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REVIEW ARTICLE

Influence of the sediment delivery ratio index on the analysis of silting and break risk in the Plasencia reservoir (Central System, Spain)

Y. Sánchez[1] · A. Martínez-Graña[1] · F. Santos-Francés[2] · M. Yenes[1]

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Abstract Erosion and the production of sediments effect the siltation of reservoirs and create large environmental problems. This work calculates the volume of sediments caused by erosion in a hydrological basin using the Revised Universal Soil Loss Equation 2 (USLE–RUSLE2), applying, or not, the sediment delivery ratio, and is compared with the volume of sediments transported using the Lawrence method. The USLE–RUSLE2 method is validated in the study area, the Jerte Valley, using the geographic information systems. The result obtained showed an erosion of 7 Tm/ha year and low risk of siltation, which suggest that the Plasencia reservoir has a long life expectancy.

Keywords Reservoir siltation · USLE–RUSLE2 · Lawrence method · Sediment delivery ratio (SDR)

1 Introduction

In Spain, one of the major environmental issues is reservoir siltation which can lead to a series of environmental, engineering and economic problems. This includes the regression of deltas, loss of reservoir volume, degradation of the aquatic ecosystem, alteration of the

✉ A. Martínez-Graña
amgranna@usal.es

Y. Sánchez
Yolanda.ss@usal.es

F. Santos-Francés
fsantos@usal.es

M. Yenes
yenes@usal.es

[1] Department of Geology, Faculty of Sciences, University of Salamanca, Plaza de la Merced s/n, 37008 Salamanca, Spain

[2] Department of Soil Sciences, Faculty of Environmental Sciences, University of Salamanca, Avenue Filiberto Villalobos, 119, 37007 Salamanca, Spain

longitudinal slope of the riverbed and a higher propensity for developing eutrophy. This also involves a loss of efficiency that affects both the profitability of the initial investment in the hydraulic construction and trading accounts.

Thus, in the past few decades studies have been conducted that calculate the risk of erosion and the amount of sediments in different basins and riverbeds (Martínez-Graña et al. 2014), such as the Segura basin and the Isuela River (Cruchaga 2013). In addition, there are other comparative studies analyzing the different methodologies for estimating land loss: RUSLE2015 (Panagos et al. 2015), rainfall simulation (León et al. 2015) and SWAT (Roth et al. 2016). All of these have been taken into account for developing the methodology applied in the present study.

Moreover, not all of the sediments that reach the reservoirs are stored in the same place (Bodoque et al. 2001); however, it is estimated that the reservoirs in Spain lose, on average, 0.5% of their capacity per year. Considering that in Spain the amount of water contained within reservoirs is 56 km^3, in 50 years it will decrease by 25% to 44 km^3.

There are no definitive solutions for either the already existing or future reservoirs, but there are preventative measures for minimizing the effects of silting processes. Regardless the measure employed information concerning the river basin, the rate of erosion of sediments and the areas that actually produce sediments is needed (Palau 2002). GIS allows the rate of erosion to be easily calculated by applying USLE–RUSLE2 and can integrate a large number of spacial cartographies (edaphological, lithological, etc.) and the distribution of each of the factors that define the basin model (Martínez-Graña et al. 2015a, b; Chen and Lian 2016; Martínez-Graña et al. 2016a, b). Identifying the areas which produce the most sediment facilitates and optimizes the effect of any of the corrective measures used by managers or those responsible, which in turn increases the life expectancy of the reservoir and reduces costs.

The aim of this study is to analyze the risk of siltation in the Plasencia reservoir in the Jerte Valley, to characterize the volume of sediments transported by the processes of hydraulic erosion and to quantify the amount of sediments in the reservoir. For this purpose, the methods and erosion indices will be calibrated and validated, and the transport of specific sediments (USLE–RUSLE2 and the Lawrence method) will be used to calculate the state of siltation or SDR.

1.1 Study area and physical environment context

The study area corresponds to the hydrological basin of the Jerte River, a tributary of the Tagus River, which includes the Plasencia reservoir in its lowest section.

The Jerte basin has a surface area of 376 km^2 and a difference in height of 2065 m. It is located between two mountainous areas: the Tormantos mountain range, to the southeast, and the Bejar mountain range to the northeast.

The climate produces a medium yearly precipitation with a difference of 600 mm. In the center of the basin, there is an isohyet of 1000 mm, and in the lowest part of the area, to the east, there is an isohyet of 400 mm. Most of the precipitation is in the form of rain except for the occasional snowfall. The average annual amount of river water entering into the reservoir is 324 hm^3, and its capacity is 59 hm^3 (Fig. 1).

