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Disaster Waste Management: a Review Article

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Abstract

Depending on their nature and severity, disasters can create large volumes of debris and waste. The waste can overwhelm existing solid waste management facilities and impact on other emergency response and recovery activities. If poorly managed, the waste can have significant environmental and public health impacts and can affect the overall recovery process.

This paper presents a system overview of disaster waste management based on existing literature. The main literature available to date comprises disaster waste management plans or guidelines and isolated case studies. There is ample discussion on technical management options such as temporary storage sites, recycling, disposal etc.; however, there is little or no guidance on how these various management options are selected post-disaster. The literature does not specifically address the impact or appropriateness of existing legislation, organisational structures and funding mechanisms on disaster waste management programmes, nor does it satisfactorily cover the social impact of disaster waste management programmes.

It is envisaged that the discussion presented in this paper, and the literature gaps identified, will form a basis for future comprehensive and cohesive research on disaster waste management. In turn, research will lead to better preparedness and response to disaster waste management problems.

Keywords: disaster waste; disaster debris; disaster recovery; emergency management; disaster strategy.

Vitae

Charlotte Brown B.E. (Hons)(Civil) is a PhD student carrying out research into the strategic management of waste following disasters. Charlotte has five years professional experience as a civil engineer, specialising in solid waste engineering. Charlotte has experience working in both developed and developing country contexts.

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1 Introduction

Disasters occur in many forms: natural or man-made; sudden onset (such as earthquake, fire, flood, tsunami, hurricane, and volcano) or prolonged onset (such as civil conflict or drought); with varying degrees and types of physical and social impacts:

> *"A disaster is a non-routine event that exceeds the capacity of the affected area to respond to it in such a way as to save lives; to preserve property; and to maintain the social, ecological, economic and political stability of the affected region"*
> *(Pearce, 2000 cited in (FEMA, sourced 2009))*

Depending on their nature and severity, disasters can create large volumes of debris and waste. In a review of past disasters in the United States (US), Reinhart and McCreanor (1999) calculated that in some cases debris volumes from a single event were the equivalent of five to fifteen times the annual waste generation rates of the affected community. Similar ratios were found by Basnayake (2006) following the 2004 Indian Ocean tsunami. These volumes often overwhelm existing solid waste management facilities and personnel.

The presence of disaster waste impacts almost every aspect of an emergency response and recovery effort. In the immediate response disaster debris can cause road blockages. Following the 1995 Great Hanshin-Awaji earthquake in Japan, road blockages prevented building access which in turn impeded rescuers, emergency services and lifeline support reaching survivors (Kobayashi, 1995). Waste presence in a community also poses a potential public health risk. Organic wastes and standing pools of water (potentially caused by debris blocking flow paths) can become vector breeding grounds. Vector-borne diseases are a common form of communicable disease experienced post-disaster, particularly when there are large numbers of people displaced. However, the risk of outbreak is relatively low (Watson et al., 2007).

In the longer term, poor management of a clean-up can result in a slow and costly recovery. The prolonged exposure to the waste is potentially risky to public and environmental health, as identified by Srinivas and Nakagawa (2008) in post 2004 Boxing Day tsunami, Sri Lanka. If managed effectively, debris can become a valuable resource in the recovery and rebuilding process and can have a positive effect on social and economic recovery.

Improved standards for built infrastructure are decreasing the probable impact of disasters in many communities, however, increased urbanisation and dependence on complex infrastructure networks increases a community's vulnerability to a disaster. Good planning and coordination for response to disaster events is essential to minimise disruption (Gordon and Dion, 2008).

The majority of literature available on disaster waste and debris management comprises one-off case studies and debris management planning guidelines. It is a feature of disaster research that research studies are often isolated and event-specific (Chang, 2010). Issues of variability between disasters, time limitations and data access difficulties all make it difficult for quantitative, cross-disaster studies. Table 1 lists references specific to individual disasters. The table is ordered first by disaster and secondly in chronological order. Debris management planning guidelines (Solis et al., 1995; USEPA, 1995b; FEMA, 2007; USEPA, 2008; WRCDEMG, 2008; Johnston et al., 2009; JEU, 2010) generally give a range of technical and management options for disaster waste. Technical aspects include: collection and transportation; temporary debris storage; recycling; disposal; hazardous waste handling and disposal. Management aspects include: communication strategies; contract management; organisational roles and responsibilities; record keeping; MOU establishment. The guidelines are based on existing institutional frameworks (legislative, organisational and financial) applicable to the given context.

Table 1 Disaster waste management references

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In addition there are a limited number of cross case study analyses (Lauritzen, 1995; 1996/1997; 1998; Reinhart and McCreanor, 1999; Baycan and Petersen, 2002; Petersen, 2004), and technical academic studies (Dubey et al., 2007; Inoue et al., 2007; Rafee et al., 2008; Hirayama et al., 2009; 2010). The US Army Corps of Engineers (Channell et al., 2009) and Ekici et al (2009) give broader reviews, but are still limited to the US context and to technical aspects of debris management. Karunasena (2009) proposes to review disaster waste management in developing countries with an emphasis on the Sri Lankan context. However, the majority of the literature cited is US based and there is no analysis of the contextual relevance of US derived practices in developing countries.

The purpose of this review is to critically analyze the available literature, outline the key features (technical, managerial and institutional) of disaster waste management, identify the missing links in our ability to manage the problem, and establish a platform for future research on disaster waste management.

The review analyzes eight key aspects of disaster waste management:

- Planning
- Waste – including waste composition, quantities, and management phases
- Waste treatment options
- Environment
- Economics

- Social considerations
- Organisational aspects
- Legal frameworks
- Funding

For each theme there is a discussion on the issues identified in the literature. Key gaps in the current knowledge base are discussed in Section 3. A distinction will be made between developed and developing countries where this distinction strongly influences disaster waste management approaches.

2 Aspects of Disaster Waste Management

2.1 Planning

2.1.1 Developed countries

With the increasing frequency and severity of natural disasters, efficient, effective and low impact recovery is becoming increasingly important. The need to plan for disaster debris and waste has only been recognised since the development of the United States Environmental Protection Agency's (USEPA's) "Planning for Disaster Debris" (USEPA, 1995b) (updated in 2008 (USEPA, 2008)).

The USEPA planning documents are built from the experience of previous events in the US and are framed around existing legislation, organisational structures and funding mechanisms (referred to here collectively as institutional frameworks) as per the Federal and Emergency Management Agency (FEMA) debris management guidelines (FEMA, 2007). The guidelines give a range of technical and management options for disaster waste (as defined in Section 1). Specific disaster waste management plans are the responsibility of individual municipalities, for example plans prepared by the State of California (1997) and Louisiana Department of Environmental Quality (LDEQ, 2006). Recently, FEMA introduced an incentive programme, by way of increased cost share of any future disaster debris management responses, to encourage municipalities to prepare debris management plans (USEPA, 2008).

