with NASH coefficients greater than 0.6 for flow rates and sediment concentrations, respectively. On the other hand, the land cover change in Tablachaca sub-basin shows a significant reduction in erosion rates and, therefore, a significant reduction of sediments towards the Palo Redondo Reservoir.

Key words: Sedimentation, Palo Redondo reservoir, SWAT modeling, Santa River.

INTRODUCTION

The largest dams in Peru have been affected by a more accelerated sedimentation than estimated in their designs. The references of premature collapse, as consequence of the high potential of soil erosion of the Pacific basins, suggest not to build large dams in basins under these hydrological characteristics (Rocha 2006; Ortiz et al. 2015). Unless rigorous basin management and sediment control programs are implemented; preferably a little earlier or at least at the same time as the physical execution of the project.

Therefore, the construction of the Palo Redondo Dam, part of the third stage of the Chavimochic project, which captures waters from the Santa River basin, located on the Pacific Coast, has been the subject of huge discussion in the last decades. Rocha (1999) indicates that the amount of sediment estimated to reach Palo Redondo would be very high due to the large production of the basin and the deficient Chavimochic sand trap.

Given this, it arises as a question, whether the performance of the future Palo Redondo Dam

will be adequate or will suffer a premature collapse due to excessive sedimentation as occurs with dams of similar characteristics. Specifically, ¿What will be the sediment rates that will enter the Chavimochic system? ¿What structural measures can be implemented to reduce the amount of sediment that reaches the reservoir? ¿What are the methods of watershed management and in what areas of the Santa river basin should they be applied to decrease the rate of sediment production in the basin?. Therefore, this research aims to evaluate the sedimentation risk of Palo Redondo reservoir of the Chavimochic hydraulic system, located in La Libertad region of Peru's northern (Figure 1), proposing alternatives to reduce its impacts. Figure 1 shows the location of the study area, including the main hydraulic infrastructure of the Chavimochic Project (Intake, Sand trap, Dam); as well as the control stations that will feed the dam where we can estimate the amount of sediment that will accumulate in the Palo Redondo Reservoir.

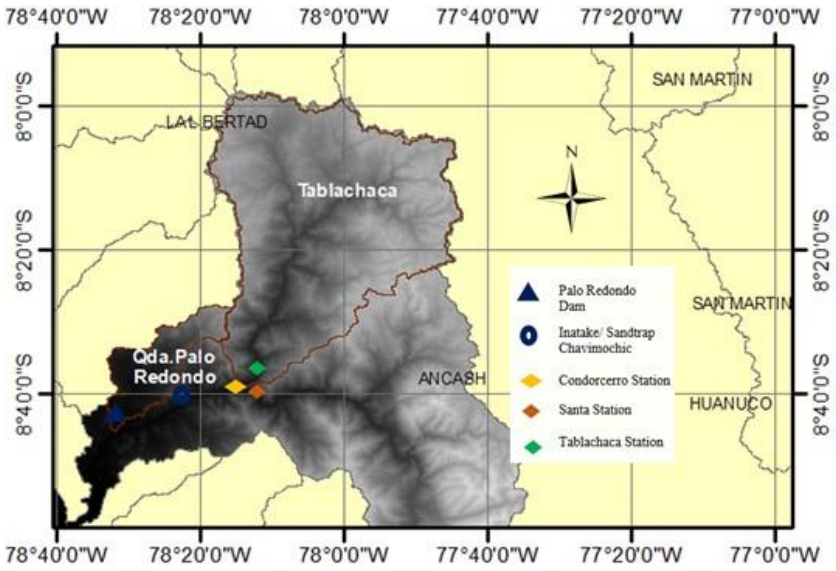

Figure 1. Location of study area

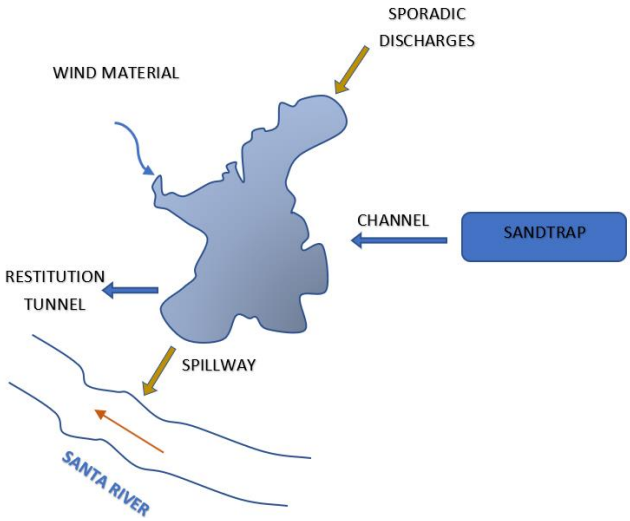

Figure 2. The Palo Redondo Dam System (PECH, 2013)

