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Disaster waste management after flood events

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Abstract

Large amounts of waste debris occur in urbanised areas when heavy rain on local geology generates flooding and landslides. Improved understanding of disaster waste management helps to support future strategies. This study aims to find management solutions that are environmentally and economically sustainable, hypothesizing three different options. There are many variables which influence the environmental impact and the operational cost. The distances between the areas of interest and the management site, the extent of a first manual sorting carried out by citizens, the economic load of each involved step. Overall, both the environmental and the economic analysis confirmed the usefulness of the non-advanced option, which includes a temporary debris storage site for a preliminary shredding. On the other hand, the impact due to a possible biological treatment is not balanced by the advantage of the further volume decrease. The article shows a simple analysis schema, easily adaptable to different geographical context, is useful as supporting tool for the decision makers in flood emergency scenarios.

KEYWORDS

disaster waste management, economic analysis, flood, life cycle assessment, natural disaster

1 | INTRODUCTION

The Centre for the Research on the Epidemiology of Disasters (CRED) is a non-profit institution that collects and studies data and information about humanitarian emergencies, particularly in public health and epidemiology. The relevant information is collected in an international emergency events database, (EM-DAT), which reports a total of 7,056 disasters in the period from 1996 to 2015. A specific focus on the floods attributes 150,061 victims to this kind of event, that represent about the 11% of the whole humanitarian emergencies (Centre for Research on the Epidemiology of Disasters, 2016). Indeed, as showed within the IPCC report, the growth of the green gas emissions and the global temperature are causing the increase of extreme weather phenomena, for example, hurricane, typhoons, storm, thunderstorm and heavy rain, with consequent floods, sometimes associated with landslides (IPCC, 2014). This recent and sudden climate change can be translated into high socio-economic costs. The Italian territory is an example of area subject to

ABBREVIATIONS: ASA, azienda servizi ambientali; CRED, Centre for Research on the Epidemiology of Disasters; EM-DAT, emergency events database; EWC, European Waste Catalogue; FEMA, Federal Emergency Management Agency; LCA, life cycle assessment; LCI, life cycle inventory; MBT, mechanical biological treatment; MSW, municipal solid waste; TDSRS, temporary debris storage and redaction site; USACE, United States Army Corps of Engineers; WEEE, waste electrical and electronic equipment..

