



A systematic approach to identify, characterize, and prioritize the data needs for quantitative sustainable disaster debris management

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ABSTRACT

Recycling and reuse are major components of disaster debris management with significant environmental, economic, and social benefits. To develop quantitative and sustainable debris management practices, a broad range of data is required. Existing studies have not comprehensively delineated the data and analysis requirements for quantitative assessment of sustainable debris management, which limits proper disaster data collection and restricts the development of approaches to efficiently quantify, characterize, and allocate disaster waste among existing and emerging debris management pathways. This study aimed to fill this gap by reviewing previous investigations to identify the data required to quantitatively assess both critical and practical aspects of sustainable disaster debris management. The literature review indicated that the most significant data for post-disaster debris management relate to i) the amount and composition of debris; ii) availability of temporary debris management sites; iii) hazards and environmental concerns; iv) economics; v) social considerations; and vi) funding policies. Considering the time-sensitive nature of different disaster debris data types, a four-phase planning framework is proposed for timely collection of data: pre-disaster, post-disaster response, short-term recovery, and long-term recovery. With significant identified data needs and finite amount of resources for data collection, particularly during post-disaster phases, social network analysis (SNA) is used to quantitatively evaluate the relative importance of the data needs. Overall, it is recommended to develop comprehensive debris management inventories that aggregate diverse pre-disaster datasets, along with integrated specialized reconnaissance investigations to collect post-disaster data, most of which are identified as high priority.

1. Introduction

The number and impacts of natural and technological disaster events have been increasing steadily (EM-DAT, 2021; NOAA, 2019). In addition to direct human and environmental impacts, the debris and wastes generated during disasters also have significant impacts on response and recovery efforts and on the broad resiliency of rural and urban environments. The United States Federal Emergency Management Agency (FEMA) (2007) and the United States Environmental Protection Agency (USEPA) (2019) have identified debris management as a critical issue when responding to natural disasters. Waste and debris generation can be substantial and exceed annual waste quantities in the affected region depending on the nature and severity of the disaster (Brown et al., 2011;

Brown and Milke, 2009). Approximately a quarter of the total costs associated with disaster response is typically associated with the management of the generated debris (FEMA 2007). In addition, disaster debris can pose safety threats and impede emergency response, recovery, and rebuilding (Luther, 2010). In the short term following a disaster event, debris can block roadways and obstruct emergency and rescue efforts and the provision of humanitarian aid (Ghannad et al., 2021). In the long term, improper management of disaster debris can impede the timely recovery of the affected area, increase costs, and result in negative human health and environmental impacts (Babbitt, 2019; Brown et al., 2011; USEPA, 2019).

Depending on the nature of the disaster event and the characteristics of the impacted area, the generated debris can contain a variety of

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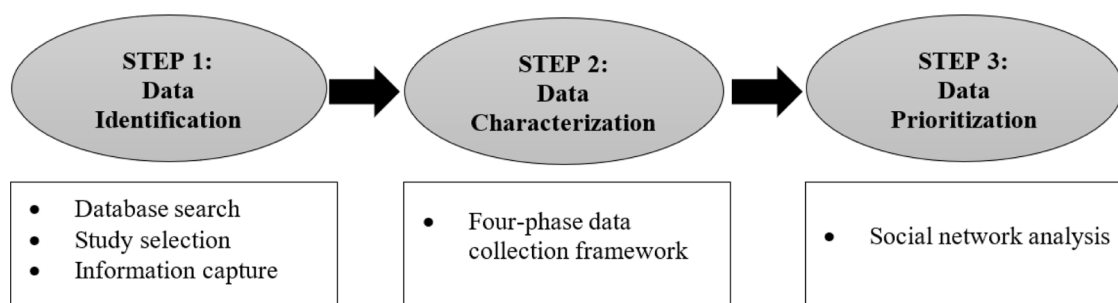


Fig. 1. Research methodology.

Table 1

Keyword allocation.

Disaster Debris Management Aspect	Keywords
<i>Amount and composition of debris</i>	Quantification, estimation, estimate, quantity, volume, amount, composition, type
<i>Availability of TDMS</i>	Temporary debris management sites, temporary disaster waste management sites
<i>Hazards and environmental concerns</i>	Health hazards, environmental hazards, environmental impact
<i>Economics</i>	Economics, costs, economic benefits
<i>Social considerations</i>	Community priorities, social capital, psychological
<i>Funding policies</i>	Funding, regulations, policy, planning, circular economy

valuable materials, the majority of which are often highly amenable to recycling and recovery, following a complete evaluation of the nature and extent of contamination (e.g., the presence of water, hazardous chemicals, as well as other organic materials). In terms of building debris, which is one of the most common disaster debris particularly from earthquakes hitting urban areas (Tabata et al., 2019), concrete can be processed to be used as aggregate for new concrete construction, repairing roadways, and landscaping purposes; drywall can be used as soil fertilizer or to enhance soil drainage; brick and tiles can be reused in new construction; and metals can be recycled into scrap parts (USEPA, 2019). As for vegetative debris, which is commonly generated in hurricane events (Thompson et al., 2011), plants can be composted to be used as fertilizer or mulched to be used as landfill cover; and wood wastes that are not chemically treated or painted can be processed into compost or mulch or be used as boiler fuel (Channell et al., 2009). Such reuse and recycling practices valorize the waste and debris materials, reduce raw resource needs, and reduce the amount of disaster debris landfilled (USEPA, 2019) along with saving landfill tipping fees (Brandon et al., 2011). In terms of environmental benefits, reuse/recycling disaster debris reduces greenhouse gas emissions through the potential reduction in debris and raw material transportation, along with conserving virgin resources (Crowley, 2017). Economic benefits result from revenue generated from salvaged materials recycled into potential end-use products. Further, through “giving life” to disaster debris, reuse/recycling practices positively impact the psychological recovery of disaster-impacted communities while serving as a resource in the reconstruction process (Brown et al., 2011).

Various factors influence effective implementation of post-disaster recycling (Brown and Milke, 2016). The amount, type, and composition of the generated debris are key determinants of how much debris can be feasibly recycled, the required recycling rate, and the need for additional recycling facilities. Accurate debris quantification methods are critical to avoid over- or under-estimation of the amount of disaster debris (García-Torres et al., 2017). Limited and insufficient number of temporary debris management sites (TDMS), which provide a buffer and space to store and process large amounts of debris in the immediate aftermath of disaster events (USEPA, 2019), is a major barrier to

sustainable debris management (Brown and Milke, 2016; Cheng and Thompson, 2016). Post-disaster reuse and recycling are also impeded by debris contamination. Sustainable management of disaster debris requires identification of potential hazards in the debris stream and minimization of the corresponding potential negative environmental impacts of the management system. Since the costs of disaster debris management can be substantial, the economic viability and cost effectiveness are also critical for the feasibility of post-disaster recycling. In addition, social considerations impact feasibility and efficiency of post-disaster reuse/recycling due to different community concerns, varying priorities, and different levels of involvement. Finally, funding mechanisms and policies governing disaster debris management substantially impact the extent of recycling as these dictate the eligibility for reimbursement of debris management costs.

The management of disaster debris is often done in an ad hoc manner (Magalhães et al., 2020), resulting in limited allocation of debris to various potential recycling pathways. The effective implementation of sustainable debris management practices requires thorough data-based assessment of the aforementioned aspects impacting the feasibility of disaster debris reuse/recycling: i) amount and composition of debris; ii) availability of TDMS; iii) hazards and environmental concerns; iv) economics; v) social considerations; and vi) funding policies. However, existing studies in the field of disaster debris management have not comprehensively delineated the data and analysis requirements for quantitative assessment of sustainable debris management practices and typically do not provide a holistic perspective. Prior studies generally are qualitative in nature (Brown et al., 2011; Zhang et al., 2019), and quantitative studies often focus on a single aspect of the debris management process. Therefore, this study aims to address the current knowledge gaps by identifying the data required to inform sustainable disaster debris planning and management by systematically reviewing the existing body of knowledge. As data requirements are time-sensitive in management of post-disaster debris, the data needs are characterized based on a four-phase data collection and planning framework: pre-disaster, post-disaster response, short-term recovery, and long-term recovery. Further, since data collection resources are often limited, particularly during the post-disaster phases, quantitative guidance on prioritization using social network analysis is included. The text is organized as follows: Section 2 describes the methodology applied in this research. Section 3 presents the results of the literature review including the identification, characterization, and prioritization of data needs related to sustainable disaster debris planning and management. These results are subsequently discussed in Section 4, where the identified knowledge gaps and future recommendations are detailed. Finally, Section 5 includes conclusions with final thoughts and future perspectives of this research.

