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Modelling the silting-up of a small reservoir fed by a temporary river: the Torrebianca reservoir study case (Puglia, SE Italy)

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Abstract

The paper presents a first attempt to quantify the siltation in a man-made reservoir (Torrebianca) in South-East Italy. The FLORENCE model was used to quantify siltation and a multi-scale modelling approach was developed to identify the main source areas of the transported material. The total specific wet sediment production at the reservoir was quantified in 13.15 t ha^{-1} yr^{-1}. The Celone river basin is the major source of both sediment and water feeds into reservoir. At sub-basin scale the modelling results show that within the Celone river basin the main source areas of sediment were the upstream zone and the valley area. The floodplain area, where the river assumes a braided morphology features, instead acts as a sink for the coarse material. Based on these results, it was estimated that, from 2000 to 2017, in the absence of appropriate removal operations, the reservoir may have lost 13.77%. These results suggest that a better management measures to reduce sediment transport and silting are needed.

1. Introduction

In Italy there are overall 1224 hydraulic operas, 665 crossbeam and 564 between tanks and reservoirs, mainly located in Umbria, Molise (Centre of Italy) Sardegna (Italian island) and Puglia (South-east of Italy), designed to meet the irrigation and industrial requirements. On the whole these operas provided to hold back an amount of 2475 Mm^3 of water [1]. These works, however, require, in addition to regular maintenance works necessary for the continued operation of all the components, also a focus, concerning the dumping of sediments in the basin itself, which in recent years is becoming increasingly important with respect to other issues [2-6]. The silting phenomenon is caused generally by heterogeneous factors [7-11] depending by intrinsic characteristics of the underlying basins, such as the soil texture and its hydrological and physical characteristics, morphology and slope of the area, rainfall and hydrological regime.

Over the years, several studies methods and tools were developed to predict reservoir sedimentation, from the Empirical methods, to the newest physical-based and Numerical methods [12-14]. Overall it is clear from the literature that empirical methodologies are simpler to use than the other ones, moreover they require less measured data and are also quicker to assess. However, their simplicity makes them useful now only in the first approximation to understand the order of magnitude of the phenomenon [15]. Physical-based and numerical methods, due to the increasing develop of computational software and to the innovation in the analysis of spatial data thorough Geographic Information System and remote sensing, are the most used methods to predict the siltation of reservoirs [16-18] [12,33,59]. Nowadays, most of the studies are conducted with the use of models based on different assumptions [19-25].

Despite these advances, the evaluation of reservoir siltation still has many aspects that need further clarification. These features regard a more accurate estimate of the volumes of sediments deposited in the reservoir, which are needed to calibrate and validate the models. In addition, it is important to identify an exact schedule of dredging and purging operations, together with proper planning for the reuse and disposal of the sediments, as recommended by the newest national and European legislation (D.Lgs art. 114 03/04/2006, D.M.A.T.T.

30/06/2004 *Criteri per la redazione del progetto di gestionedegliinvasi, Water Framemework Directory* (WFD) 2000/60/CE). Moreover, also a precise detection of areas that contribute most to the sediment production, the so-called sources areas, is needed to have a broader understanding of the changing dynamics of the basin itself [26-30]. On the other hand, source areas identification is needed to implement a Program of Measures oriented to reduce erosion and sediment transport.

In Mediterranean watersheds characterized by a large variability in physical and morphological characteristics, experimental activities at field or plot scale are difficult to conduct and their results cannot be extrapolated or up-scaled. Thus, sources areas identification is a difficult task that is generally performed by using model. However, most of the conceptual and empirical models at basin scale, commonly used to quantify erosion and identify source areas, such as Annualized Agricultural Non-Point Source (AnnAGNPS) [31], Soil and Water Assessment Tool (SWAT)[2], are not able to simulate landslides, gully erosion, wind erosion and bank erosion. This limit may have a great influence on the quantification of sediment load which may results underestimated [32,33]. In basins where there are mass movements due to landslides or the bank collapse and erosion is relevant, neural networking models developed by using an IPS (Intelligent Problem Solver) procedure may be a valid tool for estimate sediment load.