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these extreme events which contribute to the increase of the people and the environment health vulnerability (Guzzetti, 2000; Messeri et al., 2015). In this regard, a wide study by Trigila, Iadanza, Bussettini, Lastoria, and Barbano (2015), describes the hydrogeological fragility of the area, identifying more than 500,000 landslides (22,176 km^2), equal to 7.3% of the national territory and almost 70,000 km^2 with a flood risk (Trigila et al., 2015). When a flood occurs, it can destroy personal property (homes and cars), public infrastructure, such as roads and bridges, cultivated fields and the green areas. Considering the potential heterogeneity of the affected area when the water drops, there is a tendency to leave behind a wide dispersion of mud, debris and different waste typologies mixed with soil and water (United States Environmental Protection Agency, 2008). The resulting damage and the generated wastes and debris emerge at the end of the natural event, after the floodwaters recede. In this regard, Hurricane Katrina, that struck the southern states of the United States in 2005, generated an amount of waste and debris around 70–80 millions of cubic meters (May et al., 2006). Considering the significant produced volumes, it is evident that a proper management stream represents a very critical issue. There is considerable literature available, mainly focused on the frequent tropical cyclones that occur in the southern and southeast of Asia (e.g., Taiwan and Malaysia) during the rainy season, every year. Chen, Tsai, Hsu, and Shen (2007), analysed four different case studies of typhoons: Nari (2001), Toraji (2001), Mindulle (2004), Aere (2004) proposing a forecast model to predict the amount of waste and debris generated by a flood (Chen et al., 2007). The study aims at the identification of a correlation between the produced waste and the population density. The main parameters included in the analysis are the population density, the flooded area, and the building type. A nonlinear exponential equation was identified as reproducible and reliable mathematical model. On the other hand, Agamuthu, Milow, AMN, Nurhawa, and Fauziah (2015) analyse the flood that hit Malaysia from December 2014 to January 2015, mainly in the Kelantan region, focusing on the quantity and the typology of the collected debris (Agamuthu et al., 2015). The possibility to include the disaster waste management after natural disasters within the emergency management planning was evaluated by Yusof, Zawawi, and Ismail (2016) and Zawawi, Yusof, and Ismail (2016); Zawawi, Yusof, Kamaruzzaman, and Ismail (2015) research starting from Malaysian case studies (Yusof et al., 2016; Zawawi et al., 2015; Zawawi et al., 2016). The challenge is the identification of innovative strategies to overcome the management criticality during these extreme events. Further investigations consider the engineering aspects of hydrogeological phenomena using mathematical models or simulators to predict the flood trend, with rare mentions of the disaster waste management (Borga, Boscolo, Zanon, & Sangati, 2007; Dutta, Herath, & Musiake, 2003; Messeri et al., 2015; Norbiato, Borga, Sangati, & Zanon, 2007; Tingsanchali, 2012). Although many articles analyse several case studies for the proposal of waste management strategies, there is a lack of assessment of this critical issue from an environmental point of view. Indeed, the development of an approach that combines technical, economic and environmental aspects could be a useful support for the choice of the most sustainable strategy (Amato et al., 2019). The main difficulties connected with flood waste are due to both its mixed composition and the presence of mud, that make the recycling and recovery operations very difficult, as confirmed by the Italian events of Senigallia and Genova in 2014 (Gabrielli, Amato, Balducci, Magi Galluzzi, & Beolchini, 2018). With the aim to support the authorities, the United States Army Corps of Engineers (USACE) has developed an empirical formula to forecast the amount of debris after hurricanes, taking into account several factors, such as number of households, hurricane category, vegetative cover, commercial density and precipitation characteristic. The multiplication of these different parameters generates a reliable estimate of ±30% on debris production (FEMA, 2007). Nevertheless, it is a site-specific model and the geomorphological characteristics of the Italian territory do not allow its application. Considering this context, the goal of this article is the analysis of different scenarios of floods waste management, considering both the environmental and the economic impacts, following the approach used by Amato et al. (2019b) for the earthquake. With this aim, three possible alternatives were considered including different steps for the debris treatment. The Life Cycle Assessment (LCA) is chosen as a tool to quantify the emissions and environmental impacts associated with the three options, for the identification of the best practice for the flood waste management. Furthermore, the environmental evaluation is combined with an economic study, supported by a sensitivity analysis with Monte Carlo methods, to identify the cheapest waste treatment. The combination of environmental and economic studies represents a strategic tool, able to support the decision makers for the identification of the best practice for a smart DWM.

2 | MATERIALS AND METHODS

2.1 | The considered scenarios of DWM after flood

When the hydrogeological phenomena (e.g., a flood or landslide), hits an urbanised area, it can produce between 5 and 15 times the annual waste generation rates of a community (McCreanor & Reinhart, 1999). In the Italian flood case studies, the waste stream was about 10 times greater than that in normal conditions (Gabrielli et al., 2018). The material produced by a flood is a mix of mud and municipal solid waste (MSW), better classified as municipal wastes (household waste and similar commercial, industrial, and institutional wastes) including separately collected fractions, identified by the code EWC 20 00 00 by the European Waste Catalogue. This macro category includes different kind of waste: recyclable fraction (20 01 00), vegetative waste (20 02 00) and other urban waste (20 03 00). The functional unit selected for present study is 10,000,000 kg of debris with an average composition of unspecified MSW (EWC 20 03 99, around the 84%), bulky waste (EWC 20 03 07, about 15%), and WEEE (EWC 16 02 00–16 and EWC 20 01 00–99, the remaining 1%). The flow is subject to a previous macro selection, carried out by the citizen for the separation of bulky waste and WEEE. The manual sorting reduces the waste quantity for the disposal to landfilling site of about 16%, percentage which can fluctuate between 0 and 20%. Thereafter, the waste stream is treated following the scenarios detail described in Figure 1. In the first scenario, the whole amount is sent to a landfilling site, without treatment. This choice allows the reduction of the operation time and it accelerates the restoration of the affected area. In the second scenario, after the preliminary collection, the material is stored in-situ in a temporary debris storage and reduction site (TDSRS) and the debris are loaded by a mobile material handler (considered machine model: SENNEBOGEN 821 E) into the shredding and metal separation machine (considered machine model: DOPPSTADT DW 3060 K). This treatment allows a volume decrease, with the consequent reduction of the trips number necessary for the debris transport from TDSRS to landfill. In the third scenario, the shredded material is sent to an additional screening operation by sieving machine (considered machine model: DOPPSTADT SM 518). This treatment separates the overflow material (low density, to send to landfilling sites) and the underflow material (high density). The second fraction is processed by a mechanical-biological-treatment (MBT) which allows the bio-stabilisation by thermal and biological processes and the bio-drying to reduce both the specific weight (of about 17%) and the putrescible organic matter. The bio stabilisation is carried out in-situ by a mobile plant (AmbiSystem) for about 21 days (Ambientalia, 2014, 2018). The resulting flow can be disposed of with many advantages: the decrease of greenhouse gas emissions and the leaching phenomena within the landfilling site due to the biodegradable content and the reduction of transportation trips number, thanks to the volume minimization. Considering the destination of the resulting flows (the disposal in landfilling site) and the available short time during an emergency, neither an accurate separation nor a washing of the waste is required, irrespective of the selected scenario.

