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Francés, Félix

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IMPROVED ESTIMATION OF LONG TERM SEDIMENT INPUT TO RESERVOIRS

BY FÉLIX FRANCÉS

One of the factors to be considered in the design of a new dam, or in the re-assessment of an existing one, is its reservoir siltation (Figure 1). Reservoir siltation is important, and in some cases crucial to surface water management, because it affects the lifetime of the dam and, therefore, the required direct and indirect investments for maintaining the long-term dam functionality. There are many examples all around the world of dams out of operation few years after their construction. One such dam is the Doña Aldonza dam built in the 1950's on the Guadalquivir River, Spain. The dam, 32 m height with initial reservoir storage of 23 Mm^3, was fully-silted in less than 20 years due to a mean siltation rate higher than 1 Mm^3/year.

Reservoir siltation involves two main factors, namely i) the sediment yield entering the reservoir from the upstream catchment (a hydrological problem) and ii) the sediment trapping and deposition within the reservoir (a hydraulic problem). Both are equally important, but the sediment yield remains less well understood than the process of reservoir sedimentation. This article focuses on the catchment sediment delivery into a reservoir.

The best way to evaluate, quantify and predict soil erosion and sediment transport at catchment scale is through mathematical modelling. The traditional model used in engineering practice for calculating the catchment soil erosion is the well-known Universal Soil Loss Equation (USLE)[1]. This empirically-based lumped equation and most of its variants are used to calculate soil erosion as a function of the physical characteristics of the watershed. The resulting sediment production is often considered as the sediment yield into a reservoir. However, the USLE gives only annual mean value for the sediment yield, it is fully empirical and it does not account for transport and deposition within the catchment. A proper model for the estimation of catchment sediment yield needs to be distributed in space and be as much physically based as possible, where sources and sinks of sediments, connectivity and storage processes can be included.

On one hand, distributed models can reproduce not only the temporal, but also the inherent spatial variability of inputs (e.g. precipitation, temperature) and basin hydrological characteristics, include connectivity into the model conceptualization, provide important information about sediment transport, erosion and deposition zones, and incorporate Land Use/Land Cover (LULC) changes within the catchment. Using a distributed model, a map can be obtained (Figure 2), locating clearly the main sources of sediment in the watershed. Distributed models help decision-makers identify spots where interventions are necessary to prevent sediment from reaching the reservoir, and optimize future mitigation actions (*e.g.* reforestation areas, check dams, retention basins, bypass channels).

On the other hand, physically based models (or at least with physically sound parameters) have a better predictability than empirical or statistical models. Unfortunately, it is not possible to describe mathematically all physical processes involved in soil erosion, sediment transport and deposition (*e.g.* influence of vegetation cover). Therefore, some processes must be described empirically and, for this reason, parts of USLE still are and will still be in use in the near future.

Reservoir siltation has been used since the 1950s to estimate the catchment sediment yield. This approach not only requires accurate and repeated surveys of the reservoir bathymetry, but also needs estimates of the amount of untrapped sediment and the temporal evolution of the density of deposited sediments within the reservoir. All these data are highly valuable for the calibration and validation of mathematical

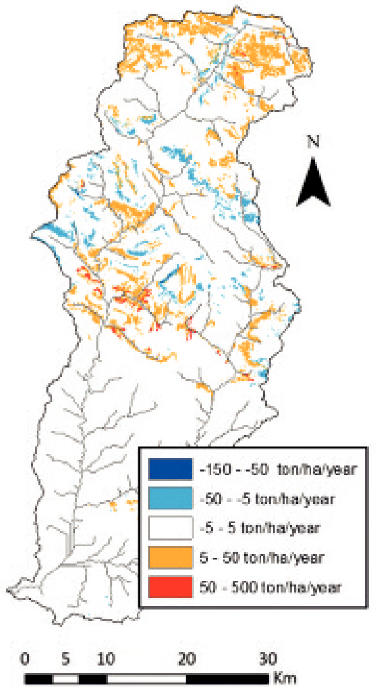
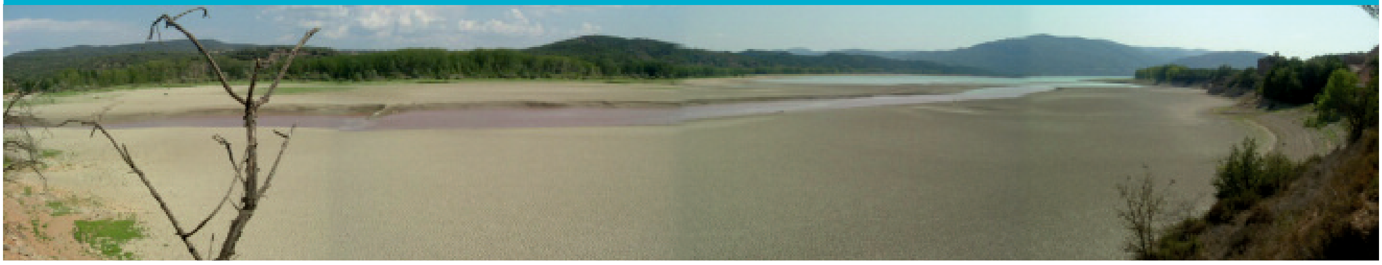
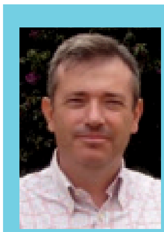


Figure 2. Spatial differences in soil erosion rate in Esera River's catchment (Barasona Reservoir is located near the outlet) between a future climate scenario and present climatic conditions.