The aims of the present paper are to (i) quantify the sediment production at basin scale for the Celone and Lorenzo river basin (Apulia, Italy); (ii) identify the sediment production for sub-basins identifying main sources areas; (iii) estimating the silting and the volume reduction of the reservoir.

We used the FLORENCE model v. 1.0 (FLOw of wateRshedsedimENts Calculator based on geographic fEature), a neural networking model that take in account every components of sediment production, such as superficial erosion, gully erosion, bank erosion and mass movements. Despite the amount of spatial analysis, necessary to run the model, it doesn't need any relevant data concerning water or sediment discharge, so it would be useful for those reservoirs fed by ungauged basins. The purpose is to contribute to improve the knowledge concerning the sediment transport in the area upstream the reservoir, where there are no previous studies, and to test the capability of the FLORENCE model in estimating silting providing a useful tool to reservoir operator and water resources managers who need inexpensive and quick tool for managing reservoir.

2. Material and Methods

2.1. Study Area

The study area is composed by the Celone river basin (85.9 km^2) and the Lorenzo river basin (51.9 km^2), which are the two inflow in the Torrebianca reservoir, in Puglia (SE of Italy). The area is characterized from an average elevation of ca. 386 m.a.s.l. that ranges from 1142 m.a.s.l. to 218 m.a.s.l. (Fig.1). The greatest part of it is localized between 200 and 500 m.a.s.l. (43%), the average slope of the basins is of scilicet 12.5%.

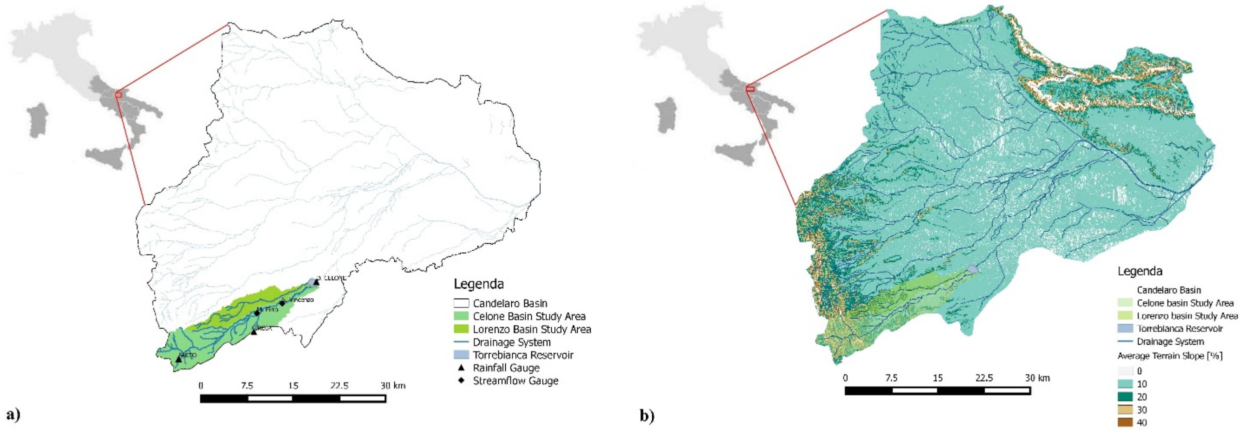


Figure 1: Study area (a), Average Terrain slope (b).

The total length of the drainage system which converges into the reservoir is of 109 km. It is mainly an agricultural area, in which the most available cultivations are durum wheat (46%), sunflower (9%), pastures (6%) and olive groves (8%), there are also frequent deciduous forests (29%).

Insight the study area there are also three wastewater treatment plants which bear to a request for about 4900 inhabitant equivalents, which comes out from the three small villages. In the basin, the agricultural practices may have great influence on the hydrological regime, through the drainage capability of the soil, strictly linked to the use of lands [34], and on the water quality of the river [35-39], mainly due to the diffuse use of fertilizers and also on the disposability of sediment sources [6,40-42], through the rearrangement of soil caused by frequent tillage, especially during the driest periods [35,43-44].

