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Title

Environmental and economic evaluation of pre-disaster plans for disaster waste management:
Case study of Minami-Ise, Japan

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Abstract

Although it is important that disaster waste be demolished and removed as soon as possible after a natural disaster, it is also important that its treatment is environmentally friendly and economic. Local municipalities do not conduct environmental and economic feasibility studies of pre-disaster waste management; nevertheless, pre-disaster waste management is extremely important to promote treatment of waste after natural disasters. One of the reasons that they

cannot conduct such evaluations is that the methods and inventory data required for the environmental and economic evaluation does not exist. In this study, we created the inventory data needed for evaluation and constructed evaluation methods using life cycle assessment (LCA) and life cycle cost (LCC) methodologies for future natural disasters. We selected the Japanese town of Minami-Ise for the related case study. Firstly, we estimated that the potential disaster waste generation derived from dwellings would be approximately 554,000 t. Based on this result, the land area required for all the temporary storage sites for storing the disaster waste was approximately 55 ha. Although the public domain and private land area in this case study is sufficient, several sites would be necessary to transport waste to other sites with enough space because local space is scarce. Next, we created inventory data of each process such as waste transportation, operation of the temporary storage sites, and waste treatment. We evaluated the environmental burden and cost for scenarios in which the disaster waste derived from specified kinds of home appliances (refrigerators, washing machines, air-conditioners and TV sets) was transported, stored and recycled. In the scenario, CO₂, SO_x, NO_x and PM emissions and total cost were 142 t, 7 kg, 257 kg, 38 kg and 1,772 thousand USD, respectively. We also focused on SO_x emission as a regional pollution source because transportation and operation of the temporary storage sites generates air pollution. If the treatment of all waste were finished in 3 years, the environmental standard would be satisfied by setting work duration to 4.8 h/d.

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43 **Keywords**

44 Pre-disaster waste management, disaster waste, Life cycle assessment, Life cycle cost, SO_x

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1. Introduction

Although it is important that disaster waste be demolished and removed as soon as possible after a natural disaster, it is also important that its treatment be environmentally friendly and economical. To achieve these dual goals most effectively, pre-disaster waste management plans for treating and/or recycling the disaster waste are quite important. He and Zhuang (2016) indicate that disaster loss is determined not only by post-disaster relief but also by the pre-disaster mitigation plans and degree of preparedness. Disaster waste must be treated quickly and differently from conventional municipal solid waste. However, the extra environmental burden, along with excessive cost, is expected to be avoided even when disaster waste treatment is involved. This is because prevention of CO₂ emission was agreed at the COP21 in 2015, and because air pollutants such as SO_x, NO_x and PM cause damage to the health of disaster victims and workers in the affected area. Pre-disaster management is extremely important to promote treatment of waste after natural disasters. The US EPA (1998) created projections of the amount and kinds of disaster waste, grasp of treatment capacity in the region, instalment of temporary storage sites and investigation of methods for treating and/or recycling as an item of preliminary examination. In particular, investigation and double-checking of enough temporary storage sites before natural disasters should be conducted to avoid illegal dumping and inadequate segregation (Milke, 2011). In Japan, post-disaster waste management was investigated after the

Great Hanshin earthquake in 1995. Japan Ministry of Environment (MOE) (2014b) also created guidelines for disaster waste management that contains methods for sorting, treating and/or recycling the disaster waste, in response to the Great east Japan earthquake in 2011. Japan Society of Material Cycles and Waste Management (JSMCWM) has also created a manual for treatment and recycling, taking into account the kinds of disaster waste (Asari et al., 2013). These have been provided to local municipalities and others.

The Japanese government remains concerned with the future occurrence of Tokyo inland earthquakes and Nankai mega-thrust earthquakes. The Nankai mega-thrust earthquakes are predicted to cause massive destruction in Japan, and will result in strong tremors over a sizeable area extending from Kanto to Kyushu. The probability of these earthquakes occurring as a class magnitude of 8 to 9 earthquake (stronger than the Great East Japan earthquake), from 1 January 2015, has been estimated to be 70 % within 30 years and 90 % within 50 years. The earthquake will cause an estimated maximum number of 323,000 deaths, and the quantity of disaster waste is estimated to be 250 million t (MOE, 2014a). Important preparations for this predicted earthquake include measures to prevent and mitigate potential damage, and to prepare resilience plans for damage prevention, mitigation, and reconstruction to allow for rapid recovery after the disaster.

83 The Japanese government created the basic disaster management plan for future natural
84 disasters (Cabinet Office, Government of Japan, 2014). This plan contains strategies for treating
85 and/or recycling disaster waste. Local municipalities have also created pre-disaster strategies for
86 waste management. For example, Mie Prefecture (2015) has been investigating strategies for the
87 disaster waste countermeasures.

88 Researchers have also conducted studies for pre-disaster management. Studies for
89 estimating disaster waste are the ones most conducted in this field of study. For example, Chen
90 et al. (2007) created an estimation model for flood damage. Xiao et al. (2012) and Yamanaka et
91 al. (2014) also estimated disaster waste for earthquakes using information gained from previous
92 earthquakes. Tabata et al. (2016) created a model to estimate the disaster waste derived from
93 consumer durables, taking into account possessions and weight of consumer durables. The
94 model created by Tabata et al. (2016) is effective for future natural disasters because this model
95 can create estimates based on household characteristics at the area affected. In another study in
96 this study field, Pramudita et al. (2014) discussed methods for construction of a transportation
97 network for disaster debris if a Tokyo inland earthquake were to happen. Onan et al. (2015)
98 created a decision-making tool to estimate disaster waste, and to investigate transportation
99 networks and the location of temporary storage sites. Brown and Milke (2016) surveyed feasibility,
100 methods and efficacy of recycling using information gained from previous major natural disasters

around the world. Lorca et al. (2015) presented a decision-making tool that enables optimizing and balancing the financial and environmental costs, duration of removal operations, landfill usage, and amount of recycled materials generated.

There are also only a few studies about conducting environmental and economic evaluations of disaster waste treatment scenarios for future natural disasters. Joana and Lisa (2016) conducted environmental and economic evaluations by focusing on energy recovery from the disaster waste in the case of the Great East Japan earthquake, but they used information gained post-natural disaster, and they focused on the energy utilization of biomass. In Japan, many local municipalities, including that containing Mie Prefecture (2015), have created scenarios for treating disaster waste. However, they cannot confirm the feasibility and effectiveness of their scenarios. One of the reasons that they cannot conduct feasibility studies is that the evaluation methods and inventory data required for the evaluation do not exist. Lorca et al. (2015) indicates that each local municipality is required to determine a number of potential disaster scenarios. If the method and the inventory data existed, this would be a feasible and effective tool for selecting environmentally friendly and economic scenarios. Then, they could use this tool for decision-making when they meet with stakeholders (businesses and members of the community) to select the scenarios.

The aim of this study was to create a method and to inventory data that would make it possible to evaluate waste treatment scenarios environmentally and economically, for pre-disaster planning of disaster waste management. This study evaluates the environmental burden and cost of such preparation in Minami-Ise, a Japanese town chosen for a case study. For the case study, we estimated the potential amount of disaster waste generated, derived from existing dwellings, if a Nankai mega-thrust earthquake were to happen. We also conducted environmental and economic evaluations of disaster waste recycling scenarios using life cycle assessment (LCA) and life cycle cost (LCC) methodologies.

2. Materials and methods

2.1. Case study area

Figure 1 shows the geographical location of Minami-Ise town. The population and the number of households in January 2016, was 13,891 and 6159, respectively. The land area was 241.89 km² (24,189 ha). However, because most of the area near the town is mountainous (Figure 2), most of the dwellings in the town are located in a maritime area (near coastal).

(Figure 1 here)

(Figure 2 here)

136

137 This town is an area predicted to be affected if a Nankai mega-thrust earthquake were to
138 happen. The Japan Meteorological Agency (JMA) has predicted the seismic intensity and
139 inundation depth for this town would be 5.4–6.6 and 0.1–7.4 m, respectively. The predicted JMA
140 seismic intensity and inundation depth are different for each district in this town. Severe coastal
141 damage is predicted from seismic, tsunami and liquefaction effects caused by such an earthquake.
142 The JMA seismic intensity scale is a seismic intensity index determined using seismic intensity
143 meters installed in the ground or on the first floor of low-rise buildings (JMA, 2015). The reason
144 we chose this town as the case study area is that, if the Nankai Mega-thrust earthquakes were to
145 happen, many small cities and towns are predicted to get severe damage. Officials in small cities
146 and towns seemed confused about disaster waste treatment in the case of the Great East Japan
147 earthquake because small cities and towns had little know-how and small budgets, compared
148 with bigger cities. Actually, although bigger cities such as Sendai were able to transport,
149 segregate and treat the disaster waste themselves, small cities and towns did not decide the
150 location of the temporary storage sites quickly, so it took a long time to treat the disaster waste,
151 even with the help of other local municipalities. Therefore, investing in small towns is significant
152 from the viewpoint of rapid reconstruction.

We set the steps needed to investigate the pre-disaster planning of waste management as the following: (1) estimation of disaster waste generation, (2) determination of temporary storage sites, (3) setting of system boundaries, and (4) data collection and inventory analysis. We explain these steps in the following section.

2.2. Estimation of disaster waste generation

Figure 3 shows the steps for estimating the disaster waste. In this study, we estimated the potential amount of disaster waste generated, based on expected seismic, tsunami and liquefaction damage. Firstly, we created a residential map to visualize the potentially damaged area by overlaying a hazard map data projected by Mie Prefecture (2014) and a residential map (Zenrin Co., Ltd., 2015). The hazard map provided us various information about JMA seismic intensity, inundation depth, P_L and so on, for each district. Secondly, we created grid data to visualize the number of dwellings by overlaying the residential map and the grid data (each square in the grid represented an area of 500 m). Then, we calculated the potential disaster waste generation for each grid by multiplying the number of dwellings, damage functions and mass per unit of disaster waste. We assumed complete treatment and removed both partly damaged and destroyed dwellings.

