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Applied methodology based on HEC-HMS for reservoir filling estimation due to soil erosion

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Abstract: Authors propose a beneficial methodology for hydrological planning in their study. Prospective evaluations of the basins' net capacity can be done using the technique presented. The HEC-HMS (Hydrologic Modelling System) software can be used to estimate in a basin, the sediment emitted. For a certain precipitation, this methodology allows estimating, within a certain range, the gradual blockage of a reservoir, and even a projected date for total blockage. This has some applications to adopt corrective measures that prevent or delay the planned blockage deadlines. The model is of the semi-distributed type, estimating the generation and emission of sediments by sub-basins. The integration of different return periods in HEC-HMS with a semi-distributed model by sub-basins and the application of a mathematical model are the differentiating element of this research. The novelty of this work is to allow prognosing the reservoir sedimentation rate of basins in a local and regional scale with a medium and large temporary framework. The developed methodology allows public institutions to take decisions concerning hydrological planning. It has been applied to the case of "Charco Redondo" reservoir, in Cádiz, Andalusia, in southern Spain. Applying the methodology to this case, an average soil degradation of the reservoir basin has been estimated. Therefore, it is verified that in 50 years the reservoir is expected to lose 8.4% of its capacity.

Keywords: Soil loss; HEC-HMS; Sediments; USLE; MUSLE; Return period.

1. INTRODUCTION

The water resource is inextricably linked to the soil resource in the case of reservoirs. Reservoirs are affected by the loss of quality of their waters and the reduction of their available quantity as they become blocked (Stephens et al., 2020). There is an urgent need to adopt methodologies that allow defining sedimentation yield (Đukić and Erić, 2021). For this purpose, current tools available for hydrological modeling, such as HEC-HMS are used (Chiang et al., 2022; Revell et al., 2021; Şengül and İspirli, 2022). The current availability of environmental information of different types (thematic cartography, diverse climatic data and others) requires a method to obtain the dates and degrees. On the other hand, the erosion of watersheds is not a problem only for reservoirs. For this reason, it may be of interest in the generation of hyper-concentrated flows, as shown in this study. To this, soil conservation for agriculture can also be considered, although the area where the methodology with attached HEC-HMS refers specifically to the blockage of reservoirs. On the other hand, the soil that is transferred to the reservoir in the form of sediments in the riverbeds and drainage basins is a valuable resource, as a part of the basin-reservoir system.

The sediments that enter the reservoir come, in the first instance, from a previously disaggregated soil (Lu et al., 2016). The soil is the support of the protective forest cover of the reservoir basin itself. Moreover, this depends on the land uses of the catchment basin, and the base of agricultural crops that provide food, if they exist in a given basin. In the past it seemed to be an inexhaustible resource, but currently, it is suffering the consequences of deforestation, its inappropriate use, and currently, the consequences of climate change (Busari et al., 2015). Thousands of tons of soil are lost every day, dumped into the sea, or end up in reservoirs that in the future will show obvious problems related to sediment deposition. Thus, this study applies a methodology to estimate and control the sediment deposition evolution in a specific case.

Institutional initiatives arose from the need to control and supervise land use. The first example that should be noted, due to its importance on a global scale, and regarding the models they defined, some of which were used in this work, is the Soil Conservation Service (SCS) of the US Department of Agriculture (USDA). The USDA is the first developer of the USLE model and its modified version to estimate sediment emission in MUSLE catchments (Devatha et al., 2015). They have also defined different functions and methodologies which in Spanish are accompanied by the acronym SCS. The USLE model, in its first models for the agro-hydrological management of watersheds, already worked with different options for soil conservation practices. The SWAT model (Soil and Water Assessment Tool) is also used to estimate sediments and is widely used in assessing soil erosion prevention and control (Akoko et al., 2021; Gassman et al., 2014). However, its application has some limitations. SWAT model underestimates the topographic factor in the sub-basins, especially when the slope is greater than 25% (Rivera-Toral et al., 2012).

The imposition of the aforementioned practices became necessary, in addition to the intervention of public powers at the legislative and instrumental level. Other countries imitated the formula with greater or lesser success, adapting it to their specific needs. In fact, at a European level, the expression "damage to the ground" OPOCE (2004) is included, and that is a precedent included in the 2006 proposal. From here, different institutional efforts were made until they reached the Resolution of the European Parliament on soil protection (2021/2548(RSP)) of April 28. This last declaration is an important declaration (of intentions), and although it is technically impossible for it to be fulfilled (emphasis added), controlling soil erosion and reducing its consequences on reservoirs is possible. It is in this context that this research has been developed.

Accompanying the aforementioned legal background is a series of documents and projects of a technical and scientific nature, which have been taken into account in this paper in some way. Firstly, studies which use HEC-HMS are reviewed. Projects of one of the authors of the software support have been of interest to perform the study (Pak et al. 2008; Pak et al. 2021). They use the tool to estimate erosion and sediment transport in a hydrological model, including a sensitivity analysis in the last referenced paper of 2015. The support of the online program is essential, which has been requested repeatedly (Teng et al., 2018). In the integration of the different return periods, an exemplification of the formulation has been selected due to its adaptation to the work carried out. The objectives of this paper can be summarized in two main points: First, to design a specific methodology to estimate the blockage of a reservoir due to water erosion of the soils present in the basin. Similarly, to apply the methodology to a specific case and estimate the interannual emission of sediments. This study corresponds to the “Charco Redondo” reservoir. Recently the situation in this specific case has worsened due to the current drought. Reservoir capacity diminished until the level 25%. In addition, the presence of fine materials due to the nature of sediments and clay soils of the basin increase turbidity, generating a deterioration of water quality.

The novelty of this research is framed in the integration of different return periods in HEC-HMS with a semi-distributed model by sub-basins, and a discrete mathematical formulation to estimate the annual rate of sediment deposition. The methodology provided is applied within the use of design hyetographs, the curve number parceling calculation, an appropriate lag time, the analysis of hydrographs propagation, and finally the annual rate of sediment deposition, using the USLE model, Modified USLE and HEC-HMS implementation of MUSLE model. While many basins studies still make use of USLE model, or the revised version, this was designed for small basins so large errors are found when this is applied to large basins studies (El Araroussi et al., 2011; Elaloui et al., 2017; Hara et al., 2018; Jaferi et al., 2016; Lamyaa et al., 2018; Sathya et al., 2021; Toumi et al., 2013).The MUSLE model take into account biophysical characteristics for better flow estimation, and while this is already on use with HEC-HMS implementations, results are limited (Ghosh et al., 2022; Konečná et al., 2019; Pak et al. 2008; Pak et al., 2015a, 2015b). Therefore, this study proposes a specific methodology where the relevant results of each model are considered to provide a estimation across several sub-basins and large return periods for scalable rate.

2. MATERIALS AND METHODS

2.1. Applied methodology

The HEC-HMS application is used in the technique, which comprises the MUSLE model by sub-basins (Djoukbala et al., 2019). For the specific case, the propagation of hydrographs and sediment graphs in three riverbed sections and a total of 16 sub-basins has been implemented with HEC-HMS. Finally, the water and sediments flow generated in an average year is estimated, using a formulation that discreetly analyses the weighted effect of storm events linked to different return periods. All mapping and geoprocessing has been done with the help of QGIS software (2021).

The model presented in this paper is based on the MUSLE model, which, in turn, uses certain parameters of the USLE model. Although the USLE and MUSLE models have already been extensively validated and calibrated in the scientific literature (Cohen et al., 2005; Kinnell, 2005; McCool et al., 1987; Odongo et al., 2013; Pongsai et al., 2010; Zhang et al.,2009). The parameters of these models have been adjusted specifically for the sub-basins which have been involved in this study. By means of HEC-HMS and a specific discrete mathematical formulation, the sediment emission referred to specific return period intervals is calculated. Through a probabilistic calculation, the value of inter-annual emission of sediments from the basin to the reservoir is obtained. Then, applying the different parameters of the reservoir, an estimation of its blockage is obtained up to a temporal horizon of 50 years.

USLE model allows a first view of the specific degradation (erosion due to soil removal). This is obtained at the level of sub-basins and for the entire basin. A common mistake is to estimate the sediment deposition of a reservoir based on the USLE in complex systems with different sub-basins and sediment spreads. USLE model considers all soil removed in an average year to be erosion. However, not all of the removed soil necessarily has to be emitted. In fact, the applied methodology requires the MUSLE model for different return periods On the other hand, from a model validation point of view, USLE is also used because they share some parameters with MUSLE, facilitating the adjustment and correction of some of these parameters (Environmental Information Network of Andalusia) REDIAM's significant data has been made available for this purpose. It is an official, governmental, public data source with great notoriety in the south of Spain. The information contained in REDIAM is protected by regional environmental and territorial planning legislation. In the calibration of the semi-distributed model by sub-basins, among other adjustments, it was determined that the K factor for sub-basin 15 was slightly undervalued, and its value should be corrected from 0.31 (initial) to 0.35 (final).