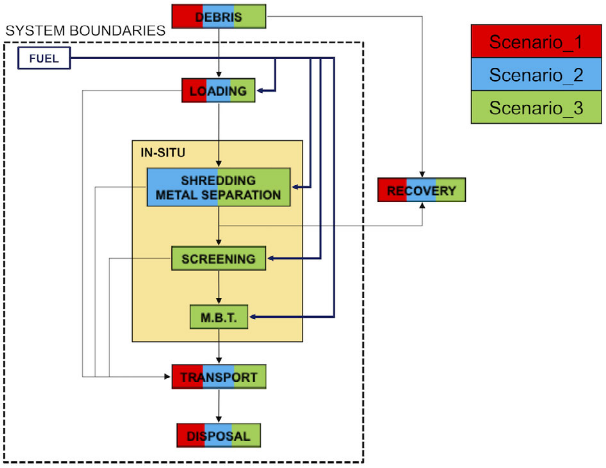

FIGURE 1 System boundaries considered for the LCA analysis (functional unit: 10,000,000 kg of debris)

2.2 | Goal and scope of LCA analysis

The goal of the analysis is the assessment of the environmental impact of the three scenarios considered and the identification of the best practice for the flood debris management. Table 1 summarises the equipment involved in the treatments and the material and energy flows used for the evaluation, with reference to 10,000,000 kg of waste (classified as MSW), chosen as the functional unit. In reference to the machine consumption, a diesel mix (suitable for road, rail, and ship transportation, electricity generation, and other consumers) was considered and expressed as litre per waste t. Moreover, Table 2 reports the detail of waste transport for each scenario. In reference to the density parameter, the disposal facility ASA Company of Corinaldo supplied the values used for Scenarios 1 and 2, referred to the real event of Senigallia flood of 2014. On the other hand, the density for Scenario 3 is calculated as a weighted average, considering 40% of the whole stream is almost free of metals (around 4%), as underflow and the 60% as overflow from the screening (Stella, 2014).

2.3 | Software and methods for the LCA

The thinkstep GaBi software-System and Database for Life Cycle Engineering (compilation 7.3.3.153; DB version 6.115) were used for the production processes of energy and raw materials and the quantification of the environmental impact of the three analysed scenarios. The software allowed to translate the mass and energy balance into the environmental load in different impact categories, thanks to its connection with the rich database. Notably, the impact categories and the related characterisation methods were

TABLE 1 Energy and raw material flows considered for the three management scenarios (functional unit: 10,000,000 kg of debris)

Scenario operation	Consumption	Equipment	References
Scenario_1			
Loading	0.17 L/t	Sennebogen 821 E	(Sennebogen, n.d.)
Landfilling	8,400,000 t	Landfill	
Scenario_2			
Loading	0.17 L/t	Sennebogen 821 E	(Sennebogen, n.d.)
Shredding/metal separation	0.50 L/t	Doppstadt DW 3060 K	(Doppstadt, n.d.-a)
Landfilling	8,064,000 t	Landfill	
Scenario_3			
Loading	0.17 L/t	Sennebogen 821 E	(Sennebogen, n.d.)
Shredding/metal separation	0.50 L/t	Doppstadt DW 3060 K	(Doppstadt, n.d.-a)
Screening	0.23 L/t	Doppstadt SM 518	(Doppstadt, n.d.-b)
M.B.T.	10 kWh/t	Ambisystem	(Ambientalia, 2014, 2018)
Landfilling	7,348,320 t	Landfill	

