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Estimation of Silting Evolution in the Camastra Reservoir and Proposals for Sediment Recovery

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Abstract: The reduction in the usable capacity of reservoirs, which is linked to the ongoing silting phenomenon, has led to the need to remove sediments to allow the storage of greater quantities of water resources. At the same time, however, the removal of sediment from the bottom results in the need to manage a large quantity of materials, for which the current prospect of discharge is both economically and environmentally unsustainable. This research work concerns the assessment of the silting volume increment of the Camastra reservoir and the phenomenon of progressing speed based on topographic and bathymetric surveys carried out in September 2022 through the use of a DJI Matrice 300 RTK drone with ZENMUSE L1 LiDAR technology, multibeam surveys, and geophysical prospecting using a sub-bottom profiler. It was possible to estimate the increase in dead volume and compare this value with that obtained from the surveys through a literature calculation model and previous silting data. The used model, which slightly underestimates the silting phenomenon, estimates the volume of accumulated sediment from the original capacity of the reservoir, which is understood as the volume that can be filled with sediment in an infinite time, from which an amount is removed depending on the characteristic time scale of reservoir filling and the level of complexity of the silting phenomenon for a specific reservoir. Furthermore, there is evidence of an increase in the speed of sediment accumulation, which is linked to the more frequent occurrence of high-intensity and short-duration meteoric events caused by climate change, which can lead to an increase in erosion and transport phenomena. Further evidence is provided by the occupation of approximately 50% of the Camastra's reservoir capacity, which makes sediment dredging policies and interventions a priority, contributing to the practical significance of the present study. In this regard, the main recovery and reuse alternatives are identified and analyzed to make the removal of accumulated material environmentally and economically sustainable, such as through environmental and material recovery applications, with a preference for applications for which sediment pretreatment is not necessary.

Keywords: dredged sediment; silting prediction; reservoir sedimentation management; sediment reuse

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1. Introduction

The reduction in the availability of water resources is one of the problems that most seriously affect the survival of the planet as a direct consequence of climate change and the yearly increase in leakages caused by the poor maintenance of faulty pipes [1,2]. Although several attempts are underway to reduce leakages through interventions aimed at restoring the pipelines to a suitable state, the ongoing phenomenon of climate change requires a review of several implemented management choices. In other words, as the climate is changing almost irreversibly, the scientific community must find feasible alternatives to adapt to the ongoing changes [3].

One of the options is to increase the water storage capacity of existing reservoirs, which are designed to hold large volumes of water but are now characterized by a reduction in the volume that can be utilized as a direct consequence of a lack of maintenance and the evolution of the silting phenomenon [4–8]. The damming of watercourses creates an obstacle, at a specific point, to the natural water flow, with the consequent retention of all solid particles generated by the erosion of riverbed bottoms and riverbanks [9–11]. Over time, the absence of reservoir management plans or the failure to implement such plans, together with national legislation that classifies dredged material mainly as waste to be characterized and disposed of, has led to the problem of accumulating silt, discouraging managing authorities from carrying out maintenance operations on drains and removing stored material [12].

Nevertheless, the management and maintenance of reservoirs, and more specifically, the dredging of sediment materials, can no longer be ignored and must become a priority for the recovery of reservoir capacity [13–15]. Furthermore, to make the process sustainable both environmentally and economically, it is necessary to identify proposals for the reuse of dredged material, negating the need for landfills [16,17]. To be able to do this, reservoir topographic and bathymetric survey activities, aimed at defining the evolution of silting and the use of numerical models, enabling the estimation of the extent of sediment deposition from the date of construction to the date of the last survey, are indispensable [18–25]. The literature can identify two types of predictive approaches to estimating the sediment deposition at the bottom of a reservoir. The first, which is mainly used to plan extraordinary maintenance of reservoirs, is based on the percentage of incoming sediment that is deposited or trapped in the reservoir [26–33]. The second, which is used to estimate soil loss due to its use or climate change, is based on the Revised Universal Soil Loss Equation (RUSLE), which calculates the sediment input to the reservoir [34–38]. However, neither approach is universally applicable since the equations governing them do not consider the entire range of variability in the parameters characterizing a reservoir [39].

This research concerns the estimation of the silting phenomenon of the Camastra reservoir as carried out through topographic and bathymetric surveys. Based on the knowledge from other research works of the curve and predictive numerical models of the evolution of silting for the studied reservoir, this research aims to verify, based on the last survey carried out, whether they are capable of correctly estimating the volumes of accumulated material or whether it is necessary to make changes [39–41]. The amount of sediment that is dead volume and possible reuses of the sediment are identified during the discussion, and the alternatives are analyzed with a view to determining their environmental and economic sustainability to avoid the disposal of dredged sediment in landfills.

2. Materials and Methods

2.1. Study Area

The area under investigation is the Camastra reservoir, a tributary of the Basento river, originating in the northern Lucanian Apennines in the Basilicata region of Southern Italy (Figure 1).

The coordinates for identifying the study area are shown in Table 1 below.

Table 1. Investigated area coordinates.

	E Coordinate	N Coordinate
N-W	15°39′30.1204″	40°38′41.5553″
N-E	16°06′48.2343″	40°38′41.5553″
S-E	16°06′48.2343″	40°17′19.9166″
S-W	15°39′30.1204″	40°17′19.9166″

The environmental vulnerability of the region, the significance of the related ecosystem functions, and the availability of past data dictated the choice of this case study.

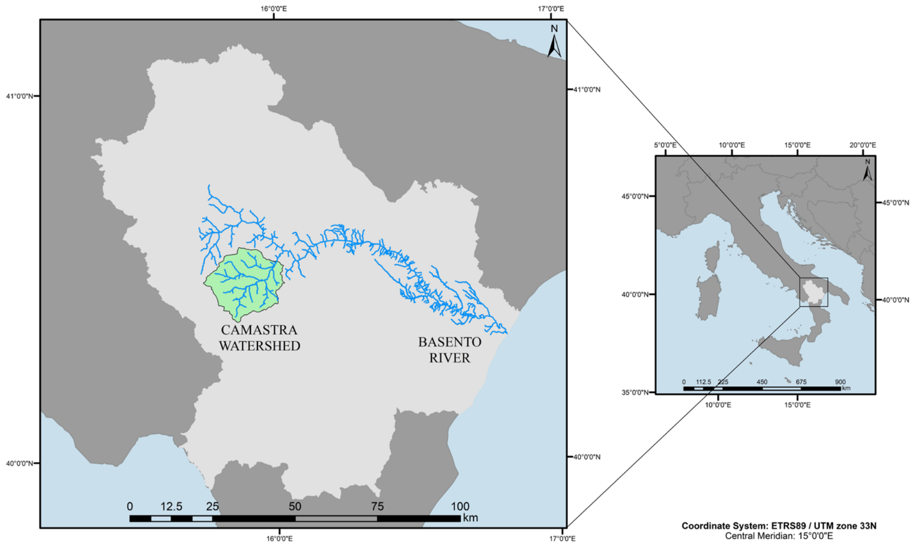


Figure 1. Study area: Basilicata (light gray), Camastra watershed (green), Basento river (blue).