METHODOLOGY

Assess the potential causes and consequences of sedimentation of the future Palo Redondo reservoir

The state of the two largest dams in Peru was studied, with problems of accelerated sedimentation: Poechos and Gallito Ciego. This allowed identifying the risks to which the Palo Redondo Dam is exposed. Likewise, the analysis of the Palo Redondo Dam System allowed identifying the origin of the solids that will be deposited in the reservoir. Figure 2 shows the solids that will enter to the reservoir come from the feeding channel, the sporadic discharges from the Palo Redondo Stream and the wind material. In this research, the sediment production was analyzed taking account the first two causes previously mentioned because of they are the ones with the greatest impact.

Assess the sediment production in the Palo Redondo sub-basin under extreme events proposing structural control measures

The study of the Palo Redondo sub-basin allowed to characterize it as a dry sub basin with scarce rainfall, but with probability of extraordinary events with serious consequences such as those caused by the El Niño Phenomenon (1983, 1998 and 2017). Therefore, the probable maximum precipitation was analyzed, as well as the resulting liquid and solid hydrograph considering a Type II rainfall distribution, by means of the Kineros model. For the delimitation and descretization of the sub-basin in Kineros Model, the Palo Redondo DEM (Digital Elevation Model) obtained from the MINAM Geoserver was required. It has a spatial resolution of 30 meters and it was projected in the 17S zone.

The model parametrization was done using the FAO soil type maps, as well as the map of use and land coverage obtained from the MINAM (2015), which was reclassified for its interpretation in Kineros under the NALC category.

Assess sediment production in critical areas of the Santa River Basin

In order to determine the areas with the greatest sediment contribution, it was necessary to analyze the Condorcerro station and two stations upstream: Tablachaca and Santa. Studies carried out by Morera (2011) and the PECH (2010), had previously determined the water and solid contribution of the mentioned stations between 2000 and 2010. It was concluded that the Tablachaca sub-basin contributes about 57.7% of the total suspend solids of the Santa River Basin (Morera, 2011).

Consequently, it was decided to analyze the sediment production in the Tablachaca sub-basin using SWAT as modeling tool. The configuration of the model, projected in the 18S zone, required a DEM, vegetation coverage map and soil type map for the Tablachaca sub-basin. It included the rainfall analysis of the stations available in the study area. In this regard, it was found that historical rainfall data were very scarce, which is why we worked with data from the PISCO tool (Peruvian Interpolate data of the SENAMHI's Climatological and Hydrological Observations), which combines data observed of weather stations and remote sensing data. It includes records of precipitation since 1981.

Likewise, the model calibration is developed thanks to the flow and sediment concentrations records of the PECH (Proyecto Especial Chavimoch) for the Condocerro y Tablachaca stations. Calibrating the model involved both quantitative and qualitative evaluation of the hydrologic

response of each subcatchment (Ingol and Mckinney 2013). This was carried out by comparing monthly observed and simulated streamflow at the outlet of the subcatchment, as well the monthly observed and simulated concentrations. The SWAT calibration results show a good model performance with NASH coefficients greater than 0.6 for flow rates and sediment concentrations, respectively. In addition, five alternative scenarios were proposed to the current land coverage of the sub-basin, which were also analyzed using the SWAT model in order to compare changes in solid and liquid flows. The first scenario reflects the current situation of the Tablachaca basin based on the vegetation map of the MINAM in 2013. The second scenario reflects an ecological improvement in the areas with Andean pajonal and shrubland bog, changing its status from poor to medium. The third scenario improves the conditions of the previous scenario to show the results of a high ecological status. The fourth scenario increases forest plantation in desert areas with insufficient vegetation cover. The fifth scenario takes into account all the previous improvements, increasing the forest plantation by up to 20%, compared to the first scenario, considering its development in the areas of greatest erosion danger in the basin.