TABLE 2 Characteristics of the transport considered within the three scenarios (articulated lorries with a payload of 27 tons, functional unit: 10,000,000 kg of debris)

Departure	Arrival	Distance (km)	Flow density (kg/m^3)	N° of trips
Scenario_1				
Disaster site	Landfill	100	344	904
Scenario_2				
In-situ site	Landfill	100	653	457
Scenario_3				
In-situ site	Landfill	100	647	421

selected in agreement with the Product Environmental Footprint (PEF) guide and the ILCD handbook (Benini et al., 2014; Hauschild et al., 2011). The impact categories included in the present analysis, with a contribution higher than 1% on the normalised and weighted result, were: acidification (mol H^+ eq.), climate change (kg CO_2 eq.), eutrophication terrestrial (mol N eq.), photochemical ozone formation—human health (kg NMVOC eq.), resource depletion—mineral, fossils and renewables (kg Sb eq.), particulate matter/respiratory inorganics (kg PM2.5 eq.), human toxicity, cancer, and non-cancer effects (CTUh). The normalisation and weighting determined the relevance of the different environmental impact categories. The first step aimed at the expression of the whole impact of a specific category in a selected scale. The weighting allowed to give the specific relevance to each category, making the impacts dimensionless and comparable (Castellani, Benini, Sala, & Pant, 2016; Finnveden et al., 2009). In the present assessment, the method described by Castellani et al., 2016 (with the related weighting factors WFsA) was chosen, taking into account a European scale, considering the peculiarity of the described scenarios (Castellani et al., 2016; Zampori, Saouter, Schau, Castellani, & Sala, 2016).

TABLE 3 Estimated costs used for the economic analysis

Phases	Unit of measure	References
Transport	8 €/km	Eqs. 1–13 supporting material
Landfill	89 €/t	(Andretta, Montresori, & Sunseri, 2010)
M.B.T.	101 €/t	(Andretta et al., 2010)
Shredding	5€/t	Eqs. 1–13 supporting material
Screening	2 €/t	Eqs. 1–13 supporting material
Loading	1 €/t	Eqs. 1–13 supporting material

2.4 | Goal and scope of economic analysis

Considering the relevance of the economic aspect for the local authorities and the decision makers during an emergency event, this analysis aims at a cost assessment for the three options. In this regard, the combination of environmental and economic results could represent a valid tool for the identification of the best practice for a smart DWM. Table 3 shows the unit cost of the most relevant treatments considered for the analysis of three scenarios of interest. Notably, the MBT and the disposal costs are obtained by an Italian sector study (Andretta et al., 2010). The remaining values of transport, shredding, screening and loading steps are elaborated following the method reported in eqs. 1–13 in the supporting materials.

