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(Citation)
Waste Management,68:688-700

(Issue Date)
2017-10

(Resource Type)
journal article

(Version)
Accepted Manuscript

(URL)
https://hdl.handle.net/20.500.14094/90004645

Title

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, 1,705 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.

Keywords

Disaster waste management, disaster waste, life cycle assessment, life cycle cost, transportation network

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

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 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 does 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 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 to 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

Figure 1 shows the location of the case study area. Mie Prefecture locates central area of Japan. The surface area of Mie Prefecture is 5,774 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, represented by Toyota Motor Corporation, are accumulated in this area. Mie Prefecture is predicted to get severe Tsunami damage in this area. Therefore, investigation for preventing generation of the disaster waste and/ or treating the disaster waste in advance is significant for preserving life and economic activities in this area. In addition, Mie

Prefectural Government (2015) has published a robust plan for disaster waste countermeasures ahead of the whole country. They planned detail treatment flows of the disaster waste. Therefore, in order to verify the feasibility of the report and to confirm the effectiveness of the method proposed in this study, a case study was attempted to evaluate in Mie prefecture.

Figure 1 here

Mie Prefectural Government (2014) has predicted the damage of a potential Nankai megathrust earthquake at the JMA seismic intensity of 5-7 and inundation depth above 2 m. In particular, an earthquake of seismic intensity 6 or above has been predicted to impact over 94.7% of the area of the prefecture with strongest seismic damage in coastal areas leading to widespread tsunami damage. In this prefecture, maximum tsunami height would be 11.7 m and flooding would impact an area of over 283 km^2, equivalent to 4.9% of the land surface of the prefecture. Although the flooded area appears to be small, it includes an industrial zone as well as many dwellings; therefore, human and economic loss would be substantial. In addition, a significant liquefaction damage is predicted for the coastal areas of Hokusei and Chu-Nansei. The maximum number of buildings that would be totally destroyed as a result of a potential Nankai megathrust earthquake is estimated as 250,400 (Hokusei: 63,400, Chu-Nansei: 73,500, Iga: 2,500, Ise-Shima: 82,700 and Higashi-Kishu: 28,300) that correspond to 35% of the total housing stock of the prefecture. The maximum number of deaths is estimated at 34,000 (Hokusei: 1,400, Chu-Nansei: 3,200, Iga: 0, Ise-Shima: 15,000 and Higashi-Kishu: 14,000).

Mie Prefectural Government (2015) has also predicted the maximum quantity of disaster waste as 33.9 million t (Hokusei: 10.3 million t, Chu-Nansei: 10.0 million t, Iga: 0.3 million t, Ise-Shima: 10.2 million t and Higashi-Kishu: 3.1 million t), which is equivalent to 52 times the annual quantity of MSW produced in Mie Prefecture. In order to manage such an increase in waste volume, Mie Prefectural Government (2015) has developed a plan to complete treatment in three years after a large-scale natural disaster. According to the plan, after disaster waste is removed from the affected region, it will be transferred to a primary temporary storage site. It will then be classified into combustibles, non-combustibles, concrete, scrap metal, wood, and miscellaneous waste in a secondary temporary storage site and recycled as secondary resources if possible. In addition, appropriate treatment and disposal methods (incineration or landfill) will be determined for disaster wastes that cannot be recycled. The capacities of incineration plants, landfill, and different treatment facilities for general waste and industrial waste in Mie Prefecture are currently being inventoried. In addition, the possibility of treating the disaster waste within the region or in other regions is also being studied. Mie Prefecture policy is to carry out treatment within the region as long as it is possible and consider the treatment outside the region only if the former option is infeasible. Mie Prefecture is also considering establishing primary and secondary temporary storage sites in each municipality and installing temporary incineration facilities if necessary. However, when formulating the disaster waste treatment plan, the locations of the temporary storage sites were still unspecified. It is the responsibility of municipal governments to decide the locations of the temporary storage sites after negotiations with local residents. Urban parks and school grounds are obvious candidates for temporary storage sites.

2.2. Evaluation steps

The present study was carried out in four steps as explained below. The disaster waste mainly considered in this study is combustibles (wood) from dwellings. However, Steps (1) and (2) consider disaster waste other than combustibles and tsunami debris because the disaster waste is not removed separately by type, but is removed and transported all together to the primary and secondary temporary storage sites. Consequently, if only combustibles are considered, the necessary surface area at the temporary storage sites cannot be accurately calculated.

(1) Estimation of the potential production of disaster waste

Mie Prefectural Government (2015) has estimated the potential production of disaster waste in units of municipality, not in grid units. Estimation by grid units would allow the study of environmental burden and costs inherent in the transport of disaster waste in more detail; therefore, in this study, the estimation of potential production of disaster waste and analysis of the spatial distribution are carried out in grid units, using GIS.

(2) The necessary surface area of temporary storage sites

Candidate locations for temporary storage sites are selected, focusing on urban parks and school grounds present in each municipality in Mie Prefecture. In addition, the required surface area of temporary storage sites is calculated from the results of the estimation of potential production of disaster waste and the supply and demand gap compared with the surface area is investigated.

(3) Construction of a disaster waste treatment system and transportation network

In this section, we discuss the construction of the integrated disaster waste treatment system with reference to the disaster waste treatment system provided by Mie Prefectural Government (2015). The system includes a transportation network with information on the locations of the sites where disaster waste will be produced, primary temporary storage sites, secondary temporary storage sites, incineration plants, and the landfill. Optimization models were constructed, in which the objective function was the minimization of CO_2 emissions and costs. This makes it possible to visualize the transportation networks used in local and regional waste treatment.

(4) Environmental and economic evaluation of the disaster waste treatment system

Environmental burden and costs resulting from the removal, transport, and treatment of disaster wastes are calculated by performing LCA and LCC inventory analysis.

The four steps mentioned above are described in detail in the following sections.

2.3. Estimation of potential disaster waste generation

Figure 2 shows the flow diagram of the estimation of potential residential waste production after an earthquake, landslide, and tsunami. The starting point for the estimation is to collect the grid data for the number of households (area of one grid is 1 km^2) (MIAC, 2015b). The number of dwellings per household (1.19) was calculated by dividing the number of dwellings in Mie Prefecture (831,200) by the number of households (701,000) (MIAC, 2015a). The number of dwellings includes family homes and collective residences. Multiplying this number by the number of households in each grid gives the grid-level data for the number of dwellings. Next, the number of dwellings by structural segmentation and by structure in each grid was calculated using the municipal building data classified by structural segmentation (detached houses, terraced houses, and apartment blocks) and by structure type (wooden and non-wooden buildings) (Mie Prefectural Government, 2016a). The hazard maps for earthquake damage, landslide damage, and tsunami damage were superimposed. By applying the method developed by Tabata *et al.* (2017a) to this data and multiplying the number of dwellings by percent destruction in each grid, the number of completely destroyed buildings and semi-destroyed buildings in each grid were calculated. Potential production of disaster waste was estimated by multiplying the total floor area per residence by disaster waste output units per total floor area (wooden: 0.43 [t/m^2], non-wooden: 1.42 [t/m^2]) (Nagaoka et al, 2008). In addition, these results were multiplied by the proportional composition presented in Table 1 to derive the production of disaster waste by composition. The production of tsunami debris was calculated by multiplying the reciprocal of the specific weight of tsunami debris and the actual value of the accumulated height of tsunami debris in the Great East Japan Earthquake (0.04 m) (Kochi Prefectural Government, 2013) by the grids in which tsunami damage would be produced.

Figure 2 here

Table 1 here

Mie Prefectural Government (2016b) envisaged two cases: (1) flood-preventing facilities such as flood barriers and breakwaters are not damaged by the earthquake and fulfil the role for which they are designed (Case 1: Flooding after the earthquake can be controlled) and (2) flood barriers are destroyed by the earthquake and cannot function as designed (Case 2: Flooding after the earthquake cannot be controlled). The production of disaster waste will change considerably depending on the degree of tsunami damage. Therefore, tsunami damage control is important for suppressing the production of disaster waste as well as preserving human life and household possessions. The estimation of the potential production of disaster waste was carried out predicting tsunami damage for these two cases and differences in results are discussed. The disaster was assumed to occur in 2015.

2.4. Estimation of the area available and the area required for primary and temporary storage sites

Urban parks and school grounds in each municipality are selected as candidate locations for temporary storage sites. There are 1,531 urban parks located within Mie Prefecture. Urban parks are mainly located in highly populated Chu-Nansei and Hokusei regions. According to Kochi Prefectural Government (2013), the surface area available for temporary storage of disaster waste was set at 50% of the area of the urban parks. The piled height of disaster waste was set at 5 m (Arai *et al.* 2015). According to Kochi Prefectural Government (2013), secondary temporary storage sites need to have space for sorting in addition to storing disaster waste; therefore, urban parks which could ensure at least 15 ha of ground space in one place were the strong candidates for secondary temporary storage sites. Similarly, urban parks which could ensure at least 15 ha of ground were the candidate locations for secondary temporary storage sites. As a result, there is 450 ha of surface area available for temporary storage in Hokusei region while there is only 50 ha in Higashi-Kishu region.