In addition to plans, in 2003 the USEPA launched a web-based information tool called USEPA's Suite of Disaster Debris Management and Disposal (DDMD) Decision Support Tools (Thorneloe et al., 2007). The tools are essentially a database for US users with GIS capacities, where the database includes technical information on safe waste handling, disposal options, facilities (including facility waste acceptance criteria, operator contact details), environmental and operational regulations and sample contract documents.

Many authors and government authorities outside the US have also recognised the importance of preparing disaster waste management plans - (Skinner, 1995; Solis et al., 1995; Jackson, 2008; WRCDEMG, 2008; Johnston et al., 2009) but few country or location specific guidelines exist. Many of the recommendations of these documents are based on the USEPA's guidelines and/or take a similar form. While the USEPA's documents are comprehensive from a technical and general management perspective, they are prepared alongside the FEMA emergency management system and guidelines (FEMA, 2007) which, as stated above, are based on institutional frameworks specific to the US. When transferring the USEPA guidelines to other contexts, authors do not seem to recognise the influence of these institutional frameworks and the need to assess and potentially develop context specific institutional frameworks for disaster waste management.

These tools and guides are comprehensive technical ‘how-to’ guide on debris management. However, these plans give little guidance on decision-making and option consideration in different disaster situations. There are also no guidance documents that can be readily transferrable to other developed world contexts, in particular with regard to the establishment of effective organisational, financial and legal structures for disaster waste management.

2.1.2 Developing countries

In 2005, the Hyogo Framework (ISDR) was developed to reduce disaster risk, particularly in vulnerable developing economies. Planning for disaster recovery, including management of disaster waste, is part of the disaster risk reduction strategy. However, financial, technical and expert resources in developing countries are generally a limiting, if not prohibitive, factor in achieving disaster risk reduction goals.

Consequently, disaster waste management plans in developing countries seldom exist. In many cases ‘peace time’ solid waste management programmes do not even exist – indicating that solid waste management is a low priority. The United Nations (UN) Joint Environmental Unit (JEU) have recently prepared draft currently preparing disaster waste management guidelines specifically for developing countries (JEU, 2010). This work builds on earlier work by Petersen and Baycan (2002). The work currently covers many of the technical issues addressed in the USEPA guidelines, but management and implementation strategies are designed for countries with little or no existing infrastructure and/or waste management expertise. Opportunities for livelihood promotion and maximising value from the resources are also emphasised in the draft document.

Two isolated research studies identified a range of technical, managerial and institutional factors that may be limiting factors in the future management of disaster waste. Karunasena et al. (2009) carried out an analysis of Sri Lanka's preparedness to manage disaster waste. Rafee et al. (2008) made an assessment of the likely capability of the city of Tehran to manage earthquake waste.

Aside from the JEU document, there are several documents available to guide first responders specifically in dealing with disaster waste. These include: World Health Organisation "Solid Waste Management in Emergencies" (WHO, 2005); Guidelines for Safe Disposal of Unwanted Pharmaceuticals in and after Emergencies (WHO, 1999); and the UNEP/OCHA Joint Environmental Unit "Initial clearing and debris removal" (JEU, 2006). In addition there are several emergency management handbooks that cover all aspects of emergency recovery including brief sections on waste management. Resources include Engineering in Emergencies (Davis and Lambert, 2002) and the UNHCR Handbook (2000). All these documents cover solid waste disposal very generally and tend to focus on immediate management of waste generated in an emergency, in particular, municipal wastes in displaced populations, refugee camps, or where solid waste infrastructure is not functioning. They do not generally cover management of disaster-generated waste.

There are currently numerous guides and tools available for handling hazardous wastes (both in emergencies and in general), including “A Brief Guide to Asbestos in Emergencies: Safer Handling & Breaking the Cycle” (Shelter Centre, 2009), and the Hazard Identification Tool (OCHA, 2009). Environmental assessment tools and guides are also available such as the Flash Environmental Assessment Tool (VROM et al., 2008) and the Environmental Needs Assessment in Post Disaster Situations (UNEP, 2008). These tools are not currently integrated into the disaster waste management plans / guides discussed above.

As for the planning guidelines discussed in Section 2.1, these guides are limited to technical interventions. They fail to address the managerial and institutional components that influence the effectiveness of a disaster waste management system such as funding, legislative considerations and organisational planning.

2.2 Waste

2.2.1 Waste composition

It is well recognised that different types of waste are generated depending on both the type of built environment impacted (coastal/inland, urban/rural), and the type of disaster (Kobayashi, 1995; Solis et al., 1995; Reinhart and McCreanor, 1999; USEPA, 2008). The variation occurs both in composition and manageability (ability to recycle, level of hazards, handling procedures required, etc.). Waste managers following Hurricane Katrina, for example, were challenged by the mixture of hurricane and flood-generated debris (Luther, 2008) because each required different management approaches.

The waste streams generated by disasters are:

- vegetative debris or greenwaste
- sediment / soil and rock
- household hazardous waste (refrigerant, oils, pesticides, etc)
- construction and demolition debris from damaged buildings and infrastructure (such as roads, pipe networks and other services)
- industrial and toxic chemicals (including fuel products) (Lindell and Perry, 1998; Selvaduray, 1998)
- putrescible wastes (such as rotting food)
- vehicles and vessels
- recyclables (plastics, metals etc.)
- electronic and white goods
- waste from disaster-disturbed pre-disaster disposal sites (Pilapitiya et al., 2006; UNDP, 2006; O'Grady, 2009; Sagapolutele, 2009)
- human and animal corpses

The largest component of urban disaster waste would meet the peace-time classification of construction and demolition (C&D) waste. Some components of this waste stream pose a potential health risk in peace-time which could be exacerbated post-disaster where volumes are significantly increased. These include; asbestos, arsenic treated woods (Dubey et al., 2007), gypsum leaching

(Jang and Townsend, 2001a; USEPA, 2008) and organic pollutants (Jang and Townsend, 2001b).

In addition to disaster generated waste, authors have identified other waste streams that can be indirectly generated post-event, including: excessive unwanted donations (Ekici et al., 2009), large amounts of health care wastes (Petersen, 2004), rotten food from power outages (Luther, 2008) and emergency relief food packaging (Solis et al., 1995).

Municipal waste must also be managed if the disaster affected community is still living in the area. Municipal waste collections should be considered when planning and/or implementing a disaster waste system (Baycan and Petersen, 2002). If not, municipal waste may be mixed with disaster debris (Jackson, 2008) – presenting a public health hazard, making it more difficult to separate the wastes (Baycan and Petersen, 2002) and, in the US, making it ineligible for collection under FEMA regulations (FEMA, 2007).

The terms waste and debris are used differently by different authors. But in general, debris refers specifically to largely inert building and vegetative materials generated by the disaster, and waste refers to the entire waste matrix, including post-disaster municipal waste.