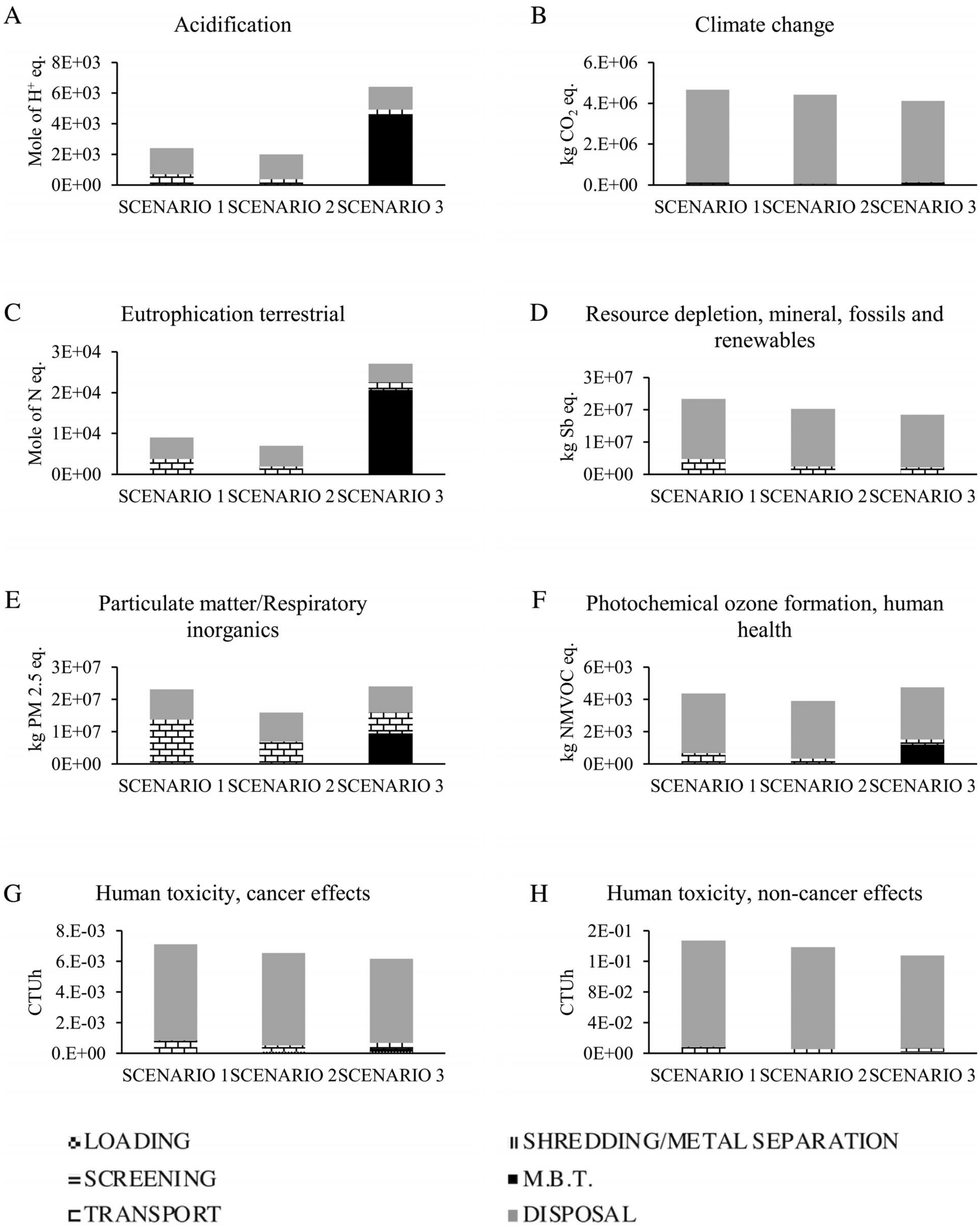

FIGURE 2 Estimation of the environmental impacts generated by the three considered scenarios, in the most significant impact categories, with a contribution higher than 1% of the whole normalised and weighted impact (functional unit: 10,000,000 kg of debris)

3 | RESULTS AND DISCUSSION

3.1 | Assessment of the different strategies of debris management

Figure 2 represents the results of classification and characterisation of the LCA, including the categories with a contribute higher than 1% of the whole normalised and weighted result. Overall, the three scenarios show comparable results, which does not exceed the 15%, in agreement with the normalisation and weighting outcome. Both acidification and eutrophication terrestrial represent an exception for the significant load of the MBT which caused an impact increase around 65%, emphasising the advantage of Scenario 2 (Figure 2a,c). This impact is mainly connected with the NOx emissions release during the biodegradation process, due to the high nitrogen content of the treated waste stream. The disposal to landfill represents the most significant environmental impact, mainly due to the great quantity of waste with a high organic content. The landfill impact is the main criticality also for the human health, as confirmed by Figure 2f–h. In this regard, the three scenarios caused comparable results, with a maximum difference of 10% between the first and the third one. The positive effect achieved thanks to the volume reduction is mainly highlighted in the category of particulate matter/respiratory inorganics with a difference between the Scenarios 1 and 2 higher than 45%.

The results obtained by normalisation and weighting of data (Figure 3) allowed an overview of the overall impact of the debris management strategies, considering all the most relevant impact categories. A comparison among the three scenarios suggests that there is not a significant difference. The clear predominance of the grey colour, which corresponds to the climate change potential, associated with the classification and characterisation values, described in Figure 2 (about 5E+06 Kg CO_2 eq.), confirms that the disposal in landfilling site has the most impact of the three scenarios. On the other hand, the categories related to the human health (cancer and non-cancer heath effect, photochemical ozone formation-human health) show a low contribution on the total impact, with values between 1 and 3%.