The Torrebianca reservoir is the most important hydraulic work in this area, it supplies water for agricultural use. It is a zoned heart dam; whose construction began in 1990 to be terminated in 1997 [45]. The main characteristics of the dam are summarized in table 1. and Fig 2. shows the plan and cross section of the work, below a satellite image. The volume in May 2017 was 16.342x10^6 m^3 and its capacity at fully supply is 25.82x10^6 m^3, flow rates hesitate from the spillway, respectively, of the bottom and the derivation is 220m^3s^{-1}, 89m^3s^{-1}, 7m^3s^{-1}.

Table1: Technical characteristic of the Torrebianca dam.

Torrebianca Reservoir technical characteristics		
Parameter	**Value**	**Unit**
Dam Height	20.98	[m]
Quota of maximum storage	150.05	[m.a.s.l.]
Total volume of reservoir	25.82*10^6	[m^3]
Useful Volume Adjustment	16.8*10^6	[m^3]
Liquid mirror surface at quota of max. storage	3.15	[km^2]
Liquid mirror surface at quota of max. regulation	2.97	[km^2]

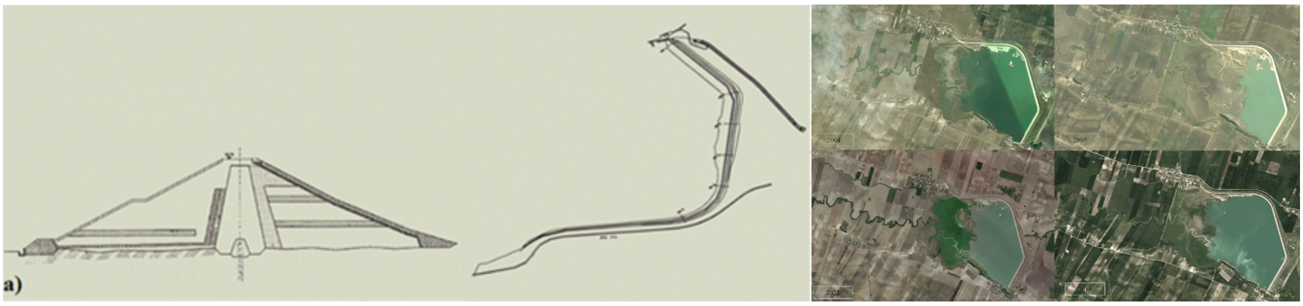


Figure 2: Plan view and cross-sectional view of the opera (a), view of different filling conditions of the reservoir, due to different water level both in wet and dry periods in 2004, 2007, 2012 and 2015 (b).

2.2. Florence Model

To evaluate the sedimentation process upstream the Torrebianca reservoir we applied the FLORENCE model v. 1.0 (FLOw of watershed sedimENts Calculator based on geographic fEature), a tool capable to estimate the basin's specific sediment production over a long period as estimation of the average annual volume of wet sediment [$m^3km^{-2}y^{-1}$]. The model wasdeveloped by the CRA-ABP (Consiglio per la Ricerca e la sperimentazione in Agricoltura- CRA-ABP Centro di Ricerca per l'Agrobiologia e la Pedologia di Firenze) to predict the reservoir siltation[8]. This tool relates the volume of sediment, deposited in artificial reservoirs, with physiographic variables, climatic and land use of the underlying basins.

The sediment production estimation already takes in account the sub basin's internal re-deposition, furthermore, the model takes in account every components of sediment production, such as superficial erosion, gully erosion, bank erosion and mass movements. This is a neural networking model developed by using an IPS (Intelligent Problem Solver) procedure [46,47]. This procedure has led to the identification of the best neural network, starting from a 23 variables data set in FLORENCE, then growth to 24 variables with the introduction of the SDR (Sediment delivery Ratio) [1,48-50]. The sensitivity analysis for the input variables of FLORENCE is shown in table 2.