Some authors use a simple matrix to identify expected waste categories from different disasters (see Table 2 for disasters in the US). Other authors describe not only the types of waste expected but the location and nature of waste expected and how that may impact on debris management options. As examples USEPA (2008) describe how hurricane storm surges can move industrial wastes away from their source site thereby impacting on the wider community and increasing industry clean-up responsibility; Reinhart and McCreanor (1999) observed that tornado debris in the US was often so twisted it was difficult to separate and therefore recycle; and in Haiti, following the 2010 earthquake, it was observed that communities were unable to contribute to the clean-up effort due to the weight of the collapsed masonry structure which required heavy machinery to move (Booth, 2010) – a factor also identified by Lauritzen (1998).

Table 2 Typical debris streams for different types of disasters (FEMA, 2007)

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The nature of disaster waste will not only be dependent on the type of disaster but it will also be highly dependent on the nature of the built environment being impacted. For example the nature of disaster waste generated from masonry houses will vary greatly from an environment with predominantly wooden houses. To date the studies cited only report experiences for one context. The studies also report waste composition in a variety of ways so that it is difficult to make assessments between cases.

2.2.2 Waste quantities

As with waste composition and nature, the quantity of waste will vary based on the type of disaster and the built environment impacted. Table 2 shows reported waste volumes from some large scale disasters in the last 15 years. As can be seen from the table, waste quantities are reported in terms of either mass or volume. None of the waste quantities reported explicitly stated how they were measured (for example, truck loads or landfill volumes), calculated or estimated (for example waste volumes or mass per house or per affected area). The majority of the disaster waste quantity data available is from disasters in the US. This is largely due to the established disaster waste management processes required for federal emergency funding eligibility (FEMA, 2007).

Table 3 Reported waste quantities from previous disasters

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There have been a number of studies that have retrospectively quantified disaster debris following disaster events. The studies have been conducted in an attempt to both improve disaster waste estimation techniques and to aid debris management planning, preparedness and response. In their guide to disaster debris management planning, USEPA (2008) suggest that pre-disaster waste estimations are beneficial in both pre-disaster planning and post-disaster response and can be carried out using GIS / hazard maps.

The majority of the studies carried out have been based in Japan. Studies identified by Hirayama et al. (2009; 2010) estimate debris volume / weight per house or per unit floor area. Hirayama et al. use these previous estimates to predicatively estimate waste quantities in Japan based on hazard maps. Values of between 30 and 113 t/household are used to account for a range of house and building types and levels of damage sustained. Inoue et al. (2007) investigated specific gravities of the debris generated by the 1995 Great Hanshin-Awaji earthquake, and found an average specific gravity of 0.59 t/m^3 during transportation, which increased to approximately 0.73 t/m^3 in stockpile due to consolidation processes and water addition for dust suppression.

Outside Japan several studies on disaster waste volume quantification have been carried out. Chen et al. (2007) correlated debris generated from four flooding events in Taiwan with three parameters, these are: population density, total rainfall and flooded area. Chen et al. found a significant non-linear correlation with these variables which could be used to predict future flood waste volumes in Taiwan. A study from the University of Florida quantified arsenic-treated wood following Hurricane Katrina (Dubey et al., 2007). The paper emphasises the potential environmental and public health risk of disposing of such large quantities in unlined landfills. Tansel et al. (1994) present a method of quantifying disaster waste from Hurricane Andrew, US, 1992, based on categorising the size and structural composition of affected houses.

As for the studies on waste composition discussed in Section 2.2.1, all these studies are context and disaster specific. As noted by Chen at al., the method demonstrated in their study could be transferred to other contexts, but disaster waste data from the context would be required to generate the correlations. It follows that while estimation methods may be transferred between contexts, actual waste quantities from these studies are less likely to be transferrable.

2.2.3 Waste management phases

Typically management of disaster waste (and disaster management in general) is described in the literature in three phases (Kuramoto, 1995; Baycan and Petersen, 2002; JEU, 2010):

- Emergency response (debris management to facilitate preservation of life, provision of emergency services, removing immediate public health and safety hazards such as unstable buildings, etc)
- Recovery (debris management as part of restoring lifeline restoration and building demolition)
- Rebuild (debris management of wastes generated from and used in re-construction).

The phases are not distinct and the duration of each phase varies significantly between disasters. Typically, in terms of waste management, the emergency phase involves the removal of immediate threats to public health and safety, (Reinhart and McCreanor, 1999) and generally lasts between a few days and two weeks (Haas et al., 1977). During this phase there is little scope for recycling and diversion.

The recovery phase is where the majority of the disaster generated waste will be managed. In past disasters this phase has lasted up to 5 years (New Orleans, Hurricane Katrina) (Luther, 2008). The recovery phase can be affected by a number of factors outside the control of waste managers including police/coroner investigations which can limit site access for public and waste contractors (Ekici et al., 2009) and slow resident return (New Orleans, Hurricane Katrina) (Cook, 2009).

The rebuilding phase is a much longer process and it is hard to define the 'end' of this phase. According to Haas et al. (1977) the rebuilding phase duration could be in the order of 10 years.

2.3 Waste treatment options

2.3.1 Temporary staging sites

Temporary staging areas for recycling and waste processing are identified as an important element by many authors (FEMA, 2007; Jackson, 2008; USEPA, 2008; Johnston et al., 2009) as they provide extra time to appropriately sort, recycle and dispose of the waste. However, the expense of double handling of wastes and of acquiring land can be a limiting factor in their use (FEMA, 2007).

Inappropriate location of temporary storage sites in areas such as playgrounds, swamps and rice paddies has been cited as potentially damaging to the environment and affected people's livelihoods, particularly following the 2004 Indian Ocean tsunami (Basnayake et al., 2006; Pilapitiya et al., 2006; UNDP, 2006).Pre-disaster identification of temporary storage sites has been suggested by many authors as a way to avoid this potential adverse effect (Kobayashi, 1995; Skinner, 1995; FEMA, 2007; USEPA, 2008; Johnston et al., 2009). Most of the disaster waste management guidelines reviewed (FEMA, 2007; WRCDEMG, 2008) provide guidance on temporary staging site selection; however, as identified by Channell et al. (2009), there is potential for more research to be carried out on siting and management aspects of temporary staging sites.

2.3.2 Recycling

Many components of disaster waste can be recycled. Materials can be used for in a number of post disaster applications including soil for landfill cover, aggregate for concrete, and plant material for compost (fertilisation and slope stabilisation) (Channell et al., 2009). The benefit of recycling disaster debris is shown in many ways and is evident in the analysis of many past disaster clean-ups: Marmara Earthquake (Baycan and Petersen, 2002; Baycan, 2004), Kosovo (DANIDA, 2004), Northridge Earthquake, US, 1994 (Gulledge, 1995; USEPA, 2008), Lebanon (Jones, 1996), Great Hanshin-Awaji Earthquake (Kobayashi, 1995), Indian Ocean Tsunami, Thailand and Sri Lanka (Basnayake et al., 2005; UNDP, 2006). The benefits include:

- Reduction of landfill space used.
- Reduction of the quantity of raw material used in re-build.
- Revenue from recycled debris.
- Reduction in transportation for raw materials and debris.
- Job creation (for developing countries in particular).