Next, the storage surface area of disaster waste was calculated by multiplying the potential production of disaster waste by the specific weight of the disaster waste by composition presented in Table 1. This value was used as the surface area necessary for the temporary storage of disaster waste. By comparing the surface area available for temporary storage and the surface area necessary for temporary storage, it is possible to identify the municipalities with an excess or shortfall in the surface area for temporary storage sites.

2.5. Construction of an integrated disaster waste management system and disaster waste transportation network

Figure 3 presents the disaster waste treatment system evaluated in this study. The processes considered in this section are removal at the production site (cost only), storage of disaster waste at primary temporary storage sites, storage and sorting of disaster waste at secondary temporary storage sites, incineration of combustibles, final disposal of the incineration ash, and transportation of disaster waste between each process. Although local government is responsible for removing the disaster waste at the production site, disaster victims and/ or volunteers cleans up and/ or remove the disaster waste. Removal cost is actually imaginary cost if the local governments should defray the cost. Within the transportation process, this study assumed that 4-tonne trucks will be employed from the production site to the primary temporary storage sites and 10-tonne trucks will be used for other transportation processes.

Figure 3 here

The functional units were set for treatment of the entire quantity of combustibles produced as a result of the hypothetical Nankai megathrust earthquake within three years from the disaster. In addition, the resulting environmental burden (CO_2, SO_x, NO_x, PM) and cost of treatment were calculated using an inventory analysis. CO_2 is a greenhouse gas, responsible for the increase of global temperatures; SO_x, NO_x, and PM are regional air pollutants.

The method for constructing a transportation network by using an optimization model is described in the following sub-sections. The transport process is divided into four groups based on the transport boundaries of the disaster waste treatment system in Figure 3. The same optimization model was constructed for transportation routes (1), (2), and (4), with reception capacities of the temporary storage sites and the landfill as constraints. For transportation (3), an optimization model was constructed in which the constraints were the environmental burden and costs of the incineration plants and temporary incineration facilities per tonne of waste. ArcGIS Network Analyst was used for constructing the transportation network and calculating the distances.

2.5.1 Transportation (1), (2), and (4)

Disaster waste produced in each grid is transported to a neighbouring primary temporary storage site. The same also applies to secondary temporary sites and landfill. The surface area available for temporary storage is decisive; when the quantity transported becomes larger than the capacity, the temporary storage site will overflow. Accordingly, the surface area available for temporary storage and the surface area necessary for temporary storage are compared by using linear programming, and in the case of overflow, allocation of disaster waste to another available temporary storage site is considered. The model is presented in equations (1)-(4). In order to simplify the calculations, the temporary storage sites and treatment facilities were assumed to be located at the centre of each municipality and they were modelled as central nodal points.

$$\textit{Minimize} \qquad \sum_{i}^{n}\sum_{j}^{n}\left(w_{ij} \times l_{ij}\right) \tag{1}$$

$$\textit{Subject to} \qquad \sum_{i}^{n} w_i = W_I \tag{2}$$

$$\textit{Subject to} \qquad \sum_{j}^{n} w_j = W_J \tag{3}$$

$$W_J = W_I \times \frac{S_d}{S_D} \tag{4}$$

where W: total quantity of disaster waste to be transported [t], i: disaster waste production grid, j: primary or secondary temporary storage site, or landfill, w_{ij}: quantity of disaster waste to be transported between i and j [t], w_i: the quantity of waste from the allocation source i [t], W_I: total production of disaster waste [t], w_j: the quantity of waste from the allocated destination j [t], W_J: quantity of disaster waste received by the allocated destination - primary or secondary temporary storage site, or landfill [t], l_{ij}: distance between i and j [km], S_D: capacity of primary or secondary temporary storage sites, or landfill [m^3], S_d: capacity of each primary or secondary temporary storage site, or landfill [m^3].

Next, the cost of transportation and truck transportation capacity, given the results for the allocation of the quantity to be transported, are calculated using equations (5)-(7). In addition, the number of trucks is calculated by multiplying truck transportation capacity by the number of return journeys.

$$S=\sum_{i}^{n}\sum_{j}^{n}\left(\frac{w_{ij}}{A_{ij}}\times H\times M\right) \quad (5)$$

$$A_{ij}=D_{ij}\times T\times R \quad (6)$$

$$D_{ij}=\frac{H}{2\times\left(\frac{l_{ij}}{V}+U\right)} \quad (7)$$

where S: the cost of transport [USD] A_{ij}: truck transport capacity [t/d/truck], D_{ij}: the number of return journeys per day in i-j [times/day], T: truck load capacity [t] (4-t truck = 4; 10-t truck = 10) , R: truck load percentage [-] (= 0.7), H: daily working time [h/d] (= 8 h or 24 h), V: transport speed [km/h] (ordinary roads = 37.1, high-speed roads = 66.3 km/h) (MILT, 2012), U: truck loading/unloading time [h] (= 0.16) (MOE, 2012), M: unit hourly cost of truck operation [USD/h] (4-t truck = 42.2, 10-t truck = 61.5) (MOE, 2012).

2.5.2 Transportation (3)

Combustibles stored and sorted at secondary temporary storage sites are transported to a neighbouring incineration plant or temporary incineration facility. Since incineration plants and temporary incineration facilities have a limited available treatment capacity, disaster waste which exceeds the capacity cannot be treated and the allocation of combustibles to another incineration plant or temporary incineration facility is considered using a multi-objective optimization problem (equations (8)-(13)). Here, the constraint was the quantity of CO_2 emissions or cost per tonne of combustibles. Given these constraints, equations (8) and (9) were also included in the objective functions for transport processes other than Transportation (3).

$$\text{Minimize cost} \quad \sum_{i}^{n}\sum_{j}^{n}\frac{w_{ij}}{A_{ij}}\times H\times M+\sum_{i}^{n}\sum_{j}^{n}\sum_{k}^{n}\left(w_{ij}^{k}\times g_{j}^{k}\right)+\sum_{j}^{n}\sum_{k}^{n}\left(m_{j}\times g_{j}^{k}\right) \quad (8)$$

$$\text{Minimize } CO_2 \quad \sum_{i}^{n}\sum_{j}^{n}\left(w_{ij}\times l_{ij}\right)+\sum_{i}^{n}\sum_{j}^{n}\sum_{k}^{n}\left(w_{ij}^{k}\times g_{j}^{k}\right)+\sum_{j}^{n}\sum_{k}^{n}\left(m_{j}\times g_{j}^{k}\right) \quad (9)$$

$$Subject\ \ to \qquad \sum_{i}^{n} m_i + \sum_{j}^{n} \sum_{k}^{n} w_{ij}^{k} = \sum_{i}^{n} w_i \tag{10}$$

$$Subject\ \ to \qquad \sum_{j}^{n} \sum_{k}^{n} w_{ij}^{k} \le \sum_{j}^{n} w_j^{k} \tag{11}$$

$$Subject\ \ to \qquad m_i \le y_i \tag{12}$$

$$Subject\ \ to \qquad w_{ij}^{k} \ge 0 \tag{13}$$

where, w_j^k: the reception capacity of *k* (temporary storage site, incineration plant, landfill) at the allocated destination *j* [t], g_j^k: unit cost of treatment and environmental burden per tonne [kg/t] of *k* (incineration plant) at the allocated destination *j*, l_{ij}: distance from point *i* to point *j* (transportation network) [km], m_j: quantity incinerated by the temporary incineration facility installed at the secondary temporary storage site *i* [t], y_i: capacity of the temporary incineration facility installed at the secondary temporary storage site *i* [t].

Figure 4 shows the available treatment capacity of incineration plants and landfill by region. In Mie Prefecture, the target treatment period was set at three years after the disaster; but in practice, the treatment facilities may also be damaged by the disaster, and thus, the recuperation of treatment facilities should also be considered. As a result of the calculations, the total treatment process in Mie Prefecture was estimated to be completed in 2.7 years, considering the repair and recommissioning of treatment facilities. The treatment facilities are mostly concentrated in three regions, Iga, Hokusei, and Chu-Nansei, with the facilities for treating industrial waste concentrated in the Iga region.

Figure 4 here

2.5.3 Transportation in Sole city

When disaster waste is transported within a single municipality, since temporary storage sites and treatment facilities are located at the centre of each municipality, the transportation distances for the purpose of calculation become zero. In order to solve this problem, transportation distances were calculated within a single municipality using a grid city model (Ishikawa, 1996). The grid city model makes it possible to calculate the distance of a single truck MSW collection circuit within a given area using the number of households and the number of MSW stations. This model was originally developed to predict MSW collection by Ishikawa (1996). In this study, the model has been customized so as to enable the calculation of the average distance for collection of disaster waste (equation (14)).

$$D_S = \sqrt{a \times t} \times t^{-1} \quad (14)$$

where D_S: Average transport distance within the grid [km], *a*: grid surface area [km^2], and *t*: number of temporary storage sites [sites].

