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EVALUATION OF THE APPLICABILITY OF SEDIMENT TRANSPORT MODELS TO DAM FILLING PREDICTION IN DIFFERENT ITALIAN GEOLOGICAL CONTEXTS

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EXTENDED ABSTRACT

Gli impianti idroelettrici rappresentano un sistema infrastrutturale di importanza storica per la produzione di energia, che sta diventando oggi ancora più rilevante per la crisi energetica e per i cambiamenti climatici legati al consumo di fonti fossili. Oltre a questo, gli invasi artificiali assumono grande importanza per l'accumulo di riserve idriche e per la regolazione delle portate fluviali, contribuendo alla mitigazione del rischio alluvionale per le zone abitate a valle di essi. Risulta quindi evidente che qualsiasi alterazione del "sistema diga" può comportare ripercussioni rilevanti tali da compromettere sia la resa in termini produttivi dell'impianto, sia la sua stessa sicurezza. Un fattore imprescindibile per la gestione delle dighe è l'interrimento, ovvero il progressivo accumulo di sedimenti all'interno del bacino, che risulta in una riduzione della sua capacità totale, limitandone di fatto la funzionalità, soprattutto in termini di produzione di energia idroelettrica.

Lo scopo del lavoro qui presentato è di valutare la risposta di un modello di erosione e trasporto solido applicato al problema dell'interrimento delle dighe in contesti diversi dal punto di vista geologico, che possono influenzare l'erosione e la circolazione delle acque. Il modello fisicamente basato considerato si chiama SMART-SED (*Sustainable MAnagement of sediment transpoRT in responSE to climate change conDitions*), sviluppato in anni recenti dal Politecnico di Milano. SMART-SED è capace di simulare i processi idrologici, di erosione e di trasporto solido a scala di bacino, partendo da dati di input geografici e meteorologici, spesso reperibili gratuitamente dai geoportali regionali/nazionali o da database mondiali. Gli output finali, di tipo raster, sono relativi ai diversi processi simulati, come velocità dell'acqua, altezza dell'acqua e del sedimento, infiltrazione, erosione, evapotraspirazione e valori di flusso liquido e solido per ogni *time-step* di calcolo in punti di controllo definiti dall'utente. Dal punto di vista concettuale, l'innovazione di questo modello è costituita dalla non-definizione a priori e statica delle celle di deflusso, presente nella maggior parte dei modelli simili diffusi in letteratura, identificando in maniera automatica e dinamica la rete di drenaggio. Inoltre, partendo da *database* mondiali di terreni, SMART-SED è in grado di derivare la composizione granulometrica a una risoluzione desiderata, attraverso un *downscaling* di tipo statistico.

I casi studio considerati presentano un'area compresa tra 5 e 48 km^2 e sono stati selezionati sul territorio italiano in contesti geologici differenti, che presentassero dati storici relativi all'interrimento, quali batimetrie e volumi di sedimenti rimossi negli anni. Nel territorio alpino sono stati considerati i bacini idrografici del torrente Tartano (SO) e del torrente Caldone (LC), entrambi situati nelle Alpi Orobie, nel settore geologicamente afferente al Dominio Sudalpino. Questi due bacini presentano un substrato roccioso differente, in quanto in Val Tartano affiorano prevalentemente litotipi di origine metamorfica, quali gli Gneiss di Morbegno e gli Scisti di Edolo, mentre il territorio lecchese è costituito prevalentemente da rocce carbonatiche, come il Calcare di Esino e la Dolomia Principale. Sono state poi effettuate simulazioni nella zona del Cilento, in Appennino meridionale, presso gli sbarramenti del Carmine e del Nocellito, lungo il fiume Alento (SA), dove invece il *bedrock* è costituito da torbiditi, quali le Arenarie di Cannicchio e la Formazione di San Mauro. Tutti i siti analizzati riguardano bacini artificiali interessati dalla presenza di una diga, ad eccezione del T. Caldone, che è stato comunque considerato in qualità di "caso studio pilota" per lo sviluppo del modello e per l'esistenza di un record di misure batimetriche di una vasca di sedimentazione localizzata lungo il torrente stesso.