The Camastra river falls entirely in Basilicata, which flows for approximately 1537 km, and its basin occupies approximately 3.4% of the region's total extension. The Camastra reservoir was created following the dam's construction in the 1960s.

The catchment area of the Camastra dam covers an area of approximately 340.8 km^2 on a mostly mountainous and hilly terrain with a limited flat area.

The territory's prevalent geolitological formations are limestone, dolomitic limestone, silica, and stratified sandstone rocks. Soils with variable lithologies occupy a limited area, from successions of clayey soils with limestone to deposits of loose clayey, sandy, and conglomeratic rocks.

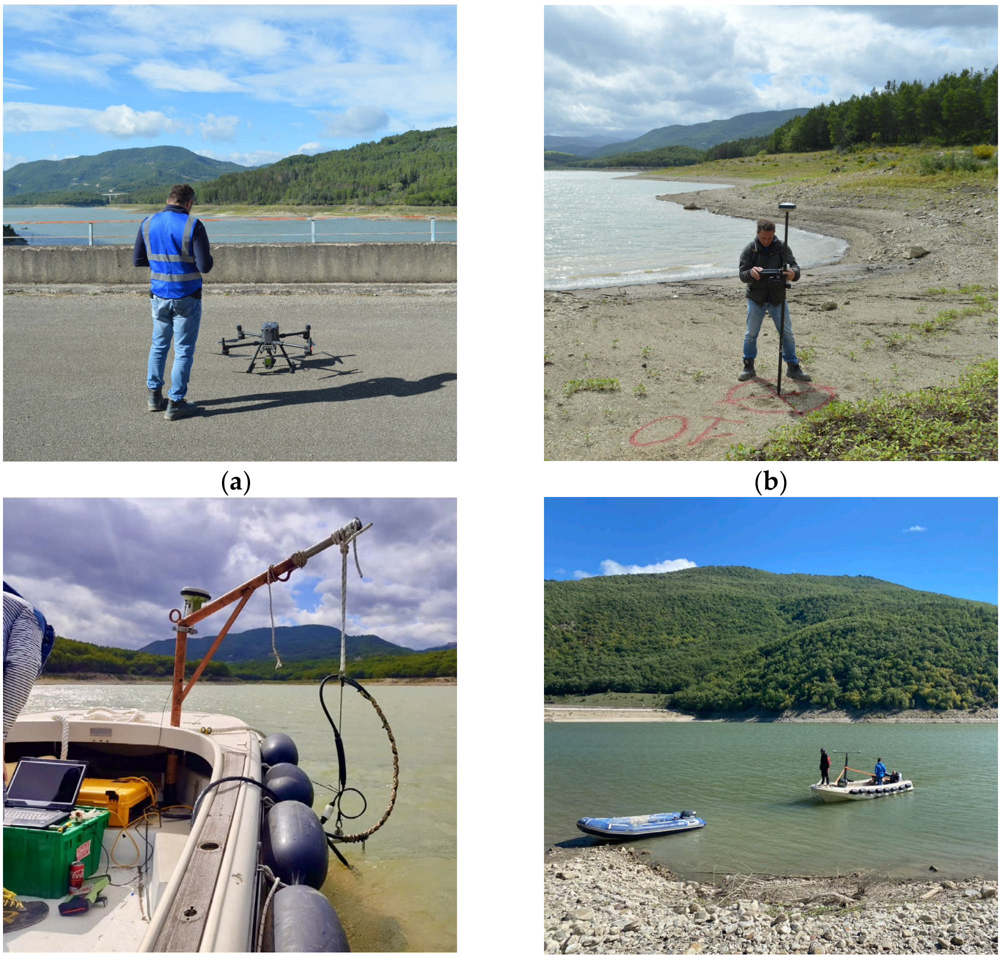
The land use classification (Corine Land Cover, 2018 [42]) shows that the investigated area has tree cover predominantly consisting of broadleaf forests, with areas characterized by arable land and hilly grasslands. In the inland areas, the climate is continental, almost rigid, and humid in the winter season; along the coastal areas, it takes on characteristics typical of the Mediterranean climate.

2.2. Data Collection

To estimate the accumulated sediment at the reservoir, several surveys were carried out in September 2022, namely the topographic shoreline survey, the bathymetric multibeam survey, and the seismostratigraphic survey of the seabed (sub-bottom profiler). The choice of the above-mentioned investigations was related to the desire to fully characterize the reservoir and achieve the purpose of defining the silting amount. In fact, the intended aim could only be achieved through knowledge of the heights and stratigraphy of the reservoir, which can be determined through seismostratigraphic surveys, and its geometry, defined through topographic and bathymetric surveys. The investigations carried out complement each other, as each provides specific information, which is useful for achieving the result.

A DJI Matrice 300 RTK model drone (DJI; Shenzen, China) with ZENMUSE L1 LiDAR technology (DJI; Shenzen, China), integrated with GPS (D-RTK 2 mobile station; DJI; Shenzen, China), was used for the topographic shoreline survey (Figure 2a). The aircraft was integrated with a Zenmuse L1 camera, which includes a Livox LiDAR module (Livox Technology Company Ltd.; Hong Kong), a high-precision IMU, and an RGB camera with 1-inch CMOS, a mechanical shutter, and 20 MP resolution on a 3-axis stabilized gimbal (DJI; Shenzen, China). The survey covered six areas, for which more than 1500 frames were obtained with a resolution of 20 MP and then processed to generate 2D and 3D views. The GPS survey (Figure 2b), performed in GSM mode, was used alongside the drone survey. It was carried out through a Leica GS18 GPS receiver (Leica Geosystems AG; San Gallo, Switzerland) with visual positioning technology and a Leica CS20 Controller (Leica

Geosystems AG; San Gallo, Switzerland) for data acquisition with Leica Captivate field software (vers. 6.65).



(**a**) (**b**) (**c**) (**d**)

Figure 2. Surveys carried out at the Camastra reservoir: (**a**) drone survey, (**b**) GPS survey, (**c**) and (**d**) morpho-bathymetric and sub-bottom profiler surveys.