The use of HEC-HMS to estimate the emission of sediments is known (Pak et al., 2015b). Nevertheless, there are no known works that apply the tool to estimate the expected dates of blockage, integrating different return periods for this. In order to estimate the sediment input data to the reservoir for an average year, it is previously necessary to know the water and sediments flows for the different sub-basins and their respective propagations, aggregated by groups of sub-basins and the total (Berteni et al., 2021). The main operations followed are indicated in the next flowchart, Figure 1.

2.2. Models and tool used

The USLE and MUSLE models are part of the basis to be able to apply the proposed methodology. The validity of your results depends on it. Specifically, a calibration of the MUSLE model at the sub-basin level is necessary, prior to the application of the discrete probabilistic model. USLE, MUSLE, and a discrete probabilistic model are the models utilized, which are described below:

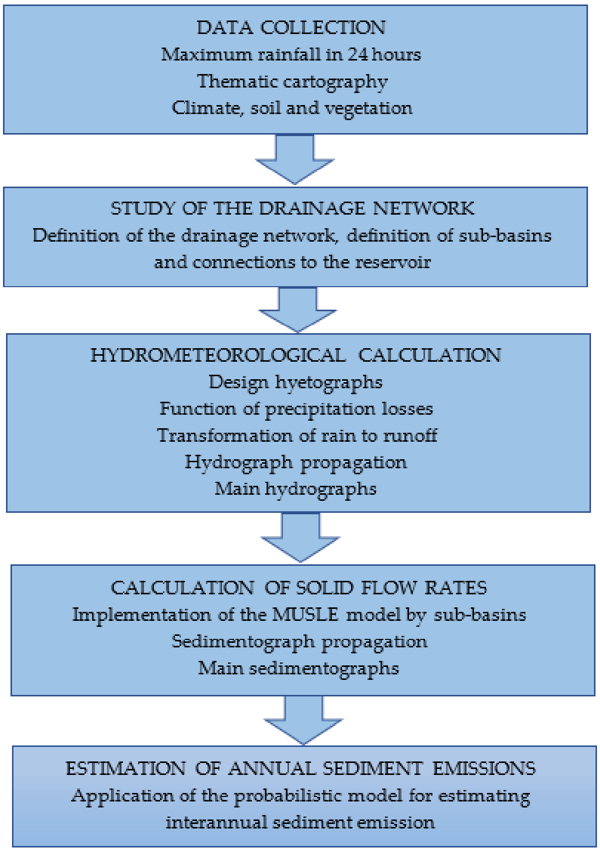

Fig. 1. Operations flowchart.

2.2.1. USLE

The USLE model is used for two reasons: to determine the risk of erosion in the basin due to soil disintegration, and to determine the five parameters that are identical to the MUSLE model. The data provided by the USLE model is essential, and the methodology would be useless without it. As a result, the methodology presented is based on reliable data from the USLE model on the basin. The form of the USLE that will be used responds to the following expression:

$$A = R \cdot K \cdot (L \cdot S) \cdot C \cdot P \tag{1}$$

where A: average annual soil loss [t/(ha year)];
R: rain erosivity index factor (the obtained value is of 199.9 Mj cm/(ha h year));
K: soil erodibility factor [t ha h/(ha Mj cm)];
L: slope length factor. It is usually grouped to the factor S [dimensionless];
S: slope factor [dimensionless];
C: crop management factor [dimensionless];
P: support practice factor. For each sub-basin it shows a value of 1 [dimensionless].

The R and K factors are the only ones with dimensions, normally referring to an average year.

2.2.2. MUSLE

For a design rainfall, the MUSLE model is utilized to calculate the soil particles emitted by each sub-basin. Its application in applied methods has two distinct characteristics: First, the model is used for each of the 16 sub-basins within each group, and secondly, it is used for return periods of $T = 2$, 5, 25, 50, and 100 years. Model is established in the following expression:

$$Y = 11.8\,(Q\,q_p)^{0.56}\,K \cdot (L \cdot S) \cdot C \cdot P \tag{2}$$

where Y: sediments yield by each sub-basin [t];
Q: runoff volume [m^3];
q_p : peak flow rate [m^3/s].

It is also possible to obtain the sediment yield referred per ha (Berteni et al., 2021).

The remaining terms are the same as those defined for the USLE model.

The phenomenon of water erosion, as a whole fact, must therefore be considered as the integration of a triple process:

- The disintegration of soil particles in each sub-basin.
- The transport of the disaggregated particles out of the sub-basin to a propagation section, or directly to the reservoir vessel, depending on the place occupied by that sub-basin.
- The propagation of particles through certain sections of riverbeds to the reservoir vessel.

2.2.3. Discrete probabilistic model

For the integration of the different hydrographs and sedimentographs for different return periods, a discrete probabilistic model has been used. This formulation couples the probability of occurrence and emission of sediments. In order to be able to refer to the sediments emitted for an average year, a statistical analysis will have to be applied based on daily precipitation. To do this, several return periods are chosen, in this case 2, 5, 25, 50 and 100 years. It has been proven that return periods with values greater than 100 years have an insignificant effect on the results for an average year. The mathematical formulation that defines the discrete probabilistic model is as follows in Equation 3:

$$Y_T = \sum_{i=1}^{100} \left[\frac{1}{2} \left(Y_{Ti} + Y_{T(i+1)} \right) \left(\frac{1}{T_i} - \frac{1}{T_{(i+1)}} \right) \right] \tag{3}$$

where Y_T: interannual emission of sediments to the reservoir [t];
Y_{Ti}: emission corresponding to a downpour with a return period T_i [t].

It is possible to get interannual sediment emission data to the reservoir using this probabilistic model after applying MUSLE by sub-basins and properly linking the hydrograms and sedimentograms according to the drainage network.

2.2.4. Tools

The following are the specific instruments used:
- HEC-HMS: hydrograms and sedimentograms calculations. Allows to implement MUSLE by subbasins for different return periods.
- HEC-DSS (Data Storage System): tool for managing the massive volume of data generated by HEC-HMS for various return periods.
- QGIS: a tool for measuring and processing environmental data in the basin. For channel measurements and other activities, other plugins like "profile tool" were utilized.

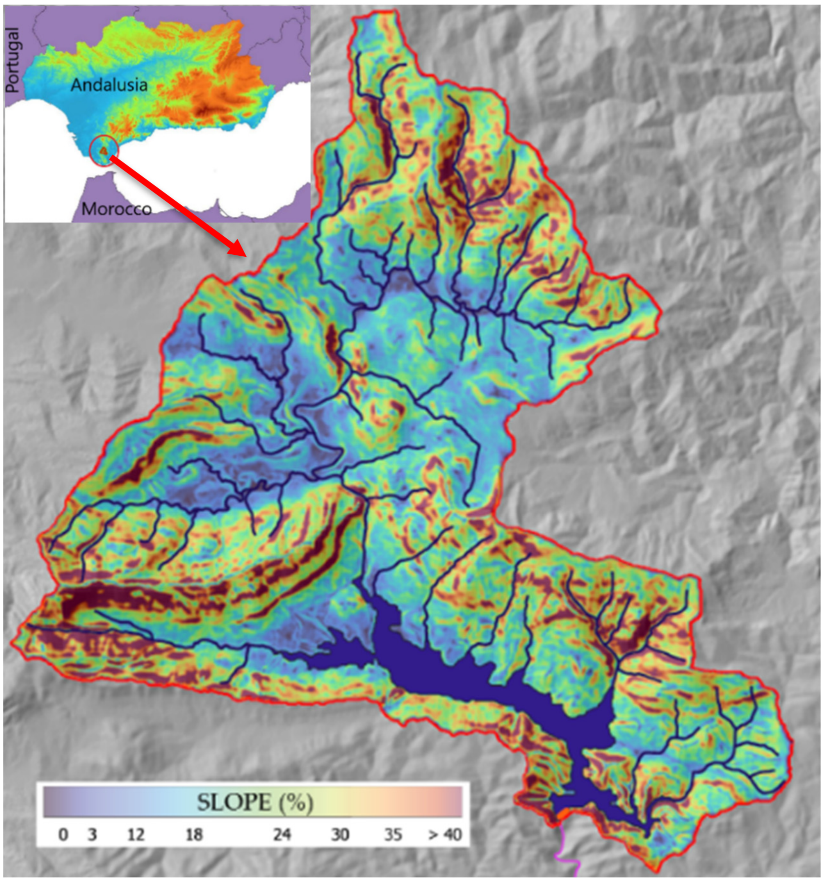

Fig. 2. Basin location and map of slopes.