2.6. Environmental and economic evaluation of integrated disaster waste management system

Environmental impact and costs were calculated by multiplying the quantities of combustibles to be transported and treated in each process by the environmental impact and cost intensity of each process. The sum of the results provides the environmental burden and cost intensity of the entire disaster waste treatment system (Table 2). Some incinerator conducts energy recovery such as heat utilization. This study supposed that more energy recovery is not conducted to enhance minimizing CO_2 emission or cost. According to MOE (2017), the treatment cost by MSW incineration furnaces within the system was 1.71 times the cost of not treating the disaster waste. Assuming that this is proportional to the increase in the load resulting from treatment of disaster waste, the total cost of MSW incineration furnaces is calculated by multiplying the waste load by 1.71. In addition, the actual performance of temporary incineration facilities in the area affected by the Great East Japan Earthquake was obtained from the interviews, and the environmental burden and cost intensity were evaluated based on that data.

Table 2 here

3. Results and discussion

3.1. Estimation of potential disaster waste generation

The results of the estimation of the potential production of disaster waste are shown in Table 3. The potential production of Disaster waste derived from dwellings and tsunami debris was estimated as 7,178,000 t and 5,012,000 t in Case 1 and 11,956,000 t and 16,040,000 t in Case 2, respectively. Disaster waste derived from dwellings was 1.7 times greater in Case 2 than in Case 1. In addition, tsunami debris in Case 2 was 3.2 times the amount in Case 1. Functioning flood-preventing facilities were shown to have a significant effect in suppressing the production of disaster waste.

Table 3 here

Next, Figure 5 shows the spatial distribution of disaster waste. Disaster waste derived from dwellings is predicted to be produced in large quantities in Hokusei, Chu-Nansei, and Ise-Shima regions because the earthquake tremor is expected to be greater in the Ise-Shima region than in the other regions and tsunami damage will be considerable in Hokusei and Chu-Nansei regions. There are a large number of residences that would generate Tsunami debris all along the coast. Especially in Case 2, there will be a significant waste production in Hokusei region. In Mie Prefecture, the total extension of the coastline is 1,088 km and up to 527 km of the coastline is occupied by flood-preventing facilities (Mie Prefectural Government, 2013a). However, most of the flood-preventing facilities were built more than 50 years ago and have become increasingly less functional due to ageing and subsidence. Consequently, there is a danger that the flood-preventing facilities will not be able to function as they are intended to in the event of a large-scale natural disaster. 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.

Figure 5 here

3.2. Comparison of the available and required areas for temporary storage

Figure 6 shows the surplus surface area and lacking surface area for temporary storage sites in cities, towns, and villages. The surface area necessary for temporary storage is 235 ha in Case 1 and 413 ha in Case 2. There is a larger excess surface area in Hokusei and Chu-Nansei regions in Case 1 than in Case 2. In coastal and inland areas of Northern Mie Prefecture, there is a surplus of available surface area, whereas there is a shortage of 35 ha (Case 1) or 60 ha (Case 2) in the Ise-Shima region. The results also suggest that candidate locations for secondary temporary storage sites are restricted to Hokusei, Chu-Nansei, and Iga regions and that it will be difficult to complete the treatment within the Ise-Shima region resulting in a need for treatment between regions.

Figure 6 here

3.3. Construction of a transportation network

Figure 7 shows the results for the transportation networks derived by cost minimization as the objective function. In Case 1, it is possible to guarantee 21 secondary temporary storage sites. The quantity of disaster waste produced is less in Case 1 than in Case 2 and there is little restriction on the capacity of treatment facilities; therefore, transportation tends to be concentrated on one incineration plant. Treatment can be completed in three years by using only the existing incineration plants within the prefecture. On the other hand, in Case 2, only 17 secondary temporary storage sites can be guaranteed within the prefecture. In addition, the comparison of the transportation networks constructed for Transportation (1), Transportation (2), and Transportation (4) in Case 1 and Case 2 indicates that the number of routes in the network is smaller in Case 1 than in Case 2. In Transportation (3), the number of routes in the network is larger in Case 1 than in Case 2, suggesting that the quantity of transported disaster waste is also higher. The transportation distances in Transportation (1) and Transportation (4) are smaller in

Case 1 than in Case 2, and transportation distances in Transportation (2) and Transportation (3) are greater because there are a few candidate locations for secondary temporary storage sites and incineration plants within the Mie Prefecture for the quantity of disaster waste produced.

Figure 7 here

Based on the constructed transportation network, in each case, the quantity of combustibles stored in primary temporary storage sites and disposed within the region was greater than the quantity treated outside the region. On the other hand, especially in Ise-Shima, where the quantity stored and sorted in secondary temporary storage sites and incinerated within the region was smaller than the portion treated outside the region, there is high dependence on other regions, especially in relation to the incineration treatment.

The big difference between Case 1 and Case 2 is that because of the larger quantity of disaster waste in Case 2 compared to Case 1, temporary incineration facilities will need to be installed in secondary temporary storage sites in order to complete treatment in three years. In Case 2, installation of temporary incineration facilities is essential. Approximately, 380,000 t of combustibles will need to be treated by temporary incineration facilities, equivalent to 17% of the total quantity of combustibles. Within the transportation network which we have constructed, temporary incineration facilities should be installed in three locations in the Hokusei region, and in one location in each of the Chu-Nansei and Higashi-Kishu regions.

3.4. Environmental and economic evaluation results

The results of the inventory analysis with cost minimization as the objective function are shown in Figures 8 and 9. For each case, the results are presented for treatment inside and outside the region. CO_2, SO_x, NO_x, and PM emissions and the cost of treatment were calculated as 258,000 t, 618 t, 1,705 t, 7.9 t, and 246 million USD in Case 1 and 526,000 t, 1,509 t, 11,688 t, 16.2 t, and 920 million USD in Case 2, respectively. Lower emissions and costs are caused by the difference in the potential production of disaster waste suggesting that renovation of flood-preventing facilities is crucial for reducing the environmental burden and treatment costs. In particular, Case 1 offers a 73% reduction in costs compared to Case 2.

Figure 8 here

Figure 9 here

The temporary storage sites and incineration processes are critical in regard to CO_2 and NO_x emissions and treatment costs. Tabata *et al*. (2017a) showed that large quantities of CO_2 and NO_x emissions are associated with temporary storage sites consistent with our results. Tabata *et al.* (2011) also showed that the environmental burden and costs of incineration are larger in the MSW treatment system although our results showed that the impacts are not restricted to MSW treatment and they also apply to disaster waste. In particular, since the installation of temporary incineration facilities becomes essential in Case 2, there is a significant increase in CO_2 emissions and costs as a result of the additional process of using temporary incineration facilities. Although a simple comparison is not possible, CO_2 increased 2.1 times and costs increased 4 times in Case 2 compared with Case 1 due to the installation of temporary incineration facilities. We also showed that the landfilling process impacted SO_x emissions and the transportation process affected PM emissions. When the calculations were carried out with CO_2 minimization as the objective function, the result was a decrease of 25% in CO_2 emissions compared with when cost minimization was the objective function because to avoid CO_2 emissions, the use of temporary incineration facilities was also avoided. On the contrary, the result was an increase of 11% in costs compared with when cost minimization was the objective function.

The results of treatment inside and outside the region showed that in Case 1, the environmental burden would be greater if the disaster wastes were treated outside the region, except for the impact of SO_x and NO_x emissions. Since the potential production of combustibles is less in Case 1 than in Case 2, the flexibility in regard to the treatment outside the region is increased. On the other hand, in Case 2, wastes are more likely treated within the region because of the installation of temporary incineration facilities, and as a result, the environmental burden are smaller than the scenario if they are treated outside the region. The proportion of incineration treatment in incineration plants intended for MSW and industrial waste was 53% and 47%, respectively, in Case 1, and 54% and 45%, respectively, in Case 2 suggesting that disaster wastes can be treated within the required timeframe by employing incineration plants intended for MSW or for industrial waste treatment within the prefecture.

The results showed the processes with the largest environmental impact and the environmental and economic effects of installing temporary incineration facilities. In addition, although treatment will mostly be carried out within the regions, treatment outside regions will also be essential to complete the clean-up of disaster wastes.

The rest of this section will discuss the extent of the environmental burden and costs determined by the inventory analysis. The results of the inventory analysis for emissions of CO_2, SO_x, and NO_x and the treatment costs were compared with the annual emissions of CO_2, SO_x, and NO_x in Mie Prefecture and the annual budget, respectively (MOE (2013) and Mie Prefectural government (2017)). Both in Case 1 and Case 2, CO_2 emissions are not higher than 1-2% of annual CO_2 emissions. NO_x and SO_x emissions are each 10% of annual emissions in Case 1, and 66% and 26% of annual emissions of NO_x and SO_x, respectively, in Case 2. The costs are 5% of the annual budget in Case 1 and 14% in Case 2. Since the amount of NO_x and SO_x emissions are at levels that cannot be overlooked, the plans to reduce regional air pollution in the region should be incorporated into the disaster waste management. In addition, the cost of treatment is high and the renovation of flood-preventing facilities is particularly important requiring a significant amount of resources. The reductions in regional air pollution emissions and savings in treatment costs can be achieved by limiting the production of disaster waste.