The morpho-bathymetric survey using Multibeam allowed the morphology of the seabed of the reservoir to be determined in detail and a Digital Elevation Model of the investigated area to be obtained, which describes the seabed depth at each point. The survey was carried out using a Multibeam model R2 Sonic 2022 (R2 Sonic; Austin, TX, USA) with an R2INS inertial platform and Side Scan Sonar option (Figure 2c,d). Also, a multibeam echo sounder (MBES—MultiBeam EchoSounder; R2 Sonic; Austin, TX, USA) was used with two probes (Valeport Mini SV probe and AGEOTEC IMSVP model self-recording profiler probe, Valeport Ltd., Totnes, UK) able to measure the speed of sound propagation in water and the return time of sound waves, to correlate this with the depth estimation. Geophysical prospecting for the definition of the stratigraphy of the sedimentation materials within the Camastra reservoir was performed using an EdgeTech 3100-P (EdgeTech; West Wareham, MA, USA) sub-bottom profiler-type acquisition system according to thirty-two profiles (Figure 2c,d). During processing, data acquired with the sub-bottom profiler in SEGY format were subsequently transformed into COD format and processed using Coda Geosurvey v. 4.3.0 software from Coda Octopus Group, Inc., New York, NY, USA.

2.3. Sedimentation Estimation

The estimation of the deposition evolution was carried out both in a GIS environment and with the aid of CAD software (vers. 2024). In this case study, a survey of the seabed carried out in 2017 was available, in which the heights of the seabed were reported at various points, acquired according to a 20 m × 20 m mesh.

Similarly, a survey carried out in 2022, as mentioned in the previous paragraph, provided updated elevations of the seabed at the same points surveyed in 2017, according to the same 20 m × 20 m acquisition mesh.

First, the digital terrain models were developed using GIS software (QGIS vers. 3.34.3), and then, using CAD software, the two elevation plans were superimposed and compared. In this way, it was possible to derive the elevation of the seabed recorded in 2022 compared with that recorded in 2017, thus obtaining the increase in siltation over the time interval considered.

2.4. Data Analysis Background

The volume of sedimented solid material is usually quantified using a survey that can be carried out using different techniques: for the submerged part, a bathymetric survey can be carried out, whereas for the emerged part, one can opt for topographic or photogrammetric surveys. The need to resort to surveying activities, characterized by a considerable economic burden, is often why there is so few silting data available at a considerable temporal distance from each other.

Therefore, attempts have often been made to identify numerical models for predictive calculations to estimate the evolution of sedimentation upstream of the dams to limit the use of field survey procedures and, at the same time, to obtain siltation values as close as possible to reality. Among the many efforts, one of the most remarkable is that of Molino et al., 2023 [39], who identified a relationship between the sedimentation volume as measured from the reservoir's structural data and the sedimentation process's characteristics. In particular, various cases examined included the Camastra reservoir, for which the authors provided an estimate of the parameters mentioned above [39].

In the present study, to have an initial figure to help us understand whether the estimate from the field survey was correct or affected by errors, the following Equation (1), from Molino et al., 2023 [39], was used to predict the silting value in the year 2022:

$$V_s = V_\infty \left\{ 1 - e^{\left[-\left(\frac{t}{\tau_0} \right)^\sigma \right]} \right\} \quad (1)$$

where Vs (m^3) is the silting volume, V_∞ (m^3) is the maximum reservoir capacity, t (years) is the number of years of prediction, starting from the date of commissioning of the dam, σ is the measure of the level of complexity of the sedimentation process, and τ_0 (years) is the characteristic time interval for filling the reservoir. For the Camastra reservoir, the parameters examined, through which it was possible to perform the predictive estimation, took the following values: V_∞ = 35.3 × 10^6 m^3, σ =0.4 ± 0.1 and τ_0 = (1.3 ± 0.6) × 10^2 years.

Finally, after calculating the average increase in silt volume and the average increase in sediment thickness in the reservoir between the two surveys analyzed, carried out in 2022 and 2017, Equations (2) and (3) were used to estimate the average rate of silting and the average rate of increase in sediment thickness:

$$v_{int} = \frac{\Delta V_{int}}{n} \quad (2)$$

$$v_{\Delta h} = \frac{\Delta h}{n} \quad (3)$$

where v_{int} (m^3/year) is the average rate of silting, ΔV_{int} (m^3) is the average volumetric increment of silted sediment, n (year) is the time interval between the two surveys taken as a reference, $v_{\Delta h}$ (m/year) is the average rate of change in sediment thickness, and Δh (m) is the average change in sediment thickness recorded between two surveys taken n years apart.

3. Results

The following paragraphs describe the main results of the assessments carried out at the Camastra reservoir.

3.1. Surveys

The geophysical and topographical survey plan made it possible to define the topographical model of the seabed, banks, and shoreline at the time of the survey. The area surveyed was 75 ha due to navigational limitations imposed by the shallow depth found in some areas of the survey area. The maximum depth was found to be approximately 10.6 m, and the seabed consists mainly of an inconsistent substrate.

The seabed generates multiple reflections as acoustic waves, passing through a water column characterized by a propagation speed of about 1500 m/s, impacting the seabed with different velocity and density characteristics. Subsequently, the signal returns to the surface, and it is again reflected by the water–air interface (which also has a high reflection coefficient), several times. In the present investigation, the multiple reflections detected appeared to have a high energy and number, persisting at almost all depths.

Figure 3 shows the multiple reflections in the sub-bottom profiler survey. Signals were strong and reverberated numerous times along the recorded traces; also, they were persistent due to the presence of a shallow seabed and the high reflection coefficient of the water–bottom interface.

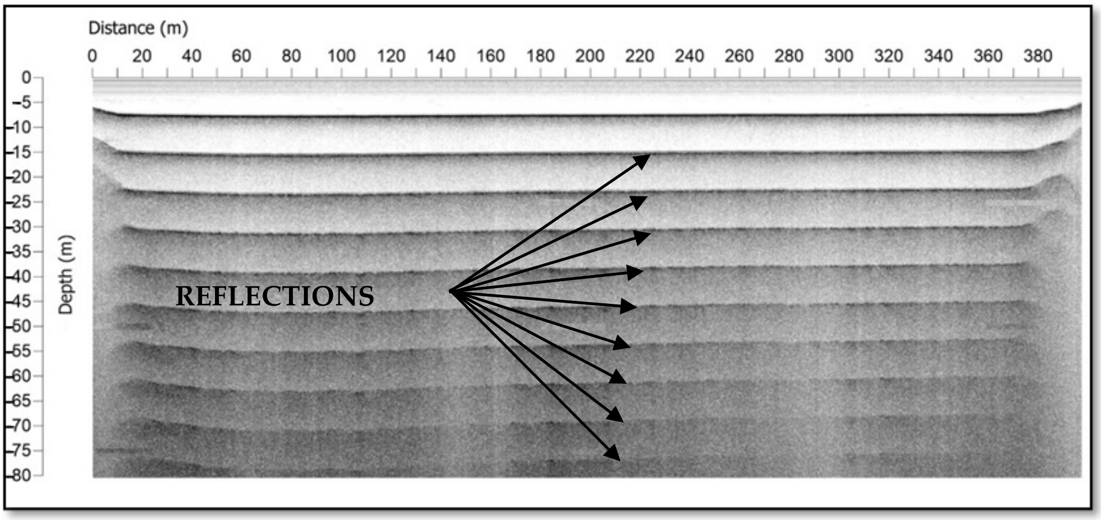


Figure 3. Multiple reflections found in the sub-bottom profiler survey of the Camastra reservoir.