2. Research methodology

A three-step methodology was used to identify, characterize, and prioritize the data required to inform sustainable disaster debris planning and management. Fig. 1 outlines the specific components of the

Table 2

Criteria used for inclusion or exclusion in paper selection.

Inclusion Criteria	Exclusion Criteria
Journal paper, conference paper, report	Editorial, commentary
Written in English	Non-English publication
The focus is on debris management	The focus is on waste management
within the context of disaster events	during peacetime
Presenting the types of data needed to	Review of a specific disaster event
carry out the research	without a focus on debris management
	Does not present any data needs

individual steps.

2.1. Data identification

An extensive literature review was conducted to obtain and synthesize data requirements for sustainable debris management using a systematic search strategy. Google Scholar and Web of Science were utilized to identify all relevant literature. In addition to academic articles, reports published by governmental organizations and agencies (e. g., FEMA and USEPA) were collected. To identify relevant literature, a structured keyword search was carried out in two general topics: 1)

disasters and 2) debris using the terms “disaster”, “natural hazards”, “emergency crisis”, and “catastrophe”. In addition, other keywords were used when searching for articles specific to each of the six aspects that affect the feasibility of sustainable disaster debris management (Table 1).

A three-step process, adopted from Sanusi et al. (2020), was followed to screen and select the most relevant literature. First, the title was examined for the selected keywords; next, the abstract was reviewed; and lastly, the full text was examined. The identified studies were reviewed following the inclusion and exclusion criteria presented in Table 2. The review process resulted in the selection of 110 documents, spanning the time period 2000–2021 and ranging across various disciplines, including disaster response and recovery, waste management, civil engineering, public policy, social sciences, and economics. A list of reviewed documents is provided in the supplementary material.

Selected documents were examined in detail and all relevant information was extracted and further organized in a meta-dataset. Each document was presented in the form of an entry with an associated objective, scope, method, contribution to each of the identified aspects of sustainable debris management, and data types used. The information from the meta-dataset was used to identify the different types of data needed to assess each of the six aspects affecting the feasibility of



Fig. 2. Four-phase disaster debris data collection and planning framework.

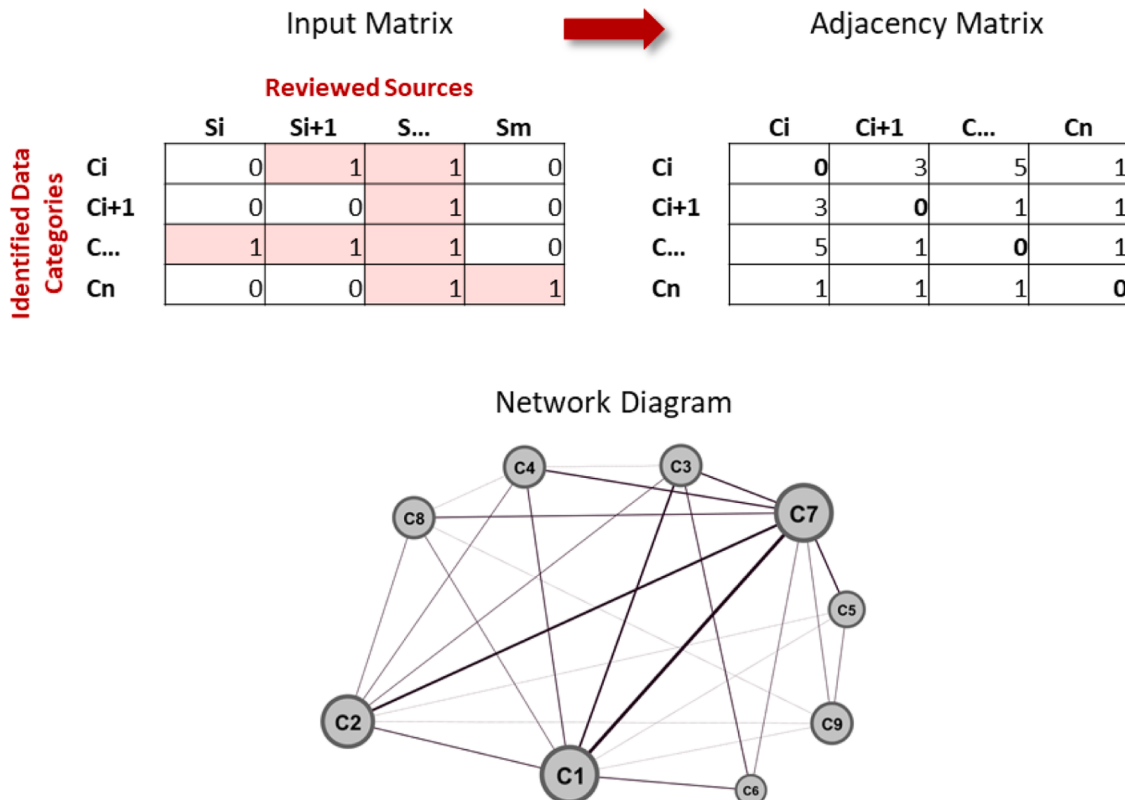


Fig. 3. Example input and adjacency matrices and resulting network diagram.

Table 3

Data needs identified and characterized for debris amount and composition estimation.

ID	Data Category	Data Types	Studies	Phase
AC1	Demographics	Population count/density in the studied area	(Chen et al. 2007; FEMA 2018c, b; a; FEMA 2007; García-Torres et al. 2017; Hirayama et al. 2010; Park et al. 2020; T. Tabata et al. 2016; Wakabayashi et al. 2017)	Pre-disaster
AC2	Vegetation data	Vegetation cover, tree density, %tree cover, tree biomass, tree canopy, average tree height, proportions of tree cover in hardwoods versus palms, crop land area	(FEMA 2010, 2018c; FEMA 2007; Heinrich et al. 2015; Park et al. 2020; Thompson et al. 2011; Umpierre and Margoles 2005)	Pre-disaster
AC3	Urban data	Housing density, density of commercial development, urban area ratio, number of households, number of dwellings	(FEMA 2018c; FEMA 2007; García-Torres et al. 2017; Hirayama et al. 2010; Wakabayashi et al. 2017)	Pre-disaster
AC4	Community-level building information	Categories of buildings, number of buildings by specific occupancy class, average area of each dwelling, number of low-rise buildings, total floor area of high-rise buildings	(FEMA 2018b; c; Hayes et al. 2020; Heinrich et al. 2015; T. Tabata et al. 2016)	Pre-disaster
AC5	Building specific information	Length, width, height, structural type, number of stories, square footage, number of occupants, and location of buildings	(FEMA 2010, 2018a; Hancilar et al. 2010; Onan et al. 2015; Poudel et al. 2018; USEPA 2013; Xiao et al. 2012)	Pre-disaster
AC6	Disaster statistics	Natural hazard maps	(García-Torres et al., 2017; Hirayama et al., 2010; Wakabayashi et al., 2017)	Pre-disaster
AC7	Disaster Characteristics	Disaster type, track, spatial hurricane wind data, floodplain boundaries, flow data, earthquake latitude, longitude, depth, and magnitude, storm wind speed, storm category according to the Saffir-Simpson scale, volcanic eruption characteristics,	(Chen et al. 2007; FEMA 2018a; b; c; FEMA 2007; Hancilar et al. 2010; Hayes et al. 2020; Heinrich et al. 2015; Hirayama et al. 2010; Onan et al. 2015; Park et al. 2020; Thompson et al. 2011; Umpierre and Margoles 2005; USEPA 2013;	Response

Table 3 (continued)

ID	Data Category	Data Types	Studies	Phase
		inundation depth, inundation areas	(Wakabayashi et al. 2017)	
AC8	Area of impacted region	Square footage of the region affected by the disaster event	(Chen et al., 2007; Heinrich et al., 2015; Park et al., 2020)	Response
AC9	Number of damaged structures	Number of damaged offices, schools, hotels, single-family residences, shopping malls, and hospitals	(Park et al., 2020; Poudel et al., 2018; USEPA, 2013)	Response
AC10	Pre-disaster Aerial imagery	Aerial photographs captured before the occurrence of the disaster	(Hansen et al., 2007)	Pre-disaster
AC11	Pre-disaster Satellite imagery	Satellite images captured before the occurrence of the disaster	(Shirai et al., 2016)	Pre-disaster
AC12	Post-disaster Aerial imagery	Aerial photographs captured after the occurrence of the disaster	(Hansen et al., 2007; Jiang and Friedland, 2016; Koyama et al., 2016; Saffarzadeh et al., 2017; Szantoi et al., 2012; Yoo et al., 2017)	Response
AC13	Post-disaster Satellite imagery	Satellite images captured after the occurrence of the disaster	(Jiang and Friedland, 2016; Shirai et al., 2016)	Response

sustainable debris management, which were subsequently grouped into categories for use in the data characterization and prioritization steps.