A seguito di una dettagliata analisi di sensitività dei parametri di *input* e di una loro calibrazione, effettuata tenendo conto dell'uso del suolo e del contesto geologico locale, SMART-SED è stato applicato ai quattro casi su intervalli di tempo di un anno, effettuando simulazioni su anni differenti per verificare la produzione di sedimenti sotto diversi regimi di pioggia. I risultati ottenuti sono stati quindi validati a partire dai dati di interrimento disponibili. È stato osservato che il modello SMART-SED, inizialmente concepito per la valutazione della pericolosità alluvionale e del trasporto di sedimenti in aree montane, è adatto anche alla stima dell'interrimento delle dighe. È stata infatti ottenuta un'approssimazione precisa dell'ordine di grandezza del volume cumulativo di sedimenti prodotti all'interno dei bacini idrografici in esame e trasportati negli invasi. Nell'ambito di un problema complesso che riguarda la produzione di energia "a basse emissioni" in un mondo che cambia, SMART-SED potrebbe quindi diventare uno strumento utile anche per la gestione delle dighe.

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ABSTRACT

Artificial reservoirs are crucial infrastructures, since they allow for the management of the water resource they store and for their role in the hydroelectric production. Water is modulated and stored inside artificial basins built upstream of the dams for hydroelectric, industrial, drinking, irrigation, and flood mitigation purposes. However, as time passes, the deposition of solid material, transported by rivers flowing into the reservoir, reduces its storage capacity. In this work, a novel physically-based erosion and sediment transport model developed by Politecnico di Milano (SMART-SED) is used to estimate dam filling in different Italian geological contexts. The present model differs from others in the literature since it can automatically detect drainage zones and it works at a basin scale, requiring few input parameters that can be easily downloaded from global or government databases. Moreover, it is based on robust and unconditionally stable numerical techniques, and it guarantees the mass conservation. The proposed model was applied to four watersheds, two in the Southern Alps and two in the Southern Apennines, with catchment areas ranging from 5 to 48 km^2.

After the model calibration on the local geological context, a validation of the obtained results was accomplished considering different time intervals and the available sediment filling data. It was observed that the SMART-SED model, initially developed for the evaluation of fluvial hazard and of sediment transport in mountainous areas, was also suitable for the estimation of dam filling. Results indeed show a precise approximation of the order of magnitude of the cumulative sediment volume produced inside the catchments and transported to the water basins. In the framework of a complex problem affecting the production of “clean” energy in a changing world, SMART-SED could become a useful tool also for dam management.

Keyword: *dam filling, sediment transport, geohazard, SMART-SED, climate change*

INTRODUCTION

In a changing world under climate warming, two problems affect the contemporary society: clean energy supply and natural hazard management. Hydropower plants represent historically important infrastructures for renewable energy production in Italy (Bórawski *et alii*, 2019). In addition, artificial reservoirs assume great importance for water storage, often needed for agricultural purposes, and they contribute to flood risk mitigation, regulating water discharges. Therefore, their management require a lot of effort on the national territory, to guarantee their productivity and to prevent dam hazard. Any alteration to the dam system can indeed lead to major impacts that can compromise both the productive performance of the plant and its own safety (Palmieri *et alii*, 2001). In particular, an unavoidable factor in dam management is the progressive accumulation of sediment within the reservoir, which results in a reduction of its total capacity that limits its functionality, especially in terms of hydropower production (Sloff, 1991; Brambilla *et alii*, 2011). The assessment of erosion rates at catchment scale and the amount of the relative sediments deposited inside the reservoir is then desirable to efficiently plan their removal and to preserve the power plant itself. In this sense, dam filling modelling could help for the reduction of the sediment removal costs.

For this purpose, the authors of the present work tested the application of a new physically-based sediment erosion and transport model to four different Italian catchments. The name of this model is SMART-SED (Sustainable MAnagement of sediment transpoRT in responSE to climate change conDitions), and it was developed by the Politecnico di Milano as an instrument for urban planning and for hydrological risk mitigation in climate change conditions in recent years (Gatti *et alii*, 2020). In particular, SMART-SED overcomes some of the common issues that similar models already available in literature present, as the a-priori and static definition of the drainage network, which is automatic in SMART-SED. Moreover, the current model requires only a few of simple input data files, contrary to the others that usually need many characteristics of the channels to be assumed (Bonaventura *et alii*, 2021).

The problem of dam filling was considered in different geological settings, which can affect sediment production and water circulation. The model was applied to four different Italian catchments, with an area ranging from 5 to 48 km2, which presented historical data on dam filling, derived, for example, after bathymetric surveys or by direct sediment removals over the years. Two catchments were selected in the Alpine area and two in the southern Apennines, in Italy. One of the alpine catchments present a bedrock of metamorphic rocks, whereas the others are composed of sedimentary rocks, carbonates or turbidites. All the tested sites concerned artificial reservoirs linked to a dam, except for one, which was taken into account as it was the ‘pilot case study’ for the development of the model itself, and for which there was a record of bathymetric measurements collected within a retention basin along the stream. After a preliminary sensitivity analysis of the input parameters and after their calibration considering the local land use and the geological framework, the SMART-SED model was applied on a time interval of one year. Different years were tested to verify the trend of sediment volumes under different rainfall regimes. The validation of the obtained results with the available dam filling data confirms the initial hypothesis of the possibility of simulating this process using a model initially developed for the assessment of flood hazard and sediment transport in mountainous areas.