Other minor signals were intercepted in the recorded traces; these were some hyperbola-shaped signals that could be related to structures in the reservoir and objects on the seabed. As noted in Figure 4, the sub-bottom survey revealed the main structures that characterize the reservoir. Specifically, the device detected the presence of the dam (Figure 4a), the jamming produced by vegetation or boulders (Figure 4b), which are quite common in the investigated area, and the disturbance generated by the bridge connecting the two banks of the reservoir (Figure 4c).

No signs related to the deep stratigraphy of the reservoir or any lithological changes at depth were found due to the presence of lithologies with poor reflection coefficients and little stratification.

The morphological changes observed in the study area, when comparing the 2022 survey with previous surveys, show that silting causes a higher risk of overflow for the dam due to the greater horizontal pressure applied. In addition, sediment accumulation has indirect effects on biota, which rely on the aquatic environment for reproduction, nutrition, and refuge. The change in riverbed morphology causes the loss of portions of habitat, increasing competition for these sites while affecting the structure and functionality of the macrobenthic community.

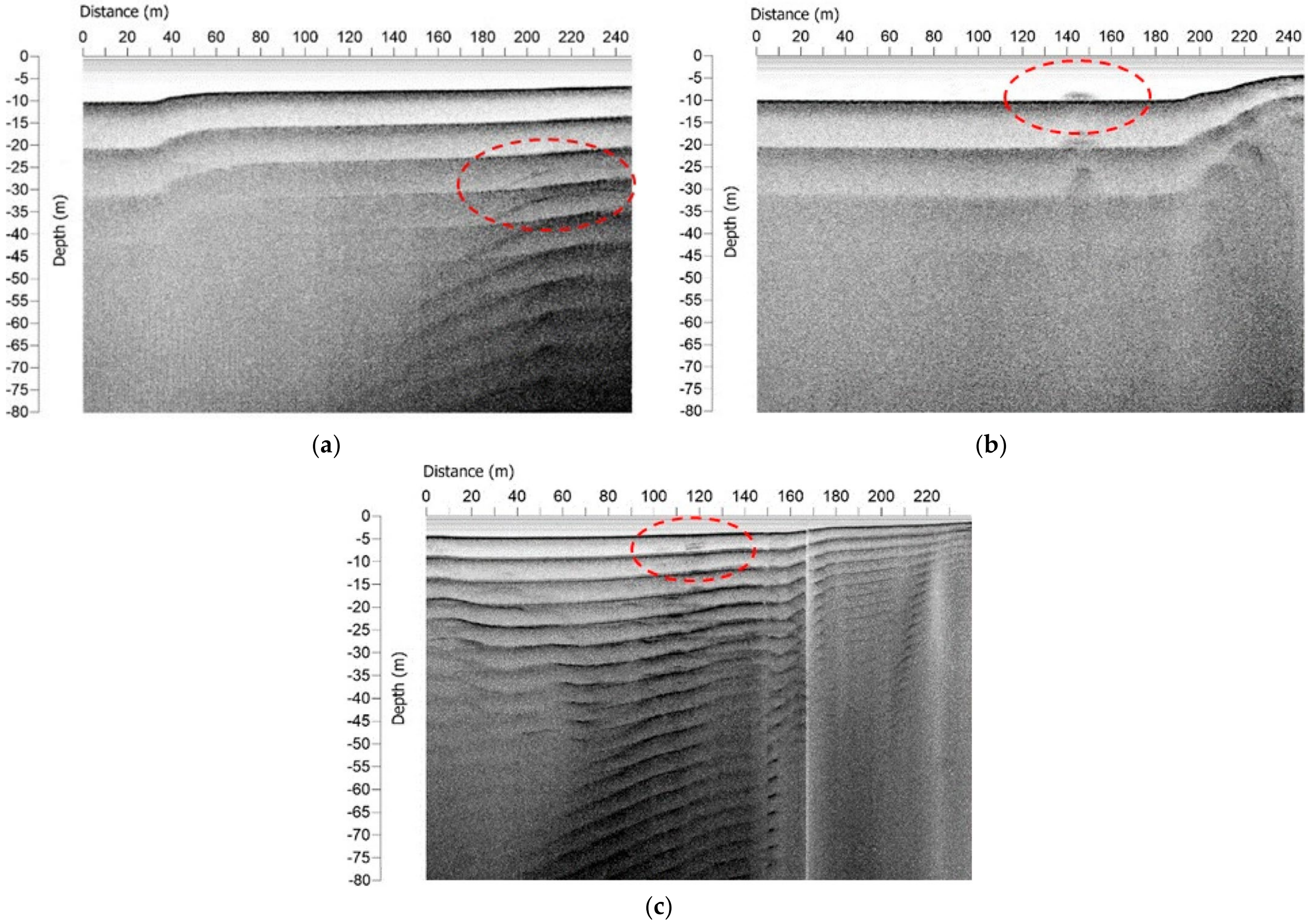


Figure 4. Examples of structures and objects present within the Camastra reservoir: (**a**) dam weir; (**b**) boulder or vegetation present on the seabed; (**c**) bridge connecting two banks of the reservoir.

3.2. Estimation of Silting Evolution

The estimate of the silting volume was obtained indirectly by comparing the measured planes of the seabed surveyed at two different times (2017 and 2022), thus determining the average incremental value of the sediment thickness. The estimate carried out was affected by an absolute error equal to the sum of the absolute errors of the two surveys, which was also estimated to be around 2–3%, so the error of the estimate was approximately 5%. These absolute errors are related to the survey methods and the precision of the devices used in the measurements and are therefore innate to the measurement procedures. It would be desirable, in subsequent research on the subject, to reduce these errors so that the estimates are as accurate as possible, for example, by using instruments characterized by greater precision or survey methodologies specifically designed to limit the measurement uncertainties inherent to the procedures.

First, to obtain an initial indication of the size orders involved, using Equation (1), an initial numerical framing of the silting volume in 2022 was carried out, which, according to the values of the parameters used, was 17.84×10^6 $m^3 \pm 0.5$. In Figure 5 below, the silting evolution over the years and the values forecast with model calculations up to 2022 are shown. The value obtained from the prediction model (green dot on the graph) lies approximately under the exponential curve, which interpolates the values of the surveys carried out from 1994 to 2017, testifying to the consistency of the calculation model used.