The major component of disaster waste, in most cases, is construction and demolition (C&D) waste. There are many existing articles which address recycling barriers and opportunities to recycling this waste stream in peace-time (Kartam et al., 2004; Blengini, 2009; Kofoworola and Gheewala, 2009). Skinner (1995) and Reinhart and McCreanor (1999) presented peace-time C&D recycling practices and data as guidance for disaster waste recycling. However, other authors have identified that potential barriers to C&D recycling after a disaster include: the time to collect and process the materials; the unavailability of specialised processing equipment (Baycan and Petersen, 2002); the inability to physically separate the materials (Lauritzen, 1998;

Baycan, 2004); the lack of desire to offset raw material use in rebuild (Lauritzen, 1998); unavailability of disposal sites (Lauritzen, 1998); cost relative to other disposal methods (Solis et al., 1995); and the unavailability of markets to absorb large quantities of material (Solis et al., 1995; Lauritzen, 1998).

While the literature provides an overview of the advantages and barriers to recycling following a disaster, there have been no quantitative assessments of post disaster recycling feasibility, and what planning / preparations are possible pre-disaster to make recycling a more viable option

2.3.3 Waste to energy

Waste to energy has been proposed by Yepsen (2008) as a potential disaster waste treatment option. Yepsen noted that there are limiting factors in using waste to energy as a treatment option in the US. These include high shipping costs, limited markets in the US, certification requirements for international movement of the biomass and FEMA emergency funding regulations (which are geared toward lowest cost debris management contracts with no incentives for beneficial use).

Small scale waste to energy has been used in the US in response to Hurricanes Katrina, Rita, Charley, Frances, and Jeanne (USEPA, 2008), but there is no review of the success of these initiatives.

2.3.4 Open burning

Open burning has been used as a disaster waste management option following the Indian Ocean tsunami (Basnayake et al., 2006), and the Great Hanshin-

Awaji earthquake (Irie, 1995). While some people accepted open burning as an acceptable management option under the circumstances, others condoned it for adverse health effects and environmental concerns. Petersen (2004) and Lauritzen (Naito, 1995) suggest open burning is a necessary management option in some cases to remove immediate hazards but give little definitive guidance on the situations for which open burning is appropriate.

As for recycling and waste to energy treatment options, no research has been carried out into open burning specifically following disasters.

2.3.5 Land reclamation and engineering fill

Several disaster responses have used land reclamation as a waste management option. Following the Marmara earthquake some municipalities used the debris as levelling fill for new housing developments and as land protection against flooding. Baycan (2004) expressed concern over the potential for hazardous wastes to be inadvertently included in the fill but gave no formal assessment of the risk or retrospective analysis on actual contamination. Contamination and/or variability in fill composition could also lead to structural instability of the fill in time.

Following the Great Hanshin Awaji earthquake, existing land reclamation programmes were requested to take earthquake debris. Significant amounts of sorting and waste segregation was reportedly required to ensure the debris was clean enough for coastal reclamation (Irie, 1995; Lauritzen, 1998). As for the Marmara earthquake, there was no post reclamation testing or assessment of effects.

2.3.6 Disposal

In many large scale disasters, waste volumes exceed permanent disposal site capacities (Petersen, 2006; USEPA, 2008). Temporary or sub-standard debris and waste disposal sites can be employed, as noted following the Marmara earthquake (Baycan, 2004). Standards at existing disposal sites have also been reduced after some disasters to increase available disposal sites (for example the expansion of waste disposal criteria at unlined Construction & Demolition landfills after Hurricane Katrina (Luther, 2008)). Authors note the potential for adverse environmental effects at these disposal sites but give little evidence on actual effects.

Disposal of hazardous substances has been identified as problematic following several disasters – Indian Ocean tsunami (Pilapitiya et al., 2006) and Hurricane Katrina (Dubey et al., 2007). Hazardous waste is disposed of in some cases without segregation as part of the overall waste matrix. Aside from the study by Dubey et al (2007) on arsenic quantities in the waste post As is the case for land reclamation, there are no post-disaster analyses on the actual environmental effects of disaster disposal sites.

2.4 Environment

Disasters and the environment are inextricably linked. Disasters cause direct physical damage to the environment and inappropriate environmental management and land use can increase the environment's vulnerability to the effects of disaster events. For example, experts believe that the impact of the Indian Ocean Tsunami would have been reduced by proper preservation and management of mangroves and coral reefs as they would have acted as a buffer against the waves (UNEP, 2005b). The selection and management of disaster waste management options, as discussed in Section 2.3, will also have an effect on the environmental impact of a disaster.

The standard 'peace-time' waste management hierarchy of source reduction, recycling and waste combustion / landfilling (USEPA, 1995a) is not always considered possible, particularly when speed of management is a primary objective of the recovery (see Section 2.6). Consequently the focus of a lot of literature on disaster waste management is on the minimising the environmental impact of disaster waste through management options such as recycling, sound disposal and appropriate handling and treatment of hazardous materials. No author has attempted to quantify the environmental impacts of altering peace-time waste management standards to manage disaster waste.

Many of the disaster waste management plans discussed in Section 2.1 emphasise environmentally responsible approaches. In developing countries disaster waste recovery is often cited as a potential opportunity for development of waste management systems and/or improvement of existing environmental practices. For example, the UNDP Indian Ocean Tsunami waste management programme included a focus on the development of sustainable waste management systems through the collection, recovery, recycling and/or safe disposal of waste materials (UNDP, 2006).

2.5 Economics

Little information exists on the economic impact, both direct and indirect, of debris management programmes. Direct costs (including management, collection, treatment and disposal costs) are straight forward to value if appropriate records have been kept. Table 3 provides an overview of the limited published cost data on debris removal works. Due to the FEMA reimbursement processes (FEMA, 2007) cost data for debris management should be readily available in the US, however, there is limited reported cost data (USEPA, 1995b; Reinhart and McCreanor, 1999; Solid Waste Authority, 2004). Costs reported are variable and sometimes only include one part of the clean-up works, for example, just the value of collection contracts, only disposal costs, costs for debris management in one affected region; and most do not seem to include costs of individual clean-ups.

Table 4 Disaster waste management costs following past disasters

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In the US, FEMA (2007) estimates that for disasters in the US between 2002 and 2007 (predominantly hurricanes and other storm events) debris removal operations accounted for 27% of disaster recovery costs.

Indirect costs following disasters however, are even more difficult to assess. Indirect costs associated with disaster waste management could include: disruption of critical infrastructure: effects on public health (Petersen, 2004); delays to rebuilding processes; impacts on local industry such as tourism (UNEP, 2005c); reduction in future landfill space; impact of waste trucks on roads (Reinhart and McCreanor, 1999); environmental impact remediation resulting from inappropriate and/or illegal dumping (UNDP, 2006); and increased resource depletion by limited resource recovery.

