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# Life cycle assessment and life cycle costs for pre-disaster waste management systems

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ABSTRACT

This study develops a method of environmental and economic evaluation of an integrated disaster waste management system that considers the spatial scale of removal, transport, and treatment of disaster waste. A case study was conducted on combustibles, which is a type of disaster waste derived from dwellings, in Mie Prefecture, Japan. First, we calculated the quantity and the spatial distribution of disaster waste derived from dwellings and tsunami debris produced as a result of a large-scale earthquake. The quantity of disaster waste was estimated as 7,178,000 t with functioning flood-preventing facilities and 11,956,000 t without functioning flood prevention facilities. Ensuring resilience in the face of earthquakes and tsunamis by renovating flood-preventing facilities is extremely important in decreasing the production of wastes, especially in coastal regions. Next, the transportation network for transporting combustibles in disaster waste to temporary storage sites, incineration plants, and landfill was constructed using an optimization model. The results showed that if flood-preventing facilities do not function properly, the installation of temporary incineration facilities becomes essential. Life-cycle emissions of $CO_2$, $SO_x$, $NO_x$, and PM and the costs of removal, storage, and treatment of combustibles were calculated as 258,000 t, 618 t, 1705 t, 7.9 t, and 246 million USD, respectively, in the case of functioning flood-preventing facilities. If flood-preventing facilities do not function, the quantity of environmentally unfriendly emissions and the costs increase. This result suggested the significance of renovation in order to maintain the conditions of flood-preventing facilities to decrease the environmental burden and costs as well as keep the production of disaster waste at a minimum.



## 1. Introduction

Natural disasters such as earthquakes generate vast amounts of disaster waste that mainly includes debris such as wood, concrete, and glass. The Great East Japan Earthquake in March 2011 generated approximately 31 million t of disaster waste (MOE, 2016), which corresponds to approximately 65% of total annual municipal solid waste (MSW) generation in Japan. Rapid removal and management of waste produced by large-scale natural disasters are essential for the recovery and reconstruction of the affected area. However, the environmental burden and costs of the waste removal and treatment should not be overlooked even in disaster situations. For example, target 12.5 of the United Nations SDGs (United Nations, 2015) states that waste generation should be substantially reduced by 2030 via prevention, reduction, recycling, and reuse. Target 12.5 also covers the environmental burden of waste management and states that waste management should be conducted in an environmentally and economically friendly manner even in the case of a disaster. The cost of disaster waste management should be kept to a minimum, with the goal of having sufficient funds to re-establish and reconstruct the affected area and to support disaster victims. Denot (2016) indicates that if a natural risk is identified, the approach is to estimate the quality and the amount of waste and develop the measures for waste prevention and management. If local municipalities have access to information such as earthquake and tsunami hazard maps, they can effectively utilize environmental and economic evaluation methods

*Abbreviations:* EPA, Environmental Protection Agency; GHG, greenhouse gases; GIS, geographic information system; JMA, Japan Meteorological Agency; METI, Japan Ministry of Economy, Trade and Industry; MILT, Japan Ministry of Land, Infrastructure, Transport and Tourism; MOE, Japan Ministry of Environment; MSW, municipal solid waste; $NO_x$, nitrogen oxide; LCA, life cycle assessment; LCC, life cycle costing; $P_L$, liquefaction potential index; PM, particulate matter; SDGs, sustainable development goals; $SO_x$, sulfur oxide.

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that encompass an entire disaster waste management system including the removal, transport, and treatment of disaster waste, and can estimate the environmental burden and costs over the life-cycle of the disaster waste from production to treatment. In 1998, the U.S. EPA created projections of the amount and type of disaster waste, and cited the determination of the treatment capacity of a region, installation of temporary storage sites, and investigation of the methods for treating and/or recycling disaster wastes as priority issues. In the aftermath of the Great East Japan Earthquake in 2011, the MOE (2014) created guidelines for disaster waste management that include methods for sorting, treating, and/or recycling disaster wastes in Japan. The Japan Society of Material Cycles and Waste Management has created a manual for treatment and recycling, considering the types of disaster wastes (Asari et al., 2013). Since the Great East Japan Earthquake in 2011, at the behest of the national government, local governments in Japan have been developing independent disaster waste treatment plans and preparing for future large-scale natural disasters. However, there are currently no methods for evaluating the environmental burden and costs resulting from the treatment of disaster wastes. There is no evaluation method that considers the location and the surface area of temporary storage sites and the location and the capacity of treatment facilities. Consequently, although local governments develop disaster waste treatment plans and formulate measures for treatment, they cannot estimate the environmental burden and costs of implementing the plans because appropriate environmental and economic evaluation methods do not exist. It is also currently not possible to study the feasibility of measures and evaluate alternative proposals.