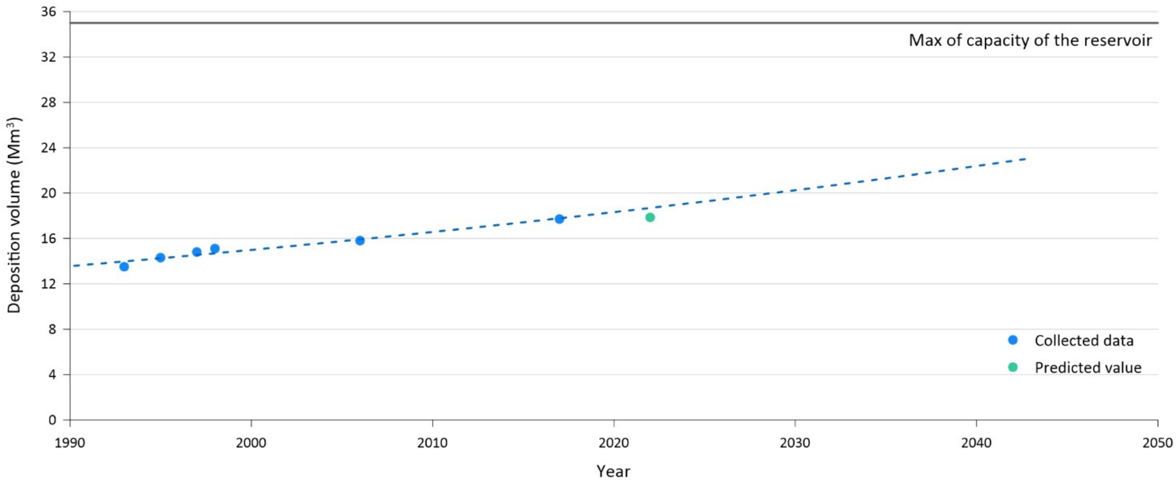


Figure 5. Silting evolution over the years and values forecast with model calculations up to 2022 (green point).

After defining the quantities involved and determine the volume of silt from the survey carried out in 2017, which was equal to 17.70 × 10^6 m^3, the average change in sediment thickness was calculated, being equal to approximately 0.60 m. The average increase in thickness recorded between the two successive surveys was then multiplied by the basin surface area obtained in the GIS environment, providing the average volumetric increase in silting, which was approximately 0.94 × 10^6 m^3; this value, when added to the average volume of sediment recorded in 2017, provided the average silting value up to 2022 of 18.65 × 10^6 m^3. Figure 6 shows the evolution of the silting phenomenon over the years, the values forecast with model calculations up to 2022 (green point), as in Figure 5, and the identification of the average value measured following the in situ survey in 2022 (red point).

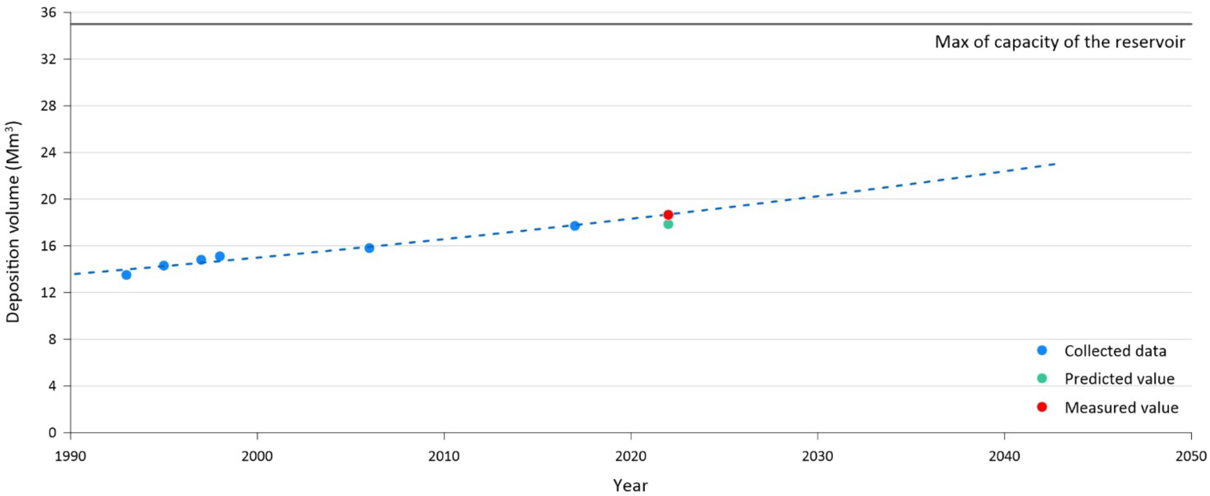


Figure 6. Evolution of the silting phenomenon over the years, forecast with model calculations up to 2022 (green point), and identification of the average value measured following the in situ survey in 2022 (red point), where the collected data are data from previous surveys and the measured value is the value deriving from the 2022 in situ survey.

Figure 6 also highlights that the silting volume identified with the 2022 survey (red point), in millions of cubic meters, was slightly greater than that obtained when applying the forecasting model. Consequently, the application of the model of Molino et al., 2023 [39], for the prediction of silting values in 2022 slightly underestimated the amount of accumulated sediments; nevertheless, the aforementioned model provides a methodological contribution, so its use and comparison with real survey data can contribute to the improvement in predictive models for studying sedimentation and accumulation phenomena in reservoirs.

In addition, the average measured value was arranged along the exponential curve, approximating previous survey data. This allowed us to identify, for the short time frame we considered (1993–2017), a new mathematical law that enables the prediction of silting evolution for the Camastra reservoir (Equation (4)).

$$y = e^{(ax-b)} \tag{4}$$

where y (m^3) is the deposition volume, x (year) is the year considered, a (m^3/year) is the constant, equal to 0.0100281, and b (m^3) is the other constant, equal to 17.348625.

Furthermore, the average thickness of the sediments in the Camastra reservoir was calculated to be approximately 12 m, whereas the average depth of the seabed recorded following the survey was 10.6 m.

It should also be pointed out that all the measured silting values lie along the exponential curve shown in Figures 5 and 6 (blue and red points), which is a result of significant importance in the context of sediment accumulation forecasts. The exponential growth, moreover, shows how the phenomenon evolved very rapidly in its first phase, approximately in the first 30 years of the reservoir's life, and slowed down from approximately 1990 onwards. Nevertheless, this type of evolution means that the silting increase proceeds, in any case, at a significant rate, threatening the reservoir's useful capacity and limiting the functions it is designed to perform.