2.2. Data characterization

Data characterization was conducted using a four-phase data collection and planning framework (Fig. 2), directly aligned with the recovery continuum presented in the National Disaster Recovery Framework established by FEMA (2011). This framework ensures that post-disaster data are collected in a timely and consistent manner before potential loss of data. This four-phase approach provides the added benefit of clearly delineating the time dependency of the data requirements, which will assist in future planning and implementation of field and virtual reconnaissance efforts to improve sustainable debris management research.

2.2.1. Pre-Disaster Phase

Pre-disaster data are available regardless of the occurrence of a disaster event. These data structures are mostly used in forecasting and guiding pre-incident planning to increase community preparedness. Example data and analysis include debris estimation for different disaster scenarios and land suitability analysis to locate potential TDMS. Pre-disaster data can be obtained from various existing sources including public agencies, private sectors (e.g., debris contractors), and subject-matter experts.

2.2.2. Post-disaster response phase

Data associated with the response phase (days/weeks) are generated in the immediate aftermath of a disaster event and are often available until debris is cleared to facilitate the provision of emergency services.

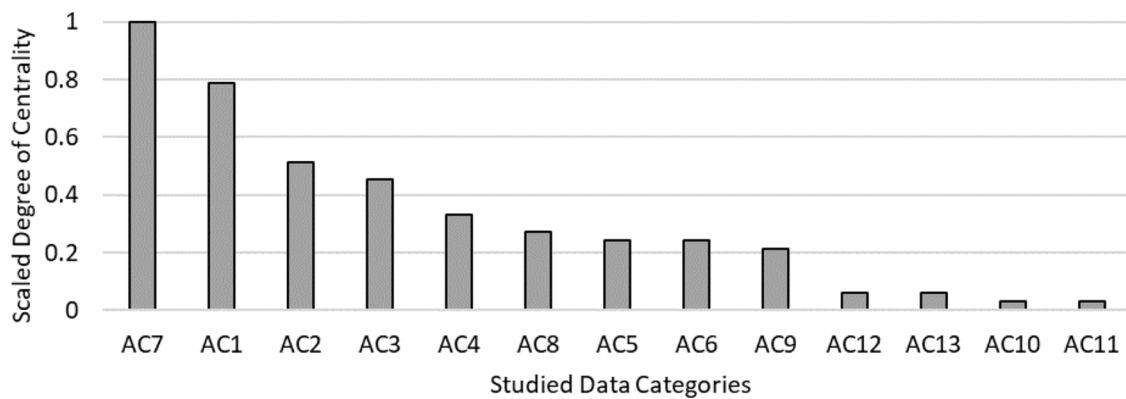


Fig. 4. Scaled degree centralities of identified data categories required for debris amount and composition estimation.

Data from this phase are critical for quantifying the generated debris, planning debris removal operations, and allocating debris to TDMS. Disaster reconnaissance investigations need to be conducted in collaboration with emergency management agencies and relevant private/public sectors for timely data collection.

2.2.3. Short-term recovery phase

Data associated with the short-term recovery phase (weeks/months) are generated during debris collection, transportation to TDMS, and storage at TDMS as well as any direct allocation to common waste management facilities such as transfer stations, recycling facilities, and landfills. Data from this phase provide further information about the composition of the collected debris, estimates of the potential amount of recyclables, and the storage, sorting, and preprocessing operations. A second reconnaissance undertaking is required in coordination with local agencies to access appropriate sites before the debris is moved to recycling and disposal facilities.

2.2.4. Long-term recovery phase

Long-term recovery data (months/years) are available during disaster debris treatment and recycling, along with the disposal of residual debris. The main purpose of data collection in this phase is to ascertain extent of recycling/reuse, describe debris recycling and reuse operations, and identify direct landfill disposal. A third and final data gathering effort is needed to collect long-term recovery data.

2.3. Data prioritization

Social network analysis (SNA) investigates networks in a holistic manner to draw objective insights using mathematical formulations derived from graph theory (El-adaway et al., 2016). SNA has been widely used in many fields with applications in social sciences, political sciences, transportation planning, healthcare, business organizations, and construction management (Cranmer and Desmarais, 2011; El-adaway et al., 2016; Eteifa and El-adaway, 2018; Lusher et al., 2012; Pow et al., 2012; Priven and Sacks, 2015; Wambeke et al., 2012). SNA has also been used in literature reviews to identify topics that have been widely studied, determine their relative importance, and identify current gaps (Abotaleb and El-adaway, 2019, 2018).

To facilitate the application of SNA in this study, a preliminary step was used to build input matrices based on the findings of the literature review. An input matrix is a table with the identified data categories as rows and the reviewed literary sources as columns (Fig. 3). Each cell in the matrix has a value of 1 or 0 depending on whether the data category was used/cited (i.e., 1) or not (i.e., 0) in the corresponding reviewed study. Each identified aspect of sustainable debris management was considered as a separate network in this study, and a distinct input matrix was built for the specific aspect. These matrices were subsequently converted into adjacency matrices by multiplying with their

transpose and substituting the numbers on the diagonals with zeros (Fig. 3). The resulting adjacency matrices are symmetric, with the values of the cells indicating the number of times data categories were used or cited with one another. Each adjacency matrix was directly used to plot a network diagram, similar to the example in Fig. 3, for each aspect of sustainable debris management. In a network diagram, the nodes represent the data categories, with larger nodes identifying the more used or cited data in the literature. The strength or weights of the links in a network are based on the values of the adjacency matrix, with thicker linking lines indicating data categories that have been used or cited together multiple times.

In network theory, degree centrality is an indicator of how influential a node is within the network (Eteifa and El-adaway, 2018; Park et al., 2011). In this study, degree centrality was used as a measure of the importance of the identified data categories derived from the frequency of their use in the reviewed literature. The degree centrality of a node can be calculated by summing the weights of all links attached to the node (Abotaleb and El-adaway, 2018). Mathematically, it is defined as

$$DC_i = \sum_j y_{ij} \quad (1)$$

where DC_i is the degree centrality of data category i ; and y_{ij} is the entry in row i and column j in the adjacency matrix. For each network corresponding to one aspect of sustainable debris management, the scaled degree centrality for each of its data categories was calculated using Eq. 2.

$$\text{Scaled } DC_i = \frac{DC_i}{\text{Maximum } DC_i \text{ in the network}} \quad (2)$$

This scaling was done to ensure that the computed values were always between 0 and 1 since the number of reviewed literature sources for each aspect of sustainable debris management was not the same.

3. Data needs identification, characterization, and prioritization

The information obtained from the literature review is used to identify, categorize, and characterize the data needs relevant to each of the six aspects that impact the feasibility of disaster debris reuse/recycling. The relative importance of each of the identified data categories is established using SNA to prioritize data collection. Because a limited number of studies were identified for social aspects (8 studies) and funding policies (7 studies), SNA could not be implemented for these two aspects.

3.1. Amount and composition of debris

Of the six aspects that control the extent of debris reuse/recycling, the highest number of research studies was identified for debris quantity

Table 4

Data needs identified and characterized for assessing the availability of TDMS.

ID	Data Category	Data Types	Studies	Phase
TD1	Hydrological data	Hydrography, 100-year floodplains, wetlands, coastal management zone boundaries, public wellfields, water reservoirs	(Cheng and Thompson, 2016; Grzeda et al., 2014; Kim et al., 2018)	Pre-disaster
TD2	Geological data	Soil types, seismic zones	(Cheng and Thompson, 2016; Grzeda et al., 2014)	Pre-disaster
TD3	Urban data	Land use, parcel data, protected areas, residential areas, public facilities (e.g., hospitals, schools), transportation networks, utilities	(Cheng and Thompson, 2016; Grzeda et al., 2014; Kim et al., 2018)	Pre-disaster
TD4	Demographics	Population count/density in the areas containing TDMS	(Cheng and Thompson, 2016; Onan et al., 2015)	Pre-disaster
TD5	TDMS operational data	Capacity of each reduction, separation, and recycling (RSR) technology at each TDMS, reduction proportion for each RSR technology, proportion of reduced debris from each RSR technology salable as recycled material, TDMS total area, unit processing time, available human resources	(Boonmee et al., 2018; Cheng et al., 2021; Wang et al., 2019)	Pre-disaster
TD6	Characteristics of the waste management system	Numbers, locations, and capacities of available waste treatment facilities, hazardous waste disposal facilities, and landfills	(Boonmee et al., 2018; Kim et al., 2018)	Pre-disaster
TD7	Feasibility Constraints	Minimum and maximum number of TDMS	(Boonmee et al., 2018; Kim et al., 2018; Wang et al., 2019)	Pre-disaster
TD8	Debris characteristics	Debris composition, debris source locations	(Boonmee et al., 2018; Onan et al., 2015; Wakabayashi et al., 2017; Wang et al., 2019)	Response
TD9	Debris logistics	Serviceability of the transportation network, distance between debris sources and TDMS, number of available collection vehicles	(Boonmee et al., 2018; Cheng et al., 2021; Kim et al., 2018; Onan et al., 2015; Wang et al., 2019)	Short-term recovery