2.3. Study area

2.3.1. Location

The methodology has been applied to a specific case: the basin of the "Charco Redondo" reservoir, located in Andalusia, a region in southern Spain, as it is possible to see in Figures 2 and 3. This region is currently suffering from a severe drought and the consequently significant decrease in water resources.

2.3.2. Climatology, soils and forest cover

The climate-soil-vegetation triad generate an interrelated and complex system. Modeling works require to know separately the characteristics of both, water and sediments flows modelling (Rodriguez-Iturbe, 2000). Climate affected by a clearly Mediterranean thermo-pluviometric regime with mild winters. The basin is located in one of the rainiest areas of Spain, in contrast to the regional climate of Andalusia, although it is currently affected by drought problems. The average annual temperature of the basin is approximately 16.5–17 ºC. The maximum values occur in the months of July and August, and the minimum in the months of January and February. Within the climatic classifications, the climate where the basin is located has been classified as sub-humid-humid Mediterranean climate of the Campo de Gibraltar (Gómez-Zotano et al., 2015).

The basin is part of the Betic System, and within it, of the southernmost mountains of the Cordilleras Penibéticas. The basin is made up of terrain from the Lower Miocene (the siliceous sandstones, such as those in the highlands of Los Garlitos) and Paleogene (the clays, marls and limestones from other areas). The geological units present in the basin are all Specific Units of the Betic Mountains and the Rif. They are specific geological units of the Campo de Gibraltar. In turn, from a structural and tectonic geological point of view, these units have a thrust development at all their interfaces. These geological units of the Campo de Gibraltar. Specifically, according to the numbering of the Spanish Geological and Mining Institute (IGME) Geological Map (López-Olmedo, 2017), there are 3 of which 102 and 104 have more surface presence in the reservoir basin. As for the soils, closely linked to the geological base, they will be divided into 2 edaphic units, one with a sandy texture, and the other, with a predominantly clayey texture, notably affecting the type of sediment predominant in the reservoir.

Regarding forest cover, the basin presents vegetation typical of a Mediterranean-subhumid phytoclimatic region with an Atlantic trend (type IV (V) according to the phytoclimatic types of (Allue, 1990). In general, the basin presents a good forest state of the protective vegetal cover, for which in the USLE and MUSLE erosion models, factor C directly linked to the vegetation, has adopted relatively high values. By strata, the basin has a very important tree stratum, being the predominant one. This stratum provides the greatest soil protection against erosion, improves infiltration and interception of rain (Moreno, 2008). The predominant species are *Quercus suber*, *Quercus faginea*, *Quercus canariensis*, *Pinus halepensis*, *Pinus pinea*, and to a lesser extent *Olea europaea* var. sylvestris. The basin also has transitional sclerophyllous and woody scrub protection against erosion is less, and even its presence, in the case of sclerophyllous scrub, can indicate soil erosion two. Regarding the herbaceous stratum, it is important in grasslands on the clay soils of the Campo de Gibraltar clays unit. It provides the least degree of protection against erosion and suffers more pronounced withering on sunny slopes. Considered as a special

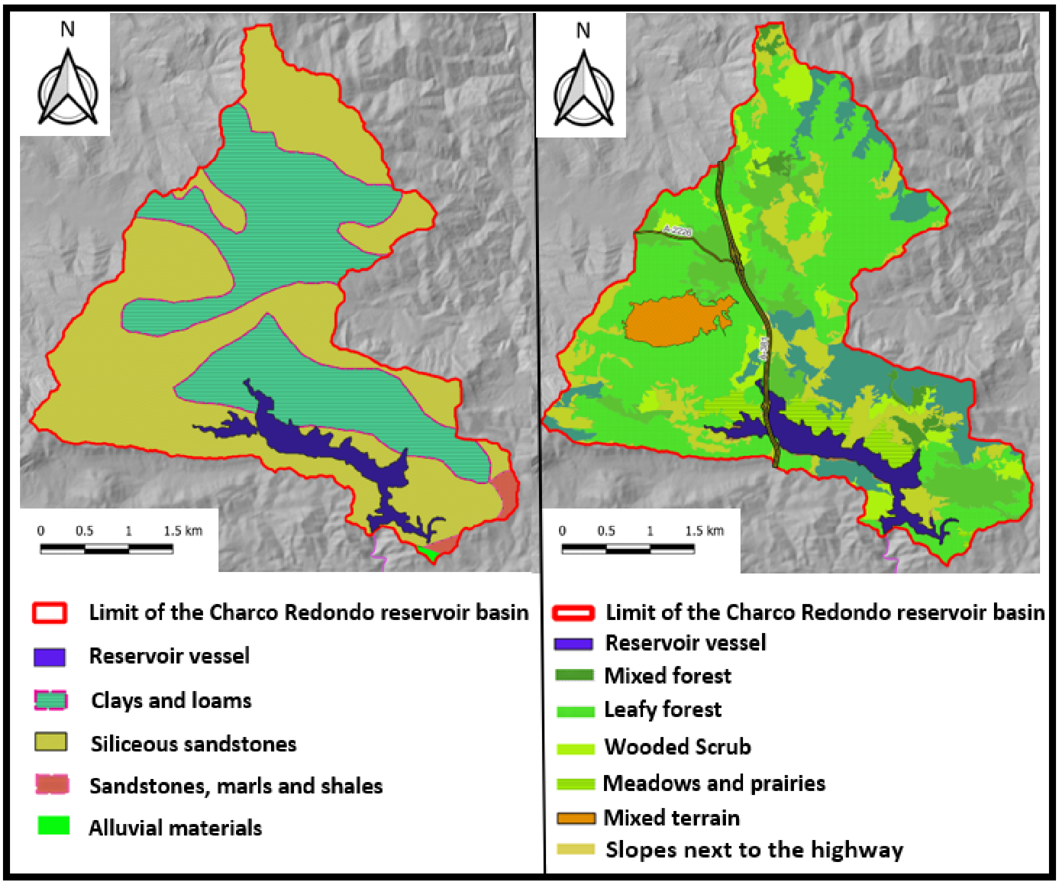

Fig. 3. Thematic maps.

stratum, Riparian vegetation is added to these strata. This is an important fact in this study since it affects the determination of Manning's roughness coefficient n, the possible delay of the flood wave, the decrease in the tractive capacity of the flow in large avenues, by slowing down the flow. Thus, it implies the consequent decantation effect of the coarsest sediments.

Summarising the previous information, Figure 3 shows the thematic maps regarding basin characteristics.

2.3.3. Drainage network model

The basin has been divided into a total of 16 sub-basins, each with its own characteristics. The criteria followed for subdivision into sub-basins are two: drainage conditions and homogeneity. The sub-basins, although initially based on the environmental information provided by REDIAM in 2021 (REDIAM, 2022), depending on Junta de Andalucía, these for the case at hand, have been modified with editing tools with QGIS software (2021) due to presenting some punctual inconsistency. By criteria of drainage and homogeneity, it is not necessary to divide the headwaters into more than two sub-basins. For the calculation of the concentration time, a proven methodology has been used for application in the Iberian Peninsula, taking into account the serial and/or parallel connections of the different sub-basins (Témez, 1978; Témez, 2003). The expression of the concentration time corresponds to Equation:

$$T_c = 0.3\left[L / J^{1/4}\right]^{0.76} = 0.3 \cdot L^{0.76} \cdot J^{-0.19} \qquad (4)$$

where T_c: concentration time [h];
L: length of the main course of the studied basin [km];
J: average slope of the main course of the studied basin [ratio over 1].

The system is divided into sub-basins as reflected in Figure 4. The sub-basins have been grouped into 3 groups for modelling purposes

- Group I. Sub-basins 1 to 7. They follow a complex flow sum and propagation scheme. They have flow interrelation.
- Group II. Sub-basins 8 to 14. Each one forms an independent subsystem; without sharing flows and each pouring its flow directly into the glass.
- Group III. Sub-basins 15 and 16. They also form an independent subsystem, with the particularity of the absence of a main channel in sub-basin 16.

2.3.4. Propagation

The propagation of hydrographs is analysed by the Muskingum-Cunge method using HEC-HMS, Table 1. The method used in this study, in the hydrological model of propagation in channels, has been the Muskingum-Cunge method (Cunge, 1969) in the version of Ponce et al. (1978) and with the updates already included in the program of U.S. Army Corps of Engineers. In HEC-HMS, version available in 2020, there are only two methods to model the propagations that allow the joint modelling of water and sediments flows: the aforementioned method, and the "Kinematic Wave" method. The variables requested by the program are geometric, roughness of the bed and relative to the speed of the wave.