CASE STUDIES

Four case studies from different geological frameworks and different catchment area dimensions were selected for the application of the model (Fig. 1). The first two catchments are in northern Italy, in the Southern Alps Domain. The most elevated one is the Tartano catchment, ranging from 893 m a.s.l. to 2508 m a.s.l., with an area of 48 km^2. This is characterized by the typical geomorphology of the alpine environment (Brambilla *et alii*, 2011) and the outcropping rocks belong to the crystalline-metamorphic basement of the Southern Alps, here mainly paragneiss (Morbegno gneiss Unit) and micaschists (Edolo schists Unit), as fully described in the national geological map at scale 1:50000 (Boriani *et alii*, 2012). The building of the Colombera dam for hydroelectric purposes near Campo Tartano hamlet (955 m a.s.l.) in 1926 originated an artificial lake with a volume of 1.3 Mm^3. Normally, dam management plan provides for periodical removals by flushing, but, after some extreme rainfall events, the removal was performed by mechanical dredging. For example, a sediment volume of 61000 m^3 was removed in 2010, with a cost of 1 €/m^3 (ITCOLD - Comitato Nazionale Italiano Delle Grandi Dighe, 2016). This sediment removal campaign, in addition to bathymetrical surveys of the lake, provided the record of data required for the present study. These data cover a time interval between 1991 and 2006, with a mean annual sediment yield estimated as 64000 m^3 by ITCOLD, (2016). The second alpine case study is the Caldone catchment, which extends between 200 m a.s.l. and 2170 m a.s.l. over an area of 28 km^2. Contrary to Tartano Valley, Caldone river flows over carbonate rocks, as limestones (Esino Formation) and dolostone (Dolomia Principale), where karst phenomena are common (Gaetani *et alii*, 2012). This river is not dammed, but it was considered as a "pilot case study" for the development of the SMART-SED model itself and because of previous studies about sediment transport (Brambilla *et alii*, 2020; Ivanov *et alii*, 2020). Sediment data collected over the years through successive bathymetry campaigns in a sediment retention basin (Barazzetti *et alii*, 2020) were considered for the aims of the present study. Based on those measures, the annual sediment yield in 2021 was estimated to be 800 m^3.

The last two case studies regard two different dams, Nocellito and Carmine, built on two tributaries of the same stream, the Alento river in Cilento region, in the southern Apennines. In these two catchments, the elevation ranges from 576 m a.s.l. to 1513 m a.s.l. The whole dam system was built mainly for irrigation, but it is actually used also as a drinking water storage and for hydropower. Carmine basin has an area of 2 km^2 and Nocellito has an area of 5 km^2. The bedrock is composed of turbidite rocks (Cannicchio Sandstone and San Mauro Formation), mainly characterized by low permeability that implies a superficial drainage in the area (Celico *et alii*, 1993; Martelli *et alii*, 2005). In 2008, the Nocellito lake was emptied for the first time since its construction in 1982 and

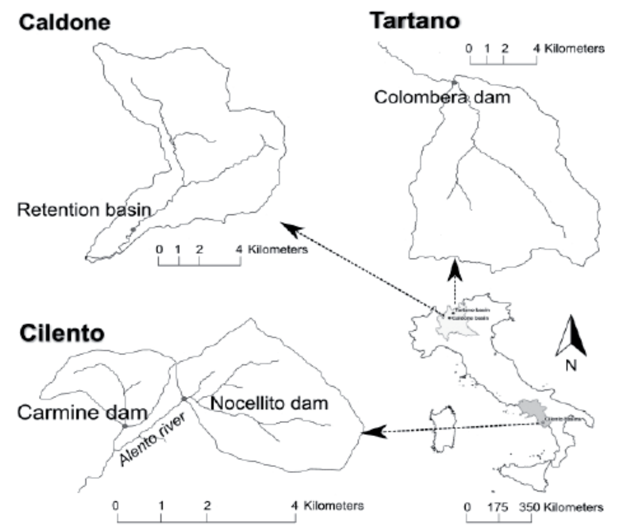

Fig. 1 - Locations of the four study cases: Tartano and Caldone basins in Southern Alps, Carmine and Nocellito basins in Southern Apennines

a sediment volume of 14467 m^3 (silt and sand) was removed. On the other hand, some bathymetrical surveys gave the estimation of a volume of sediments of 149405 m^3 inside the Carmine basin in 2008.