4. Conclusion

This study developed a method for the environmental and economic evaluation of disaster waste treatment systems. Using data from the Mie Prefecture in Japan, we constructed a system to treat combustibles, a type of disaster waste derived from dwellings, including transportation networks based on the estimates of the potential production of disaster waste. We also determined the spatial distribution of temporary storage sites and treatment facilities, and performed provisional calculations of life-cycle environmental burden and costs for the entire treatment system. Our findings can be summarized as follows:

(1) The potential production of disaster waste derived from dwellings and tsunami debris was 7,178,000 t and 5,012,000 t in Case 1 (flooding after the earthquake can be controlled) and 11,956,000 t and 16,040,000 t in Case 2 (flooding after the earthquake cannot be controlled), respectively. The generated disaster waste amount in Case 2 was 1.7 times the amount in Case 1. The potential production of disaster waste and tsunami debris was particularly significant in coastal areas. Therefore, ensuring resilience in the face of earthquakes and tsunamis by renovating flood-preventing facilities significantly decreases the production of waste, especially in coastal regions.

(2) We compared the surface area needed for temporary storage sites, obtained from the estimates of the potential production of disaster waste with the surface area available for temporary storage if urban parks in Mie Prefecture are used for this purpose. As a result, the surface area necessary for temporary storage was 235 ha in Case 1 and 413 ha in Case 2. The coastal and inland areas of Northern Mie Prefecture are highly populated and there are many urban parks; thus, there was a surplus of available surface area. On the other hand, in regions with smaller population and few urban parks, the area for temporary storage was inadequate. Consequently, complete treatment is not possible within some of the regions because of the limited resources and flexibility in treatment alternatives between regions will be needed in some cases.

(3) The results of the construction of transportation networks with cost minimization as the objective function showed that because of the differences in the potential production of disaster waste, in Case 1, 21 secondary temporary storage sites could be guaranteed, whereas in Case 2 there were no more than 17 sites. In addition, in Case 1 the potential production of disaster waste was small and there was little restriction on the available capacity of treatment facilities, and therefore, transport will be limited to a single incineration plant. In addition, in Case 1, the treatment process can be completed in three years by using

only the existing incineration plants within the prefecture. On the other hand, in Case 2, treatment between the regions will be needed and transport network will be more complicated. It will also be difficult to complete the treatment in three years only with the existing incineration plants within the prefecture, and therefore, installation of temporary incineration facilities will become essential.

(4) Inventory analysis was carried out with cost minimization as the objective function. Emissions of CO_2, SO_x, NO_x, and PM, and costs were 258,000 t, 618 t, 1,705 t, 7.9 t, and 246 million USD in Case 1 and 526,000 t, 1,509 t, 11,688 t, 16.2 t, and 920 million USD in Case 2, respectively. Smaller values in Case 1 are caused by the differences in the potential production of disaster waste and the renovation of flood-preventing facilities is important for reducing the environmental burden and costs.

(5) The comparison of the results of inventory analysis with the annual quantities of emissions and the annual budget of the study region showed that CO_2 emissions were negligible; however, maximum NO_x and SO_x emissions and the treatment costs were 66%, 26%, and 14%, respectively. This result suggests the incorporation of plans of reducing regional air pollution in the region and the treatment costs into existing disaster waste management efforts.

In Mie Prefecture, the methods for constructing a disaster waste treatment system have been studied for a hypothetical disaster caused by a Nankai megathrust earthquake. However, treatment systems considering the spatial distribution and selection of temporary storage sites have not been studied. Similarly, the environmental burden and costs resulting from the implementation of the treatment systems have not been calculated; therefore, it is not possible to discuss the efficacy of the treatment system proposed by the government of Mie Prefecture. By using the method for environmental and economic evaluation of integrated disaster waste treatment systems proposed in this study, it is possible to evaluate the environmental burden and costs of the Mie Prefecture treatment system before the event. It is also possible to identify the relevant issues in connection with the implementation of the treatment system, such as guaranteeing temporary storage sites and the increase in environmental burden and costs resulting from the operation of temporary incineration facilities. Therefore, the methodology developed in this study is useful for local governments. In particular, the finding that the renovation of flood-preventing facilities is effective for limiting the production of disaster waste and hence the environmental burden and costs associated with disaster waste treatment has not hitherto been discussed in previous studies and can serve as a reference for the waste management efforts of local governments. Using the results of this study as a basis, future studies should focus on the pros and cons of renovating the flood-preventing facilities and the scale of the renovation by performing cost/benefit analysis.

The method developed in this study employs an LCA and LCC framework, and uses data that can easily be obtained by local governments in the event of an earthquake. Although this study was conducted for Mie Prefecture, the methodology can be applied to other regions in Japan or in other countries. The data for CO_2 emissions and cost intensity of treatment facilities need significant amount of refining because in practice, the numbers will differ depending on the local government applying the methodology. However, local governments that plan to apply this methodology will have the actual values for calculating the CO_2 emissions and cost intensity of treatment facilities. There are no similar examples of this methodology in Japan or abroad and therefore the results of this study provide scientifically and socially significant insights. Natural disasters are an unavoidable problem in any country, and recuperation and reconstruction need to be achieved rapidly by the effective removal and treatment of disaster waste without overlooking the concept of a sustainable society.

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Table 1 Component and specific gravity of disaster waste and tsunami debris

		Component excluding tsunami debris [%]	Specific gravity [m^3/t]
Disaster waste derived from dwellings	Combustibles	18	2.5
	Incombustibles	18	0.9
	Concrete scrap	52	0.83
	Metal scrap	6.6	13.67
	Wood	5.4	3.8
Tsunami debris		–	0.68

Source: National Institute of Environmental Studies (2011), Kochi Prefecture (2013) and Board of Audit of Japan (2017)

Table 2 Environmental burden and cost intensity for disaster waste treatment

		CO_2	SO_x	NO_x	PM	Cost
	Unit	kg/	kg/	kg/	kg/	USD/
Removal	/t	–	–	–	–	101
Transportation (4 t truck)	/tkm	1.50E-01	7.47E-06	1.29E-05	7.91E-05	–
	/truck/h	–	–	–	–	42
Transportation (10 t truck)	/tkm	1.27E-01	6.32E-06	1.09E-05	6.68E-05	–
	/truck/h	–	–	–	–	61
Temporary storage sites	/t	4.96E+00	4.60E-04	2.04E-03	1.23E-20	283
Incinerator for MSW	/t	293E+00	0.54E+00	0.63E+00	0.01E+00	244
Incinerator for industrial waste	/t	488E+00	5.75E-02	2.39E-01	4.71E-15	145
Temporary incinerator	/t	293E+00	0.54E+00	0.63E+00	0.01E+00	370
Landfill	/t	138E+00	8.77E+00	7.38E+00	2.48E-03	61

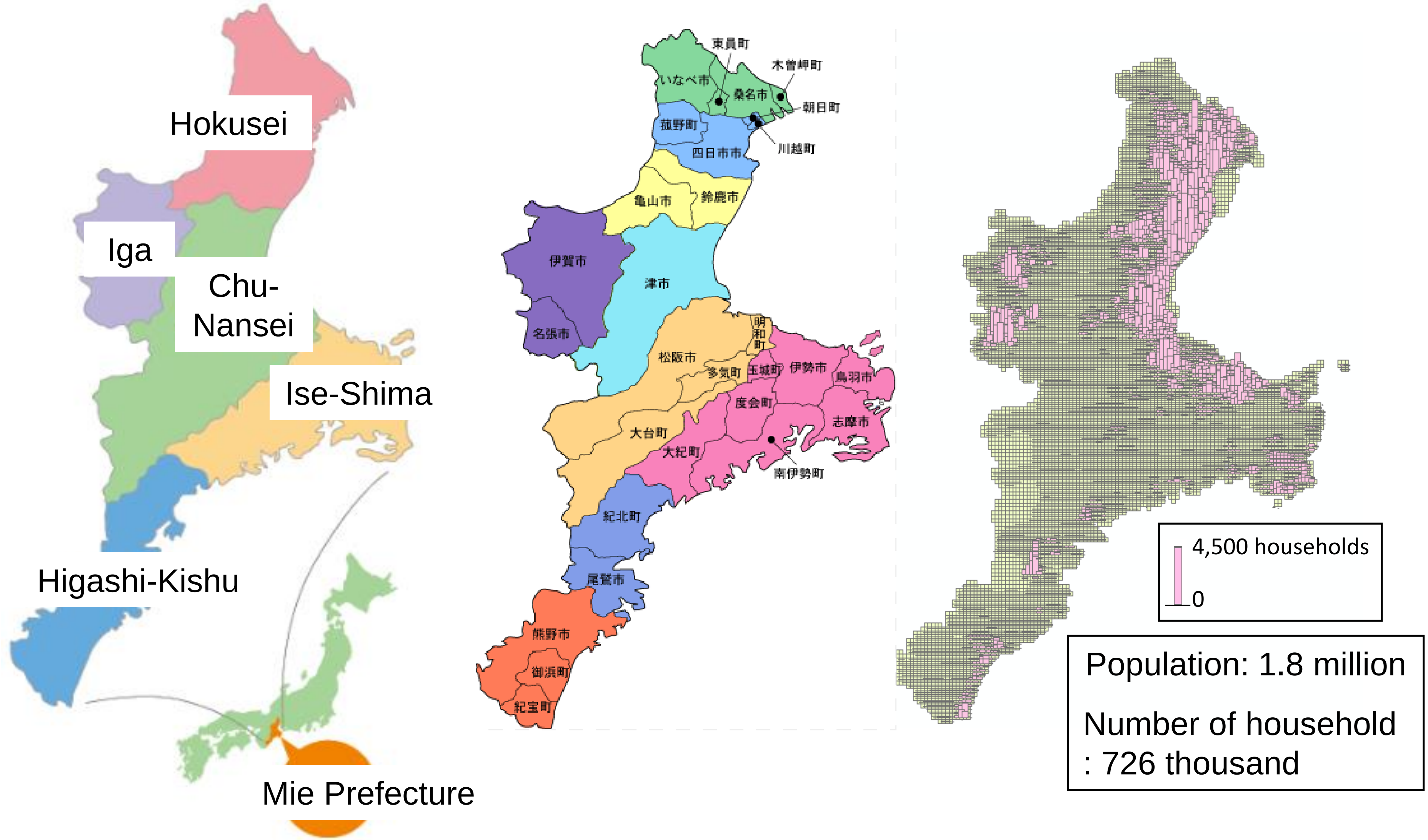
Source: Fujiwara and Kusakabe (2008), MOE (2017) and Tabata et al (2017a)