Table 4 (continued)

ID	Data Category	Data Types	Studies	Phase
		in a day, capacity of the collection vehicles, total working time of a collection vehicle in a day, total removal time limit for the debris from all sources, proportion of debris that is eligible to be treated with each RSR technology		

and composition estimation; most provided deterministic analysis with less emphasis on probabilistic approaches and risk analysis. The data used mainly varied depending on i) the employed analysis method, ii) the debris quantity estimation type (overall debris quantity versus quantity of individual debris types), and iii) the disaster type. The analysis methods provided in literature can be divided into general formulas (FEMA, 2010), computer tools (FEMA, 2018b, 2018a, 2018c; Hancilar et al., 2010; Heinrich et al., 2015; Umpierre and Margoles, 2005; USEPA, 2013), statistical/mathematical models (Chen et al., 2007; Park et al., 2020; Thompson et al., 2011), and remote sensing techniques (Ghaffarian and Kerle, 2019; Hansen et al., 2007; Jiang and Friedland, 2016; Koyama et al., 2016; Shirai et al., 2016; Szantoi et al., 2012). Individual debris categories investigated include building debris (García-Torres et al., 2017; Hayes et al., 2020; Hirayama et al., 2010; Wakabayashi et al., 2017), vegetative debris (Szantoi et al., 2012; Thompson et al., 2011), and household debris (T. Tabata et al., 2016). Disaster-dependent analysis includes hurricanes/typhoons (FEMA 2018a; Thompson et al. 2011; Umpierre and Margoles 2005), floods (Chen et al., 2007; Park et al., 2020), earthquakes (FEMA 2018c; García-Torres et al. 2017; Hancilar et al. 2010), and volcanic eruptions (Hayes et al., 2020). Upon detailed analysis of the debris amount and composition related studies, data needs are grouped into 13 categories: demographics, vegetation data, urban data, community-level building information, building-specific information, natural hazards statistics, hazard characteristics, area of impacted region, number of damaged structures, pre-disaster aerial imagery, pre-disaster satellite imagery, post-disaster aerial imagery, and post-disaster satellite imagery. The timelines associated with the data needs are identified to be either pre-disaster or response phase within the post-disaster period in line with Fig. 2 and as presented in Table 3. Post-disaster data for debris estimation need to be collected during the initial phase of disaster recovery as the quantity of the generated debris is a critical design parameter for subsequent disaster debris management and operations activities (Park et al., 2020).

The identified data categories serve distinct purposes. Certain categories are used to inform about the sources of the disaster-generated debris. These categories vary depending on the type of the debris to be quantified. Vegetation data (e.g., tree density, % tree cover, tree biomass, and land-cover classification) are used when estimating the amount of tree debris. When estimating building debris, data related to the built-environment have been used by researchers, with specific data categories varying based on the employed debris estimation method. For example, the Hazards US Multi-Hazard (HAZUS-MH) software developed by FEMA requires input information covering demographics (i.e., population count), building specific information (e.g., location and square footage), and community level building information (e.g., number of buildings by specific occupancy class) (FEMA, 2018c, 2018a, 2018b). The Earthquake Loss Estimation Routine (ELER) tool, developed by Hancilar et al. (2010), requires building specific information (e.g., structural system, height, and occupancy class) to estimate the amount

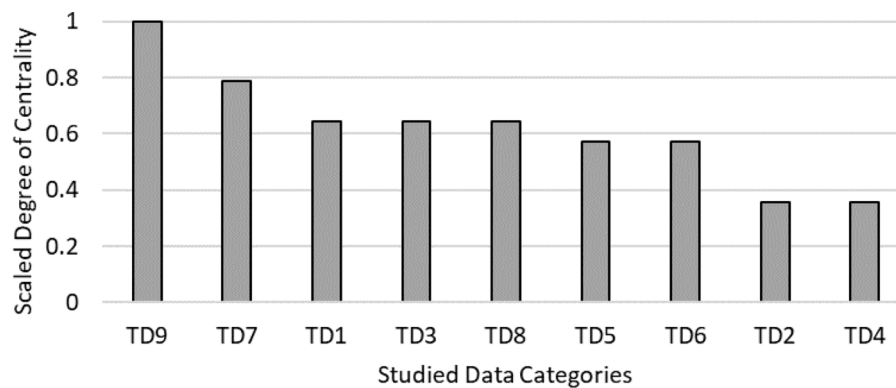


Fig. 5. Scaled degree centralities of identified data categories required for assessing the availability of TDMS.

of building debris resulting from earthquakes.

In addition to the source and composition of the debris, information about the disaster characteristics, often reported by national weather centers and geological surveys, is needed to inform the scale and magnitude of the generated debris. Depending on the nature of the disaster, distinct data are required. Hurricane-generated debris estimation models, such as HAZUS-MH Hurricane Model (FEMA, 2018a), the Hurricane Debris Estimating Model (HDEM) (FEMA, 2007), and the Hurricane Debris Estimation Tool (HurDET) (Umpierre and Margoles, 2005), require spatial hurricane wind data, storm category, and the hurricane track. The input parameters of earthquake debris estimation tools, on the other hand, include the longitude, latitude, depth, and magnitude of the earthquake (FEMA, 2018b; García-Torres et al., 2017; Hancilar et al., 2010). Along with the characteristics of the hazard, certain debris estimation methods require the area of the impacted region (Chen et al., 2007; Park et al., 2020) and the number of damaged structures (Park et al., 2020; USEPA, 2013) to simulate the disaster event and obtain the resulting damage profile.

When gathering ground-based information is time-consuming, logistically challenging and potentially dangerous, other data categories are used as a proxy to estimate the resulting damage from a disaster. For example, data under the disaster statistics category (Table 3) are used to quantify impacted structures and their damage states to estimate the amount of generated building debris. A number of studies (García-Torres et al., 2017; Hirayama et al., 2010; Wakabayashi et al., 2017) used natural hazard maps to determine the number of disaster-impacted dwellings, which were then multiplied by a basic unit of debris generation/dwelling to estimate the amount of resulting debris. Examples of debris unit generation rates provided in the literature are based on material intensity coefficients for disaster debris per building (Tabata et al., 2019; T. 2016) or material stock information; i. e., the quantities of materials used during the construction of a building (Poudel et al., 2018). Another substitute to collecting ground-based data is to use remote sensing techniques in the form of pre- and post-disaster aerial, drone, and satellite imagery. Examples of remote sensing data used in disaster debris estimation studies include Light Detection and Ranging (LiDAR) data (Hansen et al., 2007), satellite RapidEye data (Shirai et al., 2016), Synthetic Aperture Radar (SAR) data (Koyama et al., 2016), and unmanned aerial vehicle (UAV) images (Ghaffarian and Kerle, 2019). Cost and logistics are indicated to be critical considerations for aerial and satellite imagery data. Collecting satellite imagery is affected by cloud cover, whereas aerial imagery can be obtained below cloud ceilings. Acquisition of aerial imagery is limited by controlled airspace and indicated to be more expensive than the acquisition of satellite scenes (Jiang and Friedland, 2016).

The scaled degree centralities of the identified data categories required for disaster debris quantity estimation are presented in Fig. 4. The results indicate that AC7 (disaster characteristics) is the most significant data category for debris estimation, and it has been used by the

majority of debris estimation studies regardless of other types of data requirements in each study. Having detailed information about the disaster allows for representative simulations and well-calibrated debris estimation models for more accurate predictions of the amount of debris generated. AC10, AC11, AC12, and AC13 (pre- and post-disaster aerial and satellite imagery) have the lowest scaled degree centralities as these were rarely used with any of the other identified data categories in the reviewed debris estimation studies. Remote sensing studies typically included comparison of the satellite or aerial imagery collected before and after the occurrence of a disaster event; hence, no other type of data is usually required.