Table2: Technical characteristic of the Torrebianca dam.

Variable	SDR	Area	Average Temp.	Drainage Density	Rainfall	Erodible Area	N° Landslides	Av. Slope
Ratio	1.05	1.11	1.13	1.15	1.18	1.22	1.12	1.05
Rank	8.00	6.00	4.00	3.00	2.00	1.00	5.00	7.00

In FLORENCE, eight inputs data set described through the paper are needed. FLORENCE model has already been applied in Italy with success [51,52]. It requires a GIS software (ArcMap, QGIS) for the spatial analysis of the input data. In the present work QGIS was used for all the spatial data elaborations. The model can be used for estimating the contribution of sub-areas, characterized by homogeneous features, to the total load.

We applied the web application FLORENCE v. 1.0 (http://florence.homelinux.com/login.php) tool at two different spatial scales discretization of the study area. In a first application, we considered both the Celone and Lorenzo river basins, with the specific aim to evaluate the total sediment production of the whole area draining into the reservoir. Then, we evaluate only the sediment production of Celone basin, which was previously found to be the major source of both, water and sediments, for the dam.

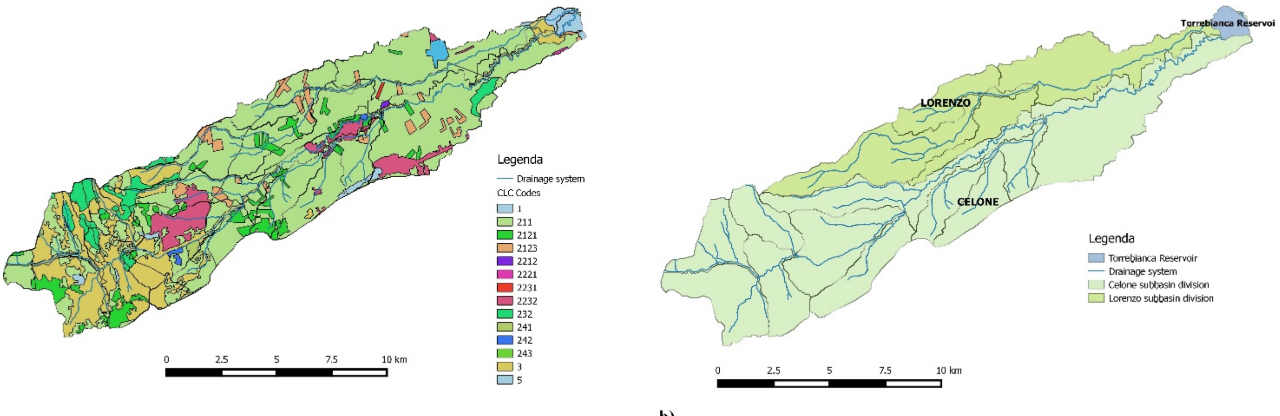
We further divided the study area of the Celone into three sub-spatial units to find the major sediment sources within the basin itself. Three sub-areas which are homogeneous units in terms of rainfall characteristics, average slope and soil texture, were identified. Spatial data were re-analyses in GIS space to set up the model.

2.3. Spatial data analysis

According to the user's guide of the model (http://abp.entecra.it/florence/istruzioni.pdf), we first assessed the drainage area after selecting the closing section [km^2], after that we estimated the erodible surface of the basin, given as a portion of the area itself [km^2], calculated by multiplying each portion of the surface with a specific land use by a given coefficient of erodibility that ranges from 0 (not erodible) to 1 (totally erodible). We used the Corine Land Cover 2012 for the scope (http://www.sinanet.isprambiente.it/it/sia-ispra/download-mais/corine-land-cover), which was reclassified through field surveys. In the study area, in recent decades, land use changes were not recorded. We estimated the stream drainage density [km^{-1}] as the ratio between the surface area of the basins and the length of its river network. The average slope of the area was evaluated through an analysis of the Digital Elevation Model of the area. Then, other inputs are automatically calculated by the model itself. Climatic data such as average temperature [°C] and rainfall [mm] are included in the model database and also the numbers of the landslides on the area are evaluated by the model once selected the municipalities included in the basin, in part or in whole. The ability to take into account, in the calculation of total wet sediment production, the influence of gully erosion, landslides and mass movements is a key point. In fact, compared to other physically based models, FLORENCE can consider the susceptibility of the stream to these phenomena, including in its database the number of known landslides in the selected municipalities. Such susceptibility is generally very high for small basins in the southern Mediterranean [53-56] possibly contributing to the production of sediment for many t / ha * year.