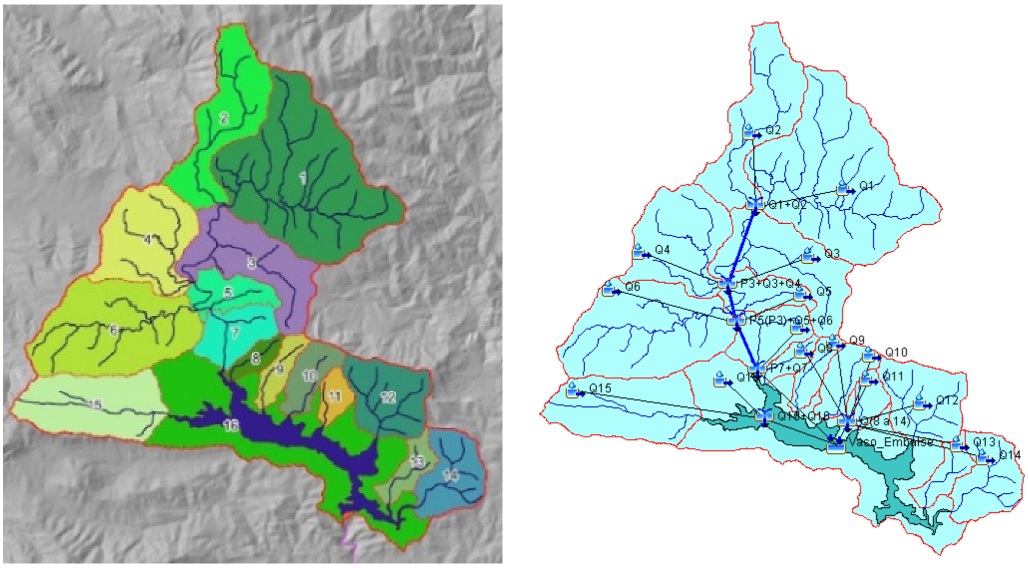

Fig. 4. Drainage network. Division into sub-basins and hydrological connection scheme in HEC-HMS.

Table 1. Soil units. Granulometry.

Sandy algibe		Campo de Gibraltar clays		**Mixed sediments**	
Diameter (mm)	% Pass	Diameter (mm)	% Pass	Diameter (mm)	% Pass
0.0005	0	0.0005	0	0.0005	0
0.0007	5	0.0008	7	0.0008	7
0.0009	6	0.0009	15	0.0009	15
0.001	7	0.001	23	0.001	23
0.002	10	0.002	40	0.002	40
0.005	15	0.005	45	0.005	43
0.01	20	0.01	50	0.01	45
0.04	35	0.04	53	0.04	50
0.05	40	0.05	55	0.05	55
0.063	42	006	56	0.06	56
0.08	50	0.08	60	0.08	60
0.1	70	0.1	63	0.1	70
0.25	90	0.25	75	0.25	90
0.5	95	0.5	85	0.5	95
1	100	1	100	1	100

The geometric values are obtained with the help of QGIS software (2021) for each section. The Manning coefficients must be selected with the minimum possible value that the reference table allows (Chow, 1959). Excessively high values give convergence errors with the application (when working together with hydrographs and sedimentograms). Specifically, in certain cases HEC-HMS warns with a WARNING 41071, which implies errors of discontinuities and jumps in the sedimentograms.

2.5. Specific degradation of the Charco Redondo reservoir basin: USLE model

The environmental information provided by REDIAM (2022) regarding erosion in Andalusia, allows us to obtain a basic reference to contrast the distributed results obtained with the USLE model. A specific validation and calibration has been applied to the USLE model. Validation, for its intended use, has involved field observations and calibration of the R, K and L·S parameters, with the variation of the K factor being relevant for sub-basin 15. The validation and calibration process has included in the first place the comparative analysis between the application of the USLE model with the data obtained from REDIAM (2022) in Campo de Gibraltar, as well as the application of USLE with an assignment of the basic parameters, plot level, by the authors. In addition to the information available in REDIAM (2022).

The L·S factor involved, among others, operations with QGIS software (2021) for its determination. Adjusting the plots with slopes greater than 30%, based on other usual values for Andalusian basins obtained by Mintegui Aguirre and Sánchez (1994). The R factor was obtained by regression according to the formulation of Spanish Nature Conservation Institute ICONA (1988). The soil erodibility K-factor in the USLE model establishes different levels of accuracy. For a more precise adjustment, a detailed description of the soils was required, with quantification of textures, structure and permeability. The formulation already used successfully in the neighboring basin of the Alhaja or Madrevieja stream (Rodríguez-González, 1998), which is based on the Wischmeier formulation (Wischmeier et al., 1971, Wischmeier and Smith, 1978). Applying the USLE model to the sub-basins of the "Charco Redondo", after validation and calibration of the USLE model, reservoir basin, next Table 3 is obtained.

2.6. Modified USLE model (MUSLE) and implementation with HEC-HMS

The extension of the USLE model to small experimental basins, starting in the 1970s, gave rise to the MUSLE model (Modified Universal Soil Loss Equation), with the aim of predicting the sediments contributed by them for a specific rainfall episode (Wischmeier and Smith, 1978). This model is used l to calculate the emission of sediments generated in the basin by sheet erosion and in rills. In this way, the "removed" soil particles that leave the basin are obtained, becoming "emitted" soil.

3. RESULTS

3.1. Hydrological calculation applied to the “Charco Redondo” reservoir basin

The differential aspects of the hydrometeorological calculation of the given methodology are developed next (Arekhi et al., 2011).

3.1.1. Parceling

The precipitation loss function used is that of the USDA Soil Conservation Service SCS (Boughton, 1989). To calculate the CN curve number, the already defined sub-basins have been used. For each sub-basin, the average CN has been obtained by the predominant categories and area, with the help of QGIS software (2021). The HEC-HMS tool allows working by sub-basins with average values of the CN curve number. This study, in the context of calculating the interannual emission of sediments, the original American tables have been used for the CN values. To obtain a global CN for each sub-basin, the average curve number is calculated as follows in Equation 5:

$$CN_{med} = \frac{\sum_{i=1}^{n} CN_i \cdot S_i}{S} \tag{5}$$

CN_{med}: average curve number for each reservoir sub-basin;
CN_i: curve number corresponding to surface i;
S_i: surface i with a certain homogeneity in soil, cover and slope (ha); S: surface area of the sub-basin (ha).

The defined plots are 150 (Figure 5). The A-381 highway at the passage of sub-basins 2, 3, 4, 5, 7, 8 and 16 has been taken into consideration. Once the CN has been calculated by sub-basins, it is possible to obtain the ratio of values necessary to work with HEC-HMS by sub-basins. The weighted CN value for the entire basin is 61.08.

3.1.2. Design hyetograms

Needed to compose the design of rainfall for different return periods, 5 design hyetograms have been prepared using the alternate block method, and associated with different return periods of 2, 5, 25, 50 and 100 years. These hyetograms are shown in Figure 6:

3.1.3. Time delay

It is important to work with the appropriate time delay “lag time” or Tlag, Table 1. According to the recommendation of the HEC-HMS program support, it is recommended to adopt it as $0.60 \cdot T_c$.

3.2. Erosion risk in Charco Redondo reservoir basin: USLE model

Applying the USLE model to the sub-basins of the “Charco Redondo”, after validation and calibration of the USLE model, reservoir basin, next Table 2 is obtained.

The estimated average erosion by disintegration of the Charco Redondo reservoir basin is 83.30 t/(ha·year), which is considered high according to the ranges applied by the Consejería de Agricultura, Ganadería, Pesca y Desarrollo Sostenible, through the map of erosion available in REDIAM (2022). The tons of soil removed in the basin amount to 377,685 t. Of this amount, a fraction will enter the reservoir in the form of sediment. As for the erosion map for the basin obtained, it is shown in Figure 7.