The Jerte River follows the fractures of the Alentejo–Plasencia fault in a NE–SW direction. Its morpho-structure is made up of cavities and tectonic columns of plutonic materials, and the lithology is comprised of granites of two micas (Fig. 2a) and biotite granite

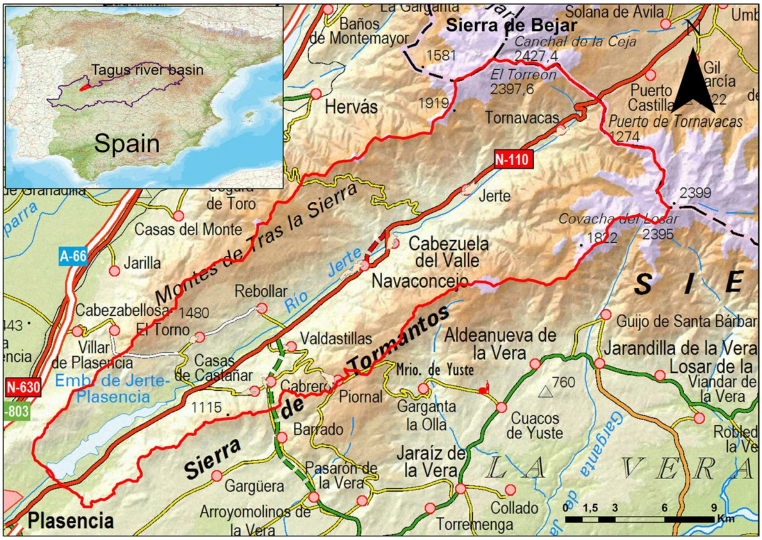

Fig. 1 Location of the Plasencia reservoir river basin

(Fig. 2b). The dolerite dikes in contact with the Alentejo–Plasencia fault are particularly noticeable (Carrasco González 1991).

The edaphology is conditioned by the high slopes and the granitic substrate, which in turn provides a sandy texture. In addition, the floors are not very developed. The cartography shows: (Fig. 2c) Chromic Cambisols and Dystric Cambisols, Chromic Luvisol, Cambic Leptosol, Dystric Regosol, Anthrosol and (Fig. 2d) Eutric Fluvisol. The land within the valley is mainly used for agricultural purposes (Fig. 2e), except for the highly sloped areas with badly developed soil, which contain shrubs and trees dispersed throughout the area (Fig. 2f).

2 Method

To calculate the life expectancy of the Plasencia reservoir, the sediment of erosion is calculated using the methods USLE–RUSLE2 and Lawrence, whereby both are compared and the percentage of sediments retained in the reservoir are calculated to estimate the life expectancy and the force that the sediment exerts on the dam (Fig. 3).

2.1 Calculation of the gross eroded sediment USLE–RUSLE2

The model used to calculate erosion is the Universal Soil Loss Equation (USLE) (Eq. 1) and its revised version (RUSLE2), which estimates the average loss of soil over long periods of time (Constantine and Ogbu 2015).

$$A = R \times K \times LS \times C \times P \quad (1)$$

In Eq. 1, A is the average annual soil loss (Tm/ha year), R is the average soil erosivity factor (MJ mm/ha h year), K is the soil erodibility factor (Tm ha h/ha MJ mm), L is a