3.2. Availability of TDMS

Research related to TDMS can be primarily categorized under two groups: land suitability analysis studies to identify potential TDMS locations (Cheng and Thompson 2016, Grzeda et al. 2014, and Kim et al. 2018) and debris supply chain optimization studies to determine the required number of TDMS, location of the sites, and/or allocation of debris (Boonmee et al., 2018; Cheng et al., 2021; Kim et al., 2018; Onan et al., 2015; Wang et al., 2019). Depending on the main goal of the research, different types of data have been used, each serving a unique purpose. These data needs are grouped into 9 data categories: 1) hydrological data, 2) geological data, 3) urban data, 4) demographics, 5) TDMS operational data, 6) characteristics of the waste management system, 7) feasibility constraints, 8) debris characteristics, and 9) debris logistics (Table 4). The timeline associated with the data needs are identified to be mainly pre-disaster, with only the debris characteristics and debris logistics categories identified to belong to the response and short-term recovery phases, respectively.

The assessment of the suitability of potential TDMS locations is a complex process that is generally performed based on a set of criteria covering environmental, sociocultural, logistics, and ownership conditions (Grzeda et al., 2014). These criteria are assessed using specific types of data to ensure that the TDMS location is in compliance with regulations. In terms of environmental constraints, the TDMS should not be in a location where it can adversely impact components of the ecological system (e.g., groundwater) or in environmentally restricted areas (e.g., seismic fault zones and floodplains) (Grzeda et al., 2014). To enable such environmental assessment, hydrological and geological data of the study area are used. Further, a TDMS should not be located in close proximity to residential areas, schools, local businesses, or cultural features to avoid potential danger or disruption of operations (Cheng and Thompson, 2016), which are evaluated using demographics and urban data. Also, the TDMS location should provide suitable site ingress and egress, allow access to major routes, and minimize any disruption of traffic flow (Grzeda et al., 2014). These logistical constraints can be assessed using geospatial data mapping the transportation network of the disaster area. As for ownership, publicly owned lands are often

Table 5

Data needs identified and characterized for investigating the hazards and environmental concerns from disaster debris.

ID	Data Category	Data Types	Studies	Phase
HE1	Contaminants in the debris stream	Building registers, field sampling, testing of pest presence, handheld XRF units to detect CCA-treated wood, mobile radiation detectors to detect debris contamination with radioactive material, detection of mercury, polychlorinated biphenyls, and freon	(Brandon et al., 2011; Dubey et al., 2007; Karunasena et al., 2013; Kim and Hong, 2017; Pardue, 2006; Yesiller, 2011)	Pre-disaster, response, short-term recovery, and long-term recovery
HE2	Pollutants released during debris transportation	Carbon emissions of transportation vehicles, distance between debris sources, TDMS, and recycling/landfill facilities	(Amato et al., 2019; Boonmee et al., 2018; Habib et al., 2019; Hu and Sheu, 2013; Tabata et al., 2017; Wakabayashi et al., 2017)	Response, short-term recovery, and long-term recovery
HE3	Pollutants released at TDMS	Carbon emissions from TDMS	(Boonmee et al., 2018; Habib et al., 2019; Hu and Sheu, 2013; Lorca et al., 2017; Tabata et al., 2017; Wakabayashi et al., 2017)	Short-term recovery
HE4	Pollutants released at debris disposal facilities	Oil usage of heavy machinery, consumption rates of electricity and water in recycling facilities, carbon emissions of incinerators, carbon emissions in landfills, decomposition of biomass in landfills	(Amato et al., 2019; Boonmee et al., 2018; Habib et al., 2019; Hu and Sheu, 2013; Lorca et al., 2017; Tabata et al., 2017; Wakabayashi et al., 2017)	Long-term recovery
HE5	Debris recycling environmental benefits data	Mass of materials recovered, greenhouse gas savings, energy required to manufacture recycled materials from virgin sources	(Leader et al., 2018; Peng and Slocum, 2020)	Long-term recovery

preferred as potential TDMS locations over contracted private lands due to lower costs (Cheng and Thompson, 2016). Information about land ownership can be retrieved from parcel data used for urban planning.

Once a set of candidate TDMS locations are identified, optimization of the disaster debris supply chain follows by determining the optimal number and location of TDMS and allocation of debris. Operational data covering the size, debris processing capacity, and available resources for each candidate TDMS inform the total amount of debris that can be feasibly stored, separated, processed, and prepared for recycling (or landfilling). Coupled with the estimated total amount of debris generated, such information is used to determine the number of TDMS

needed. Subsequently, the optimal locations of the TDMS are selected from the candidate locations and debris is allocated to the selected TDMS using single or multi-objective mixed integer linear programming. Minimizing debris transport costs (Boonmee et al., 2018; Cheng et al., 2021; Wang et al., 2019) and debris removal and/or processing time (Cheng et al., 2021; Wang et al., 2019) are the most common objectives in debris supply chain optimization models. The cost and duration of debris transportation are mainly dependent on the debris hauling distance. Therefore, data mapping the debris location sources, potential TDMS locations, and existing waste management facilities are often used as input parameters to the optimization models to determine the debris hauling distance (Kim et al., 2018; Onan et al., 2015). In addition, data on the debris logistics (e.g., serviceability of the transportation network and available debris collection resources) are used to inform the cost and duration of debris collection and transportation. Other objectives in debris supply chain optimization include minimizing the social impact of the TDMS operations. Information on the demographics of the areas containing the TDMS is used to determine the amount of the population potentially exposed to the hazards resulting from the debris management operations at the TDMS (Onan et al., 2015).

The scaled degree centralities of the identified data categories required for assessing the availability of TDMS are presented in Fig. 5. The results indicate that TD9 (debris logistics) is the most significant data category, with data on the logistics of the debris removal operations (e.g., geospatial data mapping debris sources and TDMS), status of the transportation infrastructure, and available transportation resources identified as critical factors for optimizing the location of TDMS and the allocation of the collected debris to the selected TDMS. TD2 (geological data) and TD4 (demographics) have the lowest degree centralities, as these were the least used data categories with any of the other data in the reviewed studies.

3.3. Hazards and environmental concerns

The two main characteristics of data associated with hazards and environmental concerns identified in the literature are: i) detecting hazardous constituents in the debris stream with data varying as a function of the hazardous materials investigated (Brandon et al., 2011; Dubey et al., 2007; Karunasena et al., 2013; Kim and Hong, 2017; Pardue, 2006); and ii) environmental impacts of the disaster debris management system with data needs varying as a function of stage of debris management system (Amato et al., 2019; Boonmee et al., 2018; Habib et al., 2019; Leader et al., 2018; Peng and Slocum, 2020; Tabata et al., 2017; Wakabayashi et al., 2017). After a detailed analysis of the hazards and environmental considerations related studies, the data needs are grouped into 5 categories: 1) contaminants in the debris stream, 2) pollutants released during debris transportation, 3) pollutants released at TDMS, 4) pollutants released at debris disposal facilities, and 5) environmental benefits of recycling (Table 5). The timeline associated with the data needs are identified to extend over all data collection phases.

Identifying the extent of contaminants present in debris is crucial to investigate the condition of the debris and assess recyclability. Hazardous constituents vary with the debris stream requiring use of distinct detection methods and the collection of unique data sets. Building debris, can contain a range of hazardous components, including asbestos (in insulation, shingles, and flooring of old structures), lead (in old plumbing systems and lead-based paints), and wood treated by chromated copper arsenate (CCA) (Aydin, 2020; Brandon et al., 2011; Channell et al., 2009; Luther, 2006; Zhang et al., 2019; Zhao et al., 2010). The presence and amount of asbestos can be estimated as part of pre-disaster planning using registers of buildings in the studied disaster area (Kim and Hong, 2017) as well as through post-disaster testing; the presence of lead can be detected onsite using lead test kits; and CCA-treated wood can be detected using handheld XRF units (Dubey

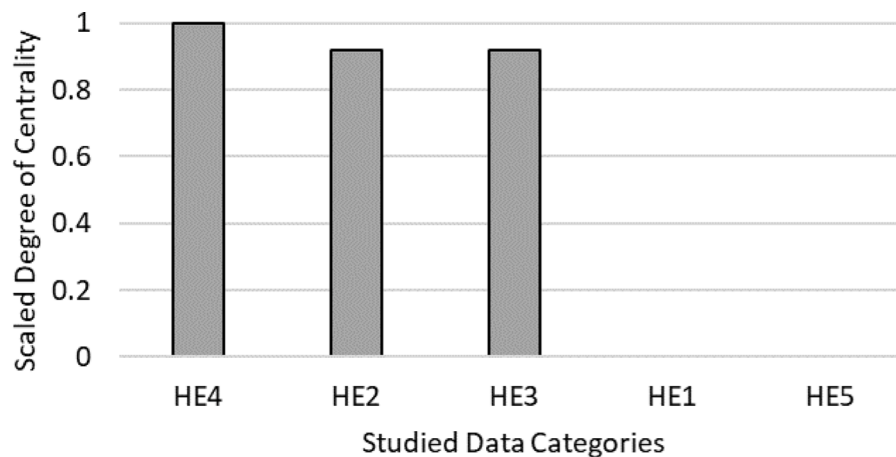


Fig. 6. Scaled degree centralities of identified data categories required for investigating the hazards and environmental concerns from disaster debris.

et al., 2007). The recyclability of electronic waste depends on the separation of constituents containing hazardous components including mercury (in electrical switching equipment) and polychlorinated biphenyls (in electrical transformers) (Brandon et al., 2011; Luther, 2006). The removal of refrigerants and organic matter is required for recycling white goods (Brandon et al., 2011; Luther, 2006). In areas with potential leakage, before disaster debris recycling programs are implemented, the debris should be screened for potential radioactive contamination which can be detected by mobile radiation detectors (Yesiller, 2011). In areas with pest concerns, vegetative debris should be screened for signs of pests (e.g., Formosan termites and ash borers) (USEPA, 2019).