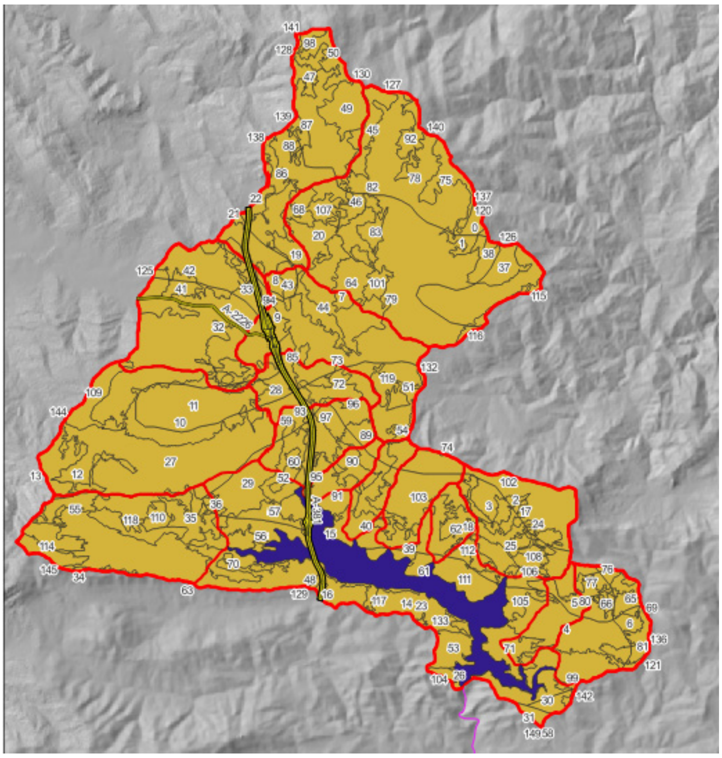

Fig. 5. CN Curve Number. Parcelling.

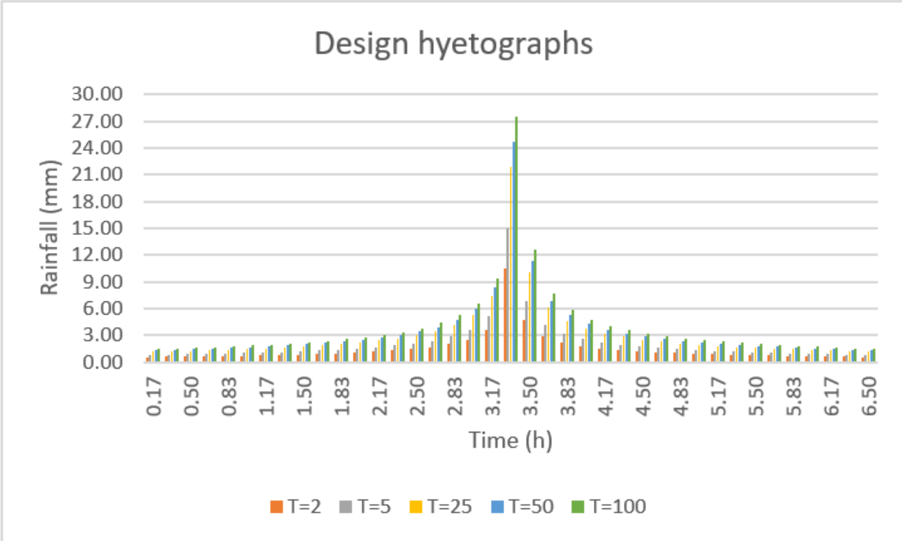

Fig. 6. Design Hyetographs. Alternate Blocks. T = 2, 5, 25, 50 and 100 years.

Table 2. Delay time by sub-basins.

Sub-basin	T_{lag} (minutes)	Sub-basin	T_{lag} (minutes)
1	86.89	9	30.90
2	84.58	10	29.78
3	78.43	11	20.91
4	70.05	12	31.01
5	26.08	13	34.56
6	76.02	14	41.41
7	36.59	15	54.26
8	26.38	16	60.00

The analysis of results has been carried out both separately and in a coupled way between the runoff and the emission of sediments according to the aspect to be illustrated. The basic information used corresponds to the results obtained with HEC-HMS for T = 2, 5, 25, 50 and 100 years; including hydrographs, sedimentograms and results tables from which a motivated selection will be extracted.

3.1. Results of runoff and sediment emission by sub-basins

Next, the results compared by groups of sub-basins and total are presented. Analyzing the results obtained for runoff, from the outlet hydrographs of the respective groups, it is evident that group I is the one that contributes the highest flows to the reservoir. If the following illustrations are observed, it is possible to see in a comparative way the inlet hydrographs to the reservoir of each group. Selecting for a 100-year return period, although it is true for all those analyzed, Figure 8 is obtained.

Regarding the sediments flows, they are broken down by generation by sub-basins, entry by groups and total to the reservoir and breakdown by the textures considered. Regarding the generation of sediments by group I, clearly, sub-basin 1 is the one that generates the largest sediments. Its larger area, but above all its steep slopes and the presence of mixed soil units, do not manage to temper the high sediments flow that it emits despite having a strong protective plant cover. In group II, it is the sub-basin of the Cebrillo stream (nº12) that generates a greater amount of sediment. In group III, sub-basin 16, which corresponds to a path on hillsides, is the one that generates the largest sediments. In addition, due to its location around the

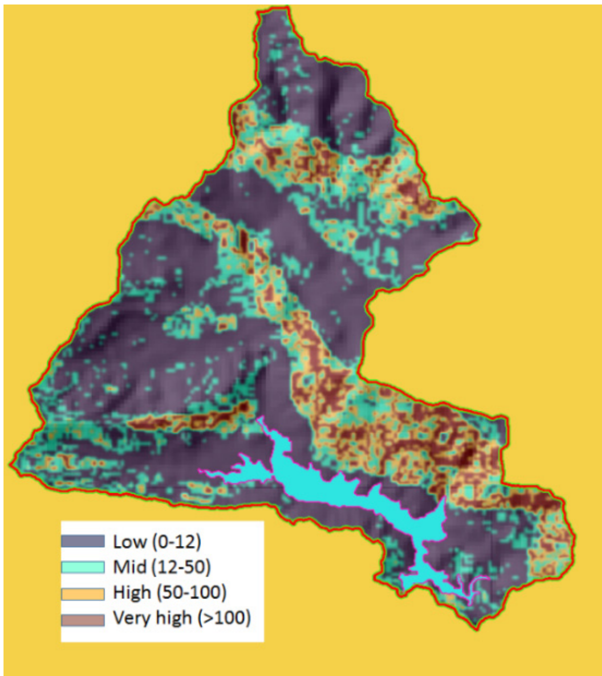

Fig. 7. Specific degradation by erosion according to USLE model (t/ha*year).

reservoir, the disaggregated and emitted soil will do so without any propagation of sediments and throughout the contour of the reservoir. Below, groups of sub-basins in Figure 9 illustrate the sedimentograms.

Next, it is possible to see the sediment input by groups of sub-basins and total to the reservoir. It is verified that group II (sub-basins 8 to 14) is the one with the greatest contribution of sediments. It is checked for all T considered. It is shown graphically for the return periods of 2, 5, 25, 50 and 100 years in Figures 10 to 12.

From the previous results, an important second conclusion is deduced: although there is a coupling between sediments flows and return periods for an isolated event; there is a decoupling between water and sediments flows from different basins. There is no possible generalization since a case has been found

Table 3. Average USLE factors by sub-basins.

Sub-basin	R	K	LS	C	P	Average erosion [t/(hayear)]	Erosion by soil removal [t/year]
1	200	0.35	5.74	0.10	1.00	41.2	70116
2	200	0.34	5.95	0.08	1.00	30.4	22109
3	200	0.36	3.96	0.12	1.00	34.1	23637
4	200	0.33	3.77	0.12	1.00	29.3	20417
5	200	0.34	3.40	0.20	1.00	46.3	11266
6	200	0.32	5.69	0.05	1.00	19.3	21042
7	200	0.37	9.00	0.07	1.00	43.3	13128
8	200	0.39	5.46	0.17	1.00	70.5	7576
9	200	0.37	8.80	0.14	1.00	89.7	13185
10	200	0.38	9.62	0.13	1.00	90.8	19946
11	200	0.40	11.00	0.13	1.00	112.2	13178
12	200	0.36	11.67	0.12	1.00	99.2	46108
13	200	0.33	5.81	0.08	1.00	31.5	5099
14	200	0.34	5.60	0.18	1.00	66.3	25665
15	200	0.35	14.44	0.04	1.00	35.8	25346
16	200	0.33	6.27	0.07	1.00	30.7	39866
TOTAL						83.30	377685

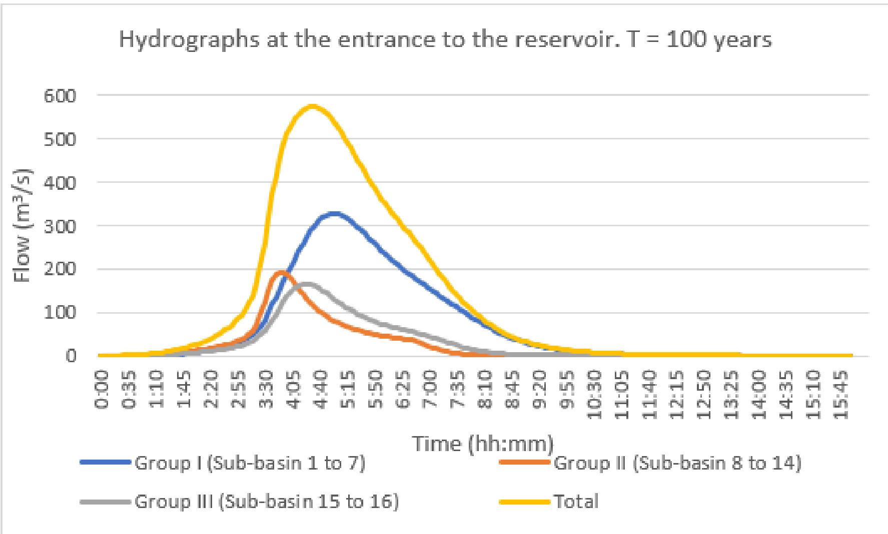

Fig. 8. Hydrographs at the entrance to the reservoir. By groups I, II and III; and total. $T = 100$ years.