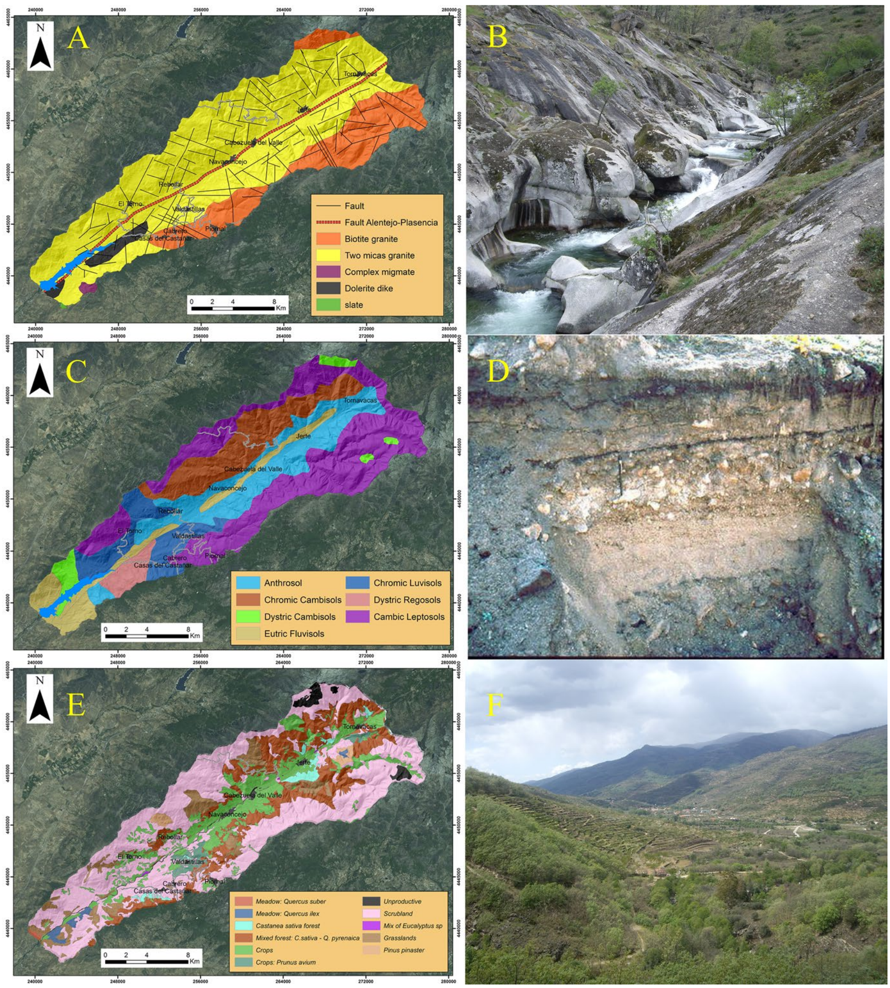

Fig. 2 Physical environment context: **a** geological cartography, **b** two-mica granite, **c** edaphological cartography, **d** eutric fluvisols, **e** vegetation cartography, **f** distribution of the Jerte Valley

soil length factor (m), *S* is the slope steepness factor (°), *C* is the cover-management factor (dimensionless), and *P* is the supporting practice factor (dimensionless).

To calculate erosion, the rainfall erosivity, based on the average of precipitation, is taken into account in order to determine the erosive capacity. Erosivity constitutes the rain's capacity to cause land erosion, which varies depending on the area where the study is carried out because of the height of the groundwater level of the soil (Zhao et al. 2014). Soil erodibility is analyzed using the textural and structural data of the edaphological profiles. In areas where there is no soil, the erosive susceptibility of the lithological substrate was taken into account. The susceptibility or vulnerability of the soil to erosion, or in contrast, its resistance to erosion, is influenced by the physical characteristics of soil (texture, structure, permeability, etc.) and the nature of the mother rock.

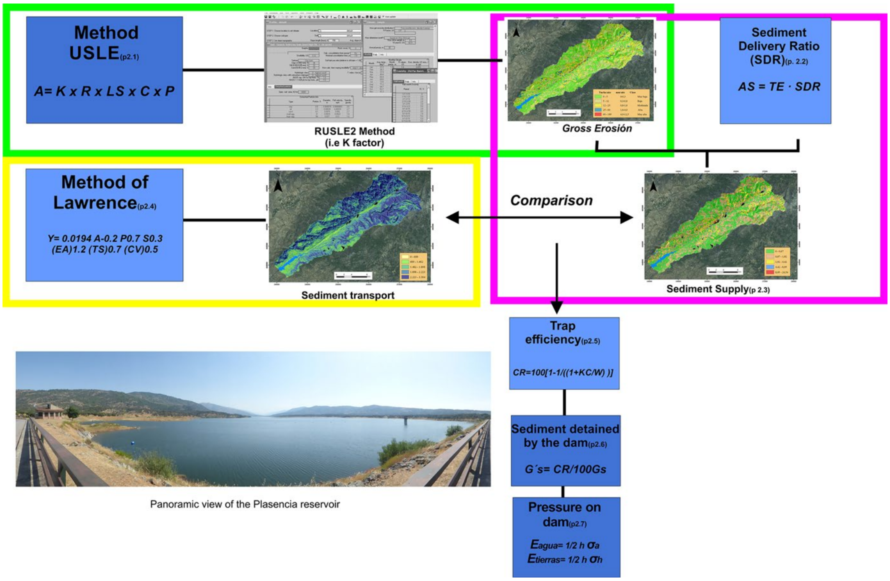

Fig. 3 Methodological development and cartography. RUSLE2 method, thrust on dam (pressure on dam, etc.) panoramic view of the Plasencia reservoir (pertains to figure)

The digital elevation model (DEM) using Laser Imaging Detection and Ranging (LIDAR) data, with a spacial resolution of 5 m/pixel, allows you to calculate slope length (L) and slope steepness (S), to estimate the soil loss.

Once the values of the previously mentioned factors were obtained, the potential for erosion was calculated using map algebra. Then, its used the values established by the Natural Resources Conservation Service (NRCS) for trees, shrubs and mixed woodlands, analyzing the percentage of cover in contact with the soil. To improve this analysis, land cover was calculated to analyze the influence of the vegetation and crop, as this would reduce the eroded volume that was taken into account.

Finally, soil conservation practices in land use were discarded so as to determine the real loss caused by natural factors.

Using GIS technology, the actual erosion of the river basin of the reservoir of Plasencia was determined (see Eq. 1).