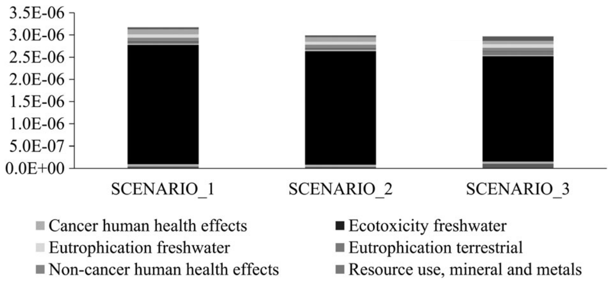

FIGURE 3 Total environmental load, normalised and weighted, generated by the three considered scenarios. The categories: ecotoxicity freshwater, eutrophication freshwater and marine, ionising radiation-human health, land use, ozone depletion, resource use (minerals and metals), and water scarcity are included within the assessment, but they are not visible for their contribution lower than 1% (functional unit: 10,000,000 kg of debris)

3.2 | Economic analysis

The cost of waste management after a flood is an evident problem, as explained by Gabrielli et al. (2018). Figure 4 shows the cost estimation for the three strategies of DWM, taken into account in present study. The first Scenario 1 seems to be the most expensive choice (around 138 €/t). The reason can be found in the low-density value of the debris (344 kg/m^3), due to the lack of a pre-treatment for the volume reduction, which increases the transport and disposal cost. In comparison option 2 halves the transport cost: thanks to the shredding treatment the density doubles (662 kg/m^3) and the number of trips needed for transportation is reduced. In this case, the cost is the lowest of the three—107 €/t. The third alternative show a high cost (around 130 €/t) in spite of the debris shredding, since the mechanical biological treatment causes a relevant contribution on the total.

The aim of the present work is to develop a general analysis useful as decision maker support for a first screening to identify the best management strategy. Nevertheless, some assumptions have been made for the preliminary economic analysis. The considered input data could be affected by specific uncertainties due to the market changes or the peculiarity of the damaged area. In order to have a more consistent result, the whole result was studied modifying the variables within specific ranges, with different combinations. Therefore, a range of variations has been hypothesized for the main variables that can have an influence on the total cost, in order to assess the accuracy of the estimations. More specifically, the unit cost of each step can vary in the range ± 10% (in agreement with the market fluctuation). Furthermore, two further key variables were considered: the distance from the interested area to the landfilling site (range of

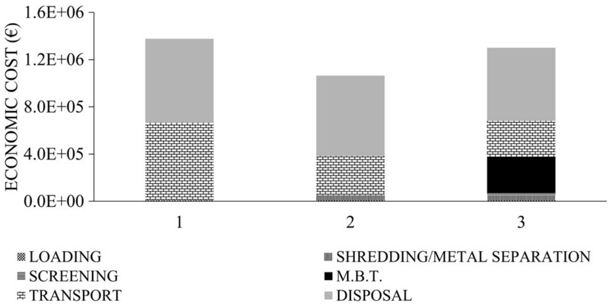

FIGURE 4 Economic assessment of the three considered scenarios (functional unit: 10,000,000 kg of debris)

variation: 0–100 km, a higher distance makes the whole management unsustainable) and the quantity of waste manually sorted by citizens, before the treatment (range of variation: 0–20%, that corresponds to 0–20,000 tons, following real case studies). The time represents a further key factor, nevertheless, unlike an earthquake events, during a flood there is not a widespread building collapse with a consequent limited human activity suspension. Usually, the population does not leave the residences (or they leave for a short period), speeding up a return to normality. Therefore, the short management time was assumed as a consequent in the present assessment and this variable was included within the distance factor since, farther, but available, landfilling sites could be chosen to make quicker the DWM. These data variations were estimated starting from the real case studies presented by Gabrielli et al. (2018), expanding the ranges to make the results as representative as possible, and the variables were combined following a Monte-Carlo algorithm. Figure 5 shows the cost of the three scenarios for all the simulations. It can be observed that the cheapest option is the second, where shredding is first carried out before the transportation to the landfilling site to reduce the trips number. There are two different critical distances: the first value, around 3 km, (Figure 5) demonstrates that, for very short distances, the in-situ shredding is useless, and the most advantageous choice is the directly transportation of the whole material. On the other hand, for longer distances (around 78 km in Figure 5), the initial treatment, that includes an additional mechanical-biological stabilisation is much more economically advantageous due to the further volume reduction. In order to assess the effect of the other variable, q (extent of manual sorting before the treatment), all the critical distances estimated for different values of q have been considered. A variation coefficient of 28% and of 1% was estimated for the shortest and for the largest distance, respectively: the 3 km become about 6 km, when no initial manual sorting is carried out. On the other hand, no significant effect of q is highlighted on the longest distance that makes the mechanical biological treatment as convenient.