For evaluating the environmental impacts of disaster debris management, environmental cost evaluation (Boonmee et al., 2018), greenhouse gas emissions or carbon footprint accounting (Amato et al., 2019; Habib et al., 2019; Peng and Slocum, 2020), and lifecycle assessment (LCA) (Tabata et al., 2017; Wakabayashi et al., 2017) have been used by researchers. Environmental burden is usually measured by quantifying the pollutants released during the various stages of the debris management process ranging from transportation, storage and processing at TDMS to material recovery facilities and landfills. Across these stages, carbon emissions have been considered by researchers (Amato et al., 2019; Habib et al., 2019; Tabata et al., 2017; Wakabayashi et al., 2017) as the main type of pollution pathway, since CO₂ is the main greenhouse gas contributing to global climate change (Ahmed and Sarkar, 2018). Since recycling operations at material recovery facilities require the use of heavy equipment, quantifying pollutants released at this stage requires the assessment of additional data including oil usage and electricity consumption rates of heavy machinery. Along with investigating the potential negative impacts of the disaster debris management system on the environment, it is also important to study the potential benefits from transitioning to a sustainable system. Debris recycling benefits are estimated using data on the reductions and savings in emission intensities and energy requirements of manufacturing end-use products from virgin sources as opposed to using recycled materials (Leader et al., 2018).

The scaled degree centralities of the identified data categories required for investigating the hazards and environmental concerns from disaster debris are presented in Fig. 6. The results indicate that HE4 (pollutants released at debris management facilities) is the most significant data category. A zero-degree centrality for HE5 (recycling environmental benefits data) implies that the environmental benefits of recycling disaster debris have rarely been considered in previous studies. Prior studies focused on the negative environmental impacts of debris management operations only, without taking into account the reduction in pollutants released and the energy savings resulting from recycling disaster debris in place of manufacturing new materials from virgin sources. HE1 (contaminants in the debris stream) also had a

degree centrality of zero, indicating that this data type was not cited or used with any of the other identified data categories in the studies reported in literature. However, this finding does not indicate that detecting contaminants and separating these from the debris stream are not significant for post-disaster debris management. The low degree centrality revealed that the studies addressing the hazardous constituents of the debris stream and their impact on the public and the environment did not necessarily study the impact of the debris management operations on the environment.

3.4. Economics

The term economics is used herein to refer to the cost and revenue arising during different phases of debris management processes. In general, economic aspects have almost always been incorporated in disaster debris management research, particularly in studies that evaluate the efficiency of the debris management process, optimize debris cleanup and treatment, or develop a decision-support tool for post-disaster debris management operations (Aydin, 2020; Boonmee et al., 2018; Cheng et al., 2021; Fetter and Rakes, 2012; Habib et al., 2019; Leader et al., 2018; Lorca et al., 2015; Peng and Slocum, 2020; Wakabayashi et al., 2017; Wang et al., 2019). After a detailed analysis of the economics studies, the data needs are grouped into 4 categories: 1) debris transportation, 2) TDMS management and operations, 3) debris recycling costs, and 4) debris recycling revenues (Table 6). The timeline associated with data needs all fall under the post-disaster period, as the costs associated with managing the debris and potential recycling revenues are dependent on the unique characteristics of the generated debris and local conditions (i.e., location of the disaster-impacted area and market conditions).

Direct economic effects of the debris management processes include the costs associated with the debris operations and the potential revenues from recycling, all of which are typically assessed using publicly available data or data obtained from debris management facilities (Zhang et al., 2019). To compute the cost of collecting and transporting disaster debris, researchers used one of two approaches: i) cost per unit distance of transporting the debris coupled with the distances between the debris source locations, TDMS, and subsequent recycling/disposal facilities (Boonmee et al., 2018); or ii) unit hourly cost of transport truck operations coupled with the capacities of transport trucks, transport speed, loading/unloading time, and number of trips per day (Wakabayashi et al., 2017). For the debris operations at TDMS and recycling facilities, the total cost consists of fixed capital costs (i.e., cost of opening each TDMS and recycling facility) and variable operating costs (e.g., labor wages, debris handling costs, and debris processing costs). To compute revenues from recycling, the amount of sellable material recovered or recycled is needed, along with the unit selling price, which

Table 6

Data needs identified and characterized for economics of disaster debris operations.

ID	Data Category	Data Types	Studies	Phase
E1	Debris transportation cost data	Distance between debris source, TDMS, and recycling/landfill facilities, fuel costs, truck load capacity, unit hourly cost of truck operation, hourly labor wages, number of trips per day, maintenance and repair costs	(Amato et al., 2019; Cheng et al., 2021; FEMA, 2007; Habib et al., 2019; Hu and Sheu, 2013; Leader et al., 2018; Lorca et al., 2015; Peng and Slocum, 2020; Tabata et al., 2017; Wakabayashi et al., 2017; Wang et al., 2019)	Response, short-term recovery, and long-term recovery
E2	TDMS cost data	Fixed cost of opening each TDMS, hourly labor wages, handling costs, cost of operating each RSR technology at each TDMS, costs of debris chipping and drying costs at TDMS computed as a function of the moisture content of the debris	(Cheng et al., 2021; Fetter and Rakes, 2012; Habib et al., 2019; Hu and Sheu, 2013; Lorca et al., 2015; Peng and Slocum, 2020; Tabata et al., 2017; Wang et al., 2019)	Short-term recovery
E3	Debris recycling cost data	Fixed cost of installation of recycling plants, cost of operating each technology at each recycling facility, recycling rate, landfilling rate, hourly labor wages at treatment and disposal facilities	(Amato et al., 2019; Fetter and Rakes, 2012; Habib et al., 2019; Hu and Sheu, 2013; Leader et al., 2018; Lorca et al., 2015; Tabata et al., 2017)	Long-term recovery
E4	Debris recycling revenue data	Volume of sellable material recovered or recycled, unit price of recovered or recycled material	(Amato et al., 2019; FEMA, 2007; Fetter and Rakes, 2012; Hu and Sheu, 2013; Leader et al., 2018; Tabata et al., 2017; Wang et al., 2019)	Long-term recovery

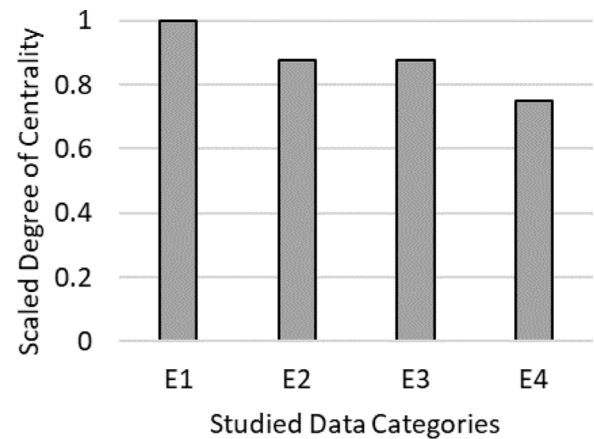


Fig. 7. Scaled degree centralities of identified data categories required for economics of disaster debris operations.

Table 7

Data needs identified and characterized for studying social considerations with regards to disaster debris.