Cost / economic considerations are evident in many of the case studies. These include minimisation of debris management costs (disposal, transportation, labour), revenue generation through recycling, and job creation Recycling in particular has potential to impact greatly on debris management costs.

As for waste quantification (see Section 2.2.2), costs associated with debris management will vary significantly depending on the disaster and the context. Apart from the FEMA estimate of 27% for overall cost of disaster waste management, there has been no attempt to quantify the direct and indirect costs of management of disaster waste.

2.6 Social considerations

While it is acknowledged that community participation and integration is an essential part of any ‘peace-time’ solid waste management programme, the authors are only aware of three publications that specifically address the social impact of a disaster waste management programme. Cook (2009) specifically reviewed the detrimental impact of the absent population on disaster waste management following Hurricane Katrina, an issue earlier identified by Luther (2008). Cook concluded that encouraging and supporting population repatriation would have significantly improved the debris removal process. Allen’s (2007) commentary on ‘environmental justice’ issues relating to Hurricane Katrina highlighted the social impact of selection of disposal sites near disaster affected communities. Denhart (2009) studied the positive psychosocial impacts of a housing deconstruction project following Hurricane Katrina. The project allowed property owners to participate fully in the hand deconstruction and resource recovery process of their property. Denhart emphasised the attachment that was felt between people and their properties. Denhart also noted that property owners were able to take control of their properties and were able to "give life" to their damaged properties by donating, selling or re-using the building materials.

In addition to these three documents, many of the disaster waste case studies reviewed indirectly identify social considerations faced during the waste management process. These are discussed below.

2.6.1 Public health and safety

Public health and safety protection is identified as a goal in many of the case studies and plans (Solis et al., 1995; WMinE, 2004; SWANA, 2005; USEPA, 2008). There are three main aspects of public health and safety relevant to disaster waste management. First, public health hazards presented by the waste matrix itself, such as vermin and vector breeding sites and health care wastes (WMinE, 2003; Petersen, 2004) have to be managed. Second, health and safety risks from waste management options must be considered. For example, following Hurricane Andrew, US, 1992, the use of air-curtain incinerator units drew (unsubstantiated) concern over the potential public and environmental health risks from burning commingled wastes (USEPA, 1995b). Lastly, health and safety protection for all those who handle the waste has to be provided either through engineering practices or protective equipment. In the aftermath of the 2001 World Trade Centre collapses, medical studies of emergency responders and clean-up workers identified some health impacts from dust particles inhaled (Landrigan et al., 2004; Lange, 2004) due to inadequate health and safety equipment. Allen (2007) commented on the inadequate provision of protective equipment for private property owners returning to clean up their properties following Hurricane Katrina. However, Brown et al. (2010) noted that even though protective equipment was available after the Victorian Bushfires, Australia, 2009, some community members elected not to use it. Channell et al. (2009) identified management of fine particulate matter during demolition and debris management processes, as a potential research area.

2.6.2 Community / psychosocial impact

Many studies state that fast disaster debris removal expedites the community recovery and rebuilding process (Solid Waste Authority, 2004; WMinE, 2004; SWANA, 2005; USEPA, 2008). Slow clean-up programmes in past events have led to illegal dumping (Baycan, 2004; Petersen, 2004; Jackson, 2008), which adds to the waste manager's job. In addition, unmanaged and visible disaster debris and waste can serve as a reminder to communities of the losses they have endured (DANIDA, 2004; Petersen, 2004). However, most programmes also include environmental and/or health and safety objectives which may contribute to a slow debris management process, such as strict recycling targets and hazardous material handling requirements. Luther (2008), for example, identified the time-consuming procedures required for asbestos management following Hurricane Katrina as particularly challenging. The challenge was to minimise exposure to asbestos while not slowing the clean-up. The conflict between a fast waste management process – to facilitate community recovery - and meeting environmental and public health objectives has not been explicitly addressed in the literature.

2.6.3 Communication

Public perception, understanding and involvement has long been recognised as the key to successful solid waste management programmes (USEPA, 1995a). However, achieving adequate community understanding in a disaster situation is a huge challenge for waste managers. According to authorities, after Hurricanes Frances and Jeanne, pre and post disaster communication, through an ongoing and consistent education programme, was identified as a key to their successful and efficient debris removal programme (Solid Waste Authority, 2004; USEPA, 2008).

Community reaction to disaster waste management options has led waste managers to alter their approaches. As discussed above, community reaction to air curtain incinerators following Hurricane Andrew, led to the abandonment of incineration (USEPA, 1995b). Following Hurricane Katrina public opposition to use of construction and demolition landfills for mixed wastes led to a lawsuit being filed and the eventual closing of one of the landfills. Waste managers were forced to find alternative disposal sites (Luther, 2008). Public consultation during the disaster waste management process may have increased public understanding of the necessary actions for efficient management of the waste, or would have identified publically unacceptable waste management options before attempts were made to implement them.

The literature to date does not investigate the way community values regarding waste management are likely to change post disaster. In addition there is no adequate guidance on the most effective way to incorporate communities into disaster waste decision making.

2.6.4 Employment and capacity building

Past disaster waste responses in developing countries and post conflict situations have included opportunities for post-disaster employment, and for expertise and governance capacity building. Capacity building of local governments, in particular, is identified as a priority by several authors (DANIDA, 2004; Petersen, 2004; UNDP, 2006; Bjerregaard, 2007) and includes development of management systems, budgeting, and technical skills.

Overall, there is limited understanding of the impact of disaster waste management on community recovery and/or the impact of a post-disaster communities' behaviour on waste management programmes.

2.7 Organisational aspects

2.7.1 Overall coordination

In past events, the management of disaster waste has too often been carried out with little or no coordination with other recovery efforts. Apart from in the US where disaster waste management roles are clearly established by FEMA (2007), past case studies show that it is generally unclear where responsibility for disaster waste management lies. After the Great Hanshin-Awaji earthquake, disaster waste management was split between private and public entities (Kuramoto, 1995). Whereas after Typhoon Tokage 2004 (also in Japan) the Ministry for the Environment was responsible for debris generated by the disaster (e.g. land slips, vegetative waste) and the Ministry of

Health, Labour and Welfare was responsible for debris from collapsed building and infrastructure (UNEP, 2005c). In Turkey following the 1999 Marmara earthquake, no department was assigned coordinative responsibility for debris which led to a report of haphazard waste management (Baycan, 2004). In other contexts, such as the 2009 Victorian Bushfires in Australia, new recovery authorities have been established to coordinate all recovery activities, including waste management (Brown et al., 2010).

In developing countries, in particular, the presence of numerous international aid organisations adds to the complexity of coordination. Often, despite coordination efforts by UN or government, inappropriate handling and disposal of debris still occurs (Petersen, 2006; UNDP, 2006). Petersen (2004), in a review of several case studies, emphasised the inclusion of waste management activities in international humanitarian responses, and of central coordination for waste management activities.