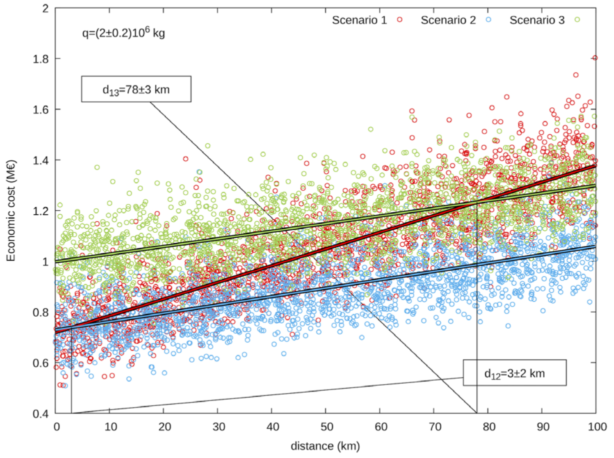

FIGURE 5 Economic cost of the three scenarios as a function of the distance for all the transport, considering a fixed quantity handled to manual sorting 2,000,000 kg (output of the Monte Carlo simulation). Functional unit: 10,000,000 kg of debris

4 | CONCLUSIONS

The literature research highlighted the possibility to develop studies for the prediction of both the environmental and the economic impact of a disaster waste management, also considering possible innovative approaches for the scraps exploitation, mainly in Japanese areas (Portugal-Pereira & Lee, 2016; Tabata, Wakabayashi, Tsai, & Saeki, 2017; Wakabayashi, Peii, Tabata, & Saeki, 2017). The papers focused on specific critical impact categories and they included defined areas, with their related peculiarities. Further studies deepened the issue of the issue of the waste produced in normal conditions, evaluating the impact due to the management of the urban flows (Cherubini, Bargigli, & Ulgiati, 2009) or specific waste classes (e.g., waste from electrical and electronic equipment) (Amato et al., 2019; Amato, Rocchetti, & Beolchini, 2017; Biganzoli, Falbo, Forte, Grosso, & Rigamonti, 2015; Pintilie, Torres, Teodosiu, & Castells, 2016). The showed results included impact categories comparable with those discussed in the present assessment, nevertheless the waste flows considered had a homogeneous composition, that simplify the management choices.

During an emergency, the prediction studies are essential to create efficient emergency plans nevertheless, it might not be enough. Indeed, after this kind of events, the decision makers must make choices to speed up the management of heterogeneous flows, often outside the regulatory framework, referred to the normal conditions. In the Italian context, the article number 191 of the Legislative Decree 152/2006 allows circumvention of the bureaucratic barriers, increasing the decision-making power to the authority (Gabrielli et al., 2018). Nevertheless, the lack of useful scientific information about DWM, useful to give support, often causes uncorrected and unsustainable management strategies, with negative effects on both the environmental and the economic spheres. Therefore, following the scheme proposed by Amato et al. (2019) for the earthquake rubbles, the present article studied different strategies for the debris management, considering the peculiarity of a flood. Three realistic scenarios have been hypothesized. Overall, the output of the life cycle assessment analysis did not highlight differences between the environmental impact of the three scenarios. Nevertheless, the possibility to focus on several impact categories, able to also include the health aspect, highlighted the advantage thanks to the TDSRS and the possible criticality of the MTB. The economic analysis confirmed that Scenario 2 is the most advantageous. Even the Monte-Carlo simulations confirm the sustainability of Scenario 2, for typical distances, thanks to the volume reduction by shredding. The assessment used average data, from realistic events. Furthermore, the simple analysis schema, combined with the use of standardised methods, make it suitable for the adaptation to specific emergencies, considering the possible peculiarity of geographical areas.

DATA AVAILABILITY STATEMENT

Research data are not shared.

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