Note: 1 USD = 113.02 JPY (17.02.20)

Table 3 Potential disaster waste generation

		Total	Hokusei	Chu-Nansei	Iga	Ise-Shima	Higashi-Kishu
Case 1: Flooding after the earthquake can be controlled							
Disaster waste derived from dwellings	Total	7,178,368	2,325,623	597,778	33,761	2,803,882	1,417,324
	Combustibles	1,292,106	418,612	107,600	6,077	504,699	255,118
	Incombustibles	1,292,106	418,612	107,600	6,077	504,699	255,118
	Concrete scrap	3,732,751	1,209,324	310,845	17,556	1,458,019	737,008
	Metal scrap	473,772	153,491	39,453	2,228	185,056	93,543
	Wood	387,632	125,584	32,280	1,823	151,410	76,535
Tsunami debris		5,012,213	5,012,472	204,692	475,960	0	3,196,232
Case 2: Flooding after the earthquake cannot be controlled							
Disaster waste derived from dwellings	Total	11,955,864	4,640,292	2,874,622	26,959	2,825,826	1,588,164
	Combustibles	2,152,055	835,253	517,432	4,853	508,649	285,870
	Incombustibles	2,152,055	835,253	517,432	4,853	508,649	285,870
	Concrete scrap	6,217,049	2,412,952	1,494,804	14,019	1,469,430	825,845
	Metal scrap	789,087	306,259	189,725	1,779	186,505	104,819
	Wood	645,617	250,576	155,230	1,456	152,595	85,761
Tsunami debris		16,039,998	16,039,998	4,283,932	5,710,206	0	4,672,584

Unit: t



(a) Region (b) Cities (c) Population distribution

Figure 1 Location of the case study area

Source: Mie Prefectural government (2013b and 2016a)