SMART-SED SET UP

As described in detail by Bonaventura *et alii* (2021), the SMART-SED model is a physically-based sediment erosion and transport model that computes hydrological processes at catchment scale. In particular, simulations are conceptually divided into two layers between shallow and ground processes, which are linked by vertical and horizontal fluxes.

At the atmospheric and surface level, meteorological forces (rain and snow), water flux and sediment yield are computed, based on temperature and slope conditions. At the same time, water infiltration, evapotranspiration and erosion are considered at the ground level.

The innovations of the present model are the automatic identification of the drainage network and the statistical downscaling of soil granulometric composition maps.

Moreover, the required input data (topographical and meteorological) are few and frequently available on national database (Brambilla *et alii*, 2020; Bonaventura *et alii*, 2021). After a sensitivity analysis of the input parameters and after a calibration of the coefficients of the empirical equations implemented in the model, as the EPM (Erosion Potential Method - Gavrilovic *et alii*, 1988; Milanesi *et alii*, 2015), the SMART-SED model was applied to the four case studies described. The calibration phase considered the different geological frameworks and the local land uses, while the sensitivity analysis regarded the influence of DEM sink filling, the values of EPM coefficients of the same class, the roughness scale factor and the localization of the control points (in the centre of the reservoir or at the outlet of streams in the lake) for the output generations. At the end of the sensitivity analysis, it was observed that the roughness parameter had a low influence on the final results, the fill sink operation influenced badly the results and the most relevant control points were the ones in nearby of the outlet of streams in the reservoirs. If more than one stream flowed in the reservoir, the total sediment volume was evaluated as the sum of the sediment volume calculated at each outlet, as in the Carmine case. Results were then compared to the available dam filling data (Table 1). All the simulations covered a time duration of a solar year due to computational time required by the model, therefore the choice of the simulated year followed the availability of the meteorological and sediment data. For the Tartano case study, years 2000 and 2002 were chosen because they were particularly rainy. When the sediment data covered a time interval longer than a year, as in the Cilento case studies, it was decided to consider as a reference an annual mean sediment value. Also, different years were tested in terms of meteorological data, to make considerations on different rainfall regimes. Comparisons among the results and the field data were carried out assuming that all the simulated sediment flux deposits in the artificial basin. The final sediment volume was then estimated integrating the simulated sediment flux next to the confluence of streams in the artificial lake.

RESULTS AND DISCUSSION

After the sensitivity analysis of the input parameters, it was verified that DEM sink filling was unnecessary at the present resolution (20 × 20 m) and that the most significative control points were at the outlet of streams into the reservoirs, and not the ones nearby the dams. Therefore, the SMART-SED results obtained after the calibration of the EPM coefficients are shown in Figure 2 and in Table 1. The simulated sediment volumes obtained are presented together with the reference data for each case study.

It is possible to observe that these values are accurate for all the case studies, in terms of order of magnitude, according to the reference data. Among the four catchments analysed, the less precise results concern the Tartano simulations (~25% relative error), which is the largest and the only one characterised by a metamorphic bedrock. Furthermore, the simulation of Tartano 2022 is the only one with an overestimation of the sediment volume. The fluctuations between Tartano 2000 and Tartano 2002 could be explained considering that the reference value is an average computed of the span of 15 years, and therefore a variation referred to a particularly rainy year as 2022 is tolerable. Moreover, the steep sediment curve in Tartano 2002 is probably due to the type of the precipitation involved in the area. This catchment is indeed, as said, at an elevation of 955 m a.s.l, where snow is abundant during winter. Therefore, precipitations fallen at the beginning of the Tartano 2002 simulation did not contribute to the surface runoff and erosion. On the other hand, the snow melting caused by the raise of temperatures in May did contribute to the drainage, and then a higher production of sediments and a higher sediment transport is observed afterwards.