There is no literature which looks critically at organisational structures in relation to disaster waste management.

2.7.2 Organisation of Physical works

The physical works associated with disaster waste management programmes - demolition, private property clearance, kerbside collection, transportation, temporary staging areas, recycling, disposal - have been implemented in a variety of ways with varying degrees of public and contractor participation. The organisation of the physical works has implications on the speed of recovery, resource availability and management of public health hazards.

As examples, the FEMA regulations (2007) generally (unless there is a significant public health and safety risk) require private property clearance to be paid for and facilitated by property owners. Kerbside collection is carried out by the municipality or the US Army Corps. Following the 2009 Victorian Bushfires, Australia, the government paid for and facilitated all private and public building demolition and debris removal works due to the high public health risk and desire for an expedient recovery. A single contractor was in turn appointed to carry out these works (Brown et al., 2010). No author has looked critically at what factors should be considered in the organisational design of the physical works associated with disaster waste programmes.

Waste composition (as discussed in Section 2.2.1), can influence how the debris is managed and what level of public participation is desirable. For example, heavy earthquake debris (Lauritzen, 1998; Booth, 2010) or hazardous substances such as asbestos after Hurricane Katrina (Luther, 2008), may be too cumbersome for private property owners to manager themselves.

In the US, disaster waste contracting is a growing industry. Contracting companies are specifically positioning themselves to respond to disaster events including procuring specialised equipment, personnel and pre-arranged contracts (Fickes, 2010). Pre-arranged contracts and rates with contractors has been identified as an important feature in facilitating effective clean-ups (Jackson, 2008) and avoiding price gouging (Jordan, accessed 2010), however, the authors have cited no studies that quantify this effect. Mismanagement of disaster waste by contractors, such as illegal dumping observed following Hurricane Katrina, (Allen, 2007; GAO, 2008) may also be avoided by having pre-arranged contracts.

Recently there has been research into the potential use of imagery and GIS technologies for pre-disaster planning and post-disaster waste management (Channell et al., 2009). Currently there is little data on suitable GIS technologies and their effectiveness. Huyck and Adams (2002) presented how satellite imagery was and could have been used following the 2001 World Trade Centre attacks.

2.8 Legal frameworks

Solid waste management, particularly in developed countries, is governed by a variety of legislation to minimise the potentially harmful effects of waste on the public and the environment. Legislation typically governs demolition procedures, waste handling, transportation, disposal etc. However, in the wake of a disaster these peace-time laws can cause significant delays in the clean-up process. For example, health and safety procedures for demolition of structures containing asbestos meant average structure demolition times of 4 days in the clean-up following Hurricane Katrina. Authorities elected to relax handling standards to reduce demolition times to one day (GAO, 2008). Strict environmental laws, in Italy (and Europe) have been reported to have prevented necessary recycling staging sites and disposal sites being permitted until eleven months after the 2009 earthquake. During this time large parts of the town were cordoned off and community members staged a number of protests (Nardecchia, 2010).

Many disaster waste management plans or guides (Solis et al., 1995; WRCDEMG, 2008) highlight the availability of emergency legal waivers on solid waste regulations such as the above example. However, it is often unclear to what degree and in what circumstances legal or regulatory relaxations are acceptable. In the previous example the relaxation of demolition procedures had the potential to cause long term health effects for waste handlers and the public.

Also following Hurricane Katrina, some landfill waste acceptance criterion were relaxed to increase the availability of disposal sites (Luther, 2008). This relaxation increased the risk of environmental contamination at disposal sites. A 2006 report for the US Congress, on Hurricane Katrina, assessed the use of environmental waivers such as these. The report described their effectiveness in the short term but raised questions over the implications of their use in the long-term (McCarthy and Copeland, 2006). Overall the report was inconclusive and gave no guidance on future use of legal waivers in the US.

Waste ownership was identified as a potential legal issue in a cross case study analysis by Baycan and Petersen (2002). Waste ownership issues are of concern when private property owners are not able to participate in the clearing of their own property and revenue is then generated from recycling of the debris.

Legislation and regulation has the potential to significantly impact the efficiency and effectiveness of a disaster waste management programme. The impact of legislative provisions on the management of disaster waste will be very context specific. As described above, past disasters have illustrated some likely areas where legislative provisions may inhibit efficient and effective waste handling, however, in depth reviews of country specific laws are required to fully understand the impact in different contexts. Brown et al. (2010 in print) present a discussion of the potential legal issues for managing disaster waste in New Zealand. The review found that while there was legal flexibility to facilitate a timely clean-up the complexity of the legislation and organisations involved may make post-disaster decision-making / assessment of legal waivers cumbersome.

2.9 Funding

The financial responsibility for disaster waste management varies between contexts and disasters. In the US, as with the organisational responsibility discussed in Section 2.7.2, payment for private property clean-up or demolition is the responsibility of the property owner / insurance, and kerbside collection and disposal is the responsibility of the municipality and FEMA (FEMA, 2007). In Australia, where there are no established guidelines on disaster waste management, the government elected to pay for demolition of buildings and debris removal on all insured and non-insured properties following the 2009 Victorian bushfires (The Premier of Victoria, 2009).

The public health threat of unmanaged solid waste means that responsibility for waste management cannot always be left to the individual. For example, in the US following Hurricane Katrina, despite the usual requirement for private property owners to clear their own properties, FEMA elected to pay for non-insured private property demolitions if the property was posing a public health risk (Bauer, 2006). The literature includes context specific funding mechanisms and case specific responses, however, it lacks any analysis of the most effective mechanism (private, public, insurance etc) for funding disaster waste management in different contexts.

Disaster response and recovery funding mechanisms vary from country to country but commonly the mechanisms stipulate lowest cost options. For example the FEMA regulations in the US (FEMA, 2008) appear to consider only direct costs and do not consider the longer term, indirect costs and/or benefits, of certain waste management options (refer Section 2.5). That is, the feasibility assessments required by FEMA are cost rather than cost-benefit focussed. In some cases a cost-only analysis does not allow disaster waste managers to meet the goals of long-term (or even current) waste management strategies (Lauritzen, 1995); on the other hand, it could be argued that environmentally preferable management options are too costly in a disaster response situation.

For example, in Los Angeles (LA), following the 1994 Northridge earthquake, FEMA originally denied funding for LA officials to establish a recycling system to supplement its insufficient landfill space, on the grounds that it was more expensive than landfilling. The city of LA was forced to prove that recycling was part of their long-term waste management strategy and that the additional cost to start up recycling facilities was justified (State of California, 1997). Currently there is no literature on how non-direct costs can be included in feasibility assessments of disaster waste management programmes.

3 Discussion

A number of missing links in the literature on disaster waste management have been identified and are discussed below.