2.4. Multi scale modelling

In the Celone basin, due to the presence of a first alluvial plain in the middle course of the river, there is a deposition of the coarse material. Here the river assumes a braided morphology features. We have applied the FLORENCE model differentiating three sub-areas. The aim was, on the one hand, to understand how a different spatial distribution of sub-basins influences the model results and, on the other hand, to estimate the Celone basin contribution to the entire phenomenon of silting of Torrebianca reservoir. We modelled the production of wet sediment through the above described spatial analysis for each sub-area.



a) **b)**

Figure 3: Land use (a), Celone and Lorenzo basins subdivision (b).

Table3: Calculated inputs for the modelling procedure applied at basin scale

		First Modelling Data inputs	
		Celone and Lorenzo river basins	**Celone river basin**
	Units		
Area	Km^2	137.77	85.9
Drainage Density	Km^{-1}	0.791	0.704
Erodible Area	Km^2	97.87	59.47
Av. Slope	%	12.82	12.71

The division of the entire Celone drainage area in three sub-areas was made taking in account the homogeneity of each sub area, both from the point of view of geo-morphological characteristics (i.e. hillslope, containment of the slopes, soil composition and land use) and hydrological/hydraulics characteristics (i.e. geometry and steepness of the river bed, and river morphology). This subdivision has led to the identification of three homogeneous subareas described as follows:

The upstream zone: it is characterized by high slope gradients (22.86%) that gives a high containment to the river [57] which here is incised. The land use mainly consists of forest territories, with some parts of the area destined to non-irrigated crops and pastures, providing a poor erodible surface (11.47 km^2).

The floodplain area: here the containment action of the slopes is minimal, almost absent, due to the reduction of its steepness (12.48%); this reduction contributes to change the river morphology [58] that becomes braided with a deposition of the coarse material. The changes of the morphology bring also an increase of the erodible area (18.22 km^2), encouraging cultivability the surrounding land [59].

The valley area: this is the final stretch of the river that flows in the reservoir, here the hillslopes and the bed slopes continue to decrease (5.63%), the river morphology returns to single channel, whereas the sinuosity increases. Here the agriculture is intensive, and the management practices support the increase of erodibility (29.78 km^2) [60,61].