Researchers have also conducted studies for pre- and/or post disaster management. For example, Brown et al. (2011) presented a detailed account of research related to the management and treatment of disaster waste under the headings of planning, waste composition, quantities, management phases, waste treatment options, environment, economics, social considerations, organisational aspects, legal frameworks, and funding. The disaster waste treatment plans by local governments usually include these elements. Environmental criteria for the transport, storage, and treatment of disaster wastes should also be included in the plans. Working hours and treatment implementation periods that satisfy environmental standards were discussed by Tabata et al. (2017a).

In a study related to the evaluation of disaster waste management, Crowley (2017) surveyed the effectiveness and efficiency of pre-disaster debris management planning in several counties in the U.S. Pramudita et al. (2014) discussed the methods of construction of a transportation network for disaster debris if a Tokyo inland earthquake were to happen. Onan et al. (2015) created a decision-making tool to estimate disaster waste amount and investigate transportation networks and the location of temporary storage sites. Cheng and Thompson (2016) conducted a land suitability analysis to select candidate temporary disaster waste management sites that provide storing, chipping, burning, and sorting for reduction, reuse, and recycling. Sasao (2016) analysed the cost and efficiency of waste treatment associated with the Great East Japan Earthquake, by using the data envelopment analysis. Lorca et al. (2015) presented a decision-making tool that enables optimization and balancing of financial and environmental costs, duration of removal operations, landfill usage, and the amount of recycled materials generated. Joana and Lisa (2016) conducted environmental and economic evaluations by focusing on energy recovery from disaster waste in the case of the Great East Japan earthquake. However, these studies do not propose a framework which would enable overall evaluation of disaster waste treatment systems. Tabata et al. (2017a) have proposed the construction of a disaster waste treatment system intended for small municipalities, with integrated removal, transport, and treatment of disaster waste, and a method of evaluation to estimate the environmental burden and costs, employing LCA and LCC. However, the study was restricted to a single small municipality. In most cases of disaster waste management, treatment is carried out over a large area by the cooperation of regional entities and thus, it is necessary to investigate the methods for constructing disaster waste treatment at a larger spatial scale.

The aim of this study is to develop a method for the environmental and economic evaluation of an integrated disaster waste processing system that considers the removal, transport, and treatment of disaster waste. We intend to offer a decision–making tool for local governments that formulate disaster waste treatment plans to consider environmental and economic aspects of the plans. We conducted a case study on combustibles, one type of Disaster waste derived from dwellings, in Mie Prefecture, Japan. In Japan, there are many incineration plants used for MSW or industrial waste, and in the event of a disaster these treatment plants are designated for treating disaster waste. However, because of the large quantity of disaster waste, all of the treatment process is rarely carried out within a region because of limited resources and sometimes, disaster wastes need to be transported to an incineration plant further away, generating significant environmental impact and high costs. Targeting the combustibles helps to simulate the extent of the network that should be put in place to cope with transport and treatment issues. Tabata et al. (2011) showed that in the treatment of MSW, the environmental impact and treatment cost of incineration was the dominant factor. In the case of the disaster waste treatment, incineration was the main $CO_2$ emitter (Tabata et al., 2017b). It is therefore important to study the combustible component of disaster waste.

The large-scale disaster considered in this study is a Nankai megathrust earthquake. The Japanese government remains concerned about the future occurrence of Tokyo inland earthquakes and Nankai megathrust earthquakes. A Nankai megathrust earthquake is predicted to cause massive destruction in Japan and result in strong tremors over a sizeable area extending from Kanto to Kyushu. The probability of such an earthquake occurring at a class magnitude of 8–9 (stronger than the Great East Japan earthquake) has been estimated as 70% within 30 years from 1 January 2015 and 90% within 50 years. Such an earthquake may cause a maximum number of 323,000 deaths and generate 250 million t of disaster waste (MOE, 2014). Preparations for this predicted earthquake include the measures and resilience plans for damage prevention, mitigation, and reconstruction to allow for rapid recovery after the disaster.

## 2. Materials and methods

### 2.1. Case study area

Fig. 1 shows the location of the case study area. Mie Prefecture locates central area of Japan. The surface area of Mie Prefecture is 5774 $km^2$. The seat of government of the prefecture is situated at 34°43′48.9″N, 136°30′31.2″E. The total population is ca. 1.8 million, with ca. 720,000 households (Mie Prefectural Government, 2013b). Mie Prefecture consists of a total of 29 municipalities. In addition, this prefecture is divided into five regions; Hokusei (Northern), Chu-Nansei (Central), Iga (Western central), Ise-Shima (Southern central), and Higashi-Kishu (Southern). The Hokusei region is home to the industrial belt with manufacturing of automobiles and semiconductors and is highly urbanized. The principal activities in Higashi-Kishu and Ise-Shima are fishery and tourism and there has been a marked population decrease in recent years in these two regions. Central area of Japan is the third largest populated area in Japan, and a lot of industrial companies and factories,