2.2 Sediment delivery ratio of the river basin

The amount of sediments that enter into the reservoir varies depending on the size of the basin: the larger the basin, the smaller the amount of sediments deposited into the reservoir, since the bigger the surface area, the larger the areas of sedimentation are within the basin. Also, the larger the slope of the river course, in our case the Jerte River with a size 4% (Fig. 4a), the greater the pulling force. Furthermore, bifurcations within the drainage network (Fig. 4b) have an influence, as the more forks there are the greater the capacity for transport.

The sediment delivery ratio (SDR) (Eq. 2) was determined using the following equation (Avendaño et al. 1994):

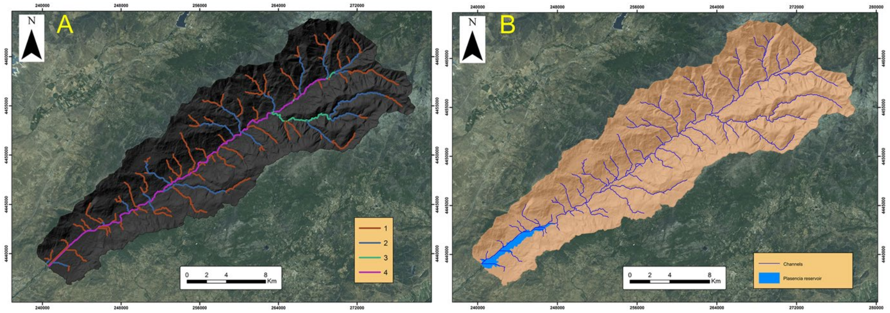

Fig. 4 Hydrology of the Jerte valley: **a** order of the channels and **b** drainage network, water channels and Plasencia reservoir

$$SDR = 36A^{-0.2} - \frac{2}{\log P} + \log BR \quad (2)$$

where SDR the total percentage of material transported into the basin that exits from the same place, A surface area (m^2), P the slope of the main course and BR the coefficient of bifurcation of the hydrographic network.

The terms that are integrated into Eq. 2 are calculated separately in order to obtain the values for area of the basin, the slope and the coefficient of the bifurcation. This was done according to Strahler (1965), for determining the size of the basins, and Horton (1945 for determining the ratio between the number of rivers with size "j" and the number of rivers with size "$j + 1$" (Fig. 4a).

The slope was estimated by digitalizing the main course of the Jerte River basin and by rasterizing the map obtained; this in turn generated a mask with the slope map of the basin, expressed in percentages.

Using the digital land model, the drainage network (Fig. 4b) of the Jerte Valley was determined, and the directions of the hydrological flow of the slope were established in order to subsequently determine the accumulation of flow of the different areas. By establishing a minimum limit over these areas, the channels within the drainage network, and their sizes, were determined for calculating the coefficient of bifurcation.

2.3 Calculation of sediment input

The input of sediments (SI) into the reservoir is a proportion of the total amount of gross eroded sediments in the area front (TE) (obtained in Sect. 2.1). This ratio is defined as the sediment delivery ratio (SDR) (obtained in Sect. 2.2) and complies with Eq. 3:

$$SI = TE \cdot SDR \quad (3)$$

where SDR sediment delivery ratio, SI sediment input and TE volume of eroded sediments.

This procedure is validated through of the quantification carried out in others reservoirs that have developed a total backfill of accumulated sediment (Bodoque et al. 2001).

2.4 Lawrence method

The Lawrence method (Lawrence et al. 2004) (Eq. 4) is based on measurements taken of reservoirs with small basins, in the semiarid regions of the west and the south of Africa. The proposed equation is the following:

$$Y = 0.0194A^{-0.2}P^{0.7}S^{0.3}(\mathrm{EA})^{1.2}(\mathrm{TS})^{0.7}(\mathrm{CV})^{0.5} \tag{4}$$

where Y sedimentation expressed in Tm/km^2/year, A area of the basin in km^2, P average annual precipitation in mm, S slope percentage, EA coefficient of active soil erosion, TS coefficient of the type of soil and drainage, CV vegetation conditions of the basin, and the coefficients EA, TS and CV are determined according to the characteristics of the basin.

2.5 Retention capacity

The capacity of the reservoir to retain materials is called trap efficiency and is expressed as a percentage (Avendaño et al. 1995). In general, reservoirs retain between 70 and 100% of the sediments coming from the basin. This parameter is calculated using empirical relationships, and for the Plasencia reservoir (Eq. 5) was used (Brown 1943), since this is the best equation adapted for headwater basin reservoirs. This equation is based on the relationship between the capacity of the basin and the surface area of the drainage basin:

$$\mathrm{CR} = 100\left[1 - \frac{1}{\left(1 + \frac{KC}{W}\right)}\right] \tag{5}$$

where CR retention capacity of the reservoir (%), W drainage area of the basin (km^2), C capacity of the reservoir (thousands of m^3) (5.9000 thousand m^3) and K coefficient.

2.6 Volume of retained sediments within the reservoir and life expectancy

Solids transported by a river's current are retained in the dam built on top of its riverbed, which decreases the storage capacity of the reservoir. When this reduction in volume reaches 80%, the reservoir becomes clogged and its lifespan is complete. (Flores 2004).

