International Soil and Water Conservation Research 13 (2025) 422–435

Contents lists available at ScienceDirect

International Soil and Water Conservation Research

journal homepage: www.elsevier.com/locate/iswcr

Original Research Article

Modelling land use changes impacts on the silting of small agricultural water harvesting reservoirs

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A R T I C L E I N F O

Article history:
Received 26 June 2024
Received in revised form
7 February 2025
Accepted 9 February 2025
Available online 11 February 2025

Keywords:
Water harvesting
Erosion
Sedimentation
Vineyards
Water balance
Sediment balance
Mediterranean
Italy

A B S T R A C T

Water harvesting with Small Agricultural Reservoirs (SmAR) represents a solution for sustainable water management in different contexts. However, many technical challenges are still open despite its widespread application. One of the most relevant, for the sustainable management of SmAR, is represented by the loss of storage volume caused by the inflow of sediments, but the analysis of the dynamics of sedimentation for such small structures has received relatively little interest so far. This study aims to implement a validated model simulating the hydrology and erosion dynamics of the catchment upstream of a SmAR in the Mediterranean basin, specifically in the hilly area of Crete Senesi, Tuscany Region (Italy). Here, wine production is particularly developed, but not within the catchment of study, where the cultivation of cereals and forage is practiced. Our analysis aimed at estimating how much the rate of sediment accumulation in the reservoir would vary with the replacement of currently arable land with vineyards. A model was implemented on the HEC-HMS software, maximizing the value of existent low-cost data (Google Earth imagery and regional erosion maps) for its validation. The validated model was then used to test alternative land use scenarios in the upstream catchment, showing its flexibility for supporting decision-making over SmAR management. The model performed with an error always below 5% on the SmAR area detected by satellite. Erosion values calculated with HEC-HMS were in line, but lower than the estimation made by the Tuscany region with a GIS-based procedure. The scenario analysis showed that the simulated land use change led to a high value of annual sediment accumulation in the reservoir (216% of the original value of erosion obtained with cereals and other crops), showing the indirect cost of changing the cropping patterns to vineyard production. The approach can be replicated at the local scale in all other contexts where similar, and relatively easy-to-get, data are available. Further development of the present approach can include the replication of similar low-cost methodologies on other case studies, refinement of the erosion modelling and sensitivity analysis.

1. Introduction

Water harvesting with Small Agricultural Reservoirs (SmAR) represents a solution for sustainable water management at the global scale (Lebon et al., 2022; López-Felices et al., 2020; Schmitt et al., 2022; Wang et al., 2022; Wisser et al., 2010). Early estimates showed that globally there were about 277,400,000 SmAR with an area of less than 1 ha, and 24,120,000 water bodies between one and 10 ha, representing more than 90% of the world's standing water bodies (Céréghino et al., 2014; Downing et al., 2006). Such structures are key for water security in Africa (Owusu et al., 2022; Rockström & Falkenmark, 2015; Saruchera & Lautze, 2019), but also in the South and the North shores of the Mediterranean (Albergel et al., 2004; Casas et al., 2011; Ogilvie

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Peer review under the responsibility of International Research and Training Center on Erosion and Sedimentation, the China Water and Power Press, and China Institute of Water Resources and Hydropower Research.

https://doi.org/10.1016/j.iswcr.2025.02.001
2095-6339/

et al., 2019), in South America (Bichsel et al., 2016; Magliano et al., 2015; Niborski et al., 2023; Ribeiro Neto et al., 2024) and in Australia (van Dijk et al., 2007).

Water harvesting through SmAR is widespread also within Italian territory. The Italian law (Law 584/94) defines "Large Dams of National Interest" all the reservoirs with a volume over 10^6 m^3 or with a height of the dam over 15 m, while smaller reservoirs are considered SmAR and their number is estimated between 12,000 and 14,000 (ITCOLD, 2017). The interest in this kind of water harvesting technologies has been fluctuating, with an initial boom in the 60s and 70s. In this period, the Italian government provided substantial economic aid with non-repayable funding for the construction of this type of work. However, starting from the 80s the development of the reservoirs suffered a marked slowdown towards a period of abandonment (Uzzani, 2012), when the maintenance problems of SmAR have become a critical issue for farmers and landowners, also due to the investment needed (Casadei et al., 2019).

Recently, however, the rediscovery of these solutions is taking place, led by the need for adaptation to climate change and recurrent droughts in the country (Casadei et al., 2019; Di Francesco et al., 2022). In this context, technical challenges are present in the planning phase, for the selection of suitable sites for the implementation of new SmAR (Napoli et al., 2014). Challenges also arise in the management of the existing structures, given the difficulty in their mapping, and in the estimation of their area (Casadei et al., 2019; Di Francesco et al., 2022), and for the evaluation of their impact on the local river sediment budget (De Rosa et al., 2016).

Among these, one of the most relevant challenges for the sustainable management of SmAR in Italy is represented by the loss of storage volume caused by the inflow of sediments from the upstream catchment. The issue is persistent for large dams in the country (Bazzoffi & Van Rompaey, 2003; Patro et al., 2022) and is still not addressed by a sufficient number of scientific investigations for small reservoirs. Therefore, a major research gap for SmAR is represented by the lack of suitable methods for calculating catchment erosion and sediment deposition in the reservoir. The few studies produced included the work by Porto et al. (2013), utilizing Cesium-137 technique to analyze the sedimentation for a small reservoir in the south of Italy, and the one by Giambastiani et al. (2022), deriving the amount of sediment in 12 SmAR in Tuscany region using an aquatic drone equipped with a sonar and a GPS receiver.

Such studies, however, provide information only on the erosion and sedimentation dynamics in the business-as-usual situation, without evaluating alternative scenarios for reducing erosion rates at the watershed level. These options are key to reducing maintenance issues, considering the high cost of dredging SmAR and the fact that dredged sediments can be considered special waste.

The analysis of the dynamics of sedimentation for SmAR received relatively little interest so far also at the Mediterranean (Ben Slimane et al., 2016) and on a global scale (Fripp et al., 2020, pp. 195–201; López-Felices et al., 2020). Caesium-137 (Ben Slimane et al., 2016; Preti et al., 1990) and remote sensing-based approaches (Valent et al., 2019; Výleta et al., 2017) are still present, while modeling approaches are often limited by the availability of data for calibrating and validating coupled hydrological and erosion models (Hlavčová et al., 2018; Xie et al., 2011).

Therefore, the purpose of this study is to implement and test a model simulating the hydrology and the erosion dynamics of the catchment of a SmAR in Tuscany Region (Italy) with the HEC-HMS software. The approach aims at maximizing the value of existent low-cost data (hydrological validation Google Earth imagery and soft validation of the erosion with regional erosion maps) for its validation at a very small scale for a SmAR in a single farm. The validated model was then used for testing alternative land use scenarios in the upstream catchment, showing its flexibility for supporting decision-making over SmAR management. The approach can be replicated at the local scale in all other contexts where similar, and relatively easy-to-get, data are available.

2. Materials and methods

2.1. Study area

The area of study, i.e. the Suvignano estate, is located about 15 km from Siena, Italy, and belongs to "Ente Terre Regionali Toscane" - an operational body established by the Tuscany Region - following the seizure of the property confiscated from the organized crime in November 2018. The estate covers approximately 640 ha, most of which are cultivated with durum and wheat, grain legumes, sunflowers, and alfalfa. This represents quite a peculiar characteristic of the estate, considering that most of the other farms in the area are cropping vineyards, leading to considerably larger erosion rates (Regione Toscana, 2015).

The Suvignano estate has four SmAR, of which the one named "Forlì", in the west of the estate, was chosen for the modeling. The reservoir was established in 1973, has a catchment area of approximately 1.1 km^2, a surface area of about 38,500 m^2 and a volume of about 86,500 m^3 (Figs. 1 and 2). The area is located within the Ombrone river watershed, in the south of Tuscany Region, which has been hit by several drought events and it is expected to undergo the impact of climate change in the coming years (Villani et al., 2022, 2024a; 2024b). However, the SmAR is currently not used for irrigation, representing a favourable case study since uncertainties given by the estimation of water use are not present.