3.1 Planning

Ideally plans should be developed prior to a disaster event; however, in many cases plans are only formulated after a disaster has struck. The tools discussed in Section 2.1 are generally comprehensive technical 'how-to' guide on debris management. These plans give little guidance on decision-making and option consideration in different disaster situations. The documents also do not consider the effectiveness of various organisational, financial and legal structures in different disaster events.

More comprehensive disaster plans considering the aspects discussed in this paper need to be produced. Rather than producing a prescriptive operational style plan, a plan based around key decisions could be a more effective approach to allow for the large variability in disaster events and impacts that may affect a region.

3.2 Waste composition and quantity

A cross-context and multi-disaster assessment of waste composition and quantities would be a valuable addition to the literature. To plan a disaster waste management system, waste compositions and quantities must be estimated. Disaster severity, the affected built environment (building type, population density etc), debris waste composition, and waste quantities all vary significantly across contexts and disaster types. However, a systematic review of previous disasters would assist in the identification of key factors that affect debris quantities. With this understanding better waste quantity estimation methodologies could be developed.

The current barrier to this analysis being carried out is the availability and consistency of post-disaster waste data. Development of a standard method of reporting disaster waste composition and quantities would enable future analysis between events and improve our ability to develop better waste estimation methodologies. Peace-time construction and demolition waste estimation techniques may be able to be adapted but a review as to their applicability in a disaster situation would be necessary.

3.3 Waste treatment options

Temporary staging sites are a common tool used in the management of disaster waste. While there are some operational guidance documents in circulation more research on the effective use of temporary storage / staging facilities would be beneficial. Factors requiring consideration include space requirement, environmental factors, noise and dust, pre-disaster site identification, land-use planning issues and cost.

A more comprehensive understanding of post-disaster recycling is required. While understanding of peace-time recycling is well established, and several models exist (Hsiao et al., 2002; Blengini, 2009), the effect of large quantities of specific debris types is not understood. Factors such as: the effect of surplus materials on existing recycling markets; the need for establishment of post-disaster markets (eg. environmental land remediation, land reclamation, waste to energy and housing reconstruction applications); the logistics involved; space requirements and associated land-use issues; and the economics of post-disaster recycling, all require further analysis in order to aid our future disaster planning and response.

The choice of disaster waste treatment options should not only include costs but also environmental and engineering risks. For example, land reclamation or engineering fill projects which use disaster recycled materials may not be able to achieve the same level of environmental and structural quality control as in peace-time. The likely speed of processing the materials and difficulty in separating mixed disaster generated wastes both contribute to increased project risks.

There is also a need for some form of quantification of the health and environmental effects of open burning different types of disaster waste. Guidance on the circumstances under which open burning should be used would assist disaster waste managers to assess and implement appropriate treatment programmes.

3.4 Environment

Environmental standards, such as the level of recycling, the use of open burning, and disposal regulations are often reduced to expedite recovery. However, the risks or effects of changes in environmental standards do not appear to be well understood by disaster waste managers. Post-disaster analyses of cases where environmental standards have been reduced – addressing why the decision was made, what information the decision was based on and what the impacts of the option was – is needed.

3.5 Economics

There is little guidance available for disaster managers on cost assessments. Development of an approach to assess the likely direct costs of various waste management options (recycling, waste to energy, landfill disposal, land reclamation, etc.) and indirect costs of those options (slower debris removal, long term environmental degradation, etc.) would greatly enhance disaster waste managers' abilities to respond appropriately to disasters in the future.

3.6 Social

There is limited understanding of the impact of disaster waste management on community recovery and/or the impact of a post-disaster communities' behaviour on waste management programmes.

First, qualitative and quantitative analysis of the likely public health threats will add to the literature, and to disaster waste managers' understanding of waste management options. The assessment should consider the public health hazards from the waste matrix, waste management options and from handling the waste.

Second, it would be beneficial for disaster waste managers to better understand the psychosocial implications of the speed of debris removal process. For example the desire the recover personal belongings (Brown et al., 2010) and the emotional attachment owners often have with their properties (Denhart, 2009). Understanding these factors will enable better planning of disaster waste systems.

Third, comprehensive guidance on the most effective ways to include communities in post-disaster waste management decision making is missing from the current literature. Waste managers need to recognise that communities can be changed by a disaster – their expectations, risk tolerance and needs will likely have changed significantly-- and so the social relations with the community must also change.

3.7 Organisation

Organisational structures for the coordination of disaster waste management programmes are likely to be context specific and will need to fit within existing governance structures. However, there would be value in further investigations into how organisational (intra-organisation) structures influence the effectiveness of waste management programmes (for example human and equipment resourcing, subcontract management, work scheduling); and how best to integrate waste management into the overall disaster recovery operation (inter-organisation) (such as coordination with rebuilding activities; allocation of shared resources, works prioritisation).

There has been no integrated research on the types of organisational models used for waste management project implementation (private vs public sector, community involvement, etc). The authors believe that different events (scale, hazard level, societal disruption) may warrant different approaches to clean-up programmes. The barriers against and opportunities for public participation, in particular, need to be identified.

3.8 Legal frameworks

The literature includes a number of examples where legislative frameworks were a hindrance to expedient disaster waste management. As noted by Kobayahsi (1995), the greater progress we make toward recycling and advanced waste treatment methods, the more our ability to cope with disaster decreases. Complex treatment and disposal processes with strict environmental standards are not designed for large acute influxes of materials.

While some research has been carried out by Brown et al (2010 in print) identifying typical legislative hurdles encountered during disaster waste management programmes, further analysis is required due to the context-specific nature of legal systems.

3.9 Funding

Funding, like organisational and legal structures is very context specific. However, there is value in the analysis of past case studies to identify the success or failure of various funding mechanisms, in particular, the determination of the factors influencing this outcome. Again, the authors believe the suitability of funding mechanism may be disaster-specific as much as it is context-specific.

4 Conclusion

There are still significant gaps in our understanding of disaster waste management. In particular, existing literature focuses heavily on technical management aspects of disaster waste management and neglects the institutional (organisational, legal and financial) frameworks. Our understanding of the impacts of disaster waste management systems, in particular economic and social impacts, is also limited.

It is envisaged that this literature review will form a framework for future comprehensive and cohesive research on disaster waste management. In turn, research will lead to better preparedness and response to disaster waste management problems.

