MODELING EROSION AND LANDSLIDES AS SEDIMENT SOURCES TO ASSESS DAM SILTATION

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ABSTRACT: Dams and water reservoirs represent key assets for water supply to people and electric power generation, worldwide more than 16% of electric energy is produced via hydropower and this percentage is going to raise in the next years. However, dams are vulnerable to degradation in capacity and safety due to the deposition of solid material inside the reservoir; this process, called siltation, is well known but often not enough considered in new projects design. Siltation affects both the functionality of dams, reducing the reservoir volume for water storage, both their safety increasing pressure on the dam body, limiting the lamination capability and the possibility to maneuver the deep drains. Thus, study and assessment of siltation arise as a crucial aspect of a dam system management and should not only be focused on quantifying sediments reaching the reservoir but mainly in understanding the causes and the processes feeding the river with solid material. Landslides hitting the watersheds provide huge amount of sediments to the drainage networks, this contribution adds to the slopes erosion due to rainfalls and build up, together with other minor processes, the total amount of solid material moving in the basin. Authors present a study about an Alpine dam, in Italy, whose basin have been analyzed to simulate the prevalent processes producing sediments. Slope erosion, active faults and diffuse landslides have been separately modeled to assess their contribution to dam siltation; results are critically discussed thanks to the exceptional availability of real data on annual sediment volume accumulated in the reservoir. This key information allowed to test models ability to predict silting ratio of the dam as a function of annual climate and thus to develop a tool for silting ratio estimate in reservoirs.

Keywords: Siltation, Erosion, Dams, drainage network

INTRODUCTION

Sediment production, movement and storing are key points in a watershed management and analysis. The life cycle of sediment is linked to a variety of processes, mainly natural, that take place in a basin and deal with sediment being eroded and transported along watercourses. Sediment yield is therefore a natural process that cannot be arrested or controlled but, anyway, its knowledge is crucial for a smart management of dams and reservoirs. At world scale dams are at the base of clean energy production and water storing both for human and agriculture purposes, more than 16% of electric energy worldwide is produced via hydropower (IEA, 2014). Moreover, sediment production and transport is the cause of fertile soil loss and pollutant transport. Sediment presence in reservoirs not only affect the economical effectiveness of the plants, limiting the water storage, but also worsen the stability condition of the dam, increasing the pressure on the upstream side and in extreme cased preventing the operability of drains and thus the safety of the reservoir itself. All the material produced and transported to the reservoir needs to be removed to maintain the design functionality of the structure. Removal of sediments poses different challenges from economic, environmental and technical points of view. Sediments can contain pollutants washed from slopes by rain and thus many countries force dam managing societies to treat them as waste. This mean that there is need to collect them and store them in dumps. Laws generally forbid any possibility to discharge them in the downstream river, at least for material that has already settled in the reservoir; therefore collection should be done mechanically and results

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in enormous costs linked both to material transport and to the out of service time of the dam.

All this facts want to highlight the consequences of a process that is often neglected or underestimated in reservoir design, to deeply estimate the impact that sediments have on dam management, the costs and losses related to them, is necessary to understand the phenomena and processed that produce and route sediments inside the streams.

INTEGRATED MODELLING

Estimating the amount of sediments reaching a reservoir is not a simple task. A variety of processes are involved and have to be understood and simulated separately and in their reciprocal interactions. To accomplish this task an integrated modeling is necessary and prior to it an accurate investigations of the processes involved. Since sediment life is being eroded, transported along slopes and then entering the drainage system a first attempt to create a model leads to a division between sediment erosion, slope movements and stream transport.

Sediment production is due to different sources both concentrated and scattered in the basin, a brief analysis of sources is necessary to introduce their modeling; among scattered sources slope erosion, little debris flows, fault zones and bank erosion are the main ones. Concentrated sources are mainly due to large or medium landslide that are worth single modeling. The model integration is the key to link slope erosion and landslide movements to the solid transport in rivers.