(Figure 3 here)

Figure 4, Figure 5 and Table 1 show damage functions for seismic, tsunami and liquefaction damage (Tokyo Metropolitan Government, 2012). We assumed that dwellings in the case study area consisted of wooden materials, based on the Housing and Land Survey (Ministry of Internal Affairs and Communications (MIAC), 2015). Table 2 shows mass per unit of disaster waste in dwellings. We classified the components of disaster waste as dwelling materials or consumer durables. The reason that we focused on only five items as consumer durables, is that these items made up approximately 95.4 % of total consumer durables by weight (Tabata et al., 2016). Therefore, we decided that other consumer durables were negligible. We also adjusted the potential disaster waste generation in relation to each type of damage to avoid double counting the same disaster waste, using the method of Osaka Prefectural Government (2015). According to the method, firstly, (a) the number of dwellings totally and partly destroyed by seismic damage was calculated utilizing Figure 4. Then, (b) the number of dwellings totally and partly destroyed by seismic damage subject to double-counting was calculated by subtracting (c) (the number of dwellings totally and partly destroyed by liquefaction damage) from (a). Next, (d) the number of dwellings totally and partly destroyed by tsunami damage was calculated utilizing

Figure 5. Finally, the number of dwellings totally and partly destroyed by tsunami damage subject to double-counting was calculated by subtracting (b) and (c) from (d).

(Figure 4 here)

(Figure 5 here)

(Table 1 here)

(Table 2 here)

2.3. Temporary storage sites

Based on the results of the estimation of the potential disaster waste, we calculated the land area required for temporary storage sites, using the calculation method published by MOE (2014b). According to this method, the land area required for temporary storage sites is calculated using the following formula.

$$A = \frac{W \times d}{H} \times \frac{1}{r} \quad (1)$$

where A : land area of the temporary storage site [ha], W : collected disaster waste [t], d : apparent relative density of the disaster waste [t/m^3] (d values for combustibles, incombustibles, gravel and cement, metal, and wood are 0.4, 1.1, 1.2, 0.07, and 0.26, respectively), H : height for stacking

the disaster waste [m] (Limitation is 5.0 m or less; in the case of combustibles, 3.0 m or less.),

and r: ratio of waste storage to total storage area [%] (60 %).

The storage area ratio requires a brief explanation. Some space will be needed at the temporary

storage site for storage of the disaster waste and some space will be needed to provide

passageways for trucks and for operation of heavy machinery such as forklifts and sorting

equipment. The ratio of storage area indicates the proportion of space to be used for storage of

disaster waste if the total land area of the temporary storage site were 100 %.

Then, we selected candidate sites to satisfy the required land area. Candidate sites were

supposed to be located near districts in which there was potential for generation of a great deal

of disaster waste. Public domain land (e.g. school grounds) and private land (e.g. car parking

space) were used for the candidate waste storage sites.

2.4 Environmental and economic evaluation of pre-disaster waste

management

2.4.1 System boundary

We calculated the environmental burden and cost of the pre-disaster waste management

system using LCA and LCC methodologies. We set a scenario that specified the kinds of home

appliances (refrigerators, washing machines, air-conditioners and TV sets) that would be carried,

stored, segregated and recycled. One reason that we picked these up was that these specific kinds of home appliances must be recycled (via the law for the 'Recycling of specified kinds of home appliances': Japan Ministry of Economy, Trade and Industry (METI), 1998). These specified kinds of home appliances should be recycled if these products are damaged in natural disasters. Therefore, local municipalities investigate plans for recycling of these products.

Figure 6 shows the system boundaries of disaster waste treatment. In the plant, the disaster waste generated by demolishing buildings in the affected area is transported to the first temporary storage sites. At first, the waste is stored in unsegregated condition. Next, it is transported to the secondary temporary storage site, where it is stored and segregated. Segregated waste is transported to recycling plants and recycled. Recycled materials are sold to recycled materials buyers, and the residue is sent to landfills. In this study, we took into account the following processes (Figure 6): (a) Operation of primary temporary storage sites, (b) Transportation (1), (c) Operation of secondary temporary storage sites, (d) Transportation (2), (e) Recycling, (f) Landfill and (g) Recycling by materials buyers. We did not take into account transportation from the affected area to the primary temporary storage sites because these sites are supposed to be located near the affected areas, so that the transportation distance is quite short.

(Figure 6 here)

A function unit is 1 t of recycled disaster waste. Targeted components of the environmental burden include CO₂ as the global pollution source, and SO_x, NO_x and PM as the regional pollution sources. Cost was targeted through the system boundaries. We also took into account the environmental benefit by saving natural resources and the economic benefit by selling recycled materials.

2.4.2 Data collection for environmental and economic evaluations

We collected the required data and created the inventory data needed to conduct the LCA and LCC methodologies through the system boundaries, according to the following settings.

Operation of the temporary storage sites (primary and secondary)

We supposed that heavy machinery would be operated at the temporary storage sites. It is necessary to collect the light oil usage and cost data by each operation. To collect such kinds of data, we conducted interviews in local municipalities about affected areas where temporary storage sites were operated when the Great East Japan earthquake happened. Costs include rental charges for heavy machinery and leased land, labour charges and so on. Unfortunately, the data collected was combined for all kinds of operations, and it is difficult to determine the cost

for each item of expense. Based on this restriction, we calculated light oil usage and cost by operation per 1 t of the disaster waste to create inventory data. We also supposed that primary and secondary temporary storage sites utilized the same inventory data.

As the result of the interviews, we were able to collect complete data from seven local municipalities. We conducted regression analysis to explain the variables such as light oil usage and cost. By conducting the analysis taking into account the coefficient of correlation between candidates for explanatory variables, the following formulas were introduced.

$$O = 0.017 \frac{A}{(36.86)} + 0.18 \frac{Dummy}{(6.58)} + \frac{0.54}{(43.16)} \quad (2)$$

$$C = 0.0006A - 0.0008 \quad (3)$$

where O : light oil usage per tonne of the disaster waste [L/t], $Dummy$: existence or non-existence of tsunami debris dummy (Yes=1, No=0) and C : cost per tonne of the disaster waste [USD/t].

By using the above equations, local municipalities will be able to evaluate the environmental burden and cost of setting up these temporary storage sites.

We need to explain about the tsunami debris dummy. Many local municipalities transported and stored tsunami debris to a temporary storage site when the Great East Japan earthquake happened. Light oil usage and cost in local municipalities that treated the tsunami debris were different from other local municipalities that did not treat the tsunami debris. Based on this, we introduced the existence or non-existence of tsunami debris as a dummy variable.

Formula (2) was represented as multiple regression for which explanatory variables consisted of land area of the temporary storage site, and existence or non-existence of the tsunami debris dummy. The numbers in parentheses indicate t-values. As the result of the regression analysis, all of the t-values were significant. The adjusted coefficient of correlation and adjusted coefficient of determination, were concurrently 0.999. Formula (3) was represented as single regression for which the explanatory variable consisted of land area of the temporary storage site. The adjusted coefficient of correlation was 0.990. We found that both formulas are efficient for the calculation of the inventory data.

Land area of the temporary storage sites was calculated as indicated in Section 3.1. We calculated light oil usage and cost by storing 1 t of disaster waste using Formula (2) and (3). Then, environmental burden in this process was calculated by multiplying the amount of specified kinds of home appliances, light oil usage by storing 1 t of disaster waste and environmental emission intensity of light oil. Cost in this process was calculated by multiplying the amount of specified kinds of home appliances and cost by storing 1 t of disaster waste. We utilized the emission intensity published in the Japanese LCA software 'MiLCA' (Japan Environmental Management Association for Industry (JEMAI), 2014) and utility rates of electricity and water.

Transportation (1) and (2)

We supposed that transportation was conducted by 4 t trucks for transportation (1). We also supposed that transportation was conducted by 10 t trucks for transportation (2). We calculated t-kilometre by multiplying the transportation distance and transportation amount of disaster waste. The environmental burden of this process was calculated as t-kilometre and emission intensity (JEMAI, 2014). Cost in this process was calculated using the number of trucks required and the cost intensity (MOE, 2014a). We also supposed that daily working hours for waste transportation was 8 hours, based on MOE figures (2014a). If daily loading and unloading hours were set at 0.31 h (MOE, 2011), daily transportation hours were 7.69 h. We calculated the number of trucks required based on the amount of disaster waste to be transported, daily transportation hours and the loading ratio (= 0.7).

Transportation distance was identified based on real road distance from primary temporary storage sites to secondary temporary storage sites, and from secondary temporary storage sites to recycling plants. We calculated real road distance using Google Earth. To identify the real road distance, we identified where the primary and secondary temporary storage sites should be located, and where the recycling plants were located. We determined the primary and secondary temporary storage sites based upon the results from estimation of the amount of potential disaster waste. We also supposed that specified kinds of home appliances were transported and handled at the real recycling plants nearest the case study area. The law for the

'Recycling of specified kinds of home appliances' classifies specified kinds of home appliance manufacturers into Group A and Group B. For example, specified kinds of home appliances manufactured by Group A should be handled at recycling plants belonging to Group A. Recycling plants have several recycling lines such as dismantlement, and separation of materials, to treat each specified kind of home appliance. We created a ratio of the specified kinds of home appliances to transport from the secondary temporary storage site to Group A and Group B based on their market shares. We assumed 51 % of the disaster waste transported to recycle plants belonged to Group A, and 49% of the disaster waste transported to recycle plants belonged to Group B. Then, we identified the transportation amount and transportation distance of each group. Figure 7 shows transportation from the secondary temporary storage site to the recycling plants. Only Group B used two different recycling plants to handle different kinds of home appliances.

(Figure 7 here)

Recycling

We supposed that electricity and water were utilized for recycling the specified kinds of home appliances in the recycling plants. We calculated the mass per unit of electricity and water usage, and recovery rate of materials, based on the interview in a recycling company. The

environmental burden and cost of this process were calculated based on the amount of the specified kinds of home appliances, on the emission intensity in manufacturing the same materials from virgin resources (JEMAI, 2014) and on the utility rates of electricity and water. In this study, we assumed that all of the specified kinds of home appliances were recyclable, recycle based on the interviews, because these items can be recycled if not completely destroyed. We also assumed that the grade of recycled materials is same as the grade of virgin resources.

Landfill

The environmental burden and cost in this process were calculated based on the amount of residue, and on the emission intensity and cost (Tabata and Chiba, 2014).

Recycled materials buyers

The environmental burden in this process was calculated based on the amount of recycled materials and emission intensity in manufacturing the same materials from virgin resources (JEMAI, 2014). The benefit was calculated based on the amount of recycled materials and purchase price of the recycled materials.