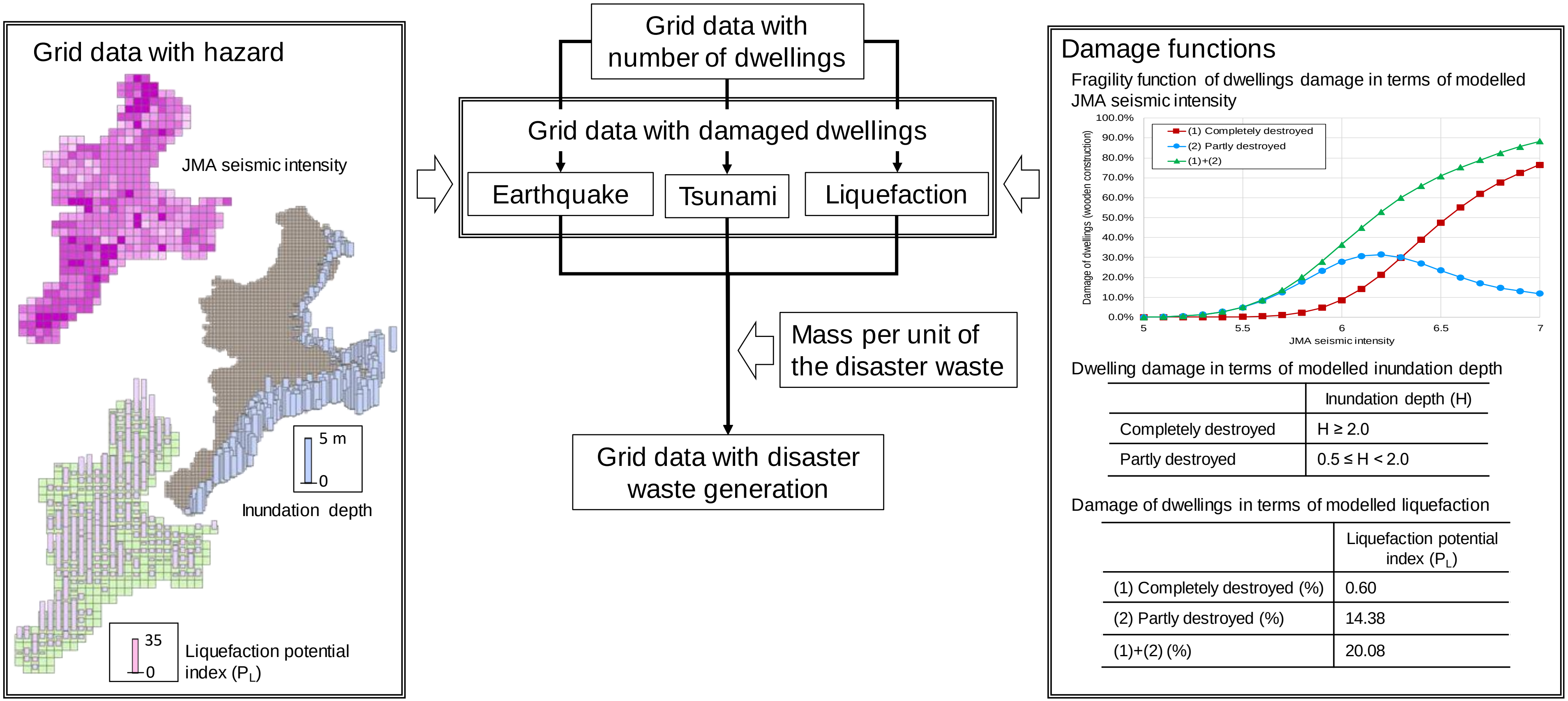


Figure 2 Steps of estimating disaster waste generation

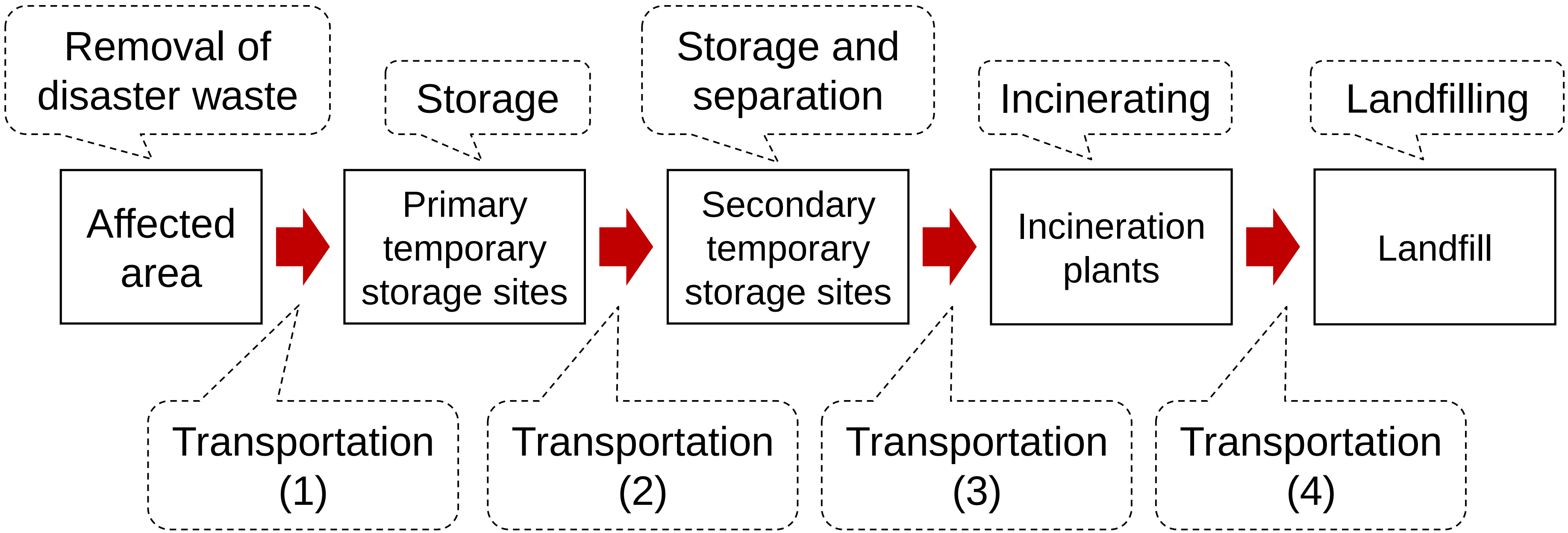
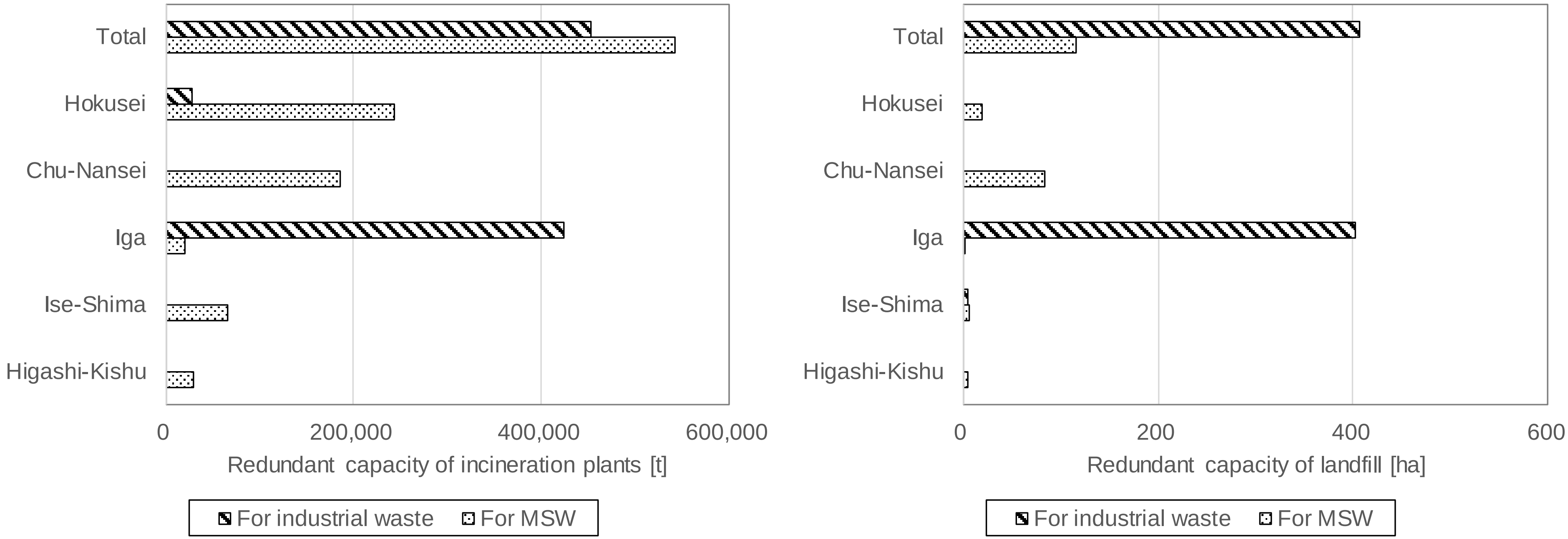


Figure 3 Disaster waste management system

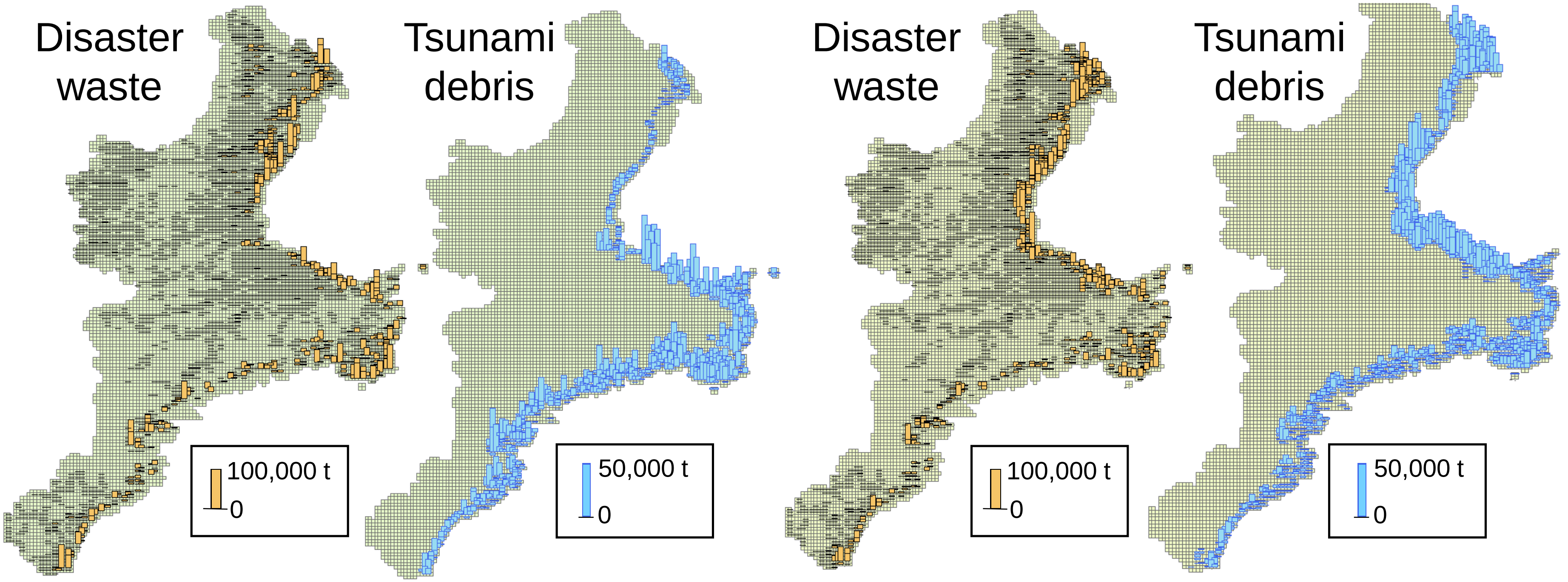


(a) Incineration plants

(b) Landfill

Figure 4 Redundant capacity of incineration plants and landfill

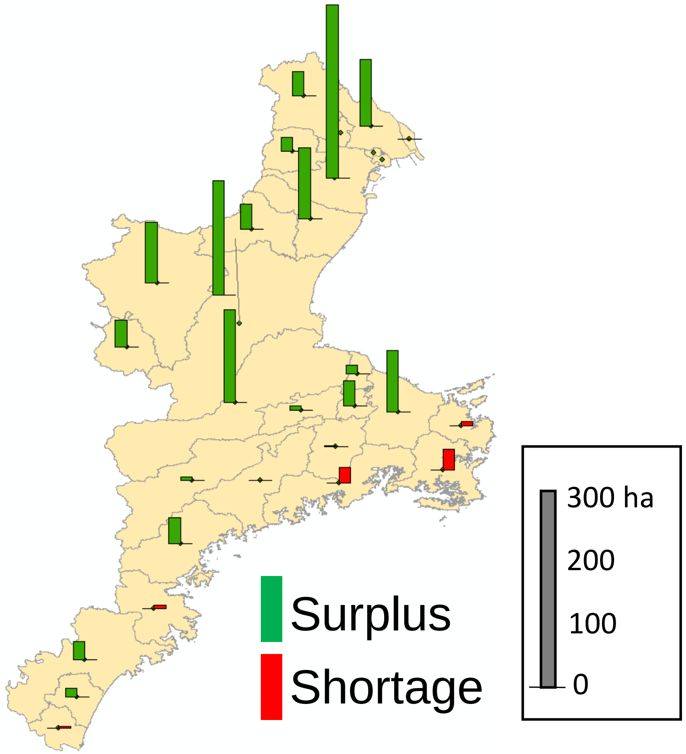
Source: Mie Prefectural government (2015)



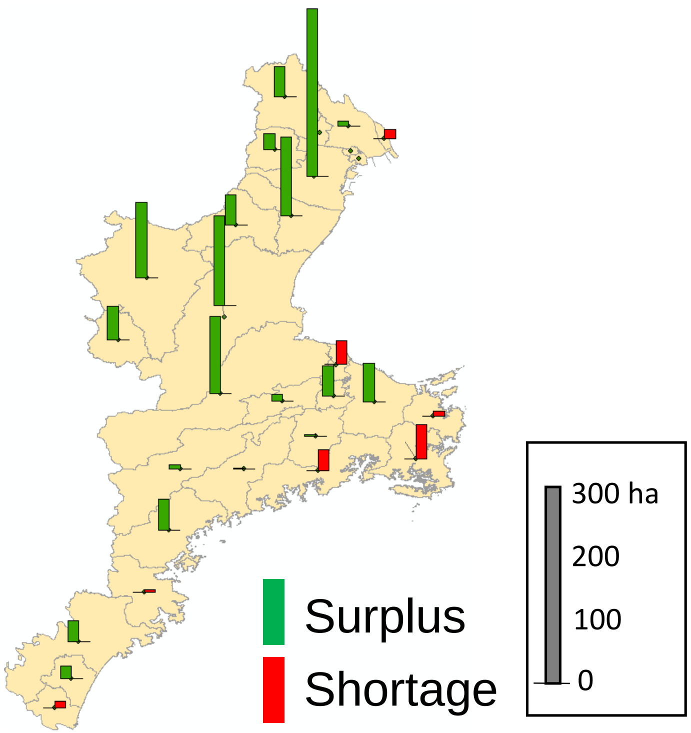
(a) Case 1: Flooding after the earthquake can be controlled