Geological and hydraulic models work on different scales, both temporal and spatial. If the temporal coupling could appear quite complex also spatial coupling poses different challenges. From a spatial point of view geological models works at basin scale for scattered processes and local scale for concentrated sources. On the other hand hydraulic models work on single stream reaches and need input data at the model starting point. Since geological model consider, in a simple way, the routing of sediments towards the outlet of the basin and the hydraulic models cannot work on too large scales, due to numerical limitations, usually a break point is introduced, as in Radice et al., 2012. A break point is a carefully chosen point that is assumed as the point where geological models compute their output, immediately fed as input data to hydraulic models. This hypothesis allows for a simple and effective connection between the two kinds of simulation.

The second problem to be solved is due to different time scales of models. Usually geological models work at yearly scale, common for scattered events, or events scale, common for single process simulation. Hydraulic models work at event scale, thus an integration is needed; different approaches can be considered and all need to downscale yearly production ratio to event scale volumes.

Geological processes and models

The main geological processes involved in sediment production will be hereby described along with their more diffuse models, to give a general insight before focusing on a case study.

Slope erosion is the most scattered process, since it takes place in every point of the basin. Many models have been developed during years to calculate the sediment yield due to erosion. Basically, erosion is due to rain drops impacts on the terrain that dethatch terrain particles, winning bounding forces, and wash them away by water flow. Models simulating erosion are usually divided into two main groups: physically based and empirical. Since physically based models are developed for limited extents, where parameters variability can be controlled, they have been discarded for basin application: the amount of data and time to gather them would be too large and costly to be of any use. The focus is moved on empirical and semi empirical models. The most common empirical models are USLE (Universal Soil Loss Equation) (Wischmeier and Smith, 1978) and its derived models RUSLE (Revised USLE, Renard et al, 1991) and MUSLE (Modified USLE). All these models have been developed for cultivated land, but can be easily applied also to basins of medium extension, proved that they are mainly devoted to agriculture. In 1976 Z.Gavrilovic developed a different method, called EPM (Erosion Potential Method), that is more suitable for mountain basins. The approach was tested on Balkanic basins in Serbia and accounts not only for sediment production but also for sediment routing inside the basin. This method will be explained in detail, since it is the chosen one for case study presented.

Gavrilovic model is basically made up of two components: an erosion evaluation equation, used to compute W, and a sediment routing equation, that determines the fraction of sediment actually reaching the closing section through the routing coefficient R. Required inputs are topographic and hydrologic features of the basin and three descriptive coefficients (land use Ξ, type and extent of erosion Φ, soil resistance to erosion Π) used to describe land erosion susceptibility. To improve accuracy of the method and to speed up its application a GIS application has been used, which allows for better zoning of the basin as tested by the authors (Brambilla et al, 2011). The following relationships allow to compute the total mean annual discharge of eroded material G [m3/year]:

$$G = W \times R \tag{1}$$

$$W = \pi \times T \times H \times F \times Z^{2/3} \tag{2}$$

$$R = \frac{(l_p + l_a) \times \sqrt{O \times D}}{(l_p + 10)} \tag{3}$$

$$T = \sqrt{0.1 + \frac{t}{10}}$$

$$Z = \Xi \times \Pi \times \left(\Phi + \sqrt{s}\right)$$

where:

G	yearly sediment yield [m^3]
W	gross erosion [m^3]
R	routing coefficient [-]
T	temperature coefficient [-]
H	annual rainfall depth [mm]
F	area of catchments [km^2]
Z	erosion coefficient [-]
l_p	length of main water course [km]
l_a	length of minor water courses [km]
O	perimeter of the catchments [km]
D	average elevation [km]
t	annual average temperature [°C]
Ξ	coefficient of soil cover [-]
Π	coefficient of soil resistance [-]
Φ	coefficient of type and extent of erosion [-]
s	average valley slope