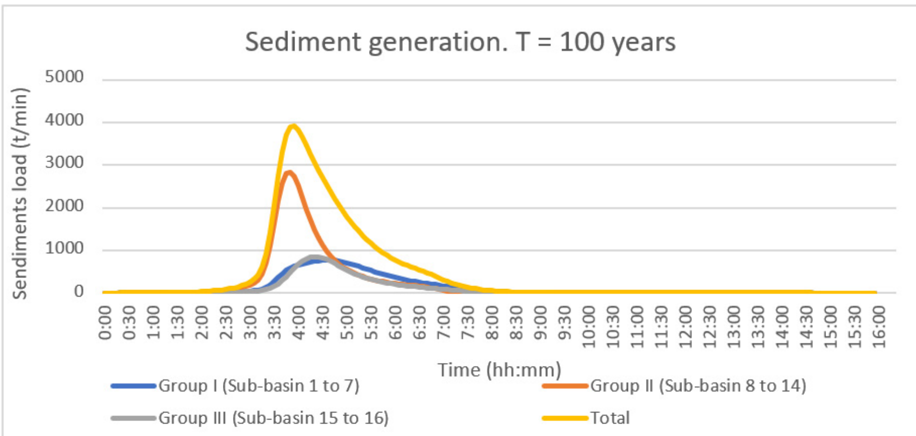

Fig. 9. Groups I, II and III. Generation of sediments by sub-basins. $T = 100$ years.

that contradicts it: group II of sub-basins 8 to 14 emits more sediment to the reservoir than group I sub-basins (1 to 7), despite the fact that group I contributes more runoff. The reason for this, observing the thematic cartography and results, is that group II has a greater presence of more erodible soils with finer grain sizes. The slopes are not very different: groups I and II have areas of steep slopes. But the presence of clay soils is more evident in group II.

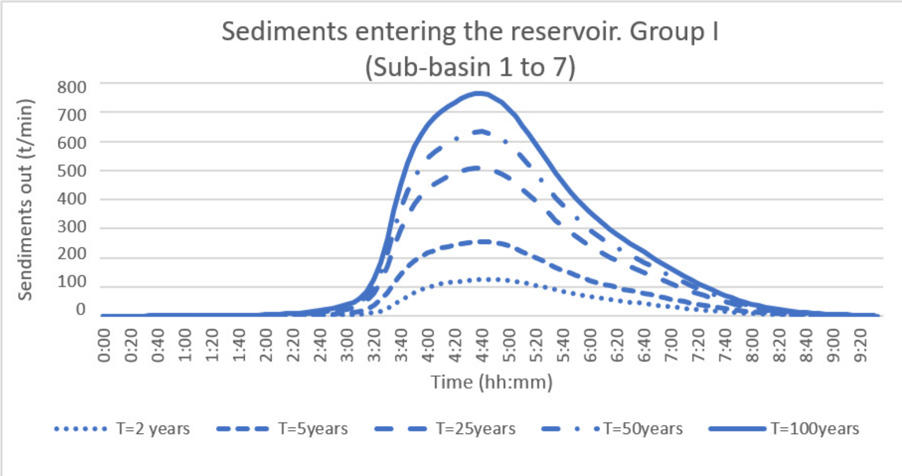

Fig. 10. Generation of sediments by sub-basins (Group I).

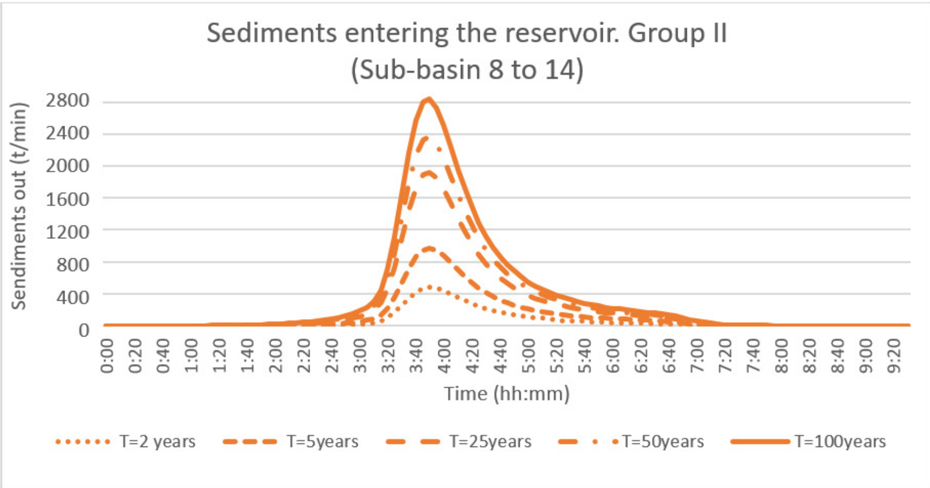

Fig. 11. Generation of sediments by sub-basins (Group II).

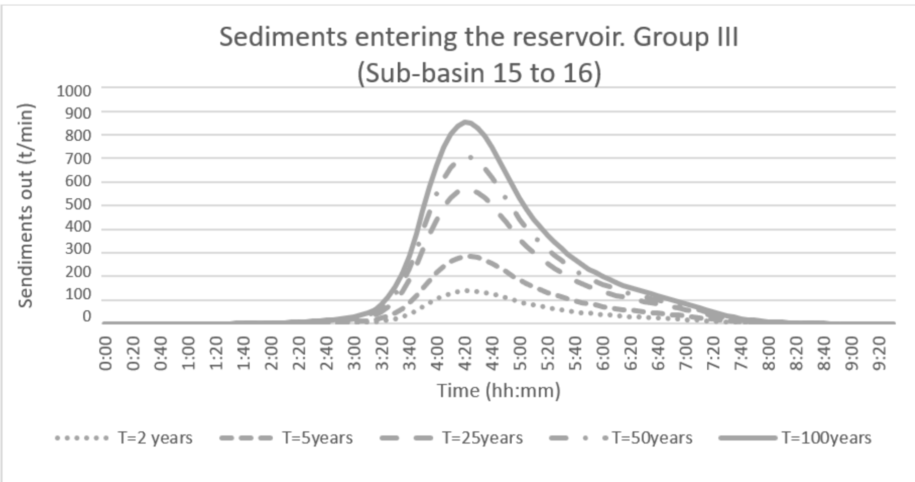

Fig. 12. Generation of sediments by sub-basins (Group III).

3.2. Emission of sediments to the reservoir by return periods and interannual emission

Using HEC-HMS, the results of sediment emission by sub-basins and total to the reservoir are obtained for each return period of 2, 5, 25, 50 and 100 years, Figure 13 and Table 4.

Using HEC–HMS, the results of sediment emission by sub-basins and total to the reservoir are obtained for each return period of 2, 5, 25, 50 and 100 years.

Applying this expression to the discrete emission data for 2, 5, 25, 50 and 100 years of return period, the results of the following Table 6 are obtained. The information collected in the Table 5 contains the key results of this study, on which the conclusions will be drawn.