ID	Data Category	Data Types	Studies	Phase
SC1	Levels of social capital	Structural social capital (i.e., "bonding", "bridging", and "linking"), cognitive social capital (i.e., "trust", "interaction and exchange" and "social participation")	(Joshi and Aoki, 2014; Kawamoto and Kim, 2019, K. 2016)	Short-term recovery
SC2	Public involvement in debris operations	Factors influencing the willingness of the public to support the plans of their governments to accommodate disaster debris, amount of debris processed by community members	(Aoki, 2018; Cook, 2009)	Short-term recovery
SC3	Status of the debris removal operations	Total debris removal time	(Hu et al., 2019; Hu and Sheu, 2013)	Short-term recovery
SC4	Recycling social benefits	Number of job opportunities generated during disaster waste recycling	(Habib et al., 2019)	Long-term recovery

3.5. Social considerations

There is limited work on social considerations associated with disaster debris management with mostly qualitative (Allen, 2007; Aoki, 2018; Cook, 2009; Joshi and Aoki, 2014; Kawamoto and Kim, 2019, K. 2016) and few quantitative investigations (Habib et al., 2019; Hu et al., 2019; Hu and Sheu, 2013). The data needs are grouped into 4 categories: 1) levels of social capital, 2) public involvement in debris operations, 3) status of the debris removal operations, and 4) social benefits of recycling (Table 7). The timeline associated with social data needs all fall under the post-disaster recovery phases.

Qualitative research on the social aspect of disaster debris management used data collected from surveys on how affected communities are involved in the disaster management process and investigated corresponding levels of social capital. Public involvement was assessed by examining the impacts of missing population on the disaster debris

is often considered volatile and highly dependent on market conditions.

The scaled degree centralities of the identified data categories required for disaster debris economics are presented in Fig. 7. The results indicate that E1 (debris transportation cost data) is the most significant data needs category. The majority of the studies on economics of the debris operations highlight and investigate the costs of transporting disaster debris emphasizing the amount of the debris removal and transportation costs relative to the rest of the debris operations costs. Overall, the data needs were all relatively significant with low variation among the specific data categories. Similar to the observations for the environmental aspects of disaster debris operations, studies on the economics of disaster debris operations did not commonly account for the economic benefits of recycling disaster debris.

Table 8

Data needs identified and characterized for studying the funding policies pertaining to disaster debris operations.

ID	Data Category	Data Types	Studies	Phase
FP1	Debris management planning	Applicable laws and regulations governing the management of disaster debris in the area under study	(Crowley, 2017; Crowley and Flachsbart, 2018; Luther, 2010; Woody et al., 2020; Yusof et al., 2016)	Pre-disaster
FP2	Monitoring requirements for reimbursement	Number of hours of actual emergency debris clearance work, documentation of truck loads (i.e., load tickets), actual quantities of debris removed, total revenue earned from recycling	(FEMA 2012, 2020)	Response and short-term recovery, and long-term recovery

management process (Cook, 2009) and the factors affecting public acceptance of local debris management plans (Aoki, 2018). Social capital, which is considered crucial for recovery from disasters and a significant element of community resilience (Aldrich, 2010; Babu, 2008; Chamlee-Wright and Storr, 2009; Nakagawa and Shaw, 2014), has been linked to the level and efficiency of the debris management operations (Kawamoto and Kim, 2019; K. 2016) and the implementation of national recovery policies from disasters (Joshi and Aoki, 2014). Since surveys are the main collection method for qualitative social data, challenges are common with regards to the reluctance or refusal of disaster-impacted community members to participate in surveys following a disaster event.

Social considerations or community priorities also were quantitatively accounted for in studies that included holistic optimization of the disaster debris management process. The social aspect was considered by trying to minimize debris removal waiting time, which impacts the psychological recovery of communities (Hu et al., 2019; Hu and Sheu, 2013), and by aiming to maximize job opportunities associated with disaster debris management, in particular in recycling operations (Habib et al. 2019).

3.6. Funding policies

The investigation of funding policies associated with disaster debris management is highly limited with the lowest number of studies identified in literature in this investigation. The 2 main categories of data needs identified were: 1) qualitative data informing about disaster debris management planning and 2) quantitative data in the form of monitoring requirements for debris management cost reimbursement (Table 8). The timelines associated with data needs included both pre- and post-disaster durations.

Applicable regulations and funding mechanisms pertaining to disaster debris management directly impact the effectiveness of debris management programs and whether recycling is employed. Collecting qualitative information about corresponding laws and guidelines is required for debris management planning. In the United States, FEMA provides guidance to state and local governments on planning for management of debris following a disaster. Prior studies investigated compliance of debris management plans with regulations (Crowley and Flachsbart, 2018); effects of pre-disaster debris management plans on post-disaster debris management efficiency (Crowley, 2017); and challenges and issues in the policies relating to disaster debris management (Luther, 2010; Woody et al., 2020; Yusof et al., 2016).

With well-monitored disaster debris management operations, chances to receive reimbursements and additional funds are high, and accordingly the feasibility of recycling increases. In the United States, FEMA requires the submission of detailed monitoring information to authorize funds for cost reimbursement. Such requirements are often in the form of quantitative data that records details of the debris management operations, including documentation of debris truck loads, amount of debris removed, and the revenue generated from debris recycling (FEMA 2012, 2020). Collection of such data often requires trained personnel to perform accurate monitoring and extensive documentation of the debris operations.

4. Discussion and recommendations

4.1. Knowledge gaps in quantitative sustainable disaster debris management research

While aiming to present valuable information and guidelines that can serve as the seed for reliable, quantitative, and sustainable debris management practices, certain gaps in the current body of knowledge were found. The majority of the reviewed scholarly work focused on technical aspects such as quantification of disaster debris amounts and recycling supply chains. The feasibility of sustainable debris management practices depends not only on technical factors but also on socio-economic factors that are scarcely studied in the literature, which prevented fully identifying data needs and prioritizing data collection.

With regards to the social aspects of sustainable disaster debris management, there is a need for more quantitative research on the social considerations pertaining to debris reuse and recycling, as highlighted in recent studies (Hu et al., 2019; Zhang et al., 2019), for a systematic decision-making process. In addition, while public health risks and environmental threats have been identified in the literature as sources of social concerns in disaster debris management (Aoki, 2018), further investigation of their impacts on the debris management operations, particularly in terms of debris collection time and location of debris management facilities, is needed. The feasibility of debris recycling may be impacted, especially when affected communities adopt a NIMBY (not-in-my-backyard) attitude towards the location of TDMS and recycling facilities, which operate most efficiently when located near the affected areas. Equity concerns and environmental injustice, which have been associated with debris management activities in some previous disaster events (Allen, 2007), also need to be further studied to facilitate development of sustainable and equitable disaster debris management plans that address the vulnerabilities and prioritize the needs of minorities and impoverished communities. Consideration of social equity and environmental injustice in sustainable management of disaster debris is of increasing significance to effectively assist disadvantaged communities in mitigating the intensifying effects of global climate change.

Current guidelines and studies on funding provide general disaster debris funding policies and requirements, which often justify the debris treatment method with the lowest direct cost in place of identifying sustainable alternatives such as debris reuse and recycling. Few regulatory agencies attempt to incentivize or promote recycling/reuse in disaster affected communities. The lack of such incentives or funding sources to acquire the needed technology and equipment for recycling can create a critical barrier to implementing eco-industrial, sustainable practices in post-disaster debris management (Ardani et al., 2009). In addition to the recycling and recovery infrastructure, the pre-establishment of an eco-industrial network within a given community will provide the necessary framework for local industries, recycling and recovery facilities, waste management authorities, and citizens to partner and cooperate during the disaster response and recovery effort to promote holistic sustainable debris management practices (Ardani et al., 2009). Funding mechanisms are recommended to be investigated broadly with consideration not only to short-term cost considerations,