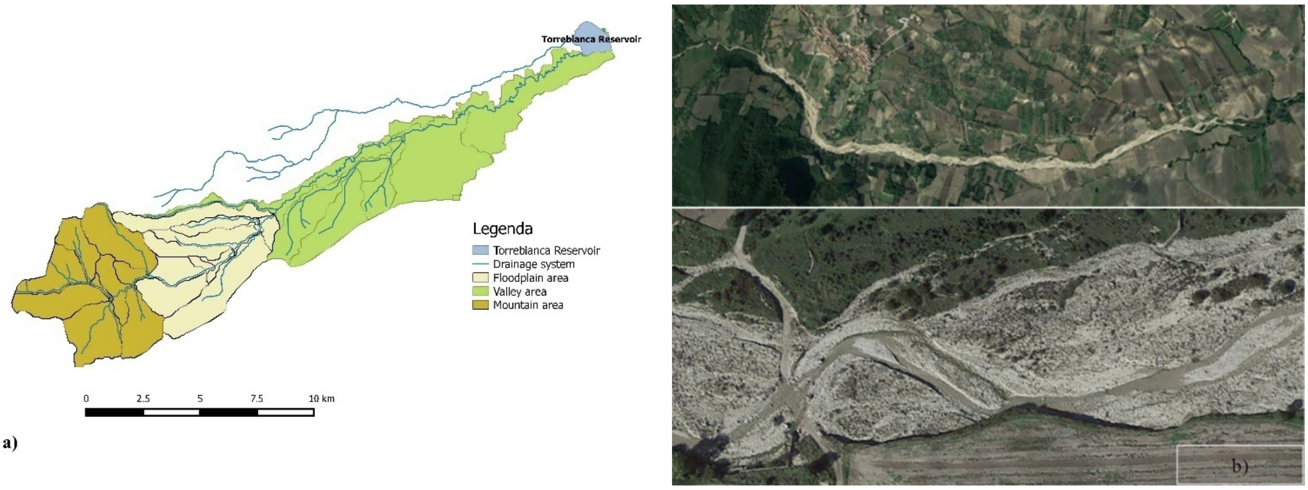


Figure 4: Subareas division of the Celone river basin (a), floodplain area satellite images (b)

Table4: Calculated inputs for the modelling procedure applied at sub-basin scale.

		Second Modelling Data inputs		
		Upstream zone	**Floodplain Area**	**Valley Area**
	Units			
Area	Km^2	27.92	25.95	32.12
Drainage Density	Km^{-1}	0.62	0.82	0.75
Erodible Area	Km^2	11.47	18.22	29.78
Av. Slope	%	22.86	12.48	5.63

3. Results and discussion

3.1. Sediment Production

The results of the model applied to the whole drainage area showed a total production of wet sediment of 1518.63 $m^3km^{-2}y^{-1}$, whilst considering only the Celone river basin it amounted to 1474.48 $m^3km^{-2}y^{-1}$. These values were then processed to obtain data of weight of sediment production, which are 13.15 t $ha^{-1}y^{-1}$ and 12.78 t $ha^{-1}y^{-1}$, respectively. We considered, in the absence of additional studies necessary for a more targeted characterization of the stratigraphic of the bottom of the riverbed, an average density value of the sediment equal to 0.866 t m^{-3} [1]. The results show that the contribution to total sediment yield per hectare from the Lorenzo basin is higher than that calculated for the Celone basin, however, in absolute terms considering the drainage area the contribution of the Celone is higher than that of Lorenzo. At sub-basin scale, analysing the modelling results of the first sub-area, we have found that the wet sediment production was of scilicet 1011.55 $m^3km^{-2}y^{-1}$, which corresponds to 8.76 t $ha^{-1}y^{-1}$,once reported in the specific production of sediment with the above transformation. This value is comparable with other specific sediment production data for mountain basins of small extent [27,62,63]. The same procedures are also been adopted for the second (floodplain area) and third (valley area) sub area, individually, the results are shown in tab.5.

Table5: Calculated outputs for the entire modelling procedure

	Outputs	
	Volume of wet sediment [m^3 $km^{-2}y^{-1}$]	**SpecificSediment Production [t $ha^{-1}y^{-1}$]**
Celone and Lorenzo river basins	1518.63	13.15
Celone river basin	1474.48	12.78
Upstream zone of Celone river basin	1011.55	8.76
Floodplain area of Celone river basin	662.7	5.74
Valley area of Celone river basin	1085.35	9.4

3.2. Silting phenomenon and water resource reduction

The amount of wet sediment in terms of volume obtained for the entire drainage area, 1518.63 $m^3km^{-2}y^{-1}$, was subsequently adopted as input to assess the silting thorough two indexes [42]: the average annual silting rate, TI% (Eq.1), and then the silting degree of the global volume of the dam, GI% (Eq.2).

$$TI=((V\_int)/V\_ti)*100 \quad \text{(Eq.1)}$$

$$GI=((V\_int*\Delta T)/V\_ti)*100 \quad \text{(Eq. 2)}$$

Where: V_int is the wet sediment volume of the entire drainage into the reservoirs (1518.63x137.77), V_ti is the adjustment volume of water of the reservoir at the initial time step ($25.82x10^6$ m^3), ΔT is the working period of the opera (17 yr^{-1}).