The land cover of the catchment area was derived from the data of the Tuscany Region (Regione Toscana, 2019). About 88.5% of the catchment is occupied by arable land, approximately 7.7% is covered by forest areas and the reservoir itself occupies about 3.8% (Fig. 1(b)).

The types of cultivation present within the catchment (Fig. 1(c)) were then analyzed in detail by referring to the information provided by Agenzia Regionale per le Erogazioni in Agricoltura (ARTEA, 2022). The most widely used crop is hulled wheat, which makes up about 40% of total area; a large fraction of the land is also cultivated with clover (*Trifolium alexandrinum*, about 33%) and wheat (about 18%), while the rest is covered by minor crops. Soil data were retrieved from the Soil database of the Tuscany Region (Regione Toscana, 2017) at a scale of 1:10.000 indicating that almost all the catchment has silty clay soils.

2.2. Meteorological dataset

Daily precipitation, temperature, and wind speed data were obtained for the Monteroni d'Arbia Biena station (ID: TOS11000082) from January 1, 2012 to December 31, 2021 (Servizio Idrologico Regionale, 2023). For shortwave solar radiation and relative humidity data, we relied on estimates from the NASA POWER Dataset (NASA, 2022). Longwave solar radiation and evapotranspiration values were estimated with the Penman-Monteith method (Allen et al., 1998).

2.3. Modelling process

The Hydrologic Modeling System (HEC-HMS), version 4.10, was used to simulate the hydrological processes in the basin. HEC-HMS is designed to simulate the hydro-sedimentological processes that occur within a watershed and is used for the simulation of both event scale analysis and for continuous hydrological modeling

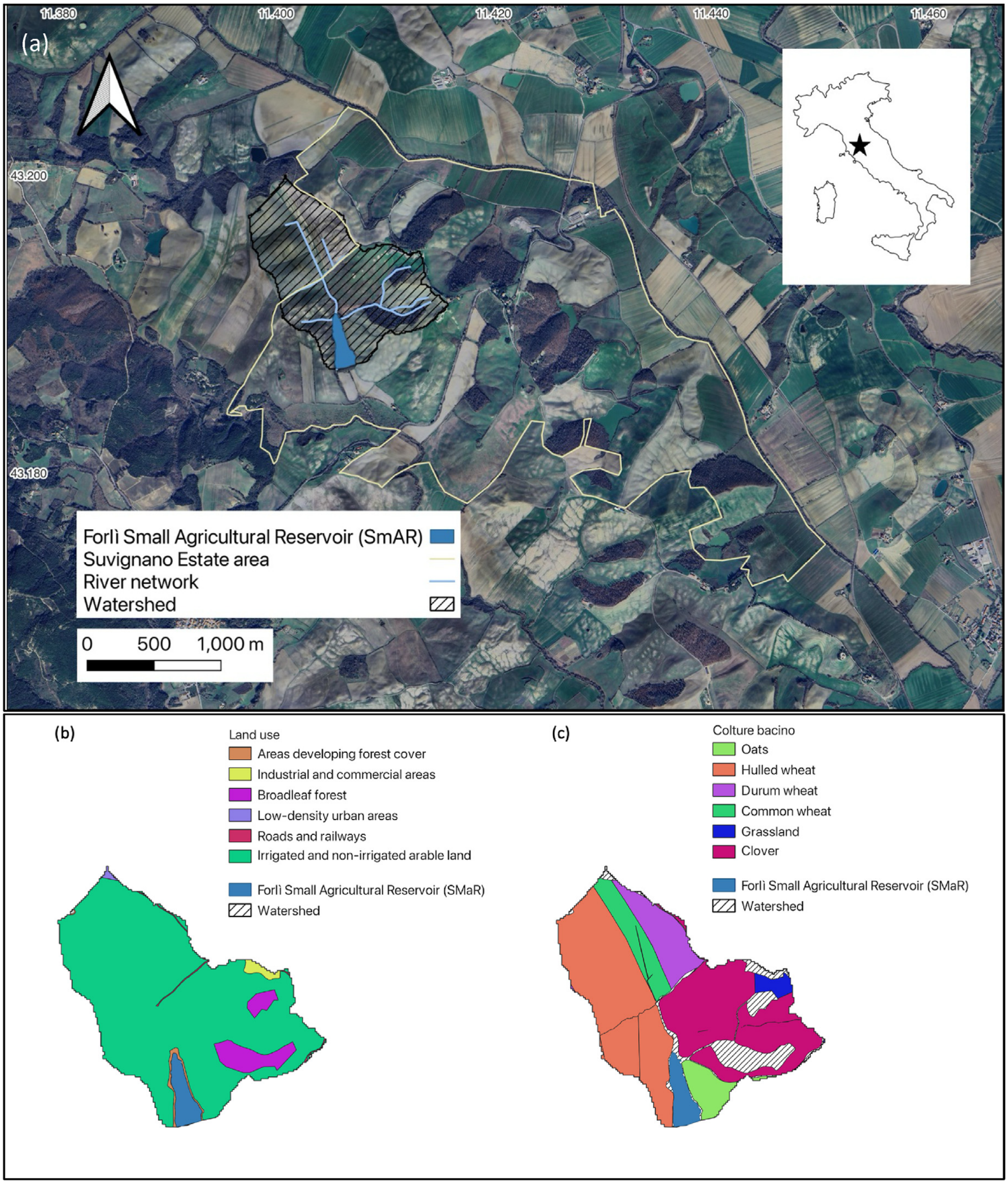

Fig. 1. Study area: (a) overview of the study area with Google Earth background elaborated on QGIS and temporary river network. (b) Land use map. (c) Crops map.

(Hydrologic Engineering Center, 2022). For the modeling of the processes that occur within the watershed, HEC-HMS provides a series of packages designed to represent a specific component. Table 1 shows the methods chosen for hydrological simulation in HEC-HMS. The watershed was divided into 5 sub-watersheds, connected by simple junctions and by a routing channel as shown in Figs. 3 and 4. The model was run in the period of the meteorological data availability, with daily time step.

2.3.1. *Hydrological modeling*

Most of the methods reported in Table 1 represent the very standard options for modeling each water balance component within HEC-HMS, excluding the one for the basin losses for which the Curve Number method is the most used (Sahu et al., 2023). The Layered Green and Ampt loss method (Hydrologic Engineering Center, 2022; Schroeter & Associates, 1996) uses two layers to represent the dynamics of water movement in the soil. Incoming precipitation fills the canopy's storage capacity, which was determined based on values shown in Table 2. Precipitation that exceeds storage capacity will fill the surface storage, which was determined based on values shown in Table 3. After that, the infiltration rate from the surface into layer 1, i.e. the most superficial layer of the

Fig. 2. The Forlì small agricultural reservoir in the study area.

soil, is calculated with the equation of Green and Ampt (Heber Green & Ampt, 1911) as long as it is below saturation. The infiltration rate changes to the current seepage rate when layer 1 reaches saturation. Seepage out of layer 1 occurs only when the water level in the layer exceeds the field capacity. Maximum infiltration occurs when layer 1 is at saturation and declines to zero at field capacity. Similarly for the percolation from layer 2. The infiltrated water is added to the layers and the percolated water is removed from the layers together with that required for the evapotranspiration process. Contribution to baseflow will not occur until both soil layers have reached field capacity (Hydrologic Engineering Center, 2022). The method was chosen since it could represent very well the soil data produced by the Tuscany Region (Regione Toscana, 2017), based on a 2-layer description of each soil unit (Fig. 5). For other parameters, where possible, reference to Tuscany Region data was made. Where this was not possible, HEC-HMS referenced data was used.