The first step is to calculate the sediment transport rate (Gs) according to the average sediment transport rate and the area of the basin.

Then, the annual sediment rate retained by the reservoir (Eq. 6) is calculated:

$$\mathrm{G's} = \frac{\mathrm{CR}}{100} \cdot \mathrm{Gs} \tag{6}$$

where G′s rate of annual sediment retained, CR retention capacity of the reservoir (%) and Gs sediment transport rate.

Finally, to calculate the life expectancy in years (Eq. 7), considering that the dam stops functioning when more than 80% of its capacity becomes clogged, the following equation is applied:

$$\text{Life expectancy in years} = \frac{\text{80\% of the Volume of the reservoir}}{\text{Volume load of the transport of sediment annually retained}} \tag{7}$$

2.7 Structural problems of the Plasencia reservoir

To calculate the force the sediments exert on the dam once the reservoir is clogged, it is first necessary to take into account the type of dam and its characteristics.

To calculate the total pressure, the pressure exerted by the water column and the sediment is calculated independently:

- Water column pressure

$$E_{\text{water}} = \frac{b \cdot h}{2} = \frac{1}{2} h \cdot \sigma_a \tag{8}$$

$$\sigma_a = \gamma_w \cdot h \tag{9}$$

where E_{water} pressure exerted by the water (KN/m), b base (m), equivalent to σ_a, h height (m), σ_a horizontal component of the water pressure (KN/m^2), γ_w water specific weight (KN/m^3).

Thus, the pressure exerted by the water column is 8850,625 KN/m.

- Sediment column pressure

To calculate the pressure exerted by soil (Eqs. 10 and 11) over an element of contention or vice versa, the following law of unit pressure can be applied:

$$E_{\text{soil}} = \frac{b \cdot h}{2} = \frac{1}{2} h \cdot \sigma_{\text{h}} \tag{10}$$

$$\sigma_{\text{h}} = \sigma_{\text{v}} \cdot K_{\text{a}} \tag{11}$$

where E_{soil} sediment pressure (KN/m), b base (m), equivalent to σ_{h}, h height (m), σ_{h} horizontal component of sediment pressure (KN/m^2), σ_{v} vertical component of sediment pressure (KN/m^2) and K_{a} coefficient of active pressure.

- Calculating σ_{v}

To calculate σ_{v}, it is necessary to know the specific effective weight of the sediment (γ') (Eq. 12) calculated using the specific weights of the water and sediment, respectively (Eq. 13), and the height of the dam.

$$\gamma' = \gamma_s - \gamma_w \tag{12}$$

$$\sigma_{\text{v}} = \gamma' \cdot h \tag{13}$$

$\gamma_s = 15.10\,\text{KN/m}^3$ y $\gamma_w = 9.8\,\text{KN/m}^3$.

- Calculating K_{a}

The active pressure K_{a} is defined as a result of the units of pressure, σ'_{a}, which are determined (Eq. 14) using the following formula:

$$K_{\text{a}} = \left[\frac{\text{cosec}\beta \cdot \text{seno}(\beta - \phi')}{\sqrt{\text{seno}(\beta + \delta)} + \sqrt{\frac{\text{sen}(\delta + \phi') \cdot \text{sen}(\phi' - i)}{\text{sen}(\beta - i)}}} \right]^2 \tag{14}$$

where ϕ' the angle of internal friction of soil or backfilling, which in our case has a value of $\phi' = 30°$. Since none of the sediment samples were assayed, the most common value for sand, $i = 0$, was used; since once the surface soil is clogged, the reservoir becomes horizontal, δ the angle of friction between the wall and the soil or filling. In this case, in order to be close to the security, the value of $\delta = 0$ will be given and $\beta =$ the inclination of the backfilling.

3 Results

The cartographies generated to calculate the eroded sediment showed that the *R* factor, or erosivity, varied between 85.87 and 127.40 (Fig. 5a), the *K* factor, or erodibility, presented values between 0.02 and 0.38 (Fig. 5b), and the LS factor, which represents the parameters of length and slope decline, showed values between 0 and 13 (Fig. 5c). Using these values, an erosion potential of soil loss between 0 and 259 Tm/ha/year (Fig. 5e) was obtained. A large part of the Jerte basin presented a very high risk of erosion, with values between 69 and 259 Tm/ha/year.

Upon analyzing factor *C*, or vegetation, it was confirmed that the land with higher values, 0.352, corresponded to scrubland areas and pastures, and the lower values, 0.003, corresponded to land used for forestry (Fig. 5d). Conservation practices have not been taken into account for a more precise analyzes of the risk of erosion, and therefore, *P* was assigned a value of 1.

The real erosion, taking into account the protection of the vegetation cover, showed a soil loss of 0–189 Tm/ha/year (Fig. 5f), with an average annual loss of 7.07 Tm/ha/year or 0.47 mm, and predominately of low and very low erosion.