Inventory data

Table 3 shows the inventory data created by selecting the above settings. The specified kinds of home appliances treated in the recycling plants were classified as 90 % recycled

materials and 10 % residue, based on the interview survey. Inventory data in the operation of the temporary storage sites process created the result in Section 3.1.

(Table 3 here)

3. Results and discussion

3.1. Spatial distribution of disaster waste generation

As the result, we show the spatial distribution of the potential disaster waste at Minami-Ise in Figure 8, and show the potential generation of disaster waste in Table 4. The overall potential generation was approximately 554,000 t. Disaster waste derived from dwelling materials was greatest (approximately 534,000 t). The amount of disaster waste derived from consumer durables was not as much. As we mentioned above, this town would potentially have severe tsunami damage, and districts of high population density would generate a lot of disaster waste.

(Figure 8 here)

(Table 4 here)

The land area required for the temporary storage sites was calculated to be approximately 30 ha, based on the result in Table 4. Twenty temporary storage sites were determined in the case study area using Google Earth. Total land area of the determined temporary storage sites was approximately 55 ha. Figure 9 shows the determined temporary storage sites. Based on the determination, we supposed that primary temporary storage sites should be located where there was at least 1 ha of land. We supposed that the secondary temporary storage sites should be located where there was at least 10 ha of land. We labelled the primary temporary storage sites as 'A – R and T' in Figure 9, and we labelled the secondary temporary storage site as 'S'. From these results, we found that the primary temporary storage sites determined were adequate to satisfy the required land area. However, sites C, I, J, F and M has inadequate space for storing disaster waste where generated around the sites. In this study, we assumed surplus disaster waste at C is transported to D (where there is enough space); and that surplus disaster waste at I and J, and at L and N, is transported to F and M, respectively.

(Figure 9 here)

(Figure 10 here)

Light oil usage and cost at the temporary storage sites was calculated as 1.6 L/t and 290 USD/t using Formula (2) and (3). If we suppose that the loading ratio of 4-t and 10-t trucks is 0.7, the number of 4-t and 10-t trucks required was 1290 and 510, respectively.

3.2. Results of environmental evaluation

Figure 11 shows the results for the environmental burden. CO₂ emission was approximately 142 t. Transportation (2), recycling and operation of temporary storage sites were the predominant processes. SO_x, NO_x and PM emissions were 7 kg, 257 kg and 38 kg, respectively. The amount of recycled materials was approximately 3,100 t. Figure 12 shows the result of the cost. Total cost was approximately 1772 thousand USD. Operation of the temporary storage sites were the predominant processes. As mentioned in the introduction, there are only a few studies about conducting environmental and economic evaluations of disaster waste treatment scenarios for future natural disasters. We discussed the validity of these results compared with LCA and LCC results of the Municipal Solid Waste (MSW) treatment system in Japan (Tabata et al, 2009 and 2011). Based on these studies, CO₂ emission of transportation is slightly bigger than of recycling. However, emission from incineration is much bigger than transportation and recycling. The cost of transportation is almost the same as with recycling. From results in this study, CO₂ emission of transportation (1) and (2) are bigger than recycling. Although

400 cost of transportation (1) and (2) are characteristic in the total cost, the cost of recycling is quite
401 small. These trends are almost same as the case of MSW treatment. Actually, it is difficult to
402 discuss treatment of the disaster waste and the MSW at the same time. However, results in this
403 study have a certain level of validity. On the other hand, there is no existing research that provided
404 environmental and economic evaluation of the temporary storage sites. The limitation of this study
405 is that the number of samples at the actual temporary storage sites is small. Future research
406 includes refinement of inventory data by collecting more operating data because few data were
407 obtained data in this study. As we indicated above, the environmental burden and cost of
408 incineration is much greater than other processes. We can easily predict that the disaster-waste
409 derived from combustibles is an important factor to discuss for pre-disaster waste management.
410 Another future research effort includes investigating the combustibles treatment system to find
411 how to reduce the environmental burden and cost for the pre-disaster waste management.

412 Generally speaking, the environmental burden and cost were small. This was because this case
413 study focused on one small town and the amount of specified kinds of home appliances were
414 relatively less. If we discuss these data as per capita, CO₂, SO_x, NO_x and PM emissions and cost
415 were 10.24 kg/capita, 0.00050 kg/capita, 0.018 kg/capita, 0.0027 kg/capita and 127.56
416 USD/capita, respectively. CO₂ emission per capita for the MSW treatment in FY2014 (FY means
417 fiscal year. In Japan, FY2014 starts April 2014, and ends March 2015) was 143 kg/capita

(Greenhouse Gas Inventory Office of Japan (GIO), 2015). CO₂ emission for the MSW treatment is approximately 14 times bigger than the disaster waste treatment. Cost per capita for the MSW treatment in FY2014 is also 211.56 USD (Japan average is 139.37 USD) (MOE, 2016). Cost for the disaster waste treatment is almost the same as the average in Japan.

(Figure 11 here)

(Figure 12 here)

3.3. Sensitivity analysis

If we really transport disaster waste and operate temporary storage sites, it is not realistic to treat only the specified kinds of home appliances. Therefore, we should take into account not only the specified kinds of home appliances but also cars and dwelling materials. If all the estimated disaster waste were taken into account in the transportation (1) and operation of the temporary storage processes in Figure 6, the CO₂, SO_x, NO_x and PM emissions were 7,306 t, 600 kg, 2,430 kg and 940 kg, respectively.

We focused on the SO_x emission as the representative regional pollution source. SO_x emission is a causative agent for air pollution. This agent is generated according to the usage of trucks and heavy machinery at the temporary storage sites. Therefore, generation of this agent in the

affected areas might affect the health of disaster victims, workers and so on. Although the disaster waste should be handled quickly, environmental standard should also be respected. MOE (1996) set environmental standards for SO₂, NO₂, SPM and so on in the 'Air pollution control act'. For example, the environmental standard of SO₂ is as follows. The daily average for hourly values shall not exceed 0.04 ppm (mg/kg), and hourly values shall not exceed 0.1 ppm (MOE, 1996). Based on the standard, we calculated the relationship between daily working hours and required working years for processes related to transportation and operation of the temporary storage sites, which would satisfy the environmental standards of SO₂. In this study, we only calculated SO_x emission, and the above-mentioned act focuses on SO₂, not SO_x. We chose to use SO_x emission instead of SO₂ emission to compare the environmental standard of SO₂ because SO₂ is the predominant form found in the atmosphere (The World Bank Group, 1998).

Figure 13 shows the result. In this study, we converted the weight of SO_x emission into volume basing on the atomic weight of SO₂ and its volume of 22.4 L at normal condition, and converted it to concentration to compare with its environmental standard. As a result, we found that if we set the required working year at '1', the environmental standard was satisfied by 16 h of daily work. The Japanese government finished the treatment of disaster waste in 3 years in the case of the Great East Japan earthquake (Brown and Milke, 2016). If we finished the treatment

in 3 years, taking into account the above case, the environmental standard would be satisfied by limiting the work to 4.8 h/d.

(Figure 13 here)

4. Conclusions

In this study, we created a method for environmental and economic evaluation of disaster waste treatment scenarios so that local municipalities could investigate feasible and effective pre-disaster plans for waste management. In addition, we created the inventory data that is required for the evaluation. As a method of pre-disaster planning, we estimated the potential disaster waste generation derived from dwellings. We investigated the area required for the temporary storage sites needed to store the disaster waste. We also created inventory data for each process such as transportation, operation of the temporary storage sites and treatment by interview survey. In addition, we set a scenario for environmental and economic evaluations if the specified kinds of home appliances were recycled. This took into account processes such as transportation, operation of temporary storage sites and recycling. The following conclusions are results of scenario analysis.

(1) If a Nankai mega-thrust earthquake were to happen, overall potential disaster waste generation would be approximately 554,000 t in the case study area. The potential disaster waste generation would be much greater in the maritime area.

(2) Based on the result of potential disaster waste generation, we determined that there were 20 potential sites (total land area was approximately 55 ha) in the case study area. However, several sites have inadequate space for storing the disaster waste generated around the sites. In this case, it would be necessary to transport waste to other sites with enough space.

(3) CO₂, SO_x, NO_x and PM emissions were 142 t, 7 kg, 257 kg and 38 kg, respectively. The total cost was approximately 1,772 thousand USD. Transportation, temporary storage sites and recycling were the predominant processes affecting the result of CO₂ emission. Transportation and temporary storage sites were also important processes for the result of total cost. Trends of the transportation and recycling processes were almost same as with the case of the MSW treatment system. Additional discussion about temporary storage sites process is required because the number of samples was small for creating the inventory data.

(4) We calculated the relationship between daily working hours and required working years for transportation and operation of the temporary storage sites in relation to satisfying the environmental standard of SO₂. If the treatment of all waste was finished in 3 years, the environmental standard would be satisfied by setting work duration to 4.8 h/d.

This is the first study in which inventory data for environmental and economic evaluation of pre-disaster waste management were created. This is also the first study in which environmental and economic case study was used to take into account the disaster waste treatment for a future natural disaster. These methods and inventory data have limitations that should be resolved. For example, this study focuses only on one kind of recycling of the disaster waste, but other treatments and/or recycling options should be investigated. Furthermore, in case of disaster waste incineration, inventory data for the incineration should be created. In addition, incineration is different from recycling. For example, in most cases, the size of combustibles is much larger than the specific kinds of home appliances and they need more space. Therefore, a study on a transportation network to minimize transportation cost and/or its environmental burden is required. These investigations will be conducted in our future research. Nevertheless, when local municipalities investigate the feasibility and effectiveness of their pre-disaster treatment scenarios, the methods and inventory data that we created should be useful, because if local municipalities intend to formulate a pre-disaster waste management plan, they will need to investigate the treatment and/or recycling methods of the disaster waste, while taking into account installation of the temporary storage sites, the disaster waste transportation network, etc. If they are able to evaluate the environmental burden and cost of the pre-disaster waste management system, they will be able to select the treatment and/or recycling methods with the lowest

environmental burden and/or cost. Although the treatment of the disaster waste is an important task for them, the cost of this treatment is also crucial because, in most cases, it is funded through taxes. Hence, this study provides use of tax money for citizens. In addition, the temporary storage sites could be installed in residential neighbourhoods. For this, local municipalities need to obtain the support of the local residents. This study also provides them with concrete reasons for installing the temporary storage sites within their neighbourhood and provides useful information to support decision making by the local municipalities after the occurrence of disasters.