Figure 1. General view from upstream of Barasona Reservoir in Spain. The Barasona Dam was commissioned in 1932 with an initial capacity of 71 Mm^3, increased up to 92.2 Mm^3 in 1973. Some flushing and dredging operations were conducted in the 1970's and 1990's, and nowadays the live storage capacity of the reservoir is estimated to be around 70 Mm^3





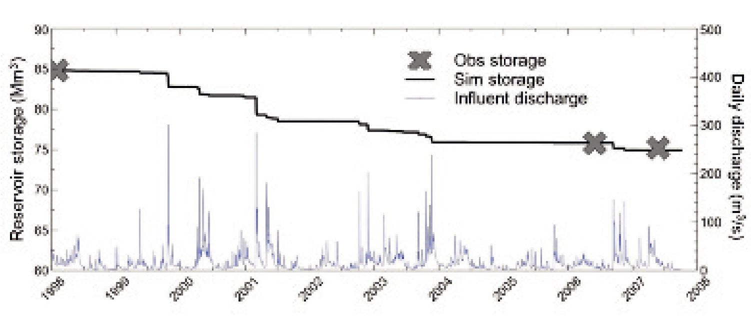
Dr. Francés is Full Professor at Polytechnic University of Valencia and leader of the Research Group of Hydrological and Environmental Modelling. He is Vice-president of the Spanish Water Technological Platform and Associated Editor of Journal of Hydrology. In 2011, Dr. Francés obtained the Engineering Innovation Award from the Spanish National Civil Engineering Association.

models[2] (Figure 3). Moreover, not only data from large reservoirs can be used, but also from smaller reservoirs, such as check dams or irrigation and water supply ponds, which can be a valuable source of information[3].

Actually, the lifetime of a reservoir is a random variable, since catchment soil erosion depends non-linearly on the magnitude of flood events, as it can be clearly seen in the jumps of reservoir storage evolution in Figure 3. If the topography and soil characteristics of a catchment are fixed in time, the sediment yield cycle will depend on climatic conditions and LULC. In most cases, these two drivers have changed over time in the past and will continue doing so in the future.

The effect of climate change on sediment yield is related to the spatial-temporal changes in rainfall patterns that can produce increased rainfall erosivity. During the last fifteen years, distributed models have been coupled with downscaled future climate scenarios and used to assess the impact of climate change on the sediment cycle at the catchment scale. One good and recent example is the application of the TETIS model[4] on the Yi'an catchment in China[5]. The modeling results for the four Representative Concentration Pathway (RCP) scenarios for climate change relative to the present conditions under the same LULC indicate an increase in water discharge in all cases (higher by 71.4% for RCP 8.5) and a more pronounced increase in the sediment yield (170% for RCP 8.5). This implies an amplification of the impact of climate change on sediment yield compared with its impact on the water cycle. In a similar study on the Barasona Reservoir in Spain (Figure 1), which is in an area with semiarid climate and has experienced severe historical siltation problems, it was found that a general reduction of future water resources due to a decrease in precipitation and increase in temperatures should be expected. In this area, all climatic models predict an increment of precipitation torrentiality, but this does not translate into an increase in the sediment yield. This is due to a decrease in soil moisture at the beginning of the storm events, reducing the runoff and erosivity[2]. In other words, the present expected lifetime of the dam is not expected to change significantly in the future due to climate change. It should be underlined that this conclusion would not have been reached without considering the interactions described above using a proper model. LULC and cropping management are also key factors affecting the catchment soil erodibility. Changes in LULC will impact the catchment sediment yield. One interesting case study is the Upper Citarum catchment in west Java (Indonesia), draining into the Saguling Reservoir, which was commissioned in 1985 with a storage capacity of 889 Mm^3. This reservoir plays a crucial role in Indonesia, supplying water and hydroelectricity for the region. Severe LULC changes within the catchment have resulted in significant increase in the sediment yield to the Saguling Reservoir. The observed reservoir sedimentation rate has increased over time, reducing the storage capacity from 889 Mm^3 in 1985 to 779 Hm^3 in 2014, *i.e.* a mean siltation rate of 3.7 Mm^3/year.

Figure 3. Simulated reconstruction of the historical storage evolution of Barasona Reservoir, Spain, using TETIS model



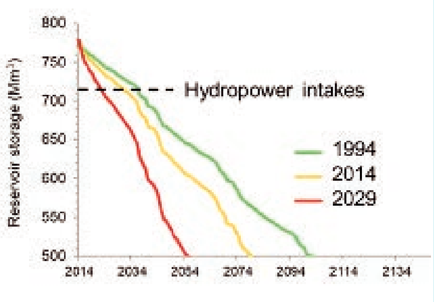


Figure 4. Storage evolution of the Saguling Reservoir in Indonesia for different LULC scenarios: past (corresponding to year 1994), present (2014) and projected LULC for year 2029

To analyse this problem from the LULC changes point of view, the TETIS model was also used. Three different LULC scenarios with present climatic conditions were tested: two historical scenarios, corresponding to years 1994 and 2014 and one forecasted scenario using a multi-layer perceptron neural network for the horizon 2029[6]. The differences in sediment yield are significant, decreasing the expected lifetime of the reservoir from 239 years predicted with the 1994 scenario to 113 years predicted with the 2029 forecast; *i.e.* LULC changes can reduce the lifetime of the reservoir by a factor of two. The energy production is threatened also, because the elevation of the hydropower water intakes corresponds to the reservoir storage capacity of 722 Mm^3 (dotted line in Figure 4), which means that problems could be expected in less than twenty years for the worst-case scenarios.

It is clear that climate change and LULC changes will affect the runoff and sediment yield in a catchment. Depending on the case, the impact can be more, or less significant and it is not possible to assess *a priori* which of these two factors, climate or LULC, will have the greater impact and in which direction (positive or negative). The good news is that there is an opportunity to use proper LULC management to mitigate the negative impacts of climate change on water flows and sediment yields. ■

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