Considering the average slope of the Jerte River, which was 11%, and the calculation of the bifurcation coefficient (Table 1) (Strahler 1965), we obtained a sediment delivery ratio (SDR) index of 13.76%. Using the SDR index and the real erosion of the basin (Eq. 5), we determined that the input of sediments received by the Plasencia reservoir from the river basin was 0.91 Tm/ha/year. The amount of accumulated sediment has been compared with the sediment extracted from other reservoirs, presenting a relation input sediments–river basin similar.

After applying the Lawrence method for the Jerte basin and using the obtained results, we observed that the rate of transport of sediments was 1968.56 Tm/km^2/year, which indicated that the amount of sediment annually accumulated was 1968.56 Tm/km^2/year; thus, the predicted half-life for the Plasencia reservoir was 96 years.

The retention capacity of the Plasencia was 99.69%, calculated using the parameters of the Brown equation (Eq. 5), where 376 km^2 corresponded to the drainage area of the basin and a reservoir capacity of hm^3. The coefficient *K* varied between 0.09 and 2.1 according to the exploitation regimen of the reservoir (Avendaño et al. 1994); in this case, the Plasencia dam was type 1, meaning that it always or almost always remained full and was therefore assigned a *K* value of 2.1.

The rate of sediment transport was 34,554,483.6 kg/year, in other words, according to the apparent density of the material caused by erosion (1510 kg/m^3), 22,883.76 m^3/year, generating an annual sediment rate retained for the Plasencia reservoir of hm^3/year. The prediction of the rate of decline of storage of the Plasencia reservoir was equivalent to the volume of sediment that entered. The increase in volume caused by silting will be, according to the predictions, 0.024 hm^3 each year. This implied that the reservoir will become clogged within approximately 1966 years from its construction, generating a silting volume of 47.2 hm^3, leaving only 20% of the total volume of stored water (11.8 hm^3). At present, 30 years have passed since the inauguration of the dam, where the volume of accumulated

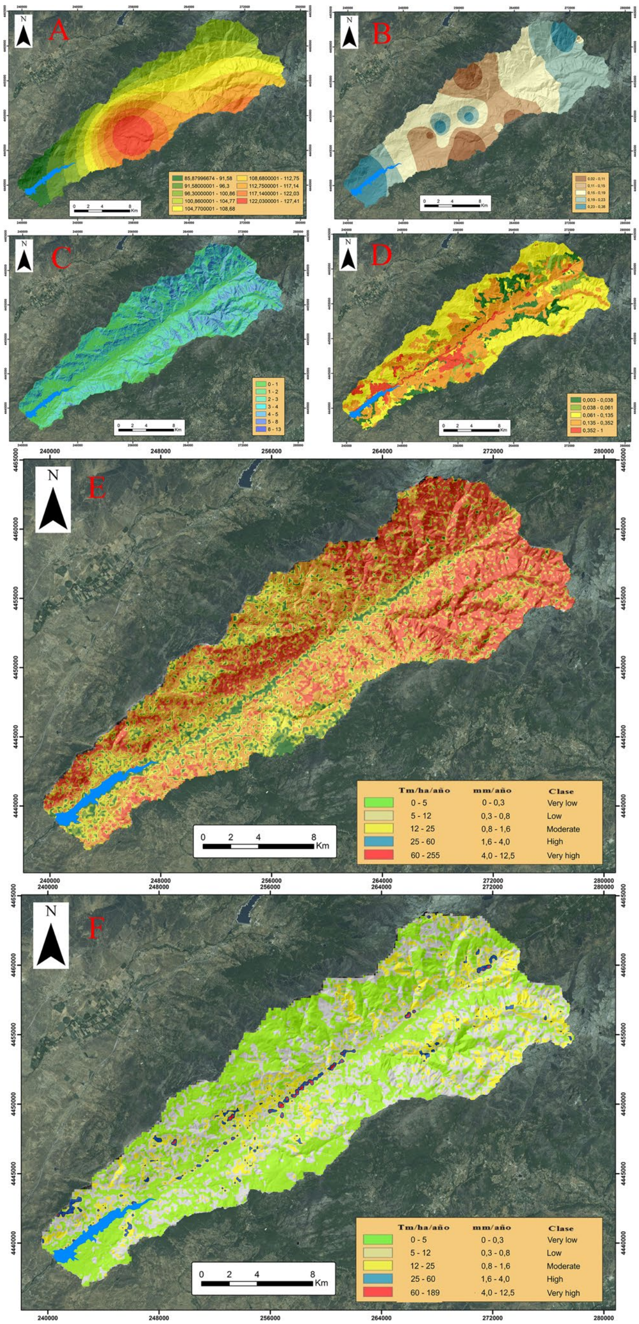

Fig. 5 Cartographic analysis using USLE–RUSLE2 to estimate the amount of sediments caused by climatic erosion: rain erosivity (**a**). Erodability of the soil and rocky substrate (**b**). Length and the slope decline (**c**). Vegetation factor (**d**). Map of the erosion potential (**e**) and map of real erosion (**f**). The color codes within the figure need to be translated