The values of Canopy storage and if and of Surface storage for each sub-watershed were calculated as the mean of the value-weighted by each land use area.

For the characterisation of the soil-water dynamics in the Layered Green and Ampt method, the following parameters were calculated for each soil layer in each sub-watershed, as the average weighted by the area of each soil unit.

- Layers initial content: the initial water content in the soil at the start of the simulation; it was set equal to the field capacity estimated with Soil-Plant-Air-Water (SPAW) software (Saxton & Willey, 2005) based on textural data of the soil map.
- Conductivity (mm/hr): the saturated hydraulic conductivity characterizes the infiltration from the surface to the most superficial layer of soil. It was set equal to the average saturated hydraulic conductivity estimated with SPAW based on textural data of the soil map.
- Max seepage (mm/hr): the maximum infiltration from the lower part of layer 1. It has been set equal to "Ksat30", i.e. the saturated hydraulic conductivity of the first 30 cm of soil, reported in the pedological data of the Tuscany Region (Regione Toscana, 2017).

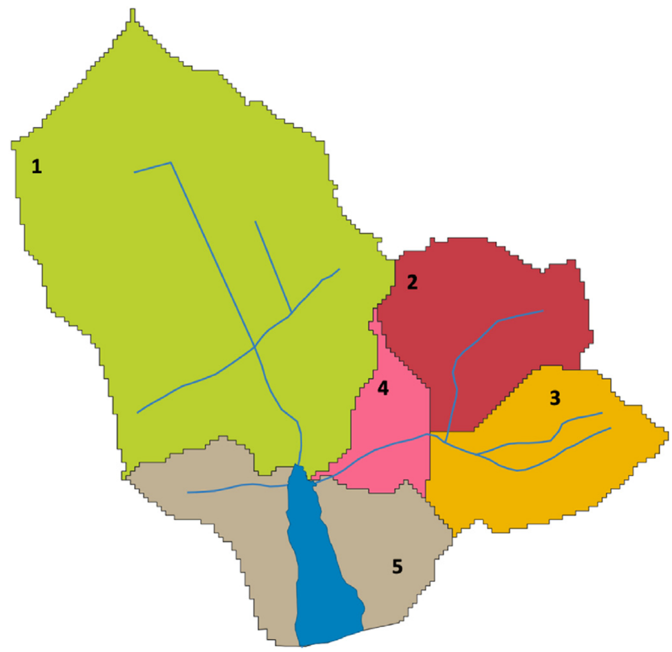

Fig. 3. Sub-watersheds used for modeling. The Forlì SmAR is visualized in blue.

Table 1
HEC-HMS methods chosen for representing the hydrological components. Each method can either be associated with a Sub-watershed or to a reach element, being representative of a process occurring on an area or o a channel.

Hydrological component	Description	Method	References	Element
Canopy	Contribution to the hydrological balance made by the interception of precipitation by plants.	Simple Canopy	Hydrologic Engineering Center (2022)	Sub-watershed
Surface	Designed to represent the surface of the soil, where water can accumulate in a surface depression	Simple Surface	Hydrologic Engineering Center (2022)	Sub-watershed
Loss	Estimation of the infiltration	Layered Green and Ampt	(Hydrologic Engineering Center, 2022; Schroeter & Associates, 1996)	Sub-watershed
Transform	Rainfall - runoff transformation	SCS Unit Hydrograph	United States - Soil Conservation Service (1986)	Sub-watershed
Baseflow	Modelling of baseflow.	Linear Reservoir	Hydrologic Engineering Center (2022)	Sub-watershed
Erosion	Erosion and transport of sediments within the basin/sub-basin.	Modified Universal Soil Loss Equation (MUSLE)	Williams (1975)	Sub-watershed
Routing	Routing within a river reach.	Muskingum Cunge	Cunge (1969)	Reach
Loss/Gain	Losses from the river reach bed.	*Neglected for the case study*	*Neglected for the case study*	Reach
Sediment transport	Transport Potential Method	Engelund-Hansen	(Engelund and Hansen, 1967)	Watershed
Sediment transport	Fall velocity	Van Rijn	Hydrologic Engineering Center (2002)	Watershed
Sediment transport	Sediment transport within a river reach.	Uniform Equilibrium	Hydrologic Engineering Center (2002)	Reach

Note: all methods can be also retrieved at: https://www.hec.usace.army.mil/confluence/hmsdocs/hmsum/4.7.

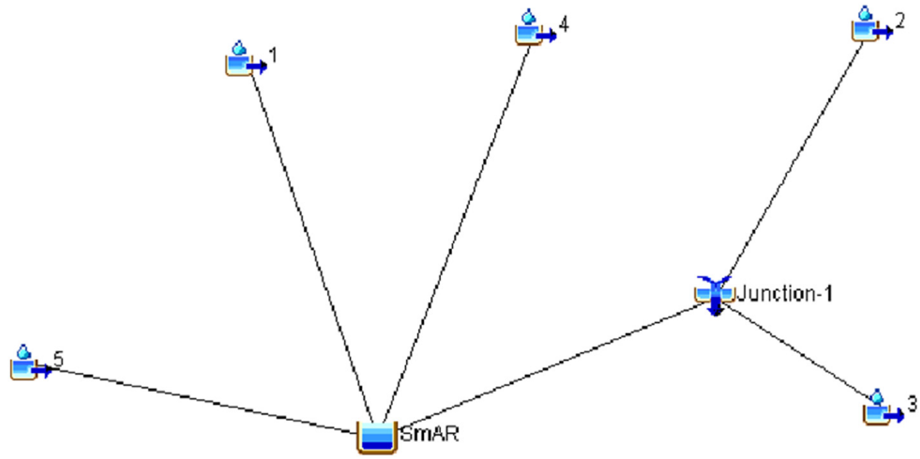

Fig. 4. Model scheme: sub-watersheds 1, 4, and 5 are draining directly in the SmAR, while sub-watersheds 2 and 3 are delivering runoff to a channel connected to the SmAR (see Fig. 3 for comparison).

Table 2
Canopy storage according to the type of vegetation according to (Holberg, 2014).

Type of vegetation	Canopy storage (mm)	Correspondent land use for the case study
Grasses and Deciduous Trees	2.032	Areas developing forest cover
Coniferous Trees	2.540	Broadleaves forest
General Vegetation	1.270	All the other land uses

Table 3
Surface storage as a function of the slope of the sub-basin according to (Holberg, 2014).

Surface description	Slope (%)	Surface Storage (mm)
Paved impervious area	NA	3.2–6.4
Steep slopes	>30	1.0
Moderate to gentle slope	5–30	12.7–6.4
Flat, Furrowed Land	0–5	50.8

- Max percolation (mm/hr): the maximum percolation from the lower part of layer 2. It has been set equal to "Ksat150", i.e. the saturated hydraulic conductivity of the lower part of the soil from the pedological data of the Tuscany Region (Regione Toscana, 2017).
- Suction (mm): the “Wetting Front Suction Head” must then be specified and it is generally assumed that it is a function of the soil structure. The “Wetting Front Suction Head” describes the attraction of water into the empty spaces of the soil column. The value of the "CAP" (capillary water) was used, obtained from the database of the Tuscany Region (Regione Toscana, 2017).
- Dry duration (hr): the amount of time that must pass after a rainfall event to recalculate the initial condition of the Green and Ampt equation. The value of 12 h recommended by the HEC-HMS manual was maintained (Hydrologic Engineering Center, 2022)
- Impervious (%): the percentage of the sub-basin area that is impervious. No losses are calculated on the impermeable area; all precipitation over that part of the sub-basin becomes excess precipitation and is subject to direct runoff. The percent of Industrial and commercial areas, Low-density urban areas, and Road and railways (Fig. 1(b)) was considered impervious for each sub-watershed.
- Thickness (mm): the thickness of the two soil layers was derived from the data made available in the Pedological Database of the Tuscany Region in relation to the “Soil Depth” field.
- The values of "Saturated Content", i.e. maximum water retention capacity in terms of volume ratio, field capacity and wilting point were calculated with SPAW starting from soil texture data and set equal for the two layers.