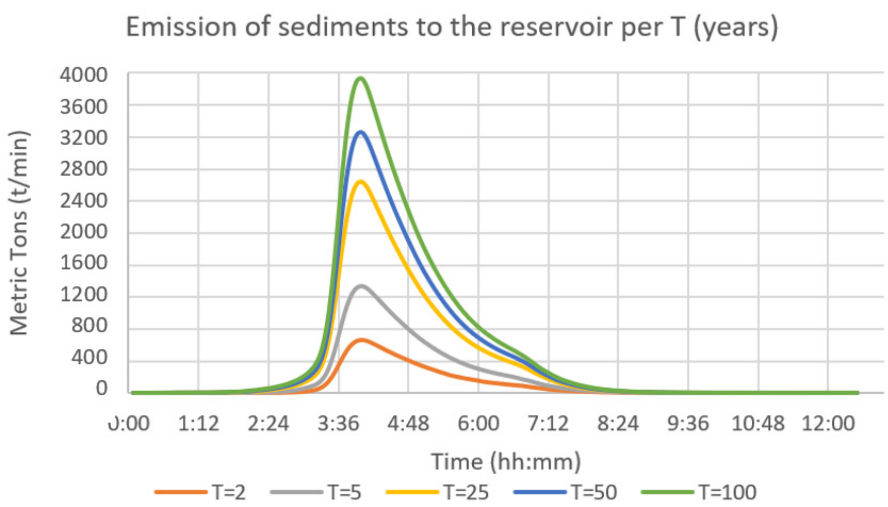

Fig. 13. Emission of sediments to the reservoir for different T (2, 5, 25, 50 and 100 years).

Table 4. Total emission of sediments in the reservoir by return periods.

	T = 2 years	**T = 5 years**	**T = 25 years**	**T = 50 years**	**T = 100 years**
TOTAL (t)	70129	141622	278600	343845	413413

Table 5. Interannual emission of sediments to the Charco Redondo reservoir.

Interval (years)	**Probability of occurrence** $\left(\frac{1}{T_i}-\frac{1}{T_{(i+1)}}\right)$	**Average sediments (t)** $\frac{1}{2}\left(Y_{Ti}+Y_{T(i+1)}\right)$	**Interannual emission (t)** $\frac{1}{2}\left(Y_{Ti}+Y_{T(i+1)}\right)\left(\frac{1}{T_i}-\frac{1}{T_{(i+1)}}\right)$
2 – 5	0.30	105875	31763
5 – 25	0.16	210160	33626
25 – 50	0.02	311272	6225
50 – 100	0.01	378629	3786
Interannual emission of sediments (average /year)			75400

Table 6. Interannual emission of sediments by intervals of T. Percentages.

Interval of T (years)	**Sediments emitted per interval (t/year)**	**Sediments emitted percentage**	**Sediments emitted by accumulated intervals (t/year)**	**Accumulated percentage emitted sediments**
2 – 5	31763	42.1%	31763	42.1%
5 – 25	33626	44.6%	65388	86.7%
25 – 50	6225	8.3%	71614	95.0%
50 – 100	3786	5.0%	75400	100.0%
Interannual emission of sediments (average t/year)			75400	100.0%

If the sediment input to the reservoir is observed for T = 2, 25 and 100 years, the evident influence of the return period can be seen. This means that, the more water flow, the more solids flow. However, what is not so evident is that it is precisely for the interval between T = 5 and T = 25 years, as can be deduced from the interannual emission calculation, where the main contributions of sediments are produced with a total of 33,626 tons. issued in an average year; while for the interval from T = 50 years to T = 100 years, only 3786 t are provided in an average year. In percentage, if 2 to 25 years of return period are grouped together, the contribution would be approximately 87% of the total sediment, compared to 5% for T from 50 to 100 years. An important conclusion is derived from these results: in the calculation of the interannual emission of sediments, low return periods of less than 5 years cannot be disregarded, since in relative terms they represent around 40% of the sediment contributions to the reservoir. The following Table 6 justifies the above estimate.

3.3. Results of the textures and concentration of the sediments in the inlet flows to the reservoir

Next, the considered textures of the sediments arriving at the reservoir are verified, as an example, for T = 100 years. It is shown in Figure 14.

In all return periods, including the one shown for T = 100, clays predominate. The granulometry of the sediment is clearly influenced by the texture of the soils present in the basin.

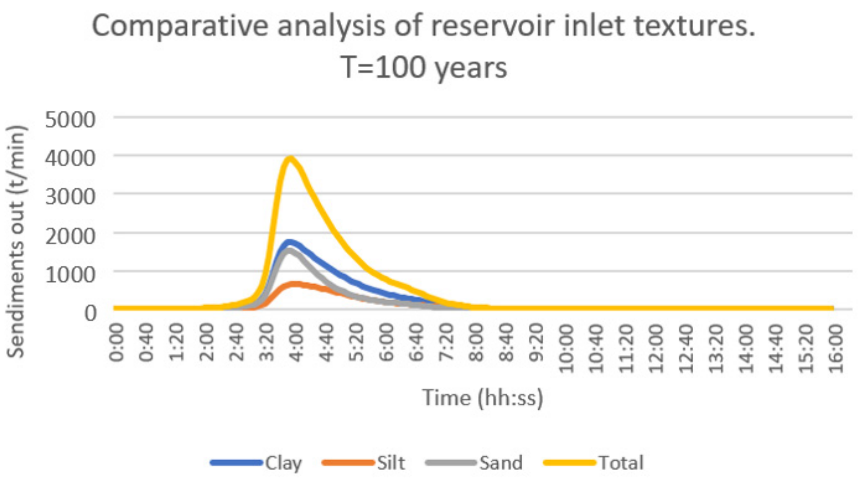

Fig. 14. Comparative analysis of textures. Sands, silts and clays. *T*=100 years.

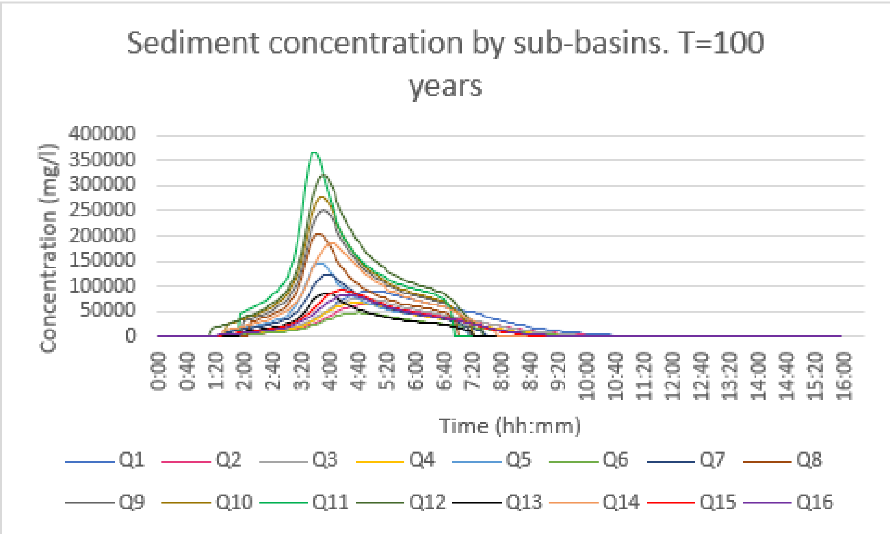

Fig. 15. Sediment concentration in mg/L by sub-basins. *T* = 100 years.

But within these soils, distributed in variable proportions without predominating any specific texture in the whole, the predominant clays in some edaphic units mark the texture of the final sediment entering the reservoir. This presence of fines will affect the quality of the water, generating turbidity. Regarding the results of a comparative analysis of the concentration of sediments in the flow by sub-basins, it is seen that the proportions between sub-basins for different return periods are invariant, so what is illustrated for the return period of 100 years according to Figure 15.

The 3 sub-basins with the highest concentration of sediments are sub-basins 11, 12 and 10. The three sub-basins correspond precisely to group II, with 12 being the “Cebrillo stream”, which due to its surface area and sedimentogram, is of some importance in the analysis. In these three sub-basins the edaphic unit Campo de Gibraltar clays is presented. Erosionability and granulometry seem to be the main variables that affect sediment concentration; being in turn both dependent variables. The highest concentration is obtained for the referred period of return T = 100 years, is 365781 mg/L, which implies a specific weight greater than 12356 N/m^3. Therefore, we are already facing a hyper-concentrated flow with the implications that it entails. Although this high concentration only occurs occasionally, it is an aspect to be considered due to the increase in the tractive capacity (and therefore erosive capacity) of the flow in question.

4. DISCUSSION

The application of the methodology with HEC-HMS provides values of water flow. Sediment emission and sediment concentration have been obtained, initially with reference to specific return periods of 2, 5, 25, 50 and 100 years. Subsequently, after applying the formulation of the probabilistic discrete model used, it is possible to obtain the values of sediment emission to the reservoir by sub-basins. The total has been obtained considering an average year. Given the impossibility of measuring the emission of sediments to the reservoir over long periods of up to 100 years, the average disintegration value has been contrasted with other studies at the regional level from the Junta de Andalucía. Consequently, the importance of knowing the granulometry of the soils present in the basin has been determined. On the other hand, data is required in the modeling with HEC-HMS, given the results by textures of the sediment entering the reservoir.