Table 1 Bifurcation coefficient

Order of the channels	Number of channels	Relation of bifurcation	Number of channels involved	Product of columns 3 and 4
1	78	4.10	97	397.70
2	19	9.50	21	199.50
3	2	2	3	6
4	1		Σ = 121	Σ = 603.20
			Bifurcation coefficient = 605.2/121 = 5.00	

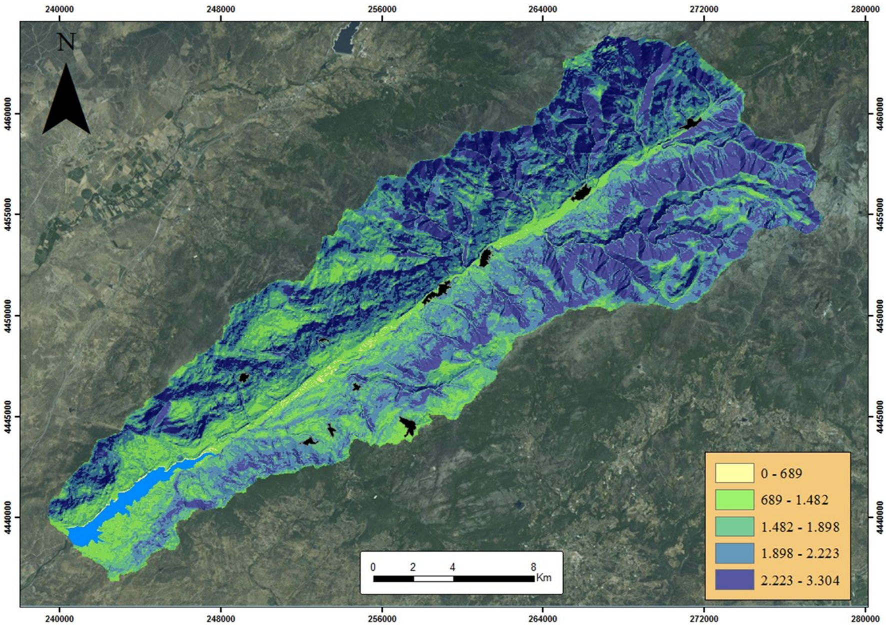

Fig. 6 Cartography of sediment transport applying the Lawrence method

sediment, according to the estimation of the model, will be 0.72 hm^3, that is to say, of the initial 59 hm^3 approximately 58.30 hm^3 will remain available (Fig. 6).

3.1 Structural problems of the Plasencia reservoir

The dam of the Plasencia reservoir was constructed using loose material with a clay nucleus, which has a height of 42.5 m and a volume (space occupied) of 832 million m^3, with two drains and a spillway with a capacity of 860 m^3/s.

Using this volume of water, we determined that the pressure exerted by the water column was 8850.625 KN/m. Then, the pressure of the column of sediment was calculated (Eqs. 10, 11), using the previously calculated vertical component of the sediment pressure, calculated σ_v produced a value of 224.8 KN/m^2 and the coefficient of active pressure, where the dam had a horizontal–vertical relationship of 2:2. The internal angle of the dam

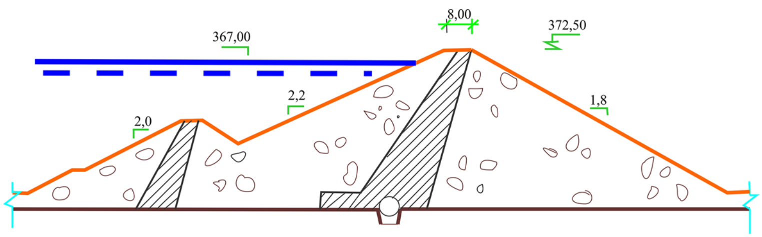

Fig. 7 Graphic diagram of the dimensions used to calculate the parameters of the dam of the Plasencia reservoir

was 25°, and therefore, the supplementary angle was 155º, that is, the tilt of the backfill (β) was 155° and K_a = 1.83 (Eq. 14) (Fig. 7), which indicated that the pressure exerted by the sediment was 8780.33 KN/m.

By adding the pressure forces of the water column and the sediment column, the exerted pressure on the dam was calculated as 17,630.95 KN/m, applied to 14.16 m of the lower base of the dam.

These calculations determined that the dam, once the reservoir becomes clogged, is subjected to twice the pressure exerted under normal conditions, which indicated that the possibility of rupture doubled. Aside from the pressure, the sediment increases the height of the watersheet, causing the upper limit of the dam to be surpassed and the water below the reservoir to overflow, provoking a great flooding catastrophe.