Precautionary principle declares that where there is reason to regard a substance or process as environmentally damaging, preventive action or regulation should be undertaken despite the absence of scientific certainty (Attfield, 2015). No one can predict when natural disasters will occur, and no one can prevent occurrence of natural disasters. Therefore, we should plan the pre-disaster waste management based on the precautionary principle. Methods and inventory data that we created should not only be basic tools but also significant for national government and local municipalities.

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Table 1 Damage of dwellings in terms of modelled liquefaction

Liquefaction Potential Index (P _L)	(1) Completely destroyed	(2) Partly destroyed	(1) + (2)
> 0	0.60 %	14.38 %	20.08 %
0	0 %	0 %	0 %
—	0 %	0 %	0 %

7

Note: “—” indicates areas within the district not covered by a sand layer.

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Source: Tokyo Metropolitan Government (2012)

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Table 2 Mass per unit of disaster waste in dwellings

Dwelling materials [kg/m ²]	Gravel	219.6	Consumer durables [kg/dwelling]	Refrigerators	80.76
	Cement	88.1		Washing machines	49.97
	Wood	2.8		Air-conditioners	133.06
	Glass	29.8		TV sets	45.24
	Pottery	76.1		Cars	2,358
	Iron	9.1			
	Aluminium	2.8			
	Others	3.0			

Source: Nagaoka et al. (2008) and Tabata et al. (2016)

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Table 3 Inventory data for disaster waste treatment

		CO ₂	SO _x	NO _x	PM	Cost
	Unit	kg/	kg/	kg/	kg/	USD/
Transportation (1)	/tkm	1.50E-01	7.47E-06	1.29E-05	7.91E-05	—
	/truck/h	—	—	—	—	44
Temporary storage site	/t	4.96E+00	4.60E-04	2.04E-03	1.23E-20	294
Transportation (2)	/tkm	1.27E-01	6.32E-06	1.09E-05	6.68E-05	—
	/truck/h	—	—	—	—	64
Recycling	/t	6.55E+00	3.96E-04	1.06E-03	1.61E-16	1.97
Landfill	/t	2.29E-03	6.20E-04	4.91E-01	6.75E-03	0.079
Recycled materials buyers	/t	-1.61E+00	-7.43E-04	-9.64E-04	-1.57E-14	-0.29

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Note: 1 USD = 108.77 JPY (2016.04.08)

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Table 4 Potential disaster waste generation

		Weight [t]			Weight [t]	Appliances [unit]
Dwelling materials	Gravel	272,070	Consumer durables	Refrigerators	1,253	30,713
	Cement	109,175		Washing machines	883	21,650
	Wood	3,470		Air-conditioners	904	22,153
	Glass	36,929		TV sets	532	13,053
	Pottery	94,242		Cars	15,924	10,982
	Iron	11,215		(2) Total	19,496	98,551
	Aluminium	3,470	Total ((1) + (2))		553,783	-
	Others	3,718				
	(1) Total	534,287				

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Figure 1 Location of case study area