The SCS (Soil Conservation Service) unit hydrograph method was used to model the transformation of precipitation excess into direct surface runoff (Hydrologic Engineering Center, 2022; United States - Soil Conservation Service, 1986). The basic parameter to be evaluated for the use of this method is the Lag Time. To estimate the parameter, we started from the calculation of the time of concentration (Tc), defined as the time needed for water to flow from the most remote point in a watershed to the watershed outlet (Grimaldi et al., 2012). The Lag Time was then set equal to 0.6·Tc.

For each sub-watershed, Tc was calculated with different formulas valid for the Italian context (Eqs. (1)–(6)). The lower and the higher values were removed, and then the average value was chosen. Such procedure was put in place to overcome the difficulty of choosing a Tc for our case study, as in Italy comparative Tc analysis is usually carried out for larger watersheds (Ravazzani et al., 2019; Giandotti, 1934; Kirpich, 1940; Pasini, 1914; Berteni et al., 2021; Haan et al., 1994; Paliaga et al., 2019).

- Giandotti : $$T_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H_m}} \tag{1}$$
- Kirpich : $$T_c = 0.066L^{0.77}\left[\frac{1000L}{0.8(H_{max} - H_0)}\right]^{0.385} \tag{2}$$
- Pasini : $$T_c = 0.108\,\frac{(AL)^{\frac{1}{3}}}{0.8\sqrt{i}} \tag{3}$$

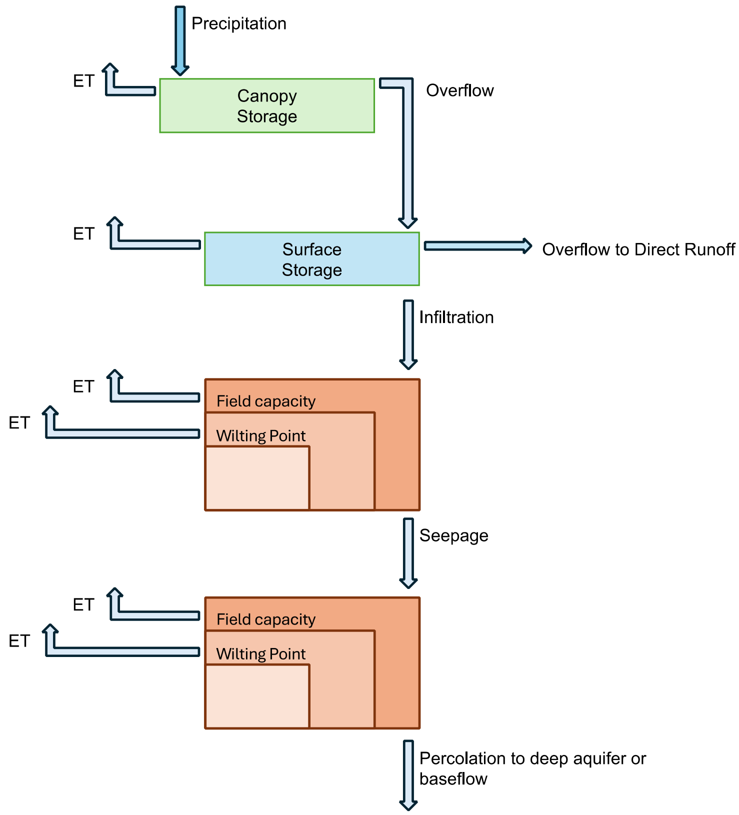

Fig. 5. Layered green and ampt loss method conceptual diagram (adapted from Hydrologic Engineering Center, 2022).

- Pezzoli : $T_c = 0.055\ \frac{L}{\sqrt{i}}$ (4)

- Tournon : $T_c = 0.369\frac{L}{\sqrt{i}}\left[\frac{A}{L^2\sqrt{\frac{i}{i_v}}}\right]^{0.72}$ (5)

- Puglisi : $T_c = 6L^{\frac{2}{3}}(H_{max} - H_0)^{-\frac{1}{3}}$ (6)

Where T_c is the concentration time in hr; A is the (sub-)watershed area in km^2; i is the mean slope of the main river stream; L is the length of the main river stream in km; H_m, H_{max}, and H_0 are, respectively, the mean, maximum and minimum elevation of the (sub-)watershed in m; i_v is the average slope of the watershed.

For the baseflow, simulated with the Linear Reservoir method, the following parameters are defined.

- Initial Baseflow (m^3/s) set equal to 0;
- Fraction of percolation flow corresponding to baseflow, set equal to 1.
- Groundwater Storage Coefficient (hr): the time constant for each groundwater layer and indicates the response time for a base runoff component within a sub-watershed.

To estimate the last value, reference was made to the HEC-HMS manual (Hydrologic Engineering Center, 2022), setting it equal to 3R, where R is the Clark Storage Coefficient, derivable with the formula:

$$R = 0.65 \cdot (T_{Cg} + R) \quad (7)$$

Where T_{Cg} is the groundwater TC calculated as

$$T_c = 2.2(L_f \cdot L_C /(Slope_{10\text{-}85})^{0.5})^{0.3} \quad (8)$$

With L_f represents the longest flowpath from the subbasin outlet to the most hydraulically-remote point upstream; L_c is the centroidal flow path, that begins at the subbasin outlet and extends upstream along the longest flowpath until it reaches the point along the longest flowpath that is nearest to the subbasin centroid; and $Slope_{10\text{-}85}$ is the average slope of the flow path corresponding to section 10% - 85% of L, that is considered more representative of flowpath slopes as it is not affected by the more extreme values. These parameters were calculated for each sub-watershed with the “characteristics tools” of HEC-HMS.

Finally, to represent the reach between the confluence of the sub-watersheds in the east of the watershed to the SMaR, the Muskingum Cunge routing method was used (Cunge, 1969). The method requires the definition of various parameters, including the length and slope of the analyzed river stretch, calculated on QGIS, the section width, and the Manning coefficient set equal to 0.02.

2.3.2. Erosion modeling

The MUSLE equation (Eq. (9)) was adapted from the original Universal Soil Loss Equation (USLE) to obtain erosion data valid at the rainfall event scale (Berteni et al., 2021; Gwapedza et al., 2018; Williams, 1975):

$$Sed = 11.8(Q_{surf}\ Q_{peak})^{0.56} \bullet K \bullet LS \bullet C \bullet P \quad (9)$$

Sed is the sediment volume for a given event in a given catchment (t); Q_{surf} [m^3] and Q_{peak} [m^3/s] are respectively the surface runoff volume and the peak runoff rate modelled with HEC-HMS; K is the soil erodibility factor [(t · ha · h)/(MJ · ha · mm)], expressing the erodibility of the soil for its chemical-physical properties; LS is topography factor, where L represents the slope length factor and expresses the effect of the slope length on the quantity of eroded material, while S is the slope factor and expresses the effect of the slope on the amount of eroded material; C is the cover and management factor that takes into account the type of existing vegetation (or crop) and the type of interventions carried out; P is the support practice factor, relating to soil restoration and conservation techniques. L, S, C, P are adimensional.

The erodibility factor was calculated according to the formula:

$$K = 2.1 \bullet 10^{-4} \bullet M \bullet 1.14 \bullet (12\text{-}OM) + 3.25 \bullet (s\text{-}2) + 2.5 \bullet (p\text{-}3) \quad (10)$$

where M is calculated from the texture of the top 15 cm of soil with Eq. (11) (Corral-Pazos-de-Provens et al., 2023):

$$M = [(100\text{-}c) \bullet (s + v)] \quad (11)$$

with c equal to the % of clay (d < 0.002 mm), s to the % of silt (d between 0.002 and 0.05 mm) and v to the % of fine sand (d between 0.05 and 0.1 mm). s represents the soil structure code and p the soil permeability class defined in the nomograph by Wischmeier & Meyer (1973). OM represents the % organic matter. All the data were retrieved from the Tuscany Region soil map (Regione Toscana, 2017).