Taking this into account, and based on the results obtained, it is possible to make a diagnosis of the system-basin with regard to the problem analyzed. The application to the specific case of "Charco Redondo", which serves as an example of the application of the methodology provided, allows us to know that this reservoir is receiving a total of approximately 75,400 tons in an average year. If an average specific weight for reservoir sediments of 1.1 t_f/m^3 is considered. A contribution of coarse material in volume of around 5% of the sediments (estimation of the safety side when verifying in situ that the coarse material is demobilized at the outlet of the channels (López et al., 2020; Williams, 2018)**,** a reservoir capacity of 82 hm^3, and the year commissioning of 1984, the gradual silting up of the reservoir can be foreseen.

For this reason, it is verified that in about 50 years the reservoir loses approximately 8.4% of its total capacity. But there are factors that can accelerate grounding. A loss of plant cover, which occurs for various reasons (forest fires, overgrazing, climate change, etc.), is dramatic in the results. It must be remembered that the soils of the reservoir's catchment basin are highly erodible, in particular, the clays present in large quantities.

Another issue that is necessary to qualify the results of silting, and which is derived from the results of sediment propagation, is the storage of sediments in the reservoir channels. These sediments represent a reservoir of unaccounted-for solid material. The reason for this is that, for them to mobilize, a flood with a tractive capacity of the flow above the floods of $T = 100$ years considered is necessary. The low frequency of the occurrence of these avenues means that their influence on the interannual emission data is scarce.

It is also important to consider the figures for filling the reservoir and the quality of the water. 8.5% of the total capacity of the reservoir, with a 50% filling, doubles the relative percentage of sediments with respect to the water in the reservoir. In addition, taking into account the current filling figures as a reference (in November 2021, around 25%), means that the concentration of solids is 34%. These values are already a reason for concern since, although the sediments are deposited and consolidated over time, the significant presence of fine material can negatively affect the quality of the water, also favoring other phenomena. The bottom drains can be seen to be blocked in the presence of these sediments, also with the knowledge that in the soils of the basin there is the presence of expansive clays.

Previous diagrams show that group II is the one which provides the biggest sediment contribution to the reservoir. Furthermore, there is a notable difference with regard to group I, which is second in terms of sediment contribution. For this reason, there is a coupling between solid flows and return periods for an isolated event. There is a decoupling between the water and sediment from different basins. A generalization for a hypothetical coupling between water and sediment is not possible since a contradictory case is found. Group II contributes a bigger sediment flow to the reservoir, even though group I contributes higher water flow. From the analysis of the thematic cartography and the results of the different tables attached, it is possible to state that the reason for the contradiction is due to the fact that group II has a greater presence of more erodible soils.

There is no significant difference between the slopes. Groups I and II have areas of steep gradient. However, the presence of clayey soils is more evident in group II. This allows the possibility that this group of sub-basins is the one which contributes the biggest amount of sediment to the reservoir. Therefore, there is a separate coupling between sediment emission and water flow for each sub-basin. Consequently, there is a direct correlation between the return period and the amount of sediments entering the reservoir from the aforementioned sub-basin. However, there is no coupling between the water and sediment flows among sub-basins. As has been mentioned, the sub-basins of group II feed a lower water flow into the reservoir than those from group I. Nevertheless, group II creates the largest contribution to the reservoir, regarding the amount of sediment flow. Considering the relative similarity, covers and slopes (see Figure Slopes map), the reason for this contribution is the proportionally greater presence of the edaphic unit "Arcillas del Campo de Gibraltar" in the sub-basins of group II. These clay soils are highly erodible. Group II sub-basins do not have a significant sediment propagation, since they directly surround the reservoir. The sediment storage volume is significantly smaller than in the group I.

Once the USLE model and the MUSLE model are applied, it is possible to verify that the differences between removed soil (around 377,700 t) and emitted soil (75,400 t) are patent. The aforementioned models implement the specific formulation, provided to obtain the annual sediment deposition. Both models provide valuable information. However, estimating the level of sediment deposition in the reservoir and the evolution of this rate over time require a specific formulation such as the one provided in this paper.

Therefore, a gradual loss of the net capacity of the Charco Redondo reservoir is expected. If the vegetation cover is maintained, a 50 years term forecast estimates a loss of the net capacity of the reservoir over the total volume of the basin of 8.4%. Nevertheless, taking into account the current reservoir water capacity (in November 2021 25% of the pool), the percentage of landfill represents 34% of the total volume. Thus, the quality of the water will be affected by the high presence of fine aggregates in the sediments emitted into the reservoir.

The basin-reservoir system with respect to sediment emission is fragile. A change in coverage due to climate change or forest fires has exponential effects on the entry of solid flow, accelerating the sediment deposition. Moreover, since the climate, the topography and the lithological base of the soil cannot be modified on a large scale, the vegetation cover is the guarantee of basic protection of the reservoir with respect to the blockage problem.

5. CONCLUSIONS

The basin-reservoir system, regarding the emission of sediments, is fragile. A change in coverage, produced by climate change or forest fires, has exponential effects on the entry of sediments flow, accelerating the silting of the reservoir. The reason for this fragility of the system is due to the combination of high soil erodibility and high dependence on plant cover to obtain erosion values contained in the figures given. The climate, the topography and the lithological base of the soils are not feasible to modify the generality of the basin. Therefore, the vegetation cover is the guarantee of basic protection of the reservoir landfill. Destruction of the protective vegetation cover will considerably increase the emission values of sediments to the reservoir, shortening the expected blockage periods.

With the methodology defined in this paper, HEC-HMS can be used to estimate the emission of sediments in an average year, interannual emission. With the interannual emission data of sediments, it is possible to estimate the gradual blockage of a reservoir, and even determine a possible approximate date for a given percentage of blockage.

From the results obtained, it can be deduced that there is an obvious overlap between sediment emission and water flow for each sub-basin separately. For this reason, the longer the return period, the greater the amount of sediment entering the reservoir from the aforementioned–sub-basin. However, there is no overlap between the flow of the water and the debris from one sub-basins to another. It is shown, by the results obtained, that, for similar conditions of vegetation cover and average slope, the presence of soils with fine grain sizes is the critical factor for the non-linear increase in emitted sediments.

In the calculation of the interannual emission of sediments, rainfall associated with low return periods of less than 5 years account for around 40% of the sediment contributions to the reservoir in interannual terms. Neglecting low return periods in the calculations implies considerably underestimating the value of the emission of sediments to the reservoir.

If the methodology is applied to the specific case of the "Charco Redondo" reservoir, an average disintegration of the reservoir basin of 83.30 t/(ha·year) has been estimated. The tons of soil removed (or broken up) in the basin amount to 377,685 t in an average year. Of this amount, 75,400 t enter the reservoir in the form of sediment in an average year. The soils that present the greatest erosion problems are the vertisols of the Campo de Gibraltar clays edaphic unit, with a predominantly clay texture. With regard to landfilling, a gradual loss of the net capacity of the "Charco Redondo" reservoir is expected. If the vegetation cover is maintained, a loss of the net capacity of the reservoir over the total volume of the reservoir of 8.4% is expected for a forecast term of 50 years. It should be noted that, since the required return periods for the interannual emission data rise until 100 years, any direct measure to verify the comparison would be unfeasible. In turn, the 100 years return period is an elevated value to guarantee the maintenance of the current conditions of greenery. However, for example, considering the current reservoir water capacity (in November 2021 25% of the pool), the percentage of landfill represents 34% of the volume. The quality of the water will be affected by the high presence of fines in the sediments to the reservoir. Water resources present a threat, both due to the drought currently affecting Spain and influencing the amount of water available, in addition to the resulting quality of the waters, which are affected by the high presence of fines when increasing the blockage.

Future studies will focus on the application of this methodology to other specific cases, establishing parameters and adjustment methodologies with greater standardization.

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NOMENCLATURE

CN_{med}	Average curve number for each reservoir sub-basin	[dimensionless]
CN_i	Curve number corresponding to surface i	[dimensionless]
S_i	Surface i with a certain homogeneity in soil, cover and slope	[ha]
S	Surface area of the sub-basin	[ha]
A	Average annual soil loss	[t/(ha year)]
R	Rain erosivity index factor	[(j cm) / (m^2 h)]
K	Soil erodibility factor	[(t m^2 h) / (ha j cm]
L	Slope length factor	[dimensionless]
S	Slope factor	[dimensionless]
C	Crop management factor	[dimensionless]
P	Support practice factor	[dimensionless]
Y	Sediments emitted by an isolated storm	[Tn]
Q	Runoff volume	[m^3]
q_p	Peak flow rate	[m^3/s]
Y_T	Interannual emission of sediments to the reservoir	[Tn]
Y_{Ti}	Emission corresponding to a downpour with a return period T_i	[Tn]