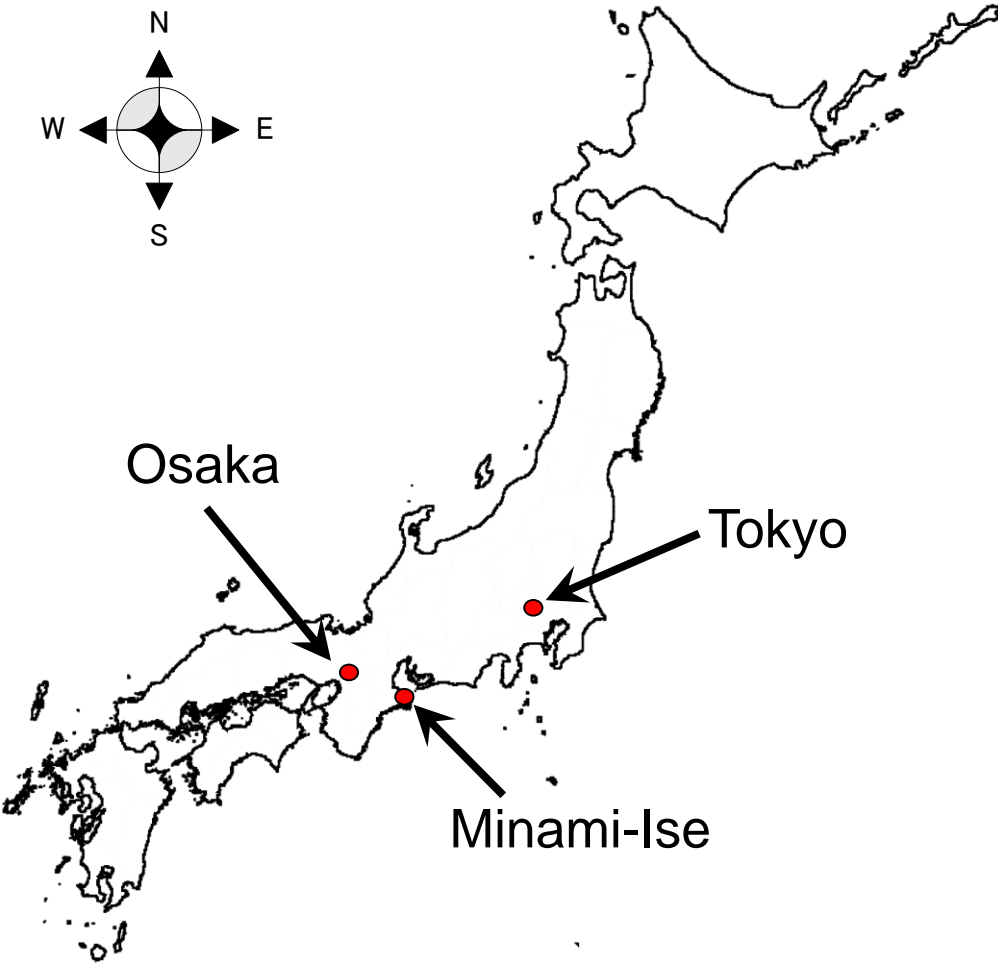


Figure 2. Geographic location of Minami-Ise

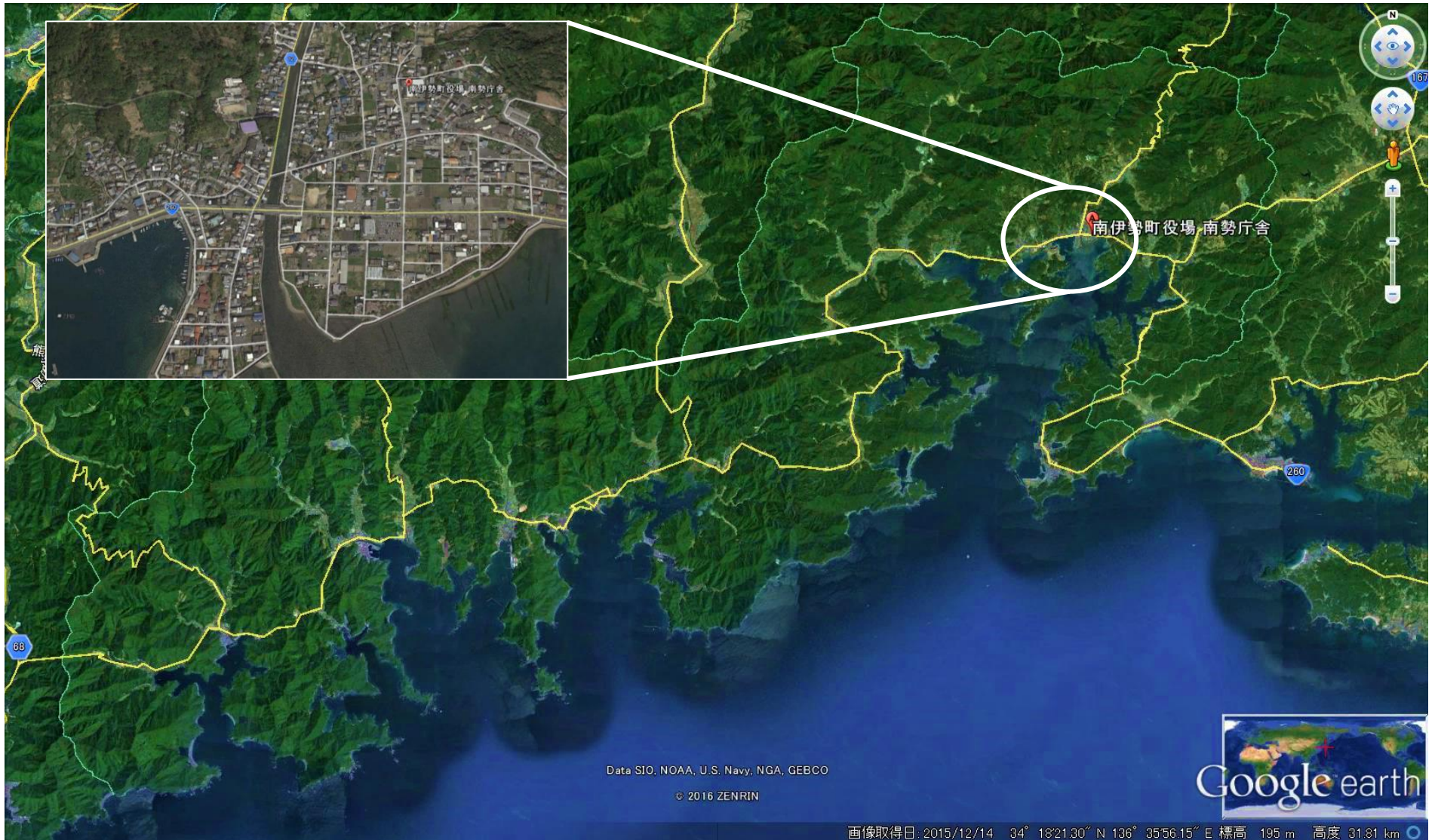


Figure 3 Steps for estimating the disaster waste

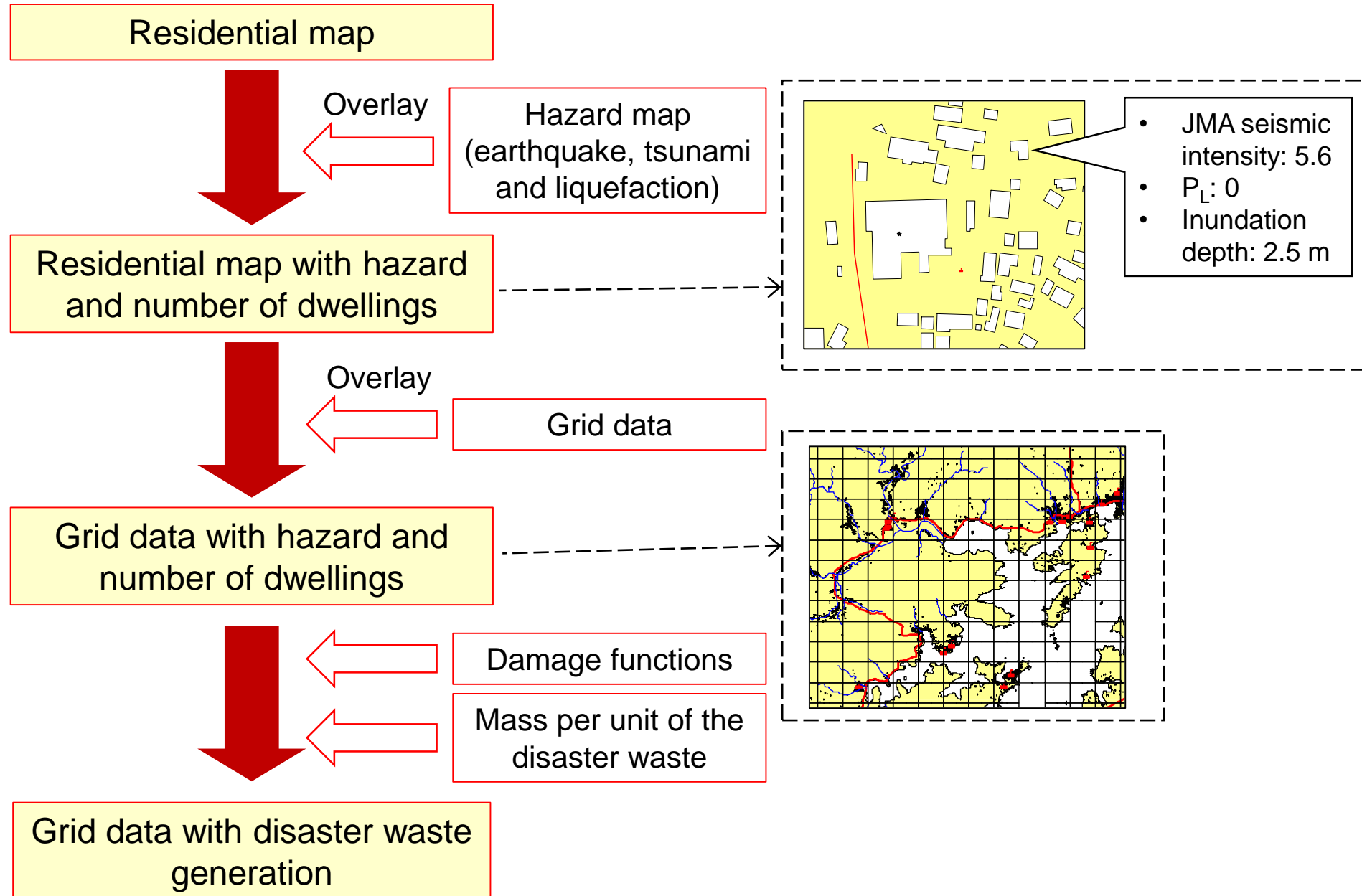
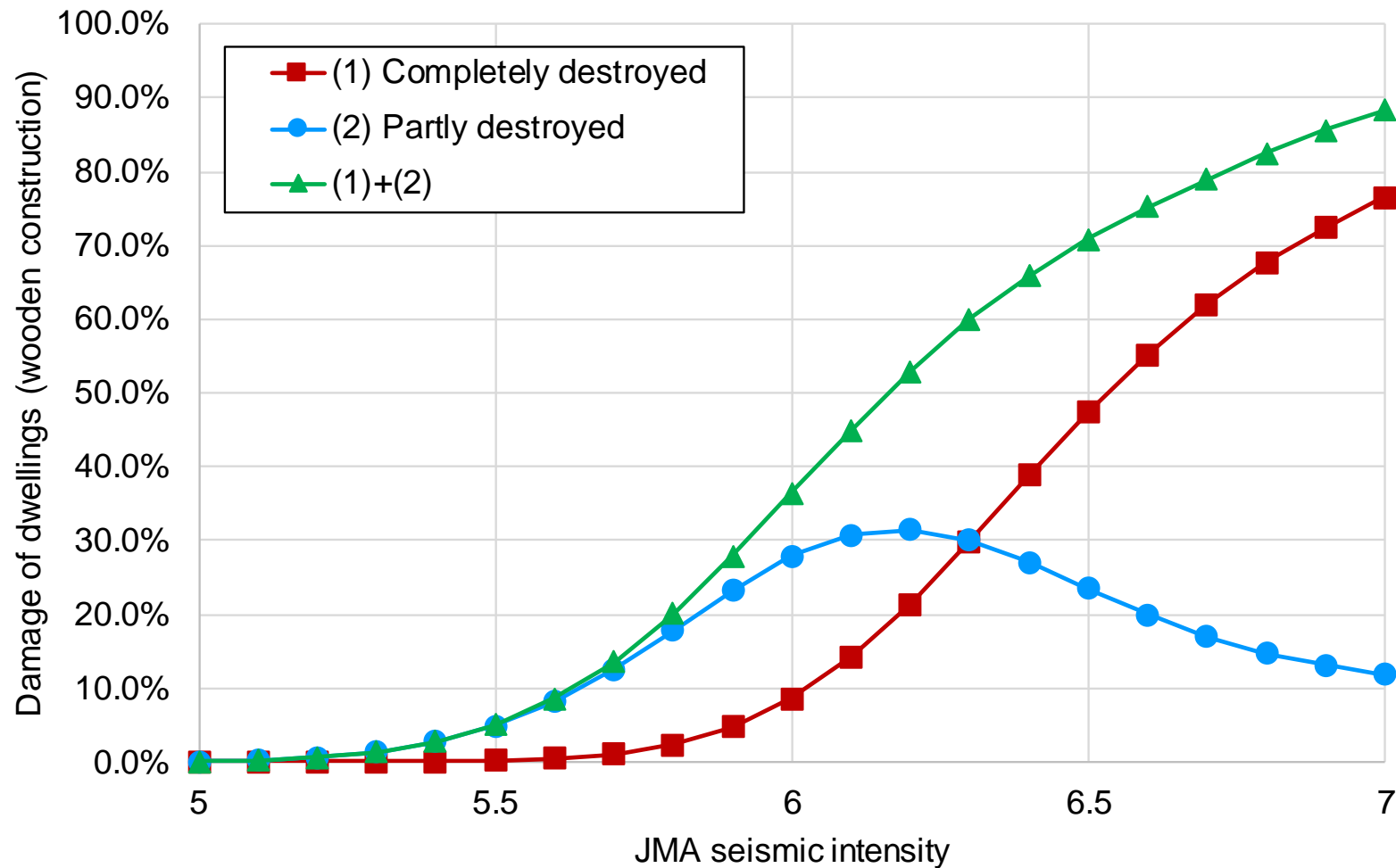
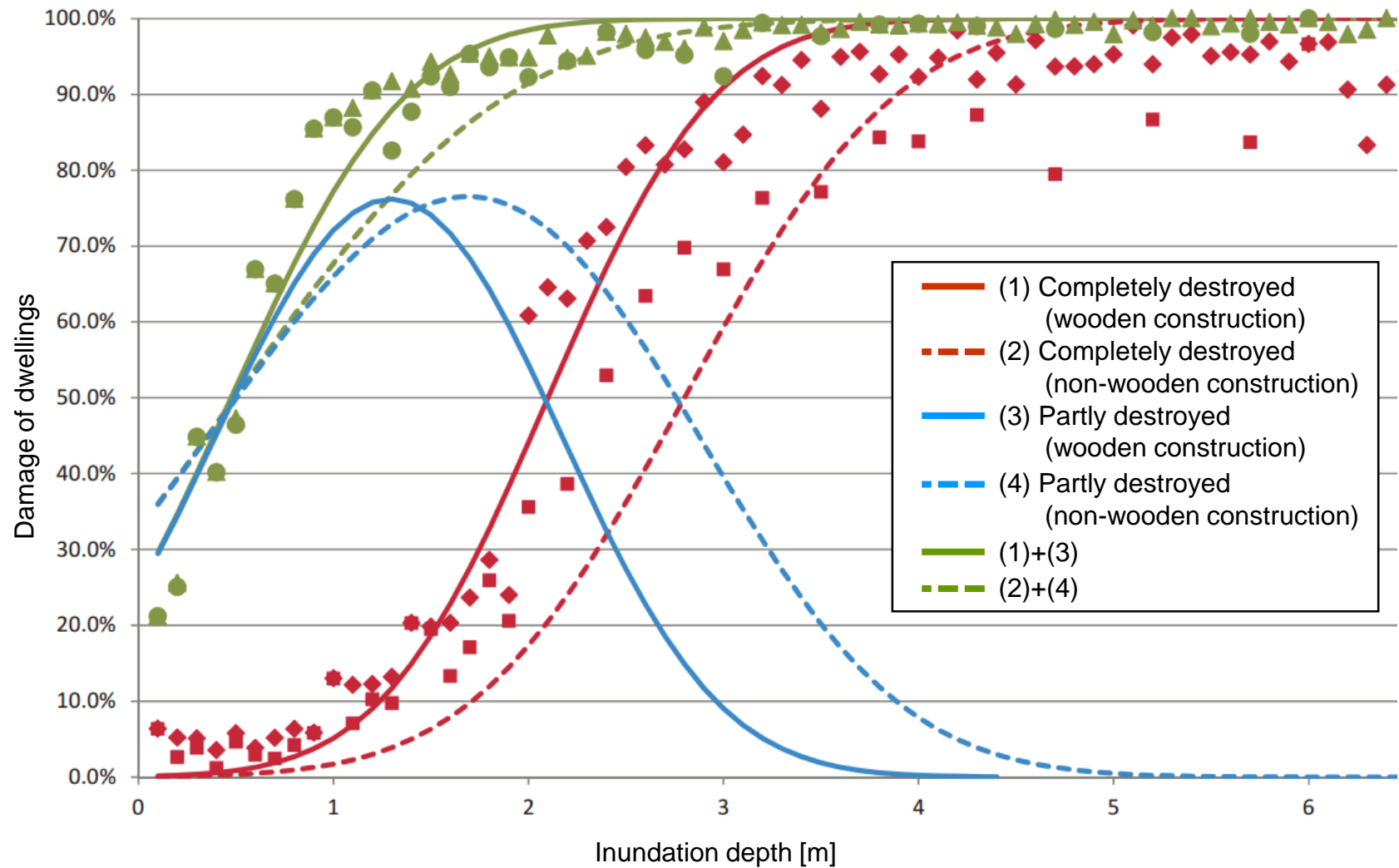


Figure 4 Fragility function of dwellings damage in terms of modelled JMA seismic intensity



Source: Tokyo Metropolitan Government (2012)

Figure 5 Fragility function of dwelling damage in terms of modelled inundation depth



Note: Authors modified a graph published by the Tokyo Metropolitan Government (2012).