In comparing the two surveys, each point on the seabed was found to have a lower elevation in 2017 than in 2022 (Figure 7). The heights recorded in 2017 have lower absolute values than those identified in 2022, reflecting the rising of the seabed floor, i.e., the increase in sediment thickness and the consequent reduction in the Camastra's useful reservoir capacity.

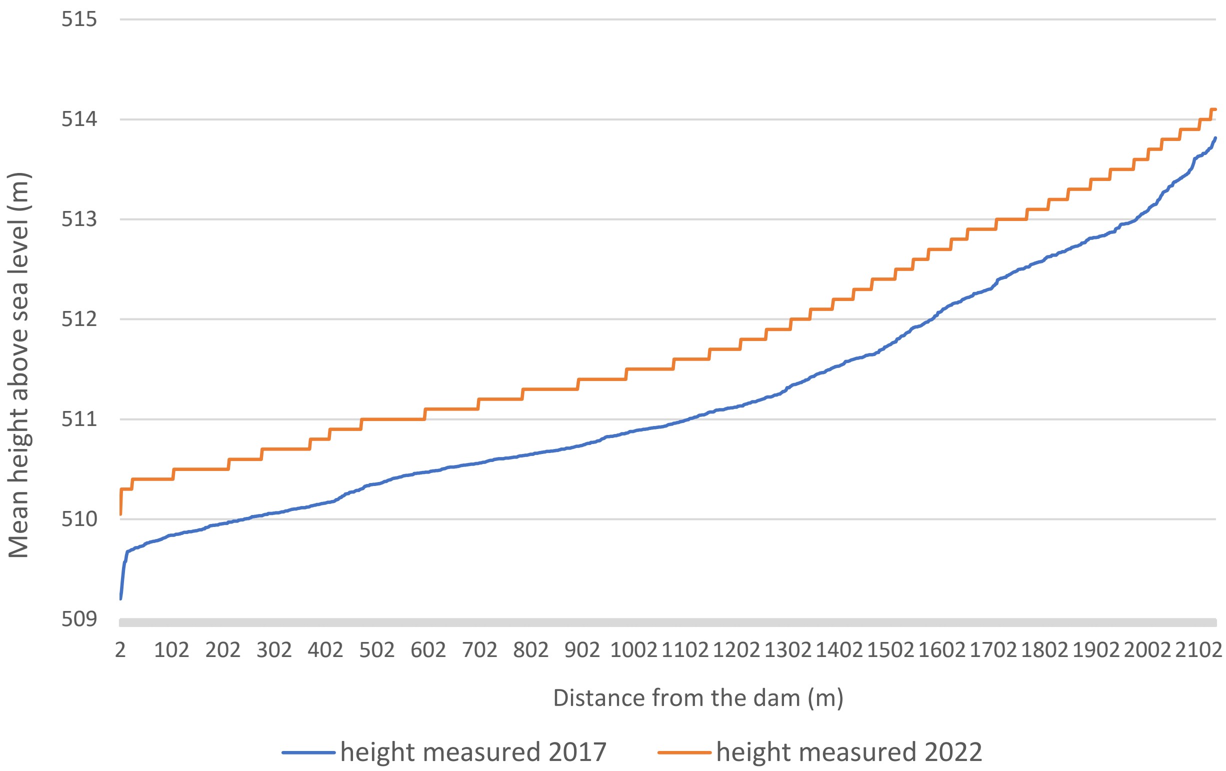


Figure 7. Comparison of seabed elevations measured in the 2017 survey (blue) and 2022 survey (orange).

Finally, using Equations (2) and (3), it was possible to calculate the average annual rate of silting and the average annual increase in sediment thickness over the time interval between 2017 and 2022. In the present case, the average annual silting rate was found to be approximately 0.19×10^6 m^3/year; a sediment thickness increase rate of approximately 0.12 m/year was also found. The average annual rate of silting was calculated by dividing the silting volume increase of 0.94×10^6 m^3 by the number of years in which it occurred, i.e., 5 years, from 2017 to 2022. The silting volumetric increase was obtained by multiplying the area of the reservoir (1,562,859 m^2) by the average difference in elevation determined by the analysis of the 2017 and 2022 surveys between all the corresponding points, being equal to 0.60 m. The average annual increase in sediment thickness was calculated by dividing the increase in sediment thickness, also equal to 0.60 m, by the number of years, from 2017 to 2002, being equal to 5 years, in which the phenomenon was analyzed. By recording the volumes of sediment accumulated in the reservoir in the various surveys and calculating the average annual silting speed for previous time intervals, it was found that the latter is increasing, as the last value obtained is more significant than all those previously identified. This may be related to the climatic changes and the variations observed in the rainfall regimes of different Mediterranean areas, which, in the last period, have been increasingly characterized by short-lasting and more intense rainfall events than in previous years. In addition, an increased intensity of precipitation causes an increase in the erosion phenomenon, due to the greater kinetic energy with which raindrops hit the ground. In fact, as observed by Wischmeier and Smith, 1978 [43], soil erosivity is related to the action of rainfall through two factors, the rainfall intensity of a single event and the energy with which the drops fall to the ground. In detail, two parameters, the rainfall momentum, M, and the rainfall kinetic energy per unit time and area, named kinetic power, P_n, can describe the rainfall impact energy on the ground. The first represents the force per unit area exerted by the precipitation, which causes the disintegration of the soil, and the second describes the energy the rain possesses when it reaches the ground, which causes the breaking of the soil particles' bonds, making them available for transport [44]. These parameters, in turn, are a function of, among other factors, the speed at which the raindrops hit the ground and their diameter. It follows that the force applied to the ground by the impact of raindrops is correlated to their size and speed, i.e., a very large raindrop that hits the ground at considerable speed applies a very high force to it, causing greater erosion [45]. The hydrological annals made available by the Basilicata Region (downloaded from http://www.centrofunzionalebasilicata.it/it/annali.php, accessed on 22 December 2023), with reference to the study area, show that, over time, meteorological events are characterized by an increasingly episodic nature, albeit with the same average annual rainfall, indicating that the same amount of water is falling in a shorter time than in the past, i.e., with a greater rainfall intensity, with which the increase in raindrop size and the speed at which raindrops fall to the ground are correlated [46]. Therefore, by virtue of what has been stated above, the impact on the ground occurs with greater energy, facilitating the disintegration of the particles, which reach the reservoir in greater quantities, causing an increase in the average annual rate of silting compared with previous observed periods.

4. Discussion

The results presented in the previous paragraph highlight the importance of carrying out in situ surveys to estimate, albeit indirectly, the volume of silting of an artificial reservoir over a time interval of N years, even though it is affected by an absolute error reflected in the comparative estimate. What has emerged from the available data underlines that the forecasting calculation model proposed by Molino et al., 2023 [39], for the Camastra reservoir is valid and approximates reality well since the silting value forecast for 2022 is rather like the value found following field surveys carried out in the same year. The two values differ by about 2%. More specifically, the calculation model shows a slight underestimation of the average silting value (Figure 5), which is probably connected to the value of the main parameters that govern it; the model, therefore, would need further calibration, considering the last survey conducted, to better identify the value of the parameters that characterize it.