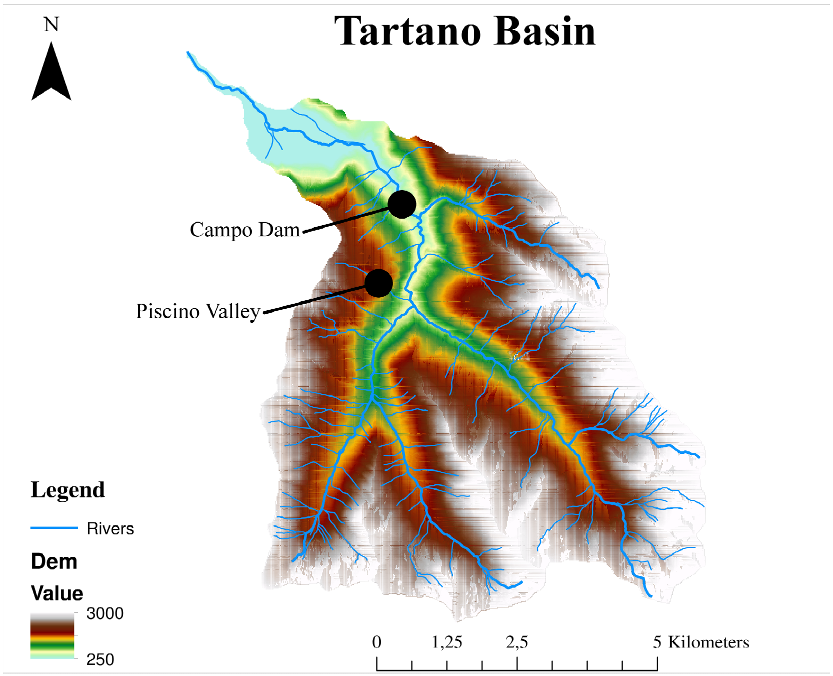

Figure 1. Tartano Basin DEM and drainage network

Little debris flows and hyper-concentrated flows are the second important source of sediment inside a mountain basins. These phenomena are for sure local but numerous in the whole basin and extremely difficult to be modelled one by one; the main difficulty is linked to the exact forecast of when they will developed. Due to these features, models that deals with them adopt a lumped approach trying to estimate the annual rate of sediments from this source for the whole basin. The model proposed is called Pesera-L and was developed by Borselli et al (2011). PESERA-L is an addendum to PESERA, a soil erosion model developed by Kirkby et al, 2008., modelling sediment yield due to shallow mass movement and debris flows in a watershed. Its objective is the simulation of the shallow landslides, which can contribute to the total sediment production. PESERA-L bases its calculation on a preexisting catalogue of shallow landslides, their distance from the drainage network, the capacity of the terrain to brake and stop landslide material and uses the infinite slope as safety factor calculation.

Bank erosion is due to the water stream in river scouring the side of its channel, taking away debris and sediments that enter the water flow. Unfortunately, the scientific community has not developed yet a valid and wide used model to simulate the quantity of debris that is eroded from banks and enter the drainage system. This process happen on two different time scales, one very short, when huge quantity of sediments are eroded by high flow rates after heavy rains and one very long and linked to geomorphological evolution of the valley. Due to time scale of geological processes compared to human activities, this second kind of erosion has no real impact on reservoir silting.

Finally some sediments can be eroded by fault zones; in mountain is common to find faults and weak zones, due to the deformation linked to the orogenesis, this layers of fractured rock are usually weak and easily eroded by flowing water. Similarly to bank erosion a comprehensive model to evaluate the sediment yield from this processes has not be developed and so case by case evaluation is still needed.

At last, singular large landslides need to be studied alone, using the traditional tools of engineering geology to assess their possible contribution to sediment yield.

The total yield in a reservoir is due to the sum of all these contribution and the transport capability of the streams. The need for a hydraulic transport explicit modeling is linked to the need of determining the quantity of solid material reaching the reservoir over short spans of time for drain operation purposes.

To show how the different contributions combine their effect a case study is presented in the following paragraph.

TARTANO VALLEY CASE STUDY

Tartano Valley is a medium basin (50 km2) situated in the Italian Alps, approximately 100 km north from Milan. It extends in height from 1,148 meters a.s.l. to 2,504 meters a.s.l., with a mean altitude of 1861 meters a.s.l.. The main river flowing in the valley, named Tartano, is blocked by a dam and thus the basin is subdivided into two parts, the area upstream of the dam is about 36.2 km2 and will be the investigate portion of the basin. It is important to notice that the authors had the opportunity to gather information about sediment yield in the reservoir. A bathymetric survey has been set up for several years providing reliable data about loss of storage capacity of the dam. Data are reported in Table 1, mean annual sediment yield is 38,038 m^3.