4 Discussion

The methodological development showed that the water erosion of the Jerte River basin is 7 Tm/ha/year, which was validated by recent data regarding soil loss in Europe obtained by the European Environment Information and Observation Network (EIONET), after applying the model RUSLE2 on a European scale (Panagos et al. 2015). However, the input of sediments into the reservoir varies depending on if the SDR index is used or not. If SDR is not taken into account, that is to say, if we assume that all of the sediments generated by water erosion in the basin will stop at the river courses and subsequently at the reservoir, the rate of sediment transport is 707 Tm/km^2/year (Table 2). The retention capacity is 99.96%, which constitutes annual accumulated sediment of 0.18 hm^3/year, which in turn predicts that the half-life of the Plasencia reservoir is 262 years.

If the SDR is taken into account, the rate of sediment transport is 91 T/km^2/year (Table 2). Given that the capacity of retention is 99.69%, which constitutes annual accumulated sediment of 0.024 hm^3/year, the half-life of the Plasencia reservoir is predicted to be 1966 years. Some studies validate the results obtained for the Jerte basin using this model owing to the correlation between the silting values of our study area with those obtained in basins that show a physiographical similarity to those of the Hydrographic Tajo Basin (Cobo 2008), as well as in the quantification carried out in the reservoirs that have developed a total backfill of accumulated sediment (Bodoque et al. 2001).

In addition, the Lawrence method used to determine the rate of transport sediments shows that in the Jerte basin the values obtained are very different: The rate of sediment transport is 1968.56 Tm/km^2/year (Table 2), which constitutes annual accumulated sediment of 0.488612 hm^3/year; thus, the predicted half-life of the Plasencia reservoir is

Table 2 Results obtained using the different models: USLE/RUSLE2 method without SDR (**a**), USLE/RUSLE2 method with SDR (**b**) and the Lawrence model (**c**)

Method	A Gross erosion	B CES + gross erosion	C Lawrence
Sediment input (*t*/km^2/year)	707	91	1968.56
Basin area (km^2)	375.96	375.96	375.96
Rate of sediment transport (Gs) (kg/year)	265,803,720	34,554,483.6	740,099,000
Specific weight of the transported material (kg/m^3)	1510	1510	1510
Rate of sediment transport (m^3/year)	176,028	22,883.76	490,132.32
Reservoir capacity (hm^3)	59	59	59
Retention coefficient	99.36	99.36	99.36
Rate of annual transport retained by the reservoir (m^3/year)	174,902	22,737.30	488,612.90
Rate of annual transport retained by the reservoir (hm^3/year)	0.18	0.024	0.488612
Life expectancy (years)	262	1966	96
Volume of sediment retained (hm^3)	47.2	47.2	46.90

96 years. These results obtained, only taking into account gross erosion, are not realistic as not all of the eroded sediment in the basin reaches the reservoir.

The more precise methodology, after analyzing the aforementioned results, is the USLE–RUSLE2, applying the sediment delivery ratio, which could be justify by the structure of the parcel-based system with the presence of terraces and terracing and the vegetation in the basin that slows down the runoff and the solid material entering into the channel.

Lastly, the results obtained by the Lawrence method are not accurate, given that it uses a lower number of parameters and presents a more global and general view and greater subjectivity, demonstrated by the lack of concordance with the silting values in adjacent basins.

5 Conclusions

The accuracy of a basin model implicitly carries a heterogeneity that needs to be calibrated with the parameters of the said model. Once calibrated, it is necessary to validate the calibration to establish the degree of reliability and the range of which it can be used.

This allows it to be applied to other reservoirs, establishing the degree of reliability in each case and the range of application for a particular space and time.

The procedure generated shows that the amount of sediments entering into the Plasencia reservoir in the Jerte River Valley is very low, and therefore, the risk of flooding is practically zero. The reduced water storage capacity decreases very slowly, and consequently, the predicted life expectancy is very long.

The use of predictive models, the most accurate as possible, generates great benefits for the management of hydrological, patrimonial and edaphological resources, among others. In addition, they are a primordial tool for risk prevention; this includes special collateral risks such as dam failure, flooding and other catastrophic events. The cartography generated in the model is a non-structural measure that is tremendously useful in the planning of resources for town halls, hydrographic confederations and other organizations implicated in the land-use planning.

Although there are no definitive solutions for the processes that lead to reservoir clogging, the implementation of preventive or corrective measures that minimize the process is necessary. It is essential to establish measures that prevent clogging rates higher than those predicted by the model and to implement maintenance and monitoring plans to control siltation. This continuous monitoring of the progress of the sediments in the reservoir allows for a better understanding of the sedimentary dynamics of the basin being studied. Additionally, the models can be projected over an empirical base that permits more precise predictions to be made regarding the rate of clogging, as this can vary owing to an increase in erosion by anthropogenic causes, such as fires and abandoned crops, as well as the disappearance of terraces, or can extend the period for which preventative measure is taken.

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