Following the USLE method (Wischmeier & Smith, 1978), the evaluation of L is carried out using the equation:

$$L = (\lambda/22.13)^m \quad (12)$$

where λ [m] represents the average horizontal distance from the point of origin of the runoff to the point where the slope decreases and deposition activity begins, 22.13 represents the length in meters of the standard parcel and m is an exponent which can be calculated as:

$$m = \beta/(1+\beta) \quad (13)$$

with $\beta = \sin(\theta)/[3\sin(\theta)^{0.8}+0.56]$, and θ equal to the slope angle of the considered side (Zhang et al., 2017).

The S factor was instead calculated with the following relations (K. McCool et al., 1989):

$$S = 10.8 \sin(\theta) + 0.03 \text{ for } \theta < 9\% \quad (14)$$

$$S = 16.8 \sin(\theta) - 0.05 \text{ for } \theta \geq 9\% \quad (15)$$

For the C factor, the Corine Land Cover (CLC) classes reported in the land use database of Tuscany Region (Regione Toscana, 2019) were linked to different C values according to Panagos et al. (2015) and Paris and Moscatelli (2005), as reported in Table 4. The C factor of the Vineyards is also reported here below even if it is not used for modeling the real-life scenarios but for testing alternative land use settings.

For the calculation of the C factor associated with the land use code 210, related to "Irrigated and non-irrigated arable land" (Fig. 1(c)), the types of crops grown within each subbasin were analyzed with higher detail (Table 5) following the same references.

2.3.3. *Sediment transport modeling*

To model the erosion and transport of sediments in HEC-HMS it is first required the definition of general parameters which are valid for the whole catchment area. These include.

Table 4
USLE-MUSLE C factor values for each land use class in the study area.

CLC class	Land cover description	C factor
1121	Low density urban areas	0.001
121	Industrial and commercial areas	0.001
122	Roads and railways	0.003
221	Vineyards	0.3454
311	Broadleaves forest	0.0013
324	Areas developing forest cover	0.0242
512	Water bodies/Forlì SmAR	0

- Transport Potential Method: It specifies how the sediment transport capacity will be calculated for non-cohesive sediments. The Engelund-Hansen method (Hydrologic Engineering Center, 2023) was chosen.
- Specific Gravity of the Sediment Grains, that was set equal to 2.65 (adimensional).
- Clay, Silt and Sand dry density, set respectively equal to 1200, 1500 and 1600 kg/m^3.
- Fall velocity: method used to calculate the fall (or sedimentation) velocity. We opted for the Van Rijn method (Hydrologic Engineering Center, 2002).
- Grade Scale: It determines the number of grain sizes used to calculate erosion and sediment transport throughout the model. The erosion, deposition, sedimentation and transport calculations are performed separately and independently for each dimension in the selected "Grade Scale". A differentiation into four subclasses was chosen: clay, silt, sand and gravel. The density of the gravel is equal to the one set for sand.

For the sediment transport modelling in the reach, the "Uniform Equilibriuum" method was chosen. This method assumes that the sediment is translated instantaneously through the reach itself. No time delay is calculated for sediments passing through the reach and entering the reach from upstream features (in our case from the Northeast and Southeast basins). The carrying capacity for each particle size, defined as the Grade Scale, is then calculated to determine whether erosion or sediment deposition occurs. In HEC-HMS the bed of a river reach is represented by a two-layer model. The upper layer represents the top of the stream bed which actively interacts with the flow field. This layer responds relatively quickly to changes to the flow rate. The lower layer is linked to the upper layer with a simple bed mixing algorithm. The lower layer represents the underlying substrate of the reach. Long-term processes that lead to a reach being either a sediment sink or sediment source within the watershed are represented through the lower layer. For this method it is required to set, in addition to the width of the section, also the depth of the bed of sediments, set equal to the 90th-percentile diameter of the reach granulometric distribution, multiplied by 30. The active layer factor was set equal to 2. For

Table 5
USLE-MUSLE C factor values for each crop in the study area.

Crops ID	Crops type	C factor
336	Grassland	0.0988
379	Clover	0.0988
1001	Oats	0.2
1002	Durum wheat	0.2
1003	Common wheat	0.2
1004	Hulled wheat	0.2

The P factor was set equal to 1.

further information about the methodology, please refer to the HEC-HMS user manual (Hydrologic Engineering Center, 2022).

2.3.4. Small agricultural reservoir (SmAR) modeling

For the modeling of the Forlì SmAR, the "Outflow Structures" component of HEC-HMS was utilized. The following methods were implemented.

- Storage Method: the "Elevation-Storage-Area" option was chosen, which requires the selection of an "Elevation-Storage" curve (above sea level elevation - volume of the reservoir) and an "Elevation-Area" curve (above sea level elevation - reservoir area). Data was retrieved from the Suvignano Estate.
- Initial condition: the initial condition sets the amount of water stored in the reservoir at the start of the simulation. The “Inflow = Outflow” method takes the inflow to the reservoir at the beginning of the simulation and uses the storage-discharge curve to determine the storage required to produce that same flow rate as the outflow from the reservoir, which is set as the initial amount of water stored.
- Spillways: the "Broad-Crested Spillway" method was used. The spillway of Suvignano SmAR is located at an elevation of 198.5 m a.s.l. and is around 12.5 m wide. A value must also be specified for the "Discharge Coefficient" (C, taking into account the energy losses in the spillway.
- Evaporation: the losses due to evaporation from the reservoir have also been estimated, which can constitute an important part of the hydrological balance. The Dragoni method was used to estimate the evaporation losses from the reservoir (Dragoni & Valigi, 1994)
- Sediment method: the "Complete Sediment Trap" method was chosen. All incoming sediments gradually deposit on the bottom of the SmAR, as the bottom outlets of the reservoir are usually closed.

Since the SmAR is currently not used for irrigation, no water abstraction is considered.

2.4. Model validation

Inflow water volumes at the SmAR, and thus runoff values, were validated by comparing the SmAR areas obtained in the model and the ones visible by Google Earth (Fig. 6). The area was calculated manually, considering that the imagery available on the software is from different commercial datasets, but almost always with resolutions below 50 cm (Agapiou et al., 2016; Reece et al., 2023). During the modelling period, five cloud-free images were available, on the following dates: August 12, 2013, August 14, 2016, June 9, 2017, July 1, 2019, May 27, 2021. The relative error of the observed area (E_R) and the relative error of the variation of the area (E_Δ) were calculated. For the erosion values, a soft calibration was performed, checking if the erosion rates estimated with the model were in line with the ones calculated by Tuscany Region (Regione Toscana, 2017). From such reference, the entire watershed is classified within class 2 which corresponds to an estimated erosion of between 5 and 10 t/ha/yr.

2.5. Land use change scenarios

Apart from the baseline scenario (BASE) with the current land use, two land use change scenarios were tested: LUC1: changing all the crops in the area of the watershed owned by the Suvignano estate to vineyards; and LUC2: changing all the crops in the watershed to vineyards.

Fig. 6. Example of a Google Earth image for the Forlì SmAR (August 14, 2016).

3. Results

3.1. Meteorological dataset

The precipitation registered from the Monteroni d'Arbia Biena station during the 10 years of simulation (2012–2021) was between 461.8 (2017) and 1155.2 (2013) mm per year, with an overall average annual value of about 856 mm. The maximum average temperatures, registered within the time range described above, vary between 28 and 32 °C in the summer months and between 10 and 15 °C in the winter months while the minimum average temperatures vary between 13 and 15 °C in the summer months and −2 and 3 °C in the winter months, with an annual average mean value of about 14 °C. Monthly averages for the period under simulations are shown in Fig. 7. As in many other areas of the centre of Italy, the hydrological year starts in August and the peak rainfall amounts are between October and December.