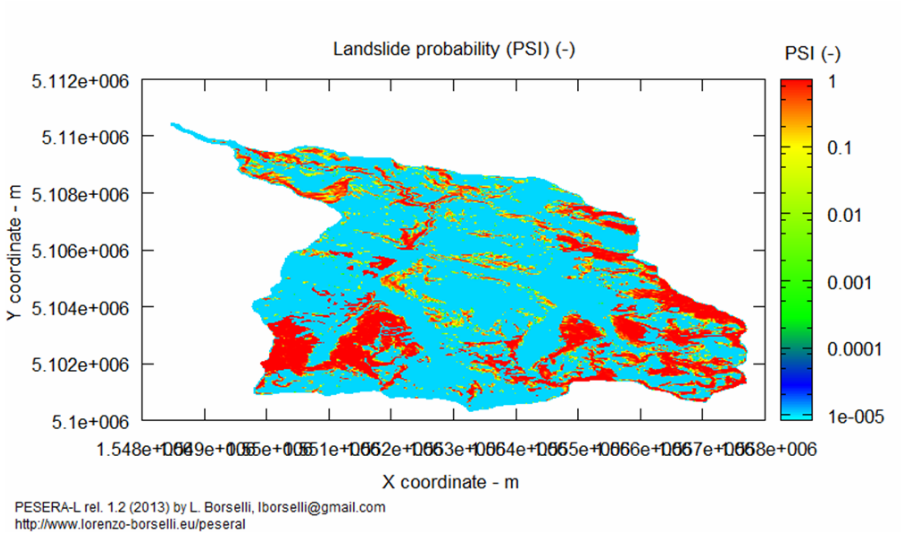

Figure 2. Landslide probability computed via Pesera-L model

Table 1. Measured sediment yield (SY) in dam

Year	**1991**	**1992**	**1993**
SY (m^3)	34,073	43,504	53,605
Year	**1994**	**1995**	**1996**
SY (m^3)	36,737	26,264	39,749
Year	**1997**	**1998**	**1999**
SY (m^3)	35,314	32,800	41,876
Year	**2000**	**2001**	**2002**
SY (m^3)	57,299	43,187	42,022
Year	**2003**	**2004**	**2005**
SY (m^3)	22,957	50,083	21,287
Year	**2006**		
SY (m^3)	27,844		

Geology of the valley comprehends four categories of outcropping rock formations: massive metamorphic rocks, schistose metamorphic rocks, strongly fractured metamorphic rocks and sedimentary rocks presenting both Paleozoic and Triassic lithological features. Talus and debris cover rock basement. Main sediment sources in the basin are landslides and faults; to the former belong.

Figure 3. Piscino valley

“Pruna” landslide, (downstream of the Campo dam) and the “Foppa dell’Orso” shallow landslide (upstream of the Campo dam). To the latter category belong two main systems: the first with a NE-SW direction, the other one with WNW-ESE direction (among them is important to recall Piscino Valley). In July 1987 high rainfall combined with other climatic conditions (e.g. snowmelt), originated a flood that caused destructions and upheavals overall the hydrographic network. The valley is interested by a variety of shallow landslides, fault zones and accelerated soil erosion. The authors computed a mean rainfall height of 1,376 mm/year and a mean temperature of 3.0°.

Slope erosion

First step was the application of the Gavrilovic method to the basin upstream of the dam; a Gis based approach has been tested and the state of the art data considered. Thanks to improved database the result could be refined: a mean value of 29,000 m3/year is obtained and represent the contribute of soil erosion. Geometrical data were gathered by Regione Lombardia map database and reported in Table 2, the empirical coefficients Ξ, Φ and Π were estimated using a use of soil map and a pedological map.

Table 2. Key parameters for Gavrilovic model

Surface of the catchment area [km^2]	36.2
Perimeter of the catchment area [km]	27.0
Length of the principal waterways [km]	28.4
Length of the secondary waterways [km]	92.6
Minimum altitude [m a.s.l.]	1,148
Mean altitude [m a.s.l.]	1,861
Maximum altitude [m a.s.l.]	2,504
Land use Ξ	0.29
Type and extent of erosion Φ	1.55
Soil resistance to erosion Π	0.59

Shallow landslides

Other contributions need to be evaluated separately: scattered debris and shallow movements have been evaluated via Pesera-L model. Table 3 reports input and output data of the model.