Figure 6 System boundary of disaster waste treatment

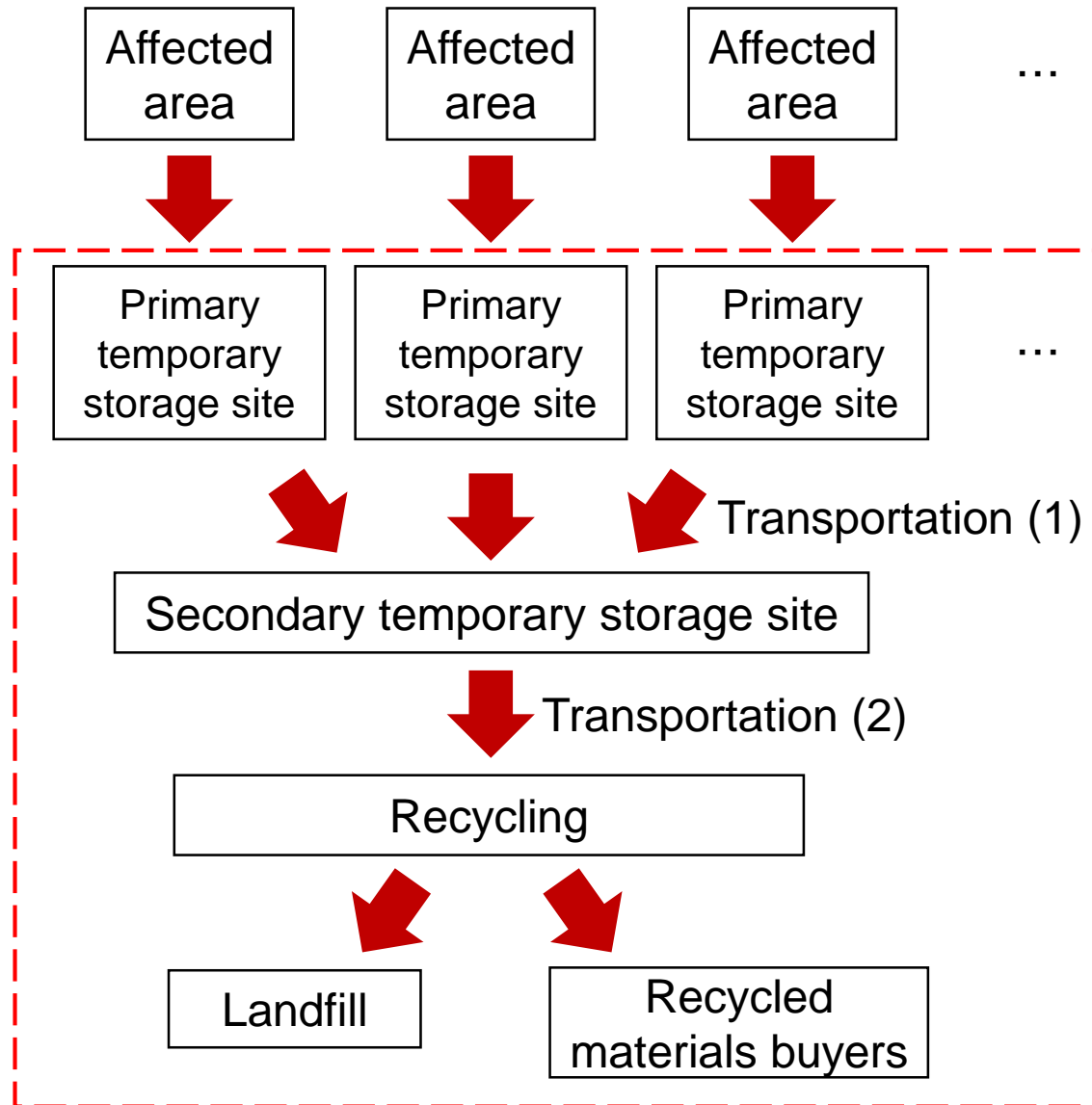


Figure 7 Transportation from the secondary temporary storage site to the recycling plants