It was also observed that the average annual rate of silting tended to increase in the five years analyzed, compared with the previous periods, and the curve of the evolution of silting takes on a more marked trend towards higher ordinates. The cause of this phenomenon is likely represented by climate change and the variation in the rainfall regime that characterizes the area examined. In recent years, we have witnessed increasingly less frequent and more intense meteoric events, marked by more kinetic energy and a more violent impact on the geological structures that comprise the Camastra reservoir's contributing watershed. This phenomenon causes an increase in erosion, as it is known to be influenced by the beating action of raindrops and the action related to the motion of water in the riverbed, which can provide the energy needed to detach, wash away, and transport soil particles. This increases the amount of sediment that reaches the weir and accumulates in the reservoir, causing the average seabed level to rise and reducing the useful capacity.

The results identified and explained in the previous chapter are similar to those of studies on the silting evolution of dams located in Algeria and Morocco, i.e., in comparable geographical and climatic conditions [47,48]. Specifically, the Algerian reservoirs analyzed, which have similar extensions to the Camastra and have been in operation for the same time interval, show a silting rate, i.e., the ratio between the volume of accumulated sediment and the useful reservoir capacity, of approximately 50%. On the contrary, for Moroccan reservoirs with the same characteristics, this value is approximately 70%, higher than that identified for the Camastra. Similarly, the Algerian and Moroccan reservoirs considered exhibited an average volumetric increase over the period 2017–2022 of approximately 0.98×10^6 m^3, similar to the value of 0.94×10^6 m^3 identified in this research. In addition, the analysis of the evolution of silting is almost similar in the case of the Algerian reservoirs, with a more accelerated exponential growth in the first phase of their life, and significantly different for the Moroccan reservoirs, whose evolutionary trends are more complex and characterized by more sustained speeds in the last period. Therefore, it is possible to state that the results of this research are more in line with the findings for the Algerian reservoirs than for the Moroccan ones, due to differences in data acquisition. In fact, whereas for the latter, only bathymetric surveys were carried out, the Algerian reservoirs were also characterized by sub-bottom surveys, which allowed for a more in-depth definition of the heights and thicknesses of the seabed, leading to a more reliable analysis, similarly to what was carried out in the present research for the Camastra reservoir.

It is undeniable, however, that sediment dredging is a necessity for all the world's reservoirs, both because of the energy demand and in relation to the satisfaction of water needs. In this sense, a strategy to fight silting in order to recover a large part of the useful reservoir capacity must be implemented and can no longer be postponed. In fact, without the pursuit of the full water capacity of reservoirs, the maintenance of hydroelectric power plants becomes increasingly expensive due to reduced energy production. Furthermore, the reduction in the water volume of the reservoirs poses significant problems to the use of water for both drinking and agricultural purposes.

Based on the evidence above, it is clear that the need to dredge sediment is becoming increasingly important, as the average thickness of the sediment is already more significant than the maximum water depth found, which is evidence of an ever-increasing reduction in the capacity to invade water resources upstream of the dam. This need, however, clashes with the legislation, which recognizes the material as waste and identifies the landfill as the leading destination for the prescribed disposal operations.

Alternatives to this scenario must be identified that allow the possibility of the recovery and reuse of dredged material as secondary raw materials in production processes or compatible activities (Figure 8). In fact, the sedimentation process involves the management of a large amount of coarse and fine sediments. The dredged materials, in addition to demolition and construction waste, could be recycled in construction materials, creating a sustainable process aiming to preserve virgin materials and, in a broader sense, the renewability of resources.

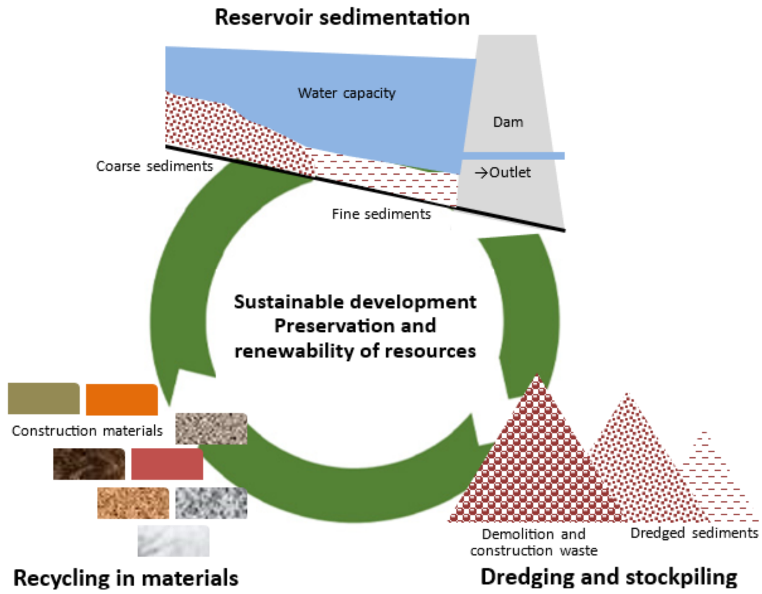


Figure 8. Overview of the processes for dredging and sediment recycling.

Therefore, from the analysis of the type of sediment deposited on the bottom of the Camastra reservoir, it is possible to propose several reuse hypotheses (Figure 9).

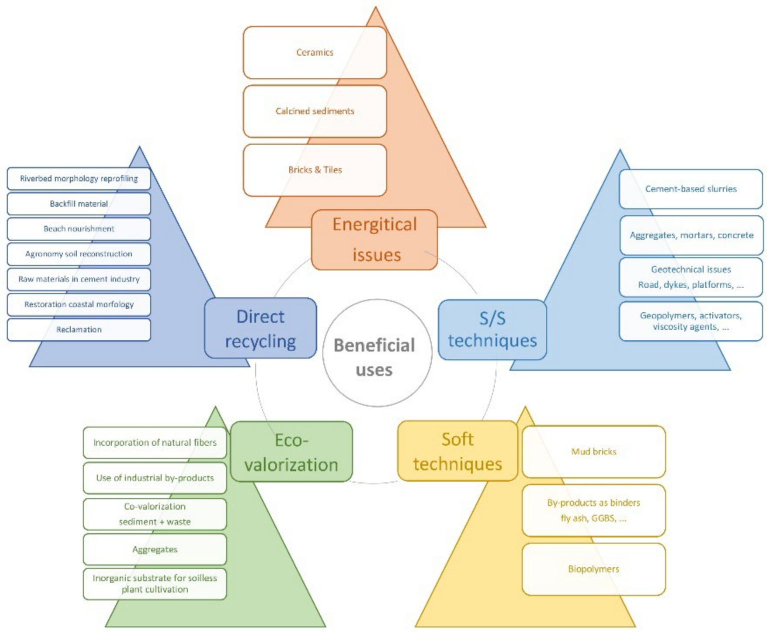


Figure 9. Panel of potential beneficial uses of the Camastra reservoir sediments.