(b) Case 2: Flooding after the earthquake cannot be controlled

Figure 5 Spatial distribution of disaster waste and tsunami debris

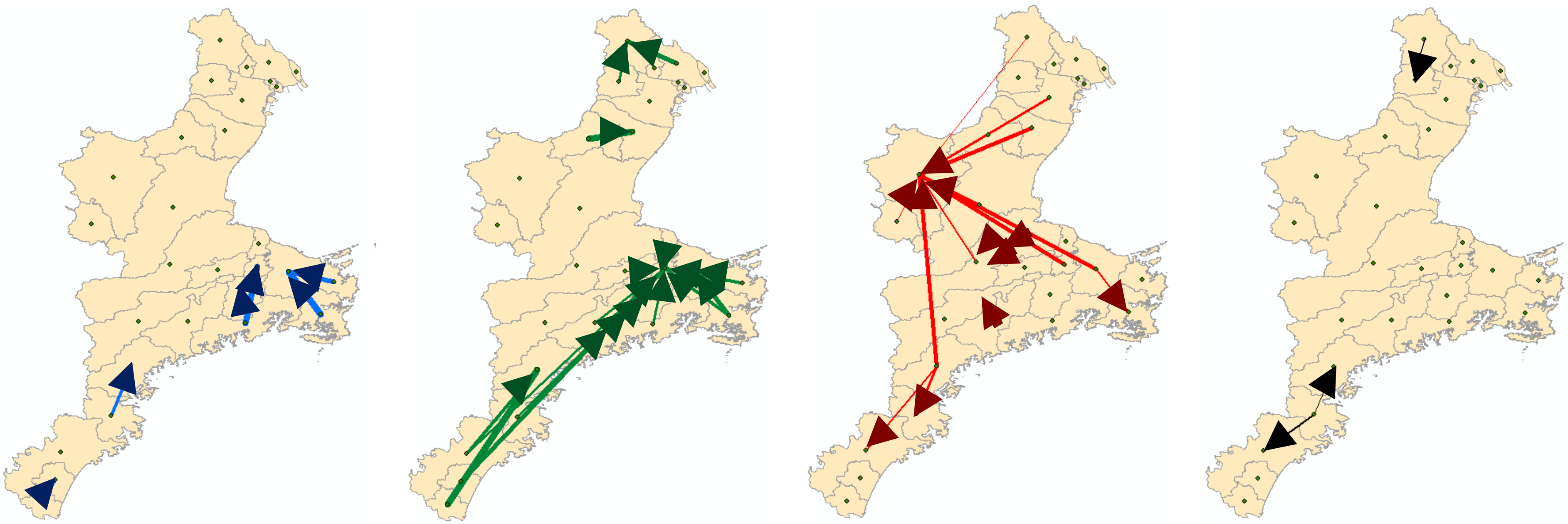


(a) Case 1: Flooding after the earthquake can be controlled



(b) Case 2: Flooding after the earthquake cannot be controlled

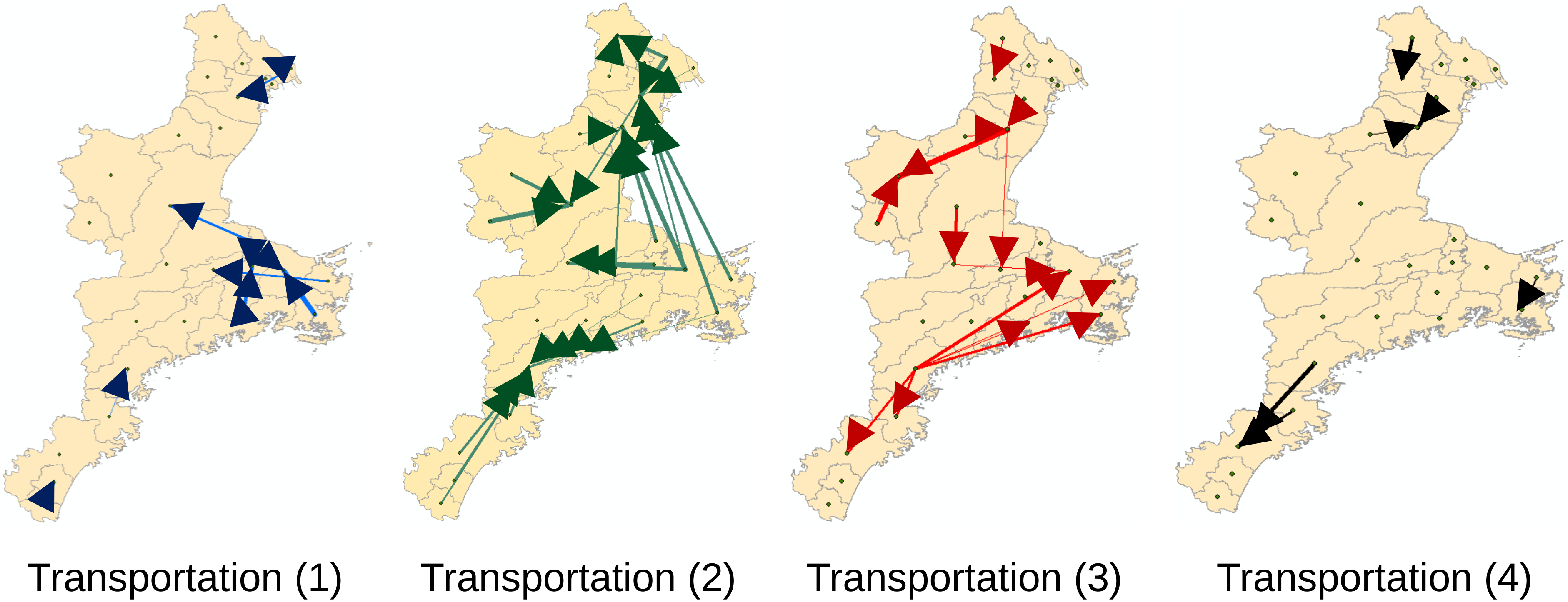
Figure 6 Excess land area of the temporary storage sites



Transportation (1) Transportation (2) Transportation (3) Transportation (4)