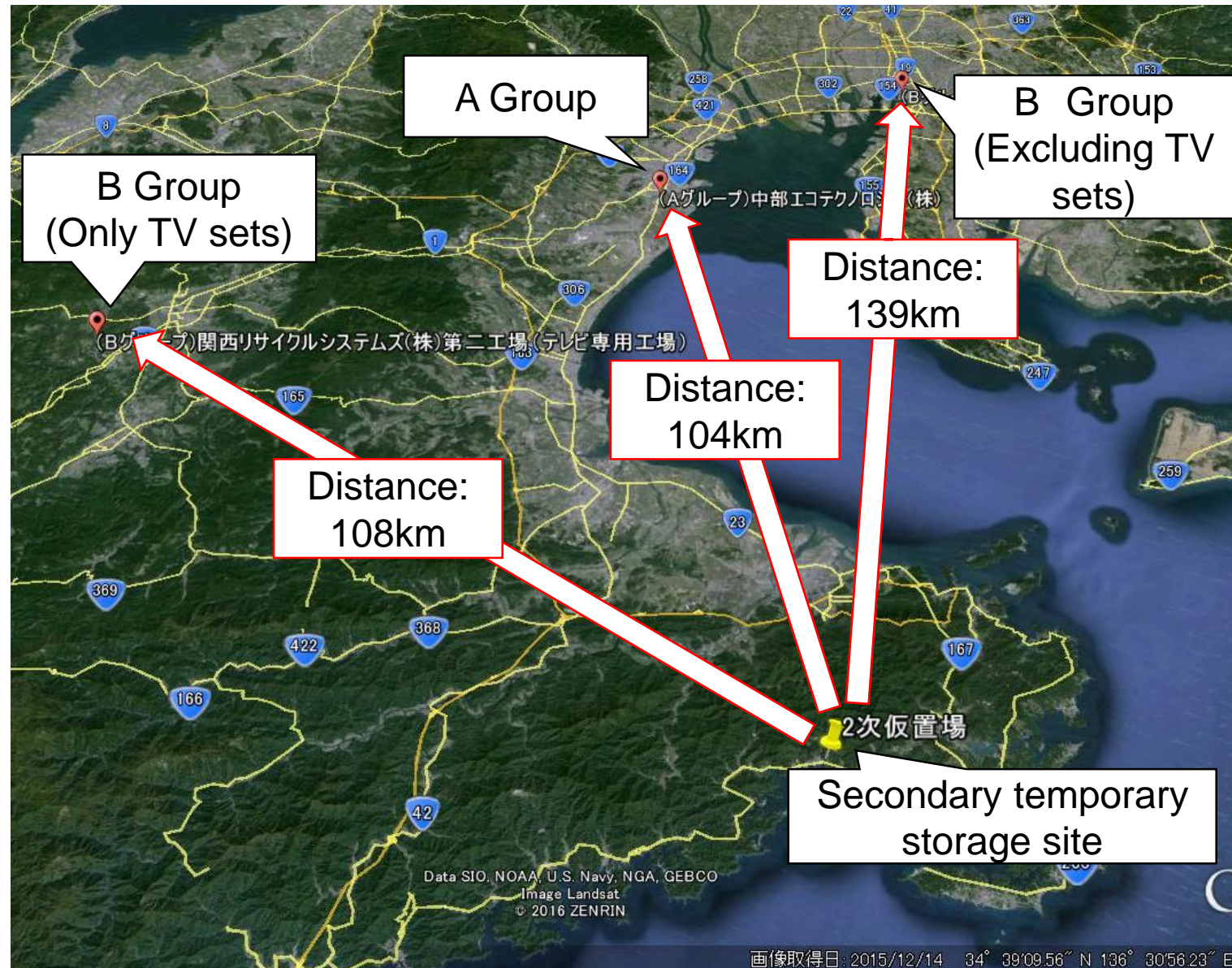


Figure 8 Spatial distribution of the disaster waste generation in Minami-Ise

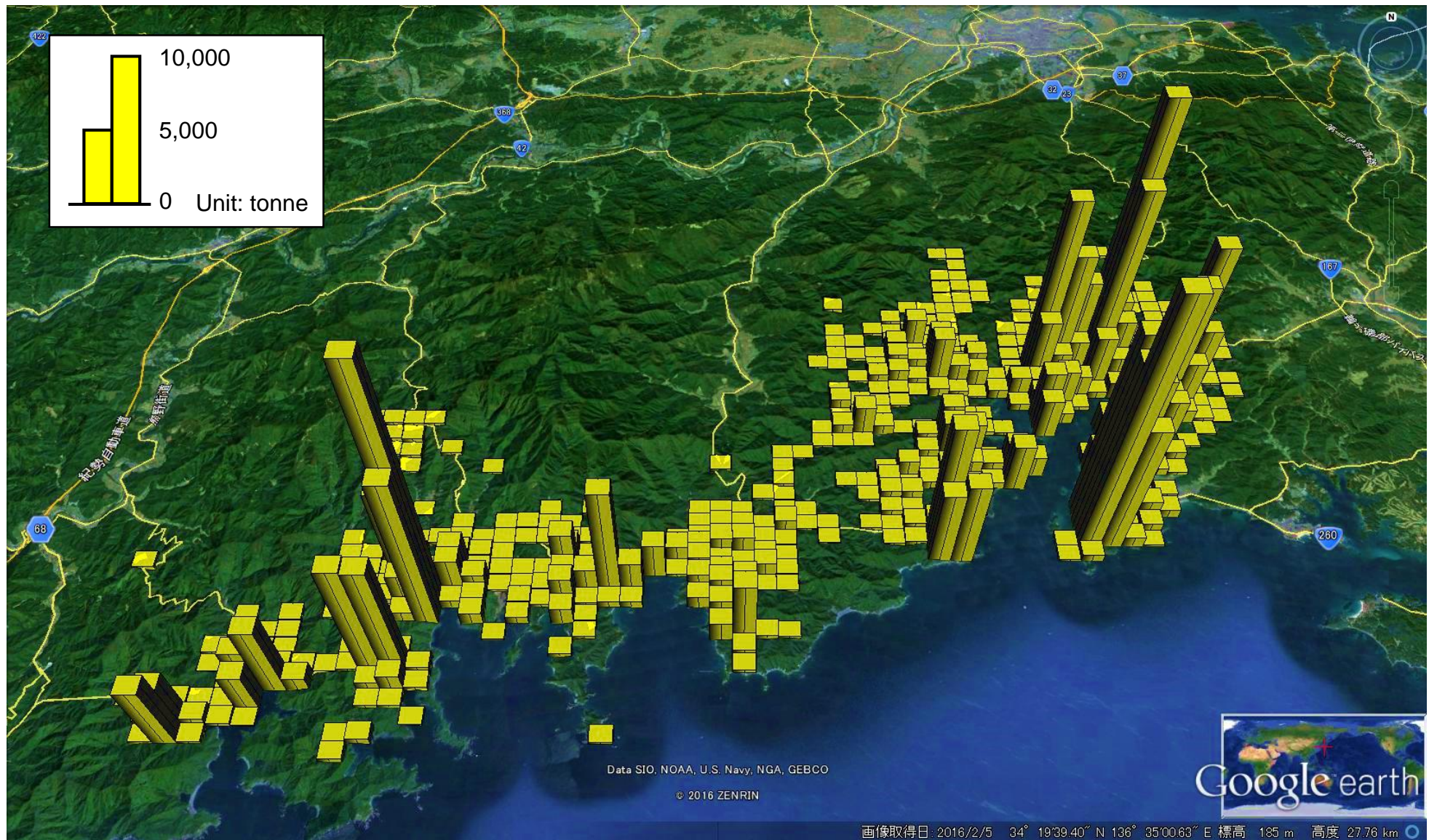
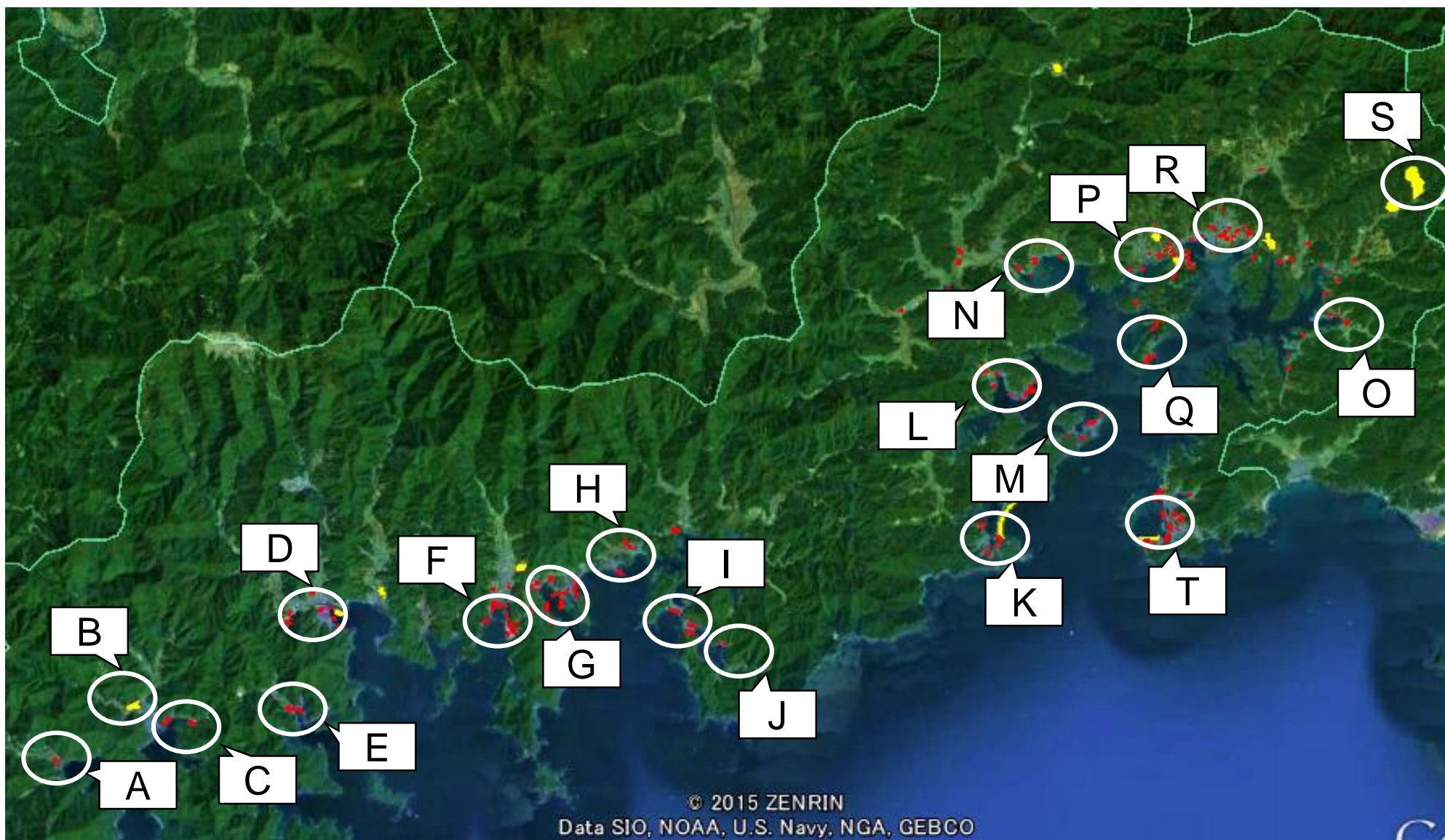


Figure 9. Locations of temporary storage sites



Note: The sites for temporary storage were labelled alphabetically.