The first index, TI, shows that the Torrebianca reservoir is affected by a silting of 0.81% of percentage of its volume corresponding to $2.09x10^5$ m^3 yr^{-1}. This implies that during 17 years of operation, from 2000 to 2017, in the absence of appropriate removal operations, the reservoir may have lost 13.77%. of its volume i.e. scilicet $3.56x10^6$ m^3. According to other studies for the Mediterranean region [64-69], it means that the filling up by sediment is the most dangerous factor to manage, notwithstanding water losses in a reservoir could be caused also by other factors, like evaporation of surface water or seepage [18,70].

3.3. Multi scale modelling validation

For the Celone river basin, considering the whole basin, the results (12.78 t $ha^{-1}y^{-1}$) are in line with that of other small and medium sized reservoirs of the Mediterranean region [16,20,27,32,71-73]. Moreover, for the same river basin, the suspended sediment load, already evaluated in previous studies [74], were estimated in a range between 1.41 and 11.23 t $ha^{-1}y^{-1}$, this range seem to be comparable with the model output, once considered the bed load part of the transport phenomenon, as the model's output is a total production of sediment [75-77], unfortunately, neither measurements of total sediment or previous studies are available concerning the Lorenzo sub-watershed.

Once divided the Celone river basin into three homogeneous macro-areas, the results show that the upstream zone has an elevated specific total sediment yield production that can be justified by high average slopes and medium-high erodible area. In the transition areas, between upstream and floodplain area, the specific total sediment production tends to decrease, passing from 8.76 t $ha^{-1}y^{-1}$to 5.74 t $ha^{-1}y^{-1}$. This behavior is explained by the sudden drop of the slopes which passes from 22.86 % to 12.4 % leading to a sharp decrease in the current-carrying capacity and therefore to the immediate release of the sediment coarser fractions [78-80], giving to the riverbed a characteristic braided morphology. We can also appreciate this release phenomenon by analyzing the satellite images of this zone Fig.4. In this macro-area, the transport phenomenon is mostly in suspension, further corroborating the comparison between the fitted suspended sediment loads already evaluated by De Girolamo et al. (2018) [81].

In the plain area, the third macro-area, there is an absence of forest and the land use is prevalently agricultural land (90% of the entire area) that implies an increase of erodible area compared with the rest of the basin. In addition, here there is a remobilization of a part of coarser grains, landing to a specific total sediment production of 9.4 t $ha^{-1}y^{-1}$.

In light of this, we can assume that the main source area of the sediments are precisely the downstream zone and the upstream zone, while the intermediate zone, floodplain area, would act on the transport phenomenon such a filter action for grains with larger diameter. This behavior has an important reply once considered the temporary characteristic of the river. In fact, the middle area itself could became an important source area of medium-large grain, deposited during the low and medium flow regime, which are more frequent than the high flow where this material could be re-mobilized by the hidden and intense peaks of discharge, properly of this kind of rivers.

Conclusion

This study is a first attempt to estimate sediment transport and silting in an area where data availability is limited. In light of the growing impact that the issue of reservoir sedimentation would have, especially on European and Italian reservoirs in the next few years, the present work would give a contribute to the current knowledge concerning the silting phenomenon. The FLORENCE model proved to be a useful tool for quantifying the sediment transport especially in ungauged basins, in which direct estimate of sediment transport represents a hard and costly task linked to an appropriate data campaign. Despite its simplicity, the model is useful for estimating the magnitude of the silting phenomenon at the reservoir closing section with appropriate accuracy. In addition, it is able to identify sources areas, feeding sediment transport, providing useful indications to the water resources managers on the zone that could be re-organized, re-projected or re-arranged to minimize the problem. Furthermore, by implementing and interpreting a similar multi-scale modeling procedure it is possible to identify the areas that are main responsible of sediment production. In this case, the fact that there are previous studies concerning the sediment transport has also allowed us to compare this result with them, finding a match.

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