Table 3. Pesera-L input and output data

Input data	Output data
Monthly Climate	Erosion (monthly)
Land-use, Crops and Planting date	Overland flow runoff
Soil Hydrologic and Erosive Parameters	Soil water deficit
Topography	Percentage rainfall interception
	Vegetation biomass
	Cover monthly
	Soil organic matter biomass

The model has been applied at the Tartano basin to simulate the contribution of shallow landslide to total sediment yield. A map of the probability of landslide is hereby presented in Figure 1, is possible to notice how landslide probability is strongly linked to slope. Total sediment yield due to shallow landslide contribution is calculated in 10,800 m3/year.

Fault zones

Since a satisfying model to simulate sediment production in fault zones is not available in literature authors chose to focus their attention on the most critical fault present in the basin, the already named Piscino Valley. An evaluation of the amount of sediments supplied by Piscino Valley can help in determining whether these sources have a key role or not in Tartano basin sediment budget.

The narrow valley lays on a fractured zone and starting from the top of the Piscino peak runs straight downwards to the river featuring high slope angles. The area is approximately 300 meters long and 20 meters wide and completely covered with talus and boulders coming from the rock walls surrounding the higher part of the valley (Brambilla et al., 2011). A little stream flows in the valley. All the material present in the valley can surely represent a source of sediment of large diameter. A survey for granulometry classification was set up in the valley (Figure 2).

The d50 value, defined as the median equivalent sediment diameter, was calculated and ranges for all the sections between 67 cm and 88cm. The key point to be evaluated is if the stream in the valley is strong enough to move a significant quantity of this sediment downwards in the Tartano river, keeping in mind the mean slope of 22° that can surely cause boulder movements even with little thrust by water stream. An application of the Schoklitsch formula, useful to define critical diameter of sediment transport on steep slopes, was developed to search for minimum discharge able to trigger some movements along the slope. The result show that even moderate events, with 1 year return time, could cause some evaluation sections debris supply to the basin, due to the impressive slope angle.

An accurate analysis of the morphology of the valley highlights how the regular movements are slow and involve a little fraction of the boulders, while some exceptional events can trigger mass movements like debris flows, which took place in 2005 in Piscino valley. Given these facts the contribute of Piscino valley to the total amount of sediment yield is probably negligible for a single year yield and biased towards big diameters that will reach the reservoir only in long times.

Bank erosion

Similarly to fault zones also bank erosion modeling is nowadays still a challenge. Authors have planned a long campaign of bank survey in Tartano basin, using terrestrial laser scanning techniques, to determine which is the impact of bank scouring on the total sediment yield. The campaign started in January 2014 and is still going on with monthly surveys; at the moment, since we are in the early stage, is not possible to assess any kind of relationship between material eroded and environmental parameters. First analysis on field data shows how bank erosion can give a contribute to the total sediment yield, even if probably the debris that enter streams in this way is less than the one from slope erosion and shallow landslides. An image of an eroded bank spot is showed in Figure 4.

Figure 4. Eroded bank in Tartano basin

CONCLUSION

This work deals with the estimation of a mountain basin reservoir silting through the evaluation and modeling of sediment production. Various processes that take place in the basin have been studied and evaluated separately to assess sources and quantity of debris. From an accurate simulation of sources emerged that slope erosion and shallow landslides are the main contributors: their summed sediment production is 39,800 m3/year. The value appear just slightly bigger than real medium sediment yield; since fault zones and bank erosion is not included in the calculation we can conclude that probably the models overestimate the production a bit. Actually, seen the big uncertainties in parameters determination, the result is good and the simulation can be considered successful.

The key objective this approach cannot reach is a temporal assessment of sediment flow inside the drainage network; a task of this kind requires complex real time simulation both of erosion and sediment transport in rivers. Such an ambitious objective requires further studies and, although appearing a possible goal for the future, still a long way is needed to get it.

Finally is possible to state that the approach presented is able to estimate with a good reliability the total volumes involved but not is variability through different years due to changing climate conditions and natural variability of weather. Anyway it is possible to apply it to life time estimation of dams and to plan debris removal intervention in long terms.

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