No gaps in the data series were observed. The Koppen classification for the study area is Csa.

3.2. Model set-up and validation

The Tc and Lag Time of the various watersheds are reported in Table 6. The results showed how the average values were almost the same for four out of five sub-watersheds, while the north subwatershed 1 had a larger Tc, coherently with its dimensions.

An example of the calculation for areas is shown in Fig. 8. The relative errors exhibited by the model are shown in Table 7. Since these errors are all below 5 for E_R below 11% for E_Δ, it can be concluded that the hydrological modeling carried out with HEC-HMS gives a good representation of the variations in the level of the reservoir in the reference period. Fig. 9 visually shows the results of the modelled and observed SmAR area dynamics. In this sense, it should be noticed how the Google Earth software suite allows a precise calculation of the area just by manual operation. While this approach is not suitable for a large number of images, since it is difficult to be automatized, it can represent a time-effective approach for SmAR applications at a local scale.

An analysis of the results shows that the level of the reservoir fluctuates by about 80–90 cm between the maximum reservoir

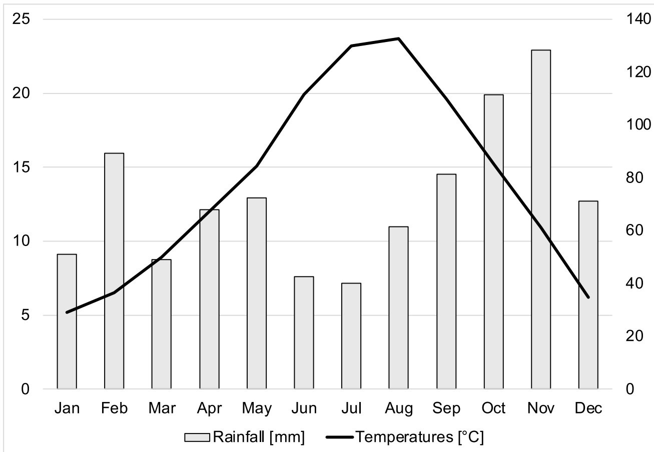

Fig. 7. Monthly averages of rainfall and temperature at Monteroni d'Arbia Biena station during the 10 years of simulation (2012–2021).

altitude of 198.5 m a.s.l. reached in the winter months, in which the reservoir recharges, and a minimum around 197.7–197.8 m a.s.l. in the driest periods. It should be observed that the SmAR is currently not used for irrigation, therefore it always keeps a high level.

The reservoir volume, on the other hand, fluctuates between 86,000–87,000 m^3 until it reaches a minimum, in periods of low rainfall, of around 60,000 m^3. Finally, the area of the reservoir fluctuates between a maximum of around 40,000 m^2 and minimum of around 29,000–30,000 m^2. These values reflect the typical seasonal variability of the rains, which are higher from the end of October to mid-April and scarce in the summer, as well as the evaporation values from the liquid mirror which are instead higher in the summer months due to the high temperatures.

The results of the erosion modelled within the watershed are shown in Table 8. The average value of the watershed, equal to 2.66 t/ha/y, is around half of the expected value from the erosion maps described in section 2.4 (between 5 and 10 t/ha/y).

3.3. *Erosion in the different scenarios*

The comparison of scenario results shows that the replacement of arable crops currently practiced within the catchment area upstream of the reservoir would lead to an increase in the volume of sediment accumulated in the reservoir itself. LUC1 almost doubled the sediment amounts if compared to the current cultivation configuration (BASE scenario) LUC2 shows an increase in sediment of more than double (Fig. 10). Fig. 9 also highlights the different sediment inflow in the Forlì SmAR which exhibit some variations through the years.

The loss of useful capacity of the reservoir caused by silting was also calculated in volumetric terms in the three scenarios analyzed (Table 9). To do this, reference was made to the density values of the various textural classes reported in par. 2.3.3 and the estimate of

Table 6
Time of concentration (Tc) for each watershed with each method used. The minimum (Italic) and maximum (Bold) were removed for the average calculation.

Tc [min]	Giandotti	Kirpich	Pasini	Pezzoli	Tournon	Puglisi	Average T_C [min]	Average Lag Time [min]
1	71.66	*14.54*	49.36	25.09	**201.43**	101.05	61.79	37.07
2	33.88	*4.72*	14.66	6.16	**59.92**	52.94	26.91	16.15
3	29.48	*4.30*	11.93	4.88	45.90	**50.08**	23.05	13.83
4	31.88	*4.12*	15.64	7.95	**69.22**	50.56	26.51	15.90
4	41.69	2.69	9.70	*2.67*	**48.68**	38.44	23.13	13.88

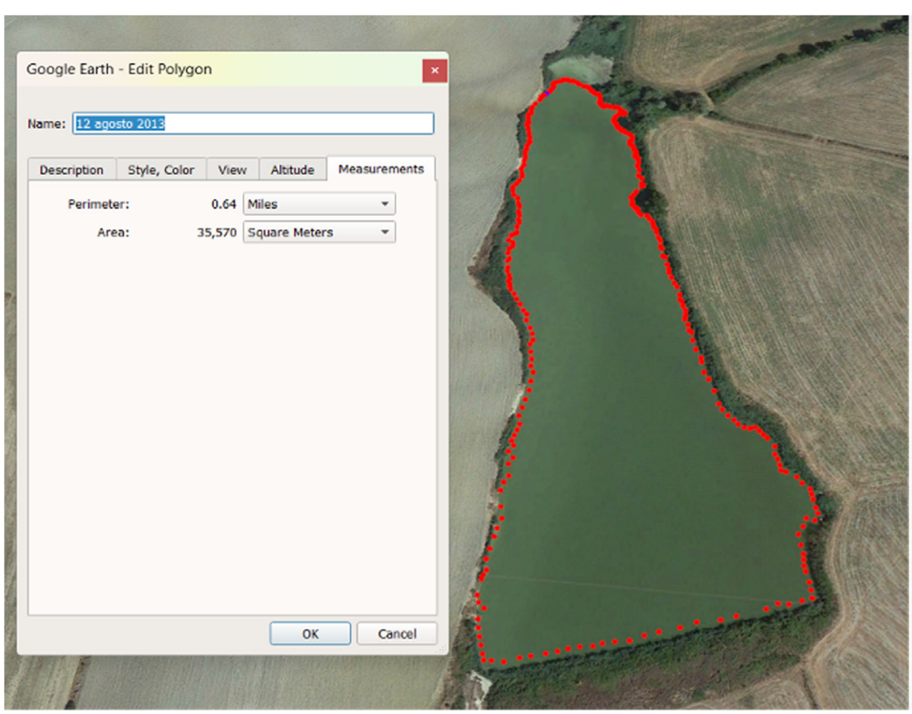

Fig. 8. Example of a Google Earth area calculation.

Table 7
Relative errors of the modelling of the SmAR area.

Date of the image	E_R	E_Δ
12.08.2013	3.57%	9.55%
14.08.2016	4.08%	10.98%
09.06.2017	2.11%	5.64%
01.07.2019	0.41%	1.13%
27.05.2021	1.52%	4.21%
Average	2.34%	6.30%

the percentage of sediments accumulated in the reservoir for each textural class.

It is interesting to notice that even the partial land use change imposed by LUC1 had a severe impact on sedimentation in the SmAR, which can lose up to 5% of its volume in 10 years under the LUC2 scenario. These simulations can measure the effects of the land use changes that happened in Val d'Orcia area in the last years, given that LUC2 results are representative of a widespread conversion of arable land to vineyards. Fig. 11 highlights these changes, showing how the erosion rates are changed spatially following the conversion of the land use to vineyards. It can be seen how sub-watershed 1 (north-west), shows only a moderated increase of erosion since it is the only one that is partially affected by the conversion of the arable land to vineyards in scenario LULC 1, while the rest of the watersheds have the same increment in erosion from scenario 1 to scenario 2.