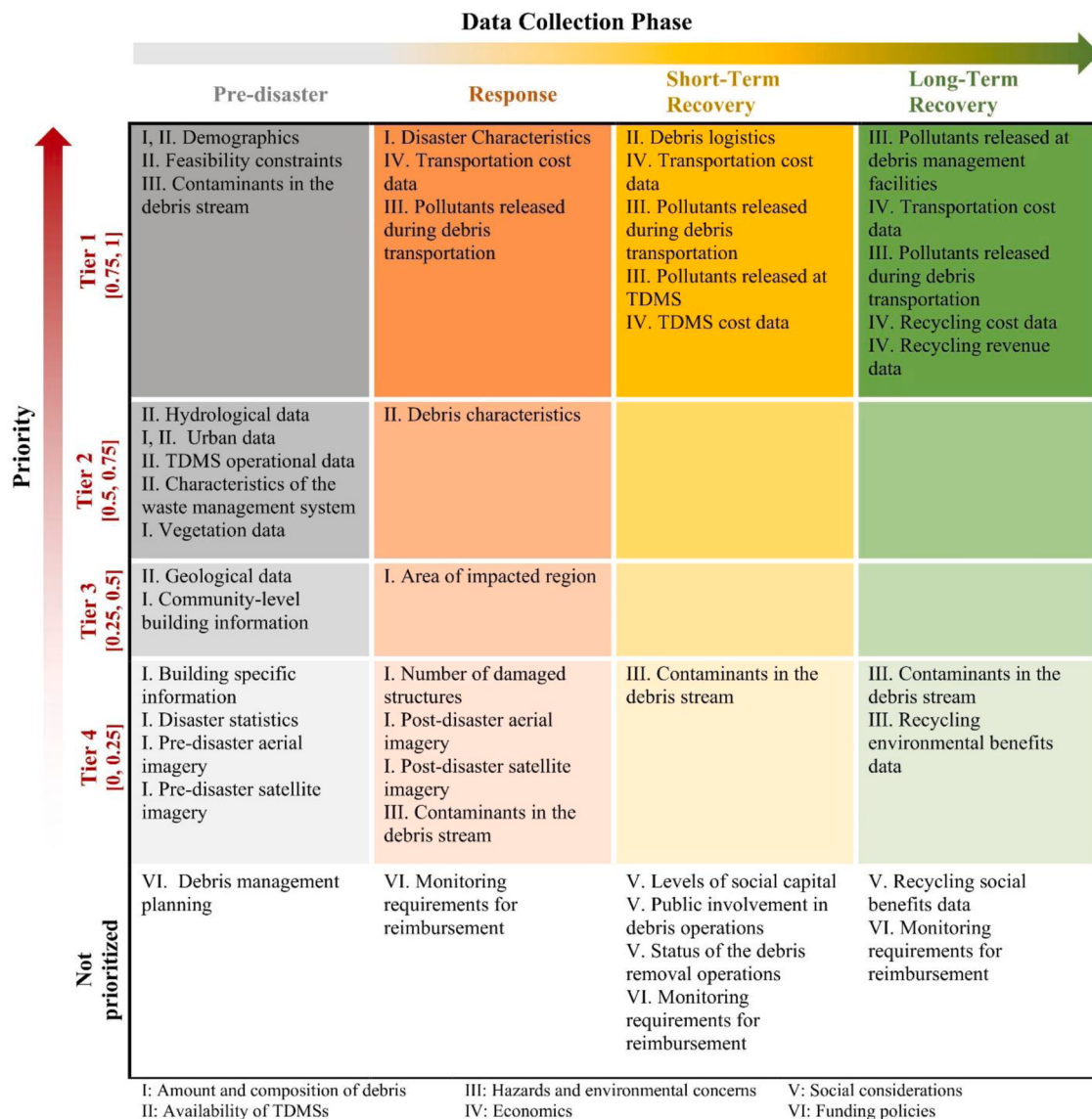


Fig. 8. Priority data categories for quantitative sustainable disaster debris management.

but with long-term considerations inclusive of lifecycle of the disaster debris in a circular economy setting and while applying principles of industrial ecology, which involve perceiving waste as a resource (Fatimah et al., 2019; Sandrucci et al., 2017). Large-scale beneficial reuse of disaster debris and wastes can significantly advance sustainable management of post-disaster materials and provide an innovative lifecycle application beyond cradle-to-cradle extending into circular economy and sustainable resilience (Blomsma, 2018; Gillespie-Marthaler et al., 2019; McDonough and Braungart, 2002).

4.2. Towards a systematic disaster debris data collection

To advance quantitative sustainable disaster debris management research, the collection of relevant technical and socioeconomic data needs to be prioritized across all distinct phases of the disaster debris management process. Fig. 8 provides a high-level overview of the main data categories identified for each of the primary aspects that impact the feasibility of sustainable management of disaster debris. The data categories are organized horizontally based on timeline of the occurrence of a disaster event and vertically based on priority, except for the data under social considerations and funding policies. The data prioritization was based on how frequently each data category was used in literature

and presented using four tiers that equally divide the range of the calculated scaled degree centrality (0 to 1).

The number of the identified data categories is inconsistent across the six main aspects of sustainable disaster debris management, where more researched aspects resulted in a higher number of data needs. The amount and composition of debris had been widely investigated with several proposed debris estimation approaches, each of which requires distinct data needs grouped into a high number of data categories. From the timeline perspective, a considerable portion of the identified data categories belongs to the pre-disaster phase, which emphasizes the significance of pre-disaster planning and preparedness. Pre-disaster planning facilitates development of enhanced debris management approaches (Channell et al., 2009), estimating required resources before a disaster event (Aydin, 2020), and affects the resulting disaster loss (He and Zhuang, 2016). The data categories under the pre-disaster phase are mostly used to estimate the potential amount of debris that will be generated by disaster events and to identify suitable locations for TDMS. The identification of the data types belonging to these categories revealed that data collection requires input from various sources at different levels of governance (i.e., federal, state, and local governments) and also the affected community. Aggregating diverse databases (e.g., cadasters, environmental geodatabases, census data, building

inventories, and waste management infrastructure mappings) requires the development of comprehensive debris management inventories that efficiently coordinate datasets and host all information relevant to sustainable debris management planning (Derrible et al., 2019).

The post-disaster phases have approximately equal numbers of identified data categories, with most identified to be high priority. It should be noted that even though certain data categories (e.g., contaminants in the debris stream) are ranked low (i.e., tier 4) based on the frequency of use in the literature, the low rating does not indicate low importance but only low occurrence in the literature. Similarly, remote sensing data acquisition and analysis are ranked low due to limited data in these areas related to disaster debris management. We expect that the application of such technologies will increase in time and the technologies will provide critical data in identifying the location of debris streams, in particular in remote areas; determining the quantity of debris masses; identifying different materials within the debris streams; and tracking movement of the debris through various stages of debris management processes. In this regard, post-disaster data collection can be improved by integrated specialized reconnaissance investigations over large geographical areas using state-of-the-art instrumentation and mobile data collection applications. Reconnaissance missions conducted along the post-disaster phases outlined herein will ensure the collection of relevant data before possible disruptions from response and recovery activities or natural phenomena such as wind or precipitation (Wartman et al., 2020). Such missions can be achieved through the establishment of specialized disaster reconnaissance organizations, similar to the Extreme Event Reconnaissance (EER) organizations established in the United States as part of the Natural Hazards Engineering Research Infrastructure (NHERI) initiative (Peek et al., 2020). These organizations bring together and train investigators with interdisciplinary knowledge to collect multifaceted post-disaster debris data based on detailed reconnaissance guidelines. Collected data can be subsequently processed and disseminated through dedicated cyberinfrastructure and data workflow, similar to the DesignSafe cyberinfrastructure component of NHERI (Rathje et al., 2020). Through specialized cloud-based tools and data repositories, collected disaster debris data can be transformed, analyzed, and publicly shared to be used in advancing sustainable disaster debris management research.

5. Conclusions

Disaster events often generate substantial amounts of debris that can impede the recovery of disaster-impacted areas and overwhelm the existing waste management systems. Recycling and reuse can reduce environmental impacts of debris, divert debris from landfills, positively affect the social recovery of impacted communities, and result in value creation in the form of recycled end-use products. The authors systematically reviewed the existing body of knowledge related to sustainable disaster debris management with the aim of holistically identifying the data and analysis requirements for investigating the main technical, economic, and social aspects that affect the feasibility of disaster debris recycling and reuse. This study (1) established a knowledge base on the data requirements for quantitative sustainable disaster debris management, (2) characterized the identified data based on the time-sensitive nature of debris materials using a four-phase data collection framework, and (3) used social network analysis to quantitatively identify the data categories that are more significant to prioritize collection.

The findings indicate that a wide range of multifaceted data has been used by researchers investigating and developing approaches to efficiently quantify, characterize, and allocate disaster waste among sustainable debris management pathways. While this is the case when focusing on the technical aspects of sustainable debris management practices, the social and funding aspects are inadequately explored, thus limiting the identification of associated data needs. Further research, particularly in a quantitative manner, is needed in these two areas to enable a more holistic and systematic decision-making framework for

disaster debris management. In addition, the characterization of the identified data needs indicated that comprehensive debris management inventories need to be established to host all relevant datasets that are part of pre-disaster preparedness and planning. Integrated multiple reconnaissance undertakings are critical to capture the post-disaster data in a timely manner while prioritizing collection. Ultimately, the information presented in this research will lead to a more informed, data-based, and systematic research on sustainable disaster debris management practices to enable and facilitate future debris recycling and reuse efforts.

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.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.resconrec.2022.106174](https://doi.org/10.1016/j.resconrec.2022.106174).

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