Figure 10 Excess land among the temporary storage sites

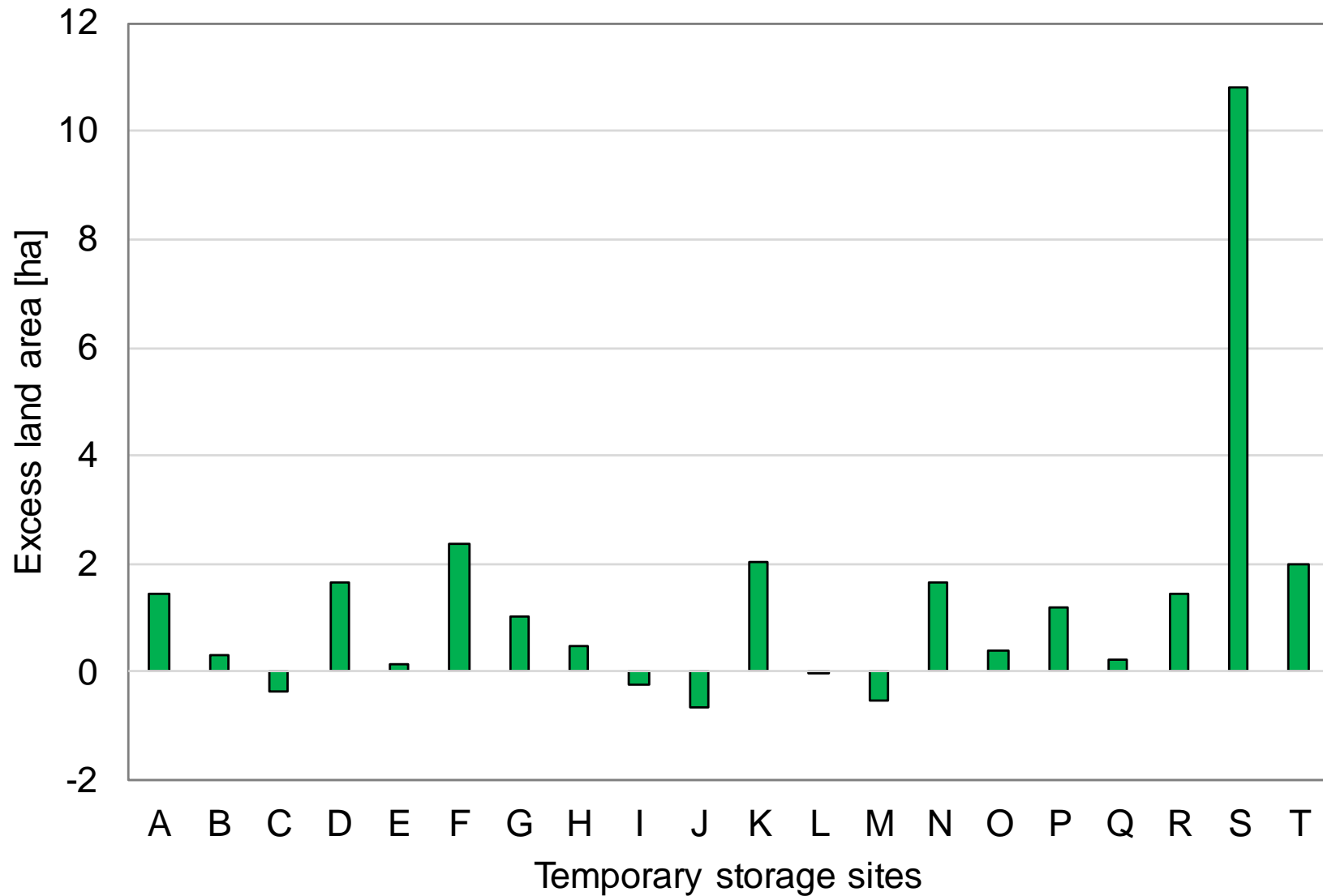


Figure 11 Environmental burden results of disaster waste treatment

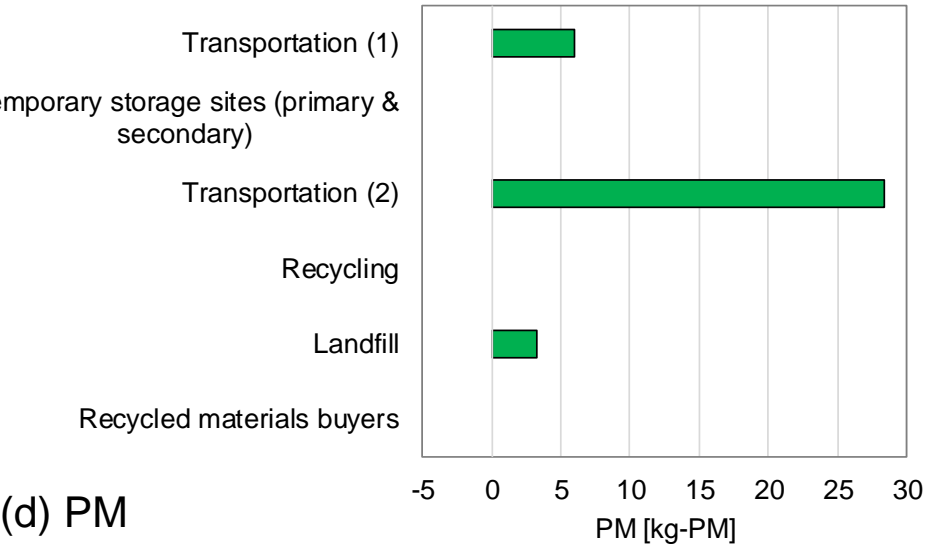
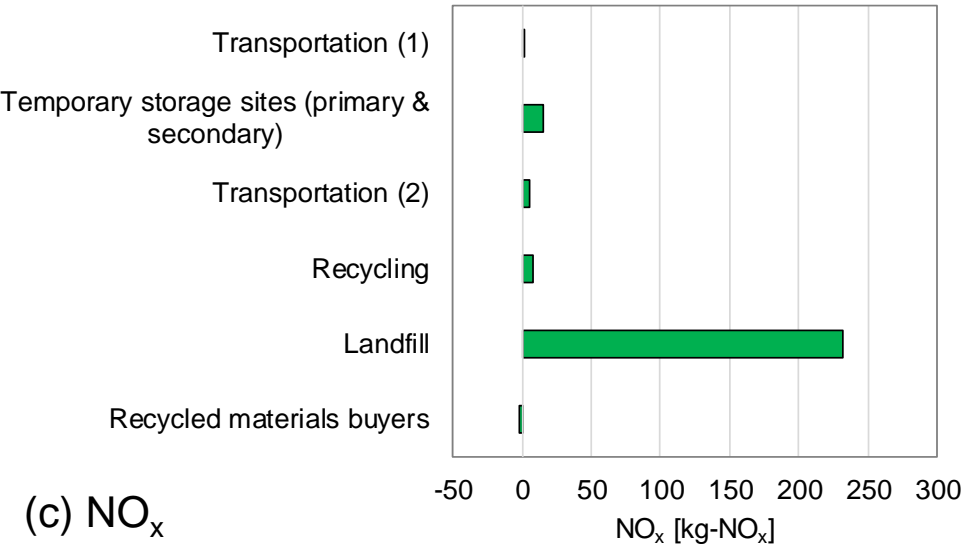
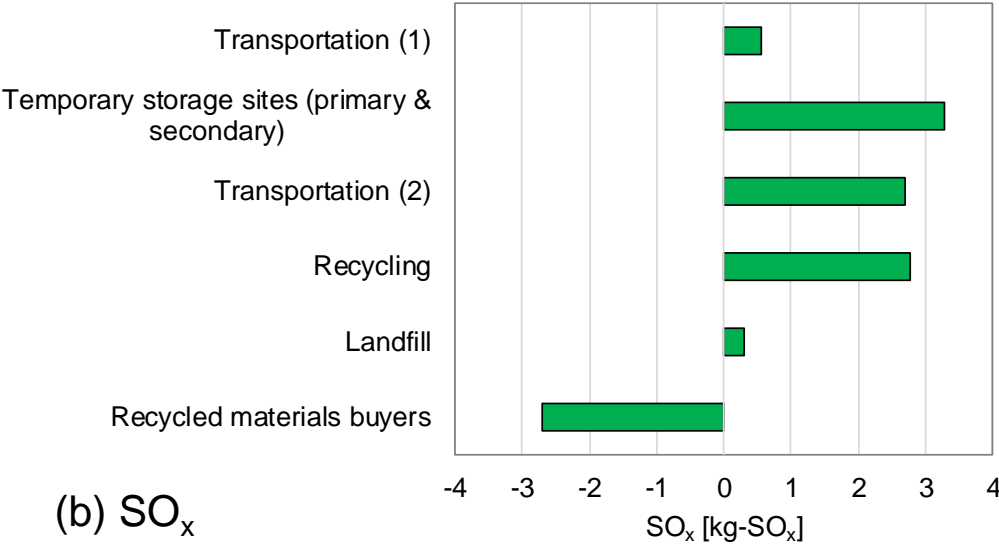
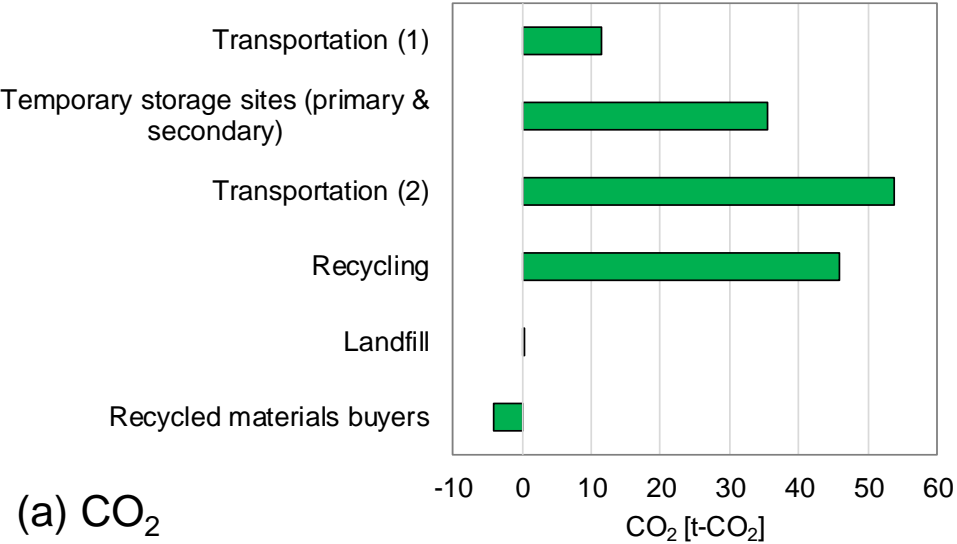


Figure 12 Cost of disaster waste treatment

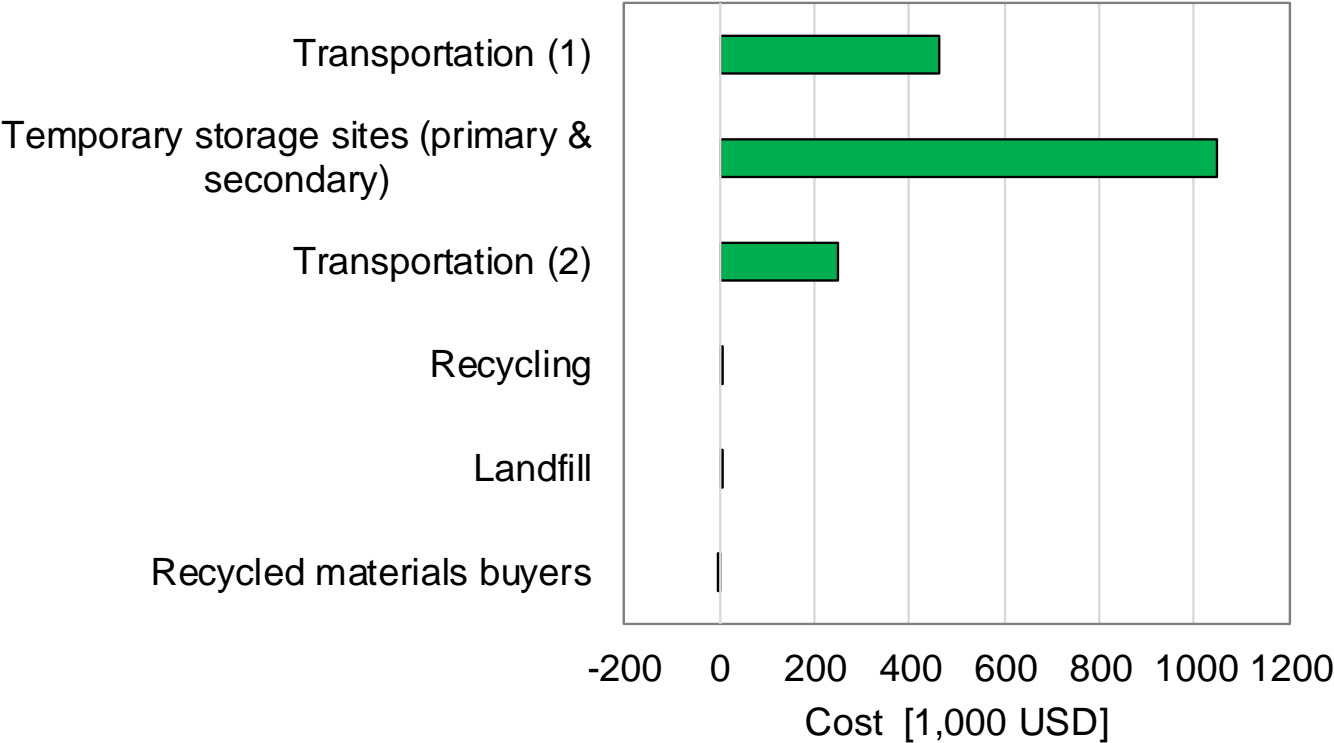


Figure 13 Working years to satisfy the national environmental quality standards