4. Discussion

The proposed methodology allowed the assessment of the sedimentation in a SmAR in the Mediterranean Ombrone catchment with a limited amount of data. To validate the model, remote sensing data was used by manually calculating the reservoir area for each available image. The use of reservoirs and SmAR for calibrating and validating hydrological models was tested by monitoring water surfaces with ground-based surveys (Molénat et al., 2021) and with remote sensing (Amitrano et al., 2014, 2015; Gal et al., 2016; Liebe et al., 2009), but mainly in arid areas of Africa and the South of Mediterranean. Specifically, Envisat advanced synthetic aperture (ASAR) images were used in Ghana (Liebe et al., 2009), while COSMO-SkyMed interferometric SAR (InSAR) images were used in Burkina Faso (Amitrano et al., 2014, 2015). Remote sensing methodologies developed with freely available datasets, and specifically the one implemented with visible and near-visible wavelengths, are rather inaccurate for estimating small reservoir area (Ogilvie et al., 2018a, Ogilvie et al., 2019; Perin et al., 2022). Our approach was based on a rather simpler tool, namely standard Google Earth imagery, which was used in other research related to the water-agriculture nexus (Agapiou et al., 2016; Reece et al., 2023), that guaranteed resolution up to 15 cm with commercial imagery. Despite the limited number of images available for the Forlì SmAR, such an approach allowed a validation of the HEC-HMS model. The results of the hydrologic validation for the case study

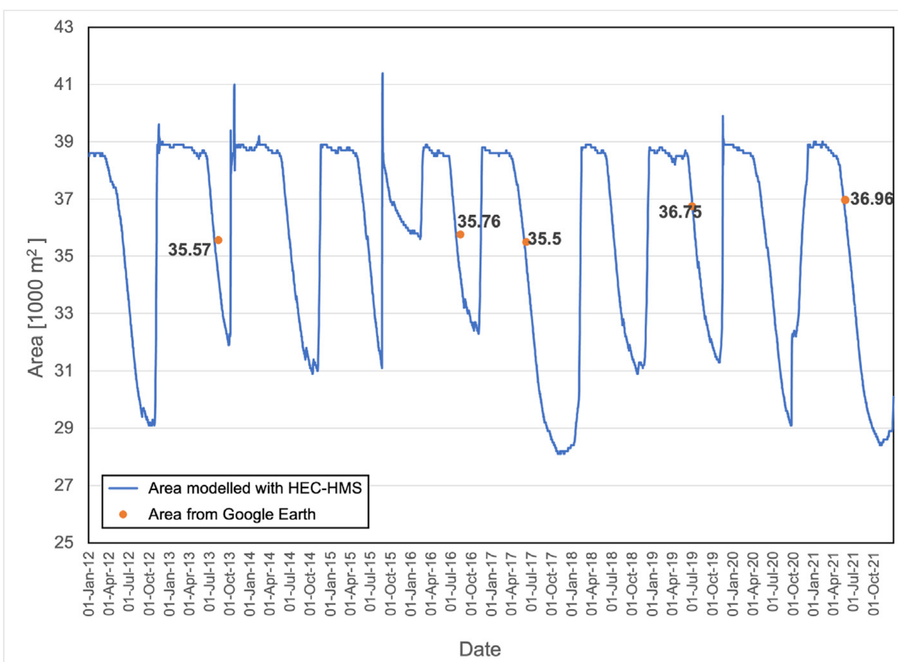

Fig. 9. Modelled and observed SmAR area.

Table 8
Sediment produced and erosion for each (sub-)watershed in the BASE scenario. The sum of the sediment produced in the sub-watersheds is lower than the full watershed one, that accounts also for the reach dynamics.

(Sub-)Watershed	Area [ha]	Sediment produced in the years of simulation [ton]	Sediment produced per year [ton/y]	Erosion rate [ton/ha/y]
1	57.83	1853.4	185.3	3.20
2	14.26	258.3	25.8	1.81
3	13.39	220.8	22.1	1.65
4	18.65	455.2	45.5	2.44
5	5.31	48.9	4.9	0.92
SmAR (full watershed)	109.44	2914.6	291.5	2.66

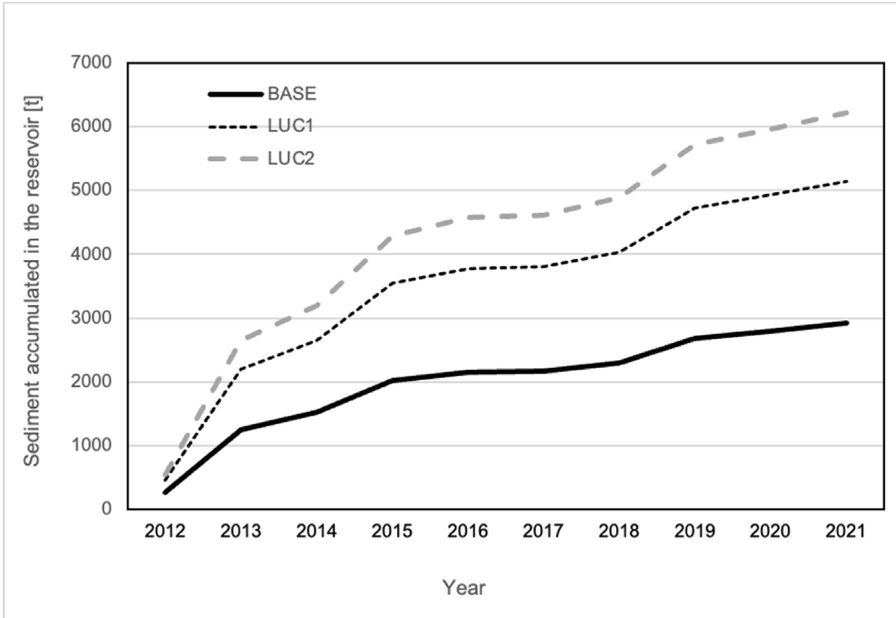

Fig. 10. Evolution of the sediment in the Forlì SmAR between 2012 and 2021.

Table 9
Results of the volume silted in the SmAR for each scenario.

Scenario	Land use change from arable land to vineyards (% of the watershed area)	Land use change from arable land to vineyards (% of the arable land area in the watershed)	Silted volume in 10 years [m^3]	Annual average silted volume [m^3]	Reference to the BASE scenario
BASE	–	–	2191.12	219.11	
LUC1	50.2%	56.7%	3865.05	386.50	176.40%
LUC2	88.5%	100%	4680.70	468.07	213.62%

are, indeed, particularly good. Therefore, for allowing a more complete evaluation of the method, similar studies should be carried out for other small reservoirs, possibly in different contexts. Moreover, a further development of the present approach can introduce some sensitivity analysis to understand which modelling parameters influence the results more, also considering the variation of some processes (e.g. testing the Curve Number for basin loss, which might adapt to different soil maps). This step, which is beyond the scope of the present paper, is an important step for hydrological modelling at any scale (Song et al., 2015). In this sense, it should be highlighted how the flexibility of the HEC-HMS modelling suite can allow testing multiple methods for each hydrological process, while other tools are less versatile (Faouzi et al., 2022).

The erosion values calculated with the model were almost in line with the estimations of the Tuscany Region (Regione Toscana, 2017), but underestimated due to several factors. In particular, the underestimation obtained by the model, is possibly due to three factors.

i) a possible low model accuracy: which could be mainly due to the parametrization of the MUSLE equation.
ii) The low erosion map resolution: this latter one has only two classes with no precise erosion values of erosion, only 5 or 10 t/ha/y and intermediate, or lower values, are not visible.
iii) The different timespan of calculation for the model and the erosion maps. The model covers data from 2012 to 2021, while the erosion maps of the Tuscany region were built with data until 2017.
iv) A different modelling approach for erosion: the Tuscany region maps were elaborated based on USLE/RUSLE equation, while the present study, based on the HEC-HMS model, is based on the MUSLE approach.