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Table 1 Disaster waste management references

Disaster	Year	References
Conflict		
Beirut, Lebanon	Post 1990	(Jones, 1996; Lauritzen, 1996/1997; Baycan and Petersen, 2002; Bjerregaard, 2009)
Mostar, Bosnia	Post 1995	(Lauritzen, 1995; Baycan and Petersen, 2002; DANIDA, 2004)
Kosovo Conflict	Post 1999	(Baycan and Petersen, 2002; DANIDA, 2004; Bjerregaard, 2009)
Earthquakes		
Loma Prieta earthquake, US	1989	(Lauritzen, 1996/1997)
Luzon earthquake, Philippines	1990	(Lauritzen, 1996/1997)
Humboldt County Earthquake, US	1992	(State of California, 1997)
Erzincan Earthquake, Turkey	1992	(Lauritzen, 1996/1997)
Northridge earthquake, US	1995	(USEPA, 1995b; Jones, 1996; State of California, 1997; USEPA, 2008)
Great Hanshin-Awaji earthquake, Kobe, Japan	1995	(Kuramoto, 1995; Lauritzen, 1995; 1998; Reinhart and McCreanor, 1999; Baycan and Petersen, 2002; Inoue et al., 2007; Hirayama et al., 2009; Hirayama et al., 2010)
Marmara earthquake, Turkey	1999	(Baycan and Petersen, 2002; Baycan, 2004)
Algiers-Boumerdes, Algeria Earthquake	2003	(Benouar, accessed 2009)
Fires		
City of Oakland Firestorm	1991	(State of California, 1997)
Coastal Fires, US	1993	(USEPA, 1995b)
Cerro Grande wildfire, US	2000	(USEPA, 2008)
Cedar and Pines fires, US	2003	(County of San Diego, 2005; USEPA, 2008)
Victorian Bushfires, Australia	2009	(Brown et al., 2010)
Floods		
Midwest floods, US	1993	(USEPA, 1995b)
Alstead Floods, US	2005	(USEPA, 2008)
Hurricane		
Hurricane Hugo, US	1989	(USEPA, 1995b)
Hurricane Charley, US	1992	(MSW, 2006)
Hurricane Andrew, US	1992	(Tansel et al., 1994; Meganck, 1995; USEPA, 1995b; Jones, 1996; Luther, 2008)
Hurricane Iniki, Hawaii, US	1992	(USEPA, 1995b)
Hurricane Opal, US	1995	(Reinhart and McCreanor, 1999)
Hurricane Fran, US	1996	(Reinhart and McCreanor, 1999)
Hurricane Georges, US	1998	(Reinhart and McCreanor, 1999)
Hurricanes Frances and Jeanne, US	2004	(Solid Waste Authority, 2004)
Seminole Florida Hurricane season, US	2004	(USEPA, 2008)
Hurricane Ivan, US	2004	(USEPA, 2008)
Hurricane Katrina, US	2005	(Harbourt, 2005; LDEQ, 2005; Pardue et al., 2005; Presley et al., 2005; SWANA, 2005; USEPA, 2005a; b; Brunker, 2006; Diaz, 2006; Esworthy et al., 2006; LDEQ, 2006; McCarthy and Copeland, 2006; Allen, 2007; Dubey et al., 2007; GAO, 2008; Jackson, 2008; Luther, 2008; Roper, 2008; USEPA, 2008; Cook, 2009; Denhart, 2009; Foxx & Company, 2009; Denhart, 2010; Moe, 2010; HHS.gov, accessed 2010)

Hurricane Rita, US	2005	(LDEQ, 2006; USEPA, 2008)
Tornadoes		
Central Florida Tornadoes, US	1998	(Reinhart and McCreanor, 1999)
Oklahoma Tornadoes, US	1999	(Reinhart and McCreanor, 1999)
Tsunami		
Indian Ocean Tsunami	2004	(Basnayake et al., 2005; Petersen, 2005; Selvendran and Mulvey, 2005; UNEP, 2005a; WMinE, 2005; Basnayake et al., 2006; Petersen, 2006; Pilapitiya et al., 2006; UNDP, 2006; Srinivas and Nakagawa, 2008; Bjerregaard, 2009)
Typhoon		
Toraji typhoon, Taiwan	2001	(Chen et al., 2007)
Nari typhoon, Taiwan	2001	(Chen et al., 2007)
Mindulle typhoon, Taiwan	2004	(Chen et al., 2007)
Aere typhoon, Taiwan	2004	(Chen et al., 2007)
Tokage Typhoon, Japan	2004	(UNEP, 2005c)
Winter storm		
Lincoln Winter Storm, US	1997	(USEPA, 2008)

Table 2 Typical debris streams for different types of disasters (FEMA, 2007)

		Typical Debris Streams								
		Vegetative	Construction and Demolition (C&D)	Personal Property / Household Items	Hazardous Waste	Household Hazardous Waste (HHW)	White Goods	Soil, Mud and Sand	Vehicles and Vessels	Putrescent
Types of Disasters	Hurricanes / Typhoons	X	X	X	X	X	X	X	X	X
	Tsunamis	X	X	X	X	X	X	X	X	X
	Tornadoes	X	X	X	X	X	X		X	X
	Floods	X	X	X	X	X	X	X	X	X
	Earthquakes		X	X		X	X	X		
	Wildfires	X		X		X	X	X		
	Ice storms	X				X				

Table 3 Reported waste quantities from previous disasters

Year	Event	Waste Quantities	Data Source
2010	Haiti earthquake	estimated 23 - 60 million tonnes	(Booth, 2010)
2009	L'Aquila earthquake, Italy	estimated 1.5-3 million tonnes	(Di.Coma.C, accessed 2010).
2008	Sichuan earthquake , China	20 million tonnes	(Taylor, 2008)
2005	Hurricane Katrina, US	76 million cubic metres	(Luther, 2008)
2004	Hurricanes Frances and Jeanne, Florida, US	3 million cubic metres	(Solid Waste Authority, 2004)
2004	Indian Ocean Tsunami	10 million cubic metres (Indonesia alone)	(Bjerregaard, 2009)
2004	Hurricane Charley, US	2 million cubic metres	(MSW, 2006)
1999	Marmara Earthquake, Turkey	13 million tonnes	(Baycan, 2004)
1995	Great Hanshin-Awaji Earthquake, Kobe, Japan	15 million tonnes	(Hirayama et al., 2009)

Table 4 Disaster waste management costs following past disasters

Disaster	Location	Debris quantity	Cost (as quoted in original reference)	Reference
2004 Indian Ocean tsunami	Sri Lanka	0.5 mill tonnes	500-600 million rupees (US$5-6 million)	(Basnayake et al., 2006)
2004 Indian Ocean tsunami	Thailand	0.8 mill tonnes	110 million Baht (US$ 2.8 million)	(Basnayake et al., 2006)
2004 Typhoon Tokage	Tokage, Japan	44,780 tonnes	Estimated US$ 15-20 million	(UNEP, 2005c)
1999 Kosovo Conflict	Kosovo	100,000 tonnes	13.7 millionDKK (building waste management system programme only) (US $2.35 million)	(DANIDA, 2004)
Hurricane Charley	Florida, US	19 mill cubic yards	US$286 million FEMA reimbursed money only	(FEMA, 2009)
Hurricanes Jeannes and Frances	Palm Beach, US		US$20 / cubic yard pickup-disposal	(Solid Waste Authority, 2004)
1998 Central Florida Tornadoes	Osceola County, US	250,000 cubic yards	US$8 million (debris removal contract only)	(Reinhart and McCreanor, 1999)