(a) Case 1: Flooding after the earthquake can be controlled

Figure 7 Transportation network of the disaster waste



(b) Case 2: Flooding after the earthquake cannot be controlled

Figure 7 Transportation network of the disaster waste

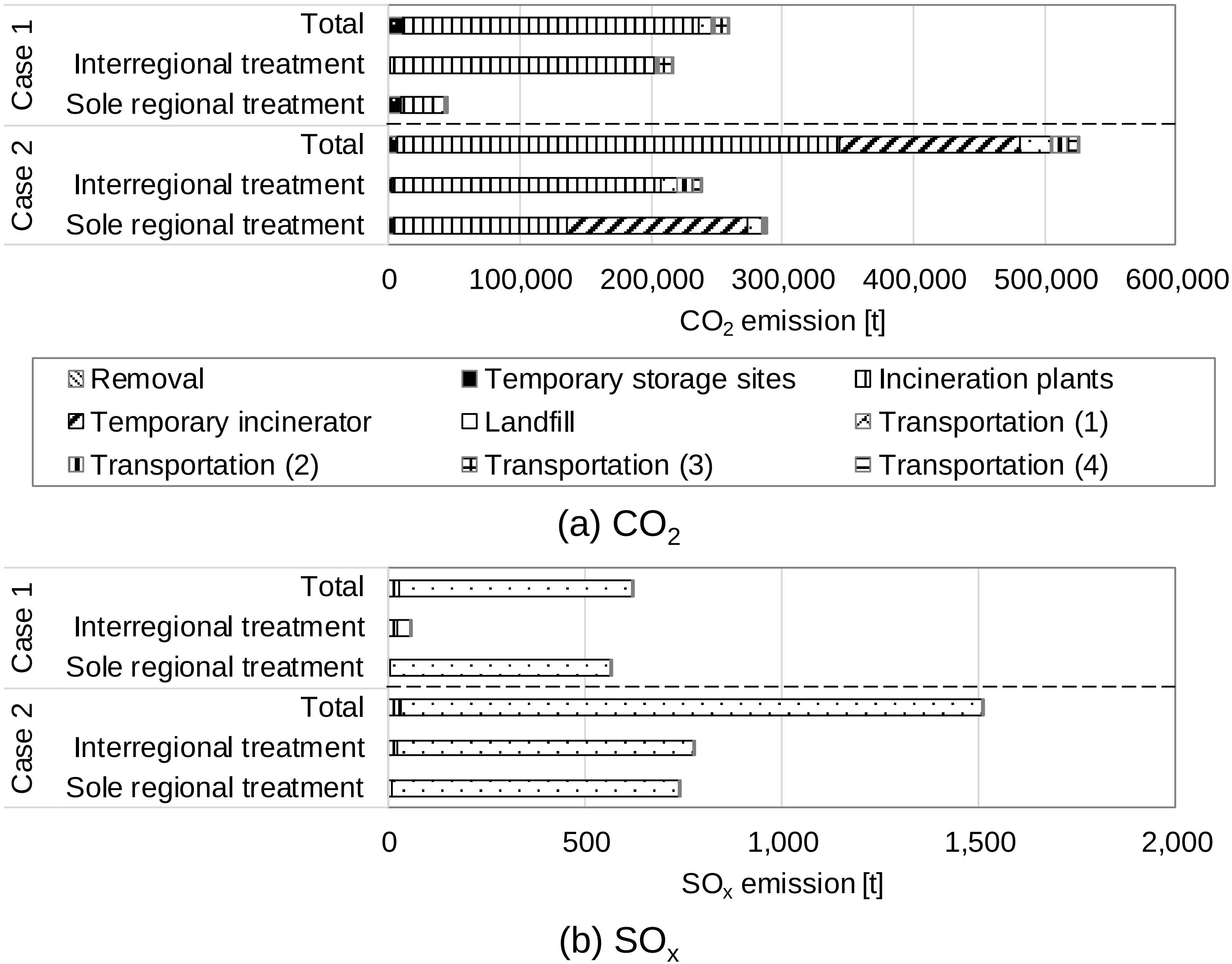
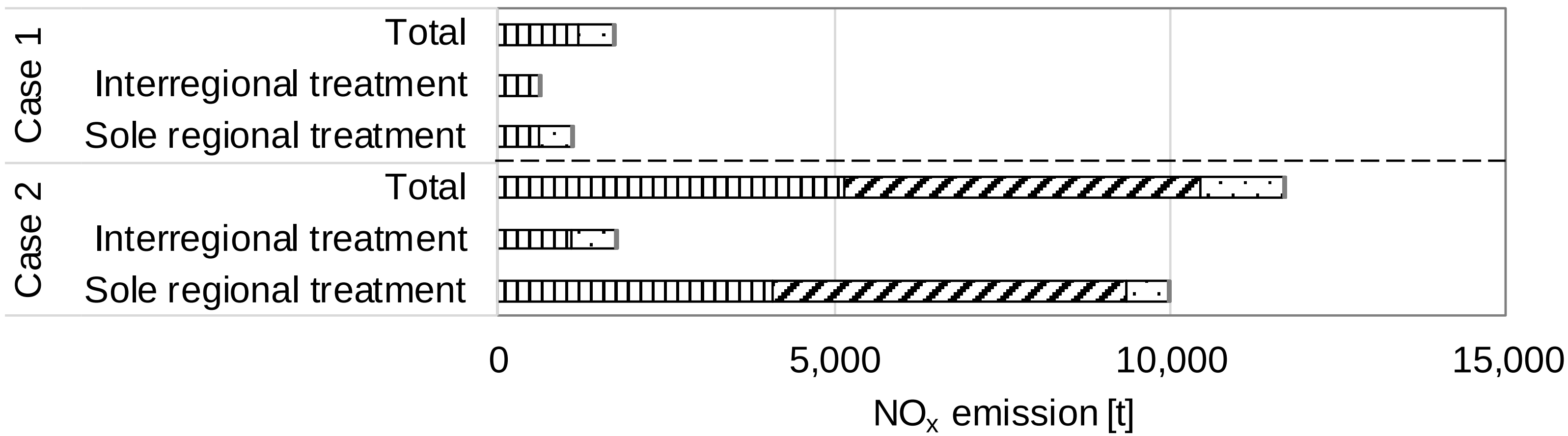
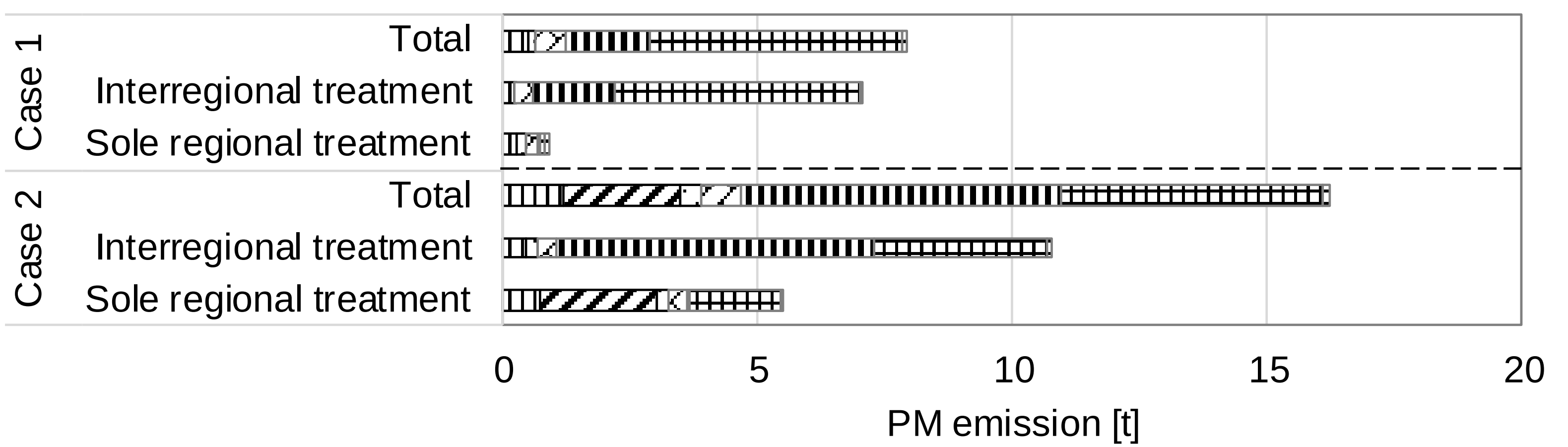


Figure 8 Results of LCA



(c) NO_x



(d) PM

Figure 8 Results of LCA

Note: Case 1: Flooding after the earthquake can be controlled, and
Case 2: Flooding after the earthquake cannot be controlled.

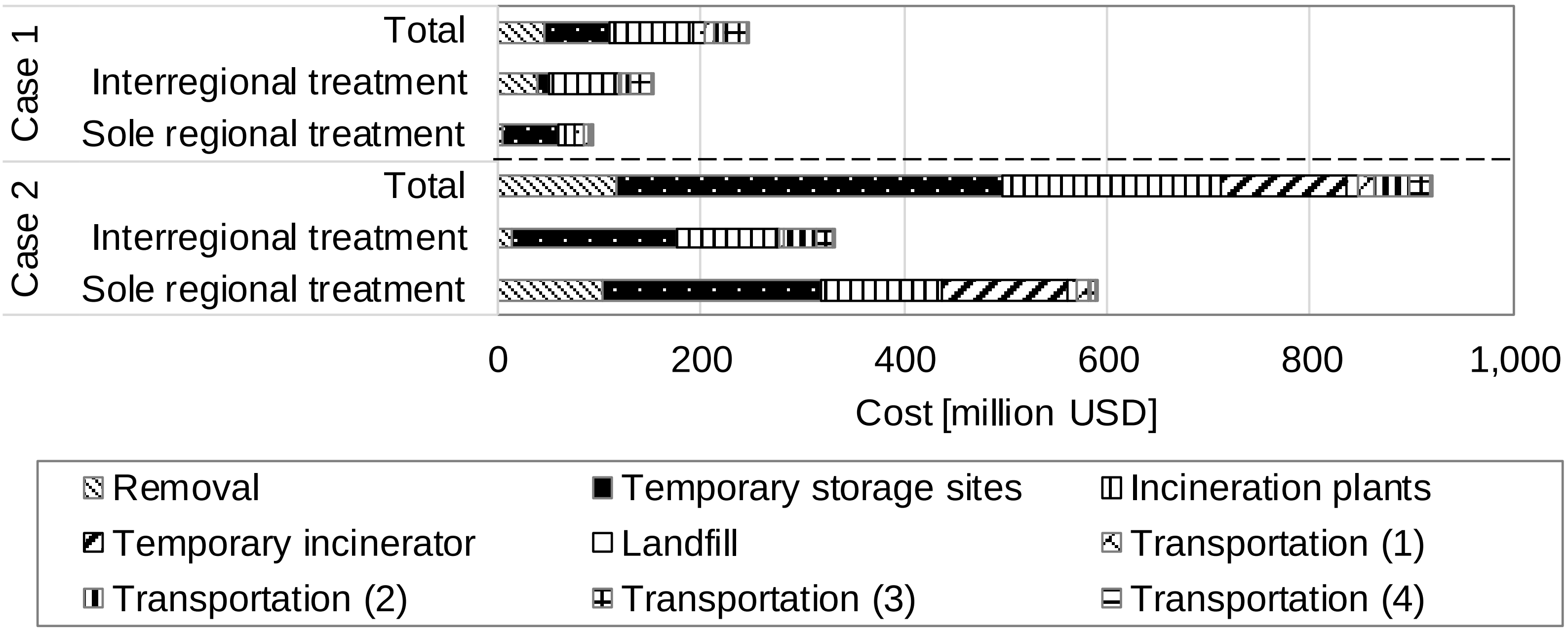


Figure 9 Results of LCC

Note: 1 USD = 113.02 JPY (17.02.20).
Case 1: Flooding after the earthquake can be controlled, and
Case 2: Flooding after the earthquake cannot be controlled.