Given these uncertainties on the map for the validation, which is not based on measured data, we assumed that the model could be considered significant at least for the analysis of the relative differences between the scenarios. However, despite this issue, the value obtained with HEC-HMS and the value from the erosion maps are still very close in terms of magnitude. It should also be noted that the Elevation-Storage and the Elevation-Area curves were calculated on the original morphological profile of the bottom of the reservoir, built in 1973, neglecting the effect of the sedimentation between this date and the start of the modelling period. Even if the impact of such change is expected not to influence the model in a dramatic way, having an updated bathymetry of the reservoir, for instance with drones (Giambastiani et al., 2022), can improve the erosion validation performances. Finally, the present study adopted that the K factor used for the MUSLE equation was assumed equal to the ones used for USLE and RUSLE methods. This practice is not physically correct, but it can be assumed acceptable (Kinnell, 2004). A possible development of the present approach can also go in the direction of testing different (M)USLE parameters.

The erosion values resulted similar to other studies in the area (Giambastiani et al., 2022), while lower than the ones obtained in more arid areas of the Mediterranean basin (Ben Slimane et al., 2016). The overall land use changes imposed with our model are representative of the general trend observed in the Siena province

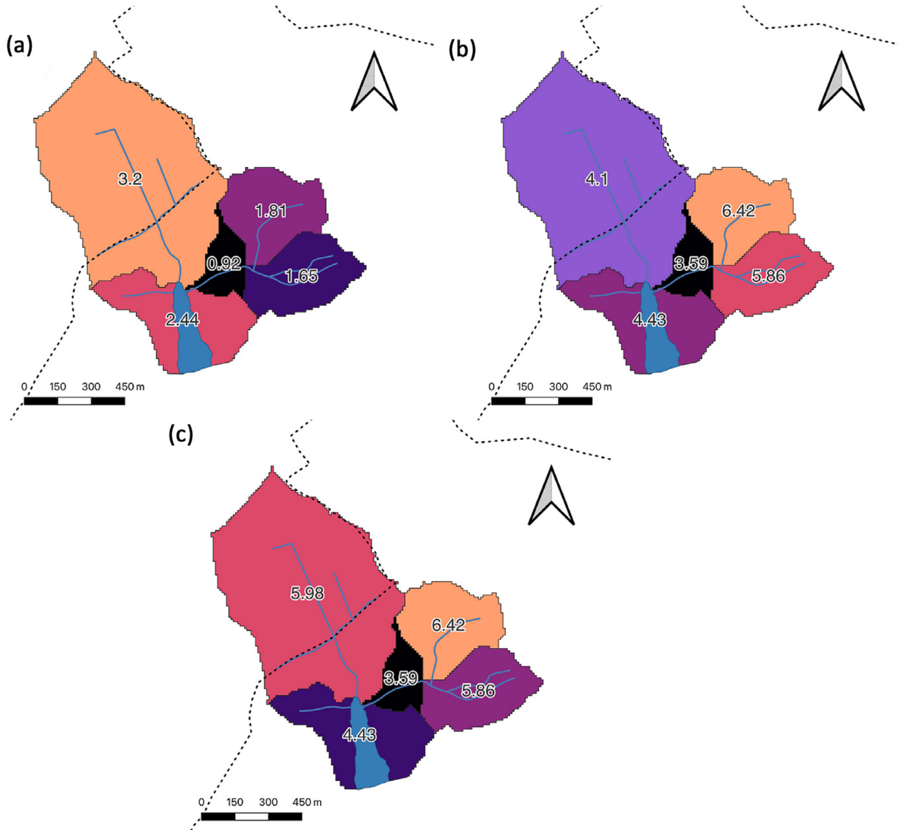

Fig. 11. Different erosion values in the sub-watersheds in [ton/ha/y]. (a) BASE, (b) LULC1, (c) LULC2. The black dashed line represents the border of Suvignano estate. In the LULC1 scenario, only the arable land in the estate was changed from arable crops to vineyard, while in LULC2 all the arable land was changed to vineyard. Darker colors quantitatively indicate relatively low erosion, while lighter (yellow) colors indicate high erosion.

(Costantini & Barbetti, 2008), and in other Italian regions (Basso, 2019; Zdruli et al., 2014). The results for future scenarios of expected erosion increase, due to the implementation of new vineyards in the area of study, were coherent with other research carried out in the Mediterranean area (Debolini et al., 2015; Roy et al., 2018). In particular, it is evident how the implementation of vineyards would almost double the erosion and, therefore, the velocity of siltation in the SmAR. This is mostly highlighted in LUC2 scenario, which is the most extreme. However, also in LUC1, the most likely in terms of farm management (Table 9), the impact of the conversion to vineyards would increase the siltation up to 176% of the original value. The direct impact of such changes is the halving of the useful life of the SmAR, leading to a considerable financial impact on the farm business, which would need to invest more often in dredging or building new reservoirs.

Our approach can be an effective decision-support system for reservoir management, allowing the calculation of the time of siltation and the need to desilting the storage volume, but also the consequences of different cropping patterns and agronomic measures for combating erosion (with the P factor of the USLE-MUSLE approach). The approach, indeed, specifically targets SmAR and small-sized reservoirs in general, since for larger dams, different remote sensing products can be used and more complex modelling and monitoring approaches can be justified. Generally speaking, however, our approach could be efficient also in such cases.

5. Conclusions

The SmAR modeling carried out in this study has allowed us to estimate the effects of the hydrological and erosive processes that occur at the watershed scale on the progressive silting of the downstream reservoir, within the Suvignano estate, in the of the Crete Senesi area in Tuscany. The model represents the area of the SmAR with an average E_R and average E_Δ, of 2.34% and 6.30% respectively, and with an erosion rate of 2.66 t/ha/y, which was slightly underestimated with reference to other erosion estimations made for the area. Our results show that the conversion of arable crops to vineyards in the study area would lead to an increase up to 213.62% of erosion and sedimentation in the SmAR, with an average settled volume up to 468.07 m^3/y in the SmAR under study, which has a maximum capacity of around 87,000 m^3. The approach utilized in the present study takes advantage of a simple modeling framework, with low computational burden and implementing a validation from standard Google Earth imagery. Further developments of the present approach can consider different methods for evaluating the hydrological processes at the watershed scale, as allowed by the HEC-HMS modelling suite, a structured sensitivity analysis, and the testing of similar methodologies in other contexts where SmAR for water harvesting are present.

CRediT authorship contribution statement

Elia Degli Innocenti: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Data curation, Conceptualization. **Giulio Castelli:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Simone Pozzolini:** Writing – review & editing, Validation, Supervision, Software, Methodology, Formal analysis, Conceptualization. **Federico Preti:** Writing – review & editing, Validation, Formal analysis. **Elena Bresci:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Formal analysis, Conceptualization. **Enrica Caporali:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

We are grateful to Ente Terre Regionali Toscane for sharing the data of Suvignano Estate and allowing us to develop the present research, and to Prof. Vincenzo Bagarello for the suggestions in developing the writing of this manuscript. This research was carried out within the **AG-WaMED project**, funded by the Partnership for Research and Innovation in the Mediterranean Area Programme (PRIMA), an Art.185 initiative supported and funded under Horizon 2020, the European Union's Framework Programme for Research and Innovation, Grant Agreement Number No. [Italy: 391 del 20/10/2022, Egypt: 45878, Tunisia: 0005874-004-18-2022-3, Greece: ΓΓΡ21-0474657, Spain: PCI2022-132929, Algeria: N° 04/PRIMA_section 2/2021]. The content of this abstract reflects the views only of the author, and the Commission cannot be held responsible for any use that may be made of the information contained therein. We are grateful to the two anonymous reviewers that with their comments greatly improved the value of this work.

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