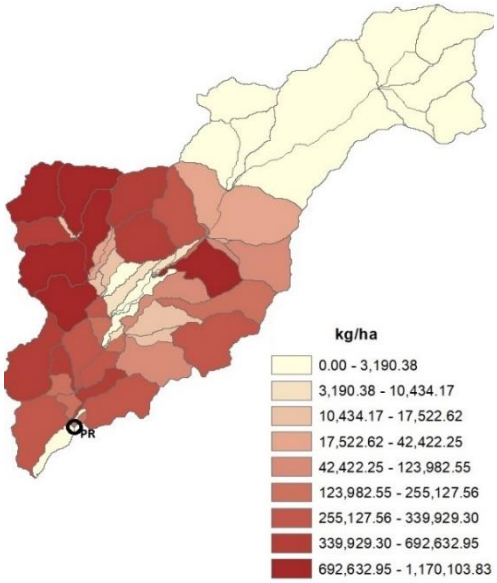

Figure 3. Erosion map of the Palo Redondo sub-basin

RESULTS

Erosion map of the Palo Redondo sub-basin

Figure 3 shows the erosion of the Palo Redondo sub-basin that would cause a storm type SCS II, simulated by Kineros model, being able to identify that the area's most prone to erosion are the closest to the area of the reservoir.

Volume of suspended sediments caused by storm

Table 1 shows results of the simulation for the total sediment rate and according to each particle size. In addition, the average specific weight of the sediment load, the total sediment load and the total volume of sediment were estimated. To estimate the sediment load, it was

considered that the PMP would only produce precipitation in 80% of the basin as suggested by PECH (1990). The results indicate an average specific weight of 1.17 Ton / m^3, which suggests a torrential flow (Costa 1988). In order not to overestimate or underestimate the results as well as considering that the Type II curve represents storms in Peruvian Coast, only the volume obtained by the Type II hietogram was considered; likewise, it was valued that only 2 storms of such intensity would occur during the reservoir lifetime. As result, it has been estimated a total of 6.62 MCM of sediments that would reach the reservoir due to two storms in the Palo Redondo sub basin.

Table 1. Volume of sediments caused by storm

Sediment	Rain Type II		
	Rate of sed. (Ton/ha)	Sed. (%)	ϒ (Ton/m^3)
Sand	25.26	20	0.30
Silt	77.03	62	0.74
Clay	22.17	18	0.13
Total	124.46	100	1.17
Ton			3,883,255
1 tormenta (MCM)			3.31
2 tormentas (MCM)			6.62
3 tormentas (MCM)			9.93

Erosion map of the Tablachaca sub-basin

Figure 4 shows the erosion of the Tablachaca sub basin, being able to identify the high rates of erosion in each sub-basin that lead to the average rate of 364 Ton / ha.

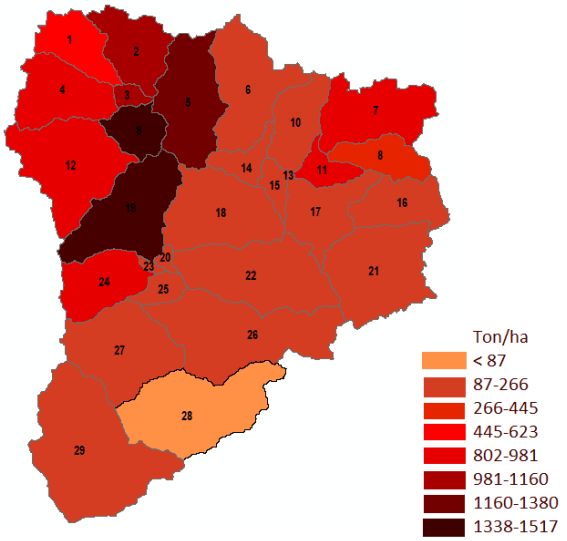

Figure 4. Erosion map of the Tablachaca sub-basin

Erosion rate of each scenario

The results in Table 2 shows a low decrease in sediment production between Scenarios 3 and

4, which could suggest that Scenario 4 be discarded. However, it is known that not all sediments are moved by the river, and that will not be important those with diameters greater than 20 mm (gravel) because the Chavimochic Intake will prevent the entry of them. That is the reason why the most important analysis is the concentration of suspended sediments.