As highlighted in the previous figure, first of all, the sediment could be used in its raw state in environmental restoration operations, mainly as backfill material for disused quarries, for the nourishment of shorelines and sandy shores, for the reconstruction of coastal morphologies, for the reprofiling of portions of the morphometry of riverbed areas, for soil reclamation, for the agronomic reconstitution of soils, as an inorganic fertilizer based on microelements or as an inorganic matrix of cultivation substrate, and in the cement industry. These alternatives prove to be viable when using considerable quantities of dredged sediments and environmentally sustainable since the virgin materials are considerably reduced and, consequently, soil consumption is limited. Furthermore, there is no need for preliminary treatment of any kind, which is of considerable economic and environmental benefit to the end user.

The use of soft and eco-valorization techniques opens further possibilities for reuse. Following a careful analysis of the chemical, physical, and biological properties of the dredged sediment, it could also lend itself to material recovery in the agronomic sphere as an inorganic substrate for soil-less cultivation systems, as well as to produce mud bricks, as an aggregate, or it could form the matrix of biopolymers. Furthermore, it could be integrated with natural fibers or mixed with waste or industrial by-products, such as binders, fly ash, and ground granulated blast furnace slag. However, unlike the previously proposed scenario, this requires the sediment to be compatible for reuse after treatment, with an added cost. Nevertheless, this possibility is still valid because of the considerable volumes that could be reused, allowing for an excellent recovery of storage capacity and a more significant reduction in dead volume.

In addition, the use of solidification/stabilization techniques (S/S techniques) provides:

- Opportunities for the valorization of dredged sediments;
- The implementation of material recovery, such as aggregate and binders, in the production of cement-based conglomerates or matrices;
- The replacement of the sandy aggregate and part of the cement.

These sediments could be reused in road embankments and sub-bases, geopolymers, activators, viscosity agents, and mortars. In this regard, various studies have shown that these conglomerates present suitable workability characteristics and mechanical strengths comparable with those of the mortars commonly found on the market, although often inferior, especially when replacing part of the binder. Therefore, it is possible to develop a reuse application that does not fulfil structural functions. In contrast, for applications with structural functions, sandy material constituting fine aggregate could be submitted to an in situ washing pretreatment to make it clean and free of the smallest parts to guarantee higher mechanical strength [49]. In addition, according to this proposed reuse application, the advantages lie in the possibility of using large quantities of dredged sediment and reducing the use of virgin materials to manufacture conglomerates. On the other hand, economically and environmentally burdensome pretreatment might be necessary to extend the possibilities of use.

Finally, we could propose reuse applications for the sediments after performing treatments to make them suitable for use in the ceramic industry for producing bricks and tiles and calcined sediments. However, the envisaged treatments have a high-energy expenditure, so this alternative should not be prioritized, considering the other types of reuses that are more environmentally and economically compatible.

In any case, exploring alternatives for the recovery and reuse of dredged sediments, with a focus on environmental and economic sustainability, provides a practical and forward-looking perspective to both scientific research on the subject and sediment management plans, which are currently, incorrectly, predominantly disposal-oriented. Also, further investigations could be carried out in order to improve predictive models, e.g., by performing periodic surveys that make more silting data available or for the assessment of ecological impacts related to sediment dredging through the definition of Impact Monitoring Plans. In addition, more recovery alternatives could be explored, for example, with reference to earthen or bio-based materials that could pose another opportunity to propose eco-materials characterized by sustainability and the renewability of resources.

5. Conclusions

Using a calculation model for the expeditious quantification of silting in the Camastra reservoir silting offers the managing authority the possibility of identifying effective strategies for adequately planning dredging operations. The use of advanced technologies such as the DJI Matrice 300 RTK drone with ZENMUSE L1 LiDAR technology, multibeam surveys, and geophysical prospecting using sub-bottom profiler reflects a contemporary and sophisticated approach to data collection. In fact, the execution of in situ surveys, and more specifically sub-bottom profiler-type surveys, carried out at intervals, has made it possible to identify the average values of the amount of sediment that constitutes dead volume. However, the estimate is affected by a certain degree of error from the combined absolute errors of the surveys considered.

Two aspects are highlighted by the assessments carried out in this work. First, the amount of sediment volume accumulated at the bottom of the Camastra reservoir is such that, to date, the dead volume is, on average, greater than 50% of the reservoir's overall storage capacity, so less area can be invaded than initially forecast. Moreover, the speed with which sediments are accumulating is increasing compared with previous periods, and, therefore, it is possible to foresee that the dead volume will tend to occupy more and more space within the reservoir in a shorter period, rapidly reducing the invadable water volumes.

Because of what has emerged, the evidence of the increasing rate of silting means that it is no longer possible to procrastinate dredging the sediments to recover the useful storage capacity that the dead volume is gradually eroding. Dredging operations are essential in order to guarantee the possibility of storing significant water volumes, the satisfaction of drinking and irrigation needs, and the production of so-called green energy.

Several options were provided to avoid landfill disposal, all equally suitable for the Camastra sediments. The recovery alternatives, in fact, are all equally valid, ranging from direct reuse (e.g., spreading in agriculture) to soft techniques (such as sustainable, green recycling). S/S techniques, on the other hand, could be used when sediment pollution levels above regulatory thresholds are detected, using geopolymers with a stabilizing function. However, the transformation of the dredged materials from waste to secondary raw material depends on the results of the characterization of the main geotechnical, physiochemical, and environmental parameters, which help to define the specific properties of sediments and to verify their suitability for reuse. In this regard, further research should be started to investigate the rationality and feasibility of the proposed reuse alternatives, which cannot be thoroughly examined in the framework of the current state of knowledge and the absence of a complete sediment characterization. In addition, due to the findings of the presented study, it is possible to suggest further developments of the research work, with particular reference to a simple but adapted characterization of possible sustainable recovery, which would save costs (local recovery), limit CO_2 emissions, and save natural resources. In this regard, direct, environmentally friendly reuse and soft techniques involving a combination of waste reuse applications and the use of biopolymers, geopolymers, and/or low-carbon binders could be pursued. Upcycling could be achieved for dredged sediment by combining it with crop wastes that improve mixes, and using it, for example, as compost for agriculture, for stabilizing earthen bricks, and for other possible uses.

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