CONCLUSIONS

In summary, an analysis of dam filling modelling was driven with the support of a physically-based sediment erosion and transport model, SMART-SED. The aim was to understand the capabilities of a new model, simple in terms of the amount of input data required, applied to a different problem from its original one and to different geological frameworks. Based on the availability of sediment volumes data, SMART-SED results were successfully validated in all the four basins tested. The estimation of sediment volumes was quite precise, even if some fluctuations in the largest catchment are present. Anyway, the authors consider these outcomes to be relevant for future developments in dam management. At present, sedimentation within water reservoirs is difficult to forecast and it causes high management costs, both because it compromises the functionality of the structure and because surveys are expensive. An efficient and easy to use tool for the modelling of their filling could reduce the expenses for the production of hydroelectricity, in a historical period of progressive abandonment of oil and gas energy supply.

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Case Study	Year	Reference sediment volume [m^3]	Simulated sediment volume [m^3]	Relative error [%]
Tartano	2000	64000	47867	25
Tartano	2002	64000	81941	-28
Caldone	2021	800	713	11
Nocellito	2007	560 (mean value)	469	16
Carmine	2007	5750 (mean value)	4968	14

Tab. 1 - Summary of simulated years and sediment volumes considered as reference data. Annual mean values, covering the span of 26 years, were reported for the Cilento case studies

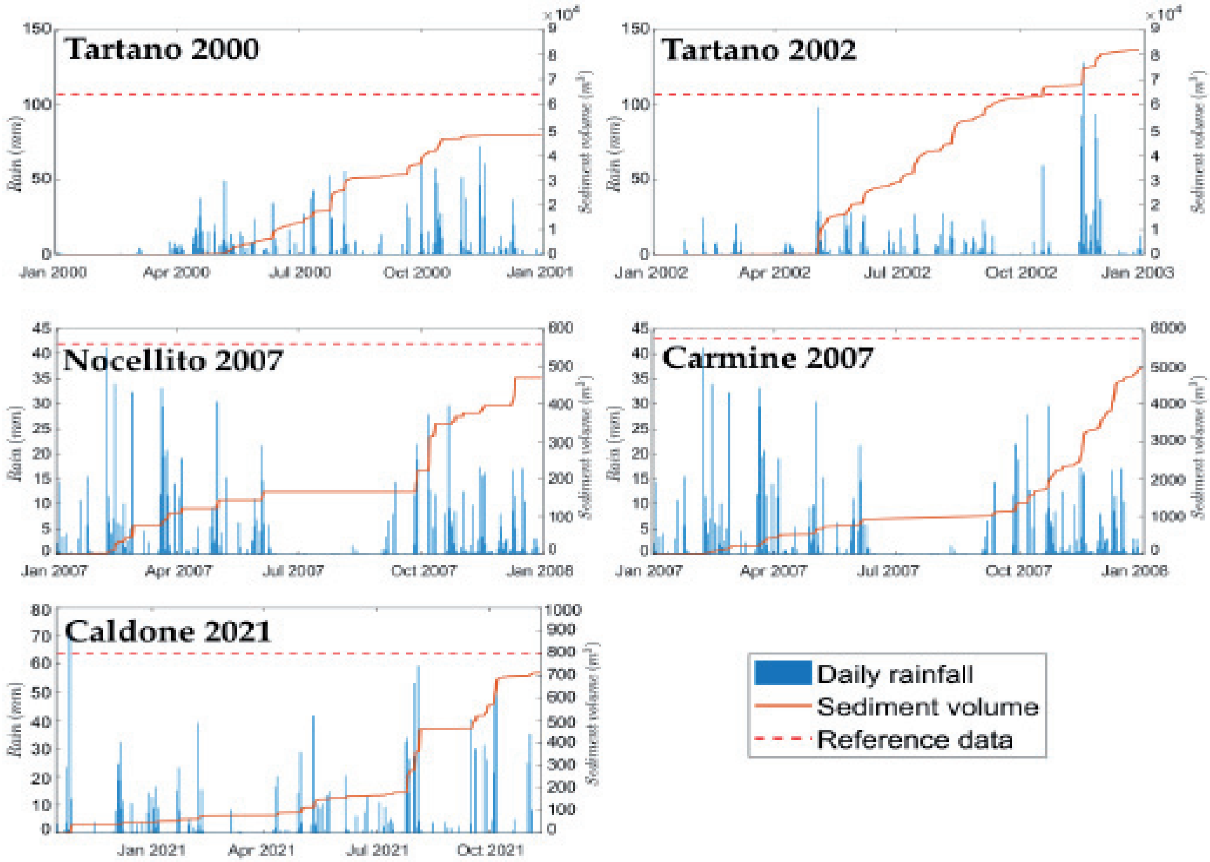

Fig. 2 - SMART-SED results. Sediment volumes simulated are reported together with daily rainfall and with the reference data, represented by a dashed line, for each case study

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