Table 2. Erosion rate of each vegetation cover scenario in the Tablachaca sub-basin

Scenario	Rate of Potential Losses (Ton/Ha/Year)	Average Erosion Rate (Ton/Ha/Year)	Decrease (%)
Esc-1	364.17	32.78	
Esc-2	314.67	28.32	14
Esc-3	289.02	26.01	21
Esc-4	280.89	25.28	23
Esc-5	233.55	21.02	36

Dead volume in the Palo Redondo dam for each proposed scenario

For each of the Tablachaca scenarios, the SWAT model was performed and the relationships between flows and concentrations were analyzed to proceed with the calculation of the sediment volume carried from the Condorcerro station that would accumulate in the Palo Redondo Dam.

Table 3. Relationship between flows and concentrations for each coverage scenario in Tablachaca Sub Basin

Scenario	Equation (C,Q)	R^2
Esc1	$C_{tab1} = 0.078 * Q_{tab1}^{0.85}$	0.98
Esc2	$C_{tab2} = 0.083 * Q_{tab2}^{0.87}$	0.98
Esc3	$C_{tab3} = 0.077 * Q_{tab3}^{0.86}$	0.97
Esc4	$C_{tab4} = 0.069 * Q_{tab4}^{0.86}$	0.97
Esc5	$C_{tab5} = 0.065 * Q_{tab5}^{0.84}$	0.98

With the expressions indicated in the previous table, and the additional considerations regarding the designs of the hydraulic system Chavimochic, the volumes presented in Table 4 were obtained. It also includes the percentage in which the volumes of each scenario are reduced with respect to the Scenario 1. If both Table 4 and Table 2 are compared, there is a clear relationship between the erosion rate of the Tablachaca sub-basin and the volume of solids that will settle in the dam. Also, the relatively low decrease between scenarios 3 and 4 is maintained.

Table 4. Volume of solids originated by the feeding channel for each scenario

Scenario	E=35% VMcanal	Decrease (%)	E=53% VMcanal	Decrease (%)	E=64% VMcanal	Decrease (%)
Esc-1	88.4		63.9		48.1	
Esc-2	78.6	11	56.8	11	43.2	10
Esc-3	72.7	18	52.5	18	39.9	17
Esc-4	68.9	22	50.6	21	38.3	20
Esc-5	59.4	33	43.0	33	32.5	33

CONCLUSIONS

The Palo Redondo dam can receive sediments caused by the activation of the Palo Redondo stream and by the constant discharges of the feeding channel, which depend on the Santa river basin and the Chavimochic catchment system. On the one hand, the greatest risk in the Palo Redondo Dam would be the activation due to a severe El Nino Phenomenon that will causes a large amount of inputs of mud flows to the dam. It is estimated a total of 6.62 MCM of solids produced due to storms in Palo Redondo sub basin. On the other hand, the Santa River basin has been identified as one of the most erosive in Peru, with an annual degradation of more than 20 Ton / ha / year and an erosion reaching 57 Ton / ha / year for heavy rain years. To give an idea of the alarming nature of this situation, it can be mentioned that the Catamayo-Chira basin (which contributes to the solid and liquid flow of the Poechos dam) has a specific erosion of 13 Ton / ha / year.

In addition, according to INADE (2002) 80% of the suspended particles of the Santa River are less than 0.15mm, therefore the Chavimochic Project sand trap only acts fully on 20% of the incoming material. Consequently, for the third stage of the Project, the same PECH estimates the efficiency of the sand trap in 50% while Rocha estimated in 32%. It is concluded that the Project has a poor collection and purge system that will make the dam susceptible to the large amount of sediments produced by the Santa River basin. When analyzing Tablachaca sub basin, the most erosive catchment, an annual production of 364 Ton / ha and a CES of 9.2% were estimated which results in an annual average erosion rate of 31.6 Ton /he has. This high values indicates that in order to decrease the average sediment rate produced by Tablachaca it is necessary to work directly in the management of this sub basin using structural and nonstructural measurements.

Furthermore, some land coverage scenarios were set up and simulated in SWAT as alternatives to reduce erosion in Tablachaca sub basin. The analysis of these scenarios was carried out through the calculation of the sediment volume coming from the feed channel under three average efficiencies of the sand trap. The results indicate that the erosion rate of the sub-basin can be reduced considerably, decreasing the concentrations of suspended sediments that would reach the Palo Redondo dam. However, it is advisable to carry out a rigorous analysis of the cost of the measures to be implemented under scenarios 3 and 5, so that these scenarios can be evaluated in relation to doing nothing.

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