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Research Paper

Estimation Method for Disaster Immunity in a Flood Disaster : A Case Study of Lowland Area of Saga

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ABSTRACT

In this study, disaster immunity—which in a broad sense means disaster prevention capability—was evaluated in cities in Japan by analyzing various data (e.g., historical precipitation data, local government expenditure). A positive correlation was identified between the ratio of flood control costs and normal annual precipitation, demonstrating a greater degree of disaster immunity in high-rainfall areas compared with low-rainfall areas; therefore, the ratio of flood control costs to expenses for each local government to date was considered to represent the "current" disaster immunity. Literally "immunity" for precipitation was evaluated. In addition, "future" disaster immunity in consideration of the social and natural environmental changes, including the impacts of climate change, was estimated based on the ratio of flood control costs. As a result, cities in Saga Prefecture are considered to have relatively higher current and future disaster immunity compared with cities in other prefectures. In addition, estimations of current and future disaster immunity have become possible for flood disasters, and the evaluation method can easily be improved in consideration of other components and expanded for types of disasters such as landslide disasters.

1. Introduction

In this study, we attempted to evaluate disaster immunity, which in a broad sense means disaster prevention capability (Oshikawa et al., 2009), with the aim of practical application in regard to flood disasters based on meteorological information (mainly precipitation), general disaster information (e.g., disaster classification, location, and details of damage), and local government financial information (mainly flood control project costs). Conventionally, disaster prevention capability is considered to be fixed, but it will necessarily change in response to external forces in the future. Most of Japan's social disaster management infrastructure was developed during a period of rapid economic growth and has therefore begun to deteriorate. In addition, the declining birthrate and aging population in Japan are remarkable. In recent years, the incidence of massive disasters such as heavy rainfall, drought, and stronger typhoons has been increasing as a result of climate change. Therefore, a new approach to disaster prevention concept is needed. The purpose of this research work is to make a reasonable index for quantitative estimation of disaster immunity in a flood disaster by using some data collected relatively easily.

In this study, we evaluate disaster immunity in Saga Prefecture, a high-risk disaster-prone area in the northern part of Kyushu in western Japan. Most of Saga Prefecture is a lowland area with a gentle slope, and as such, is susceptible to sea and river flooding. Recently, in August 2019 and 2021, the Japan Meteorological Agency (JMA) issued emergency warnings for heavy rainfall in Saga

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Prefecture that led to serious flood disasters (Teramura et al., 2021, Ota et al., 2020, Sakamoto et al., 2021). Therefore, we considered that a comparative study between the Saga area and other regions in Japan would make it possible to evaluate regional characteristics such as disaster prevention capability and disaster risk.

It is extremely important to enhance disaster prevention capability based on changes in society according to new adaptation policies that overcome the limitations of conventional concepts of disaster prevention capability in order to adapt to the increasing external forces of disasters under climate change. In particular, because the United Nations Sustainable Development Goals, which include climate change adaptation measures (Goal 13), have been advocated globally, strengthening disaster prevention capability to contribute to social adaptation to climate change has become an urgent issue. Therefore, it is necessary to review not only adaptation methods based on modern technologies introduced by developed countries, but also concepts or methods of disaster reduction and recovery that have been emphasized in developing countries to promote the social implementation of disaster reduction measures under limited social and economic circumstances. This could lead to the realization of a resilient society by the wise use of “indigenous knowledge” (Nakamura et al., 2014) based on empirical knowledge acquired before modernization, including infrastructure development.

One of the authors has proposed a disaster reduction concept called “disaster immunity,” which generalizes the conventional concept of disaster prevention capability (Oshikawa et al., 2009). This concept encompasses the unsteady and changeable “resilience of nature to disasters” according to external forces resulting from climate change, the massive renewal of infrastructures, reduced “social disaster preparedness” due to population decline and devastation in mountainous areas, disaster prevention awareness among residents, and the resilience of local communities. One reason humans around the world have been extremely vulnerable to the coronavirus disease 2019 (COVID-19) pandemic is that the pathogen, corresponding to an external force, is completely novel, meaning that we have no “immunity” to it; this has resulted in an extremely serious situation. Disaster immunity focuses on the fact that the aspects and extent of disasters depend on a relative relationship between external forces and disaster prevention capability, and in particular, disaster prevention capability in the broad sense is considered not fixed but temporally variable. Therefore, the application and spread of disaster immunity is needed because damage is remarkably more serious when such a large disaster occurs without anyone having “immunity” to COVID-19.

The GRAVITY model (The “GRAVITY Team”, 2002.) evaluates physical exposure based only on past disaster information and does not take into account changes in disaster prevention capability due to future climate change. The community-based disaster risk index (Birkmann, 2006) is a sum of exposure, vulnerability, and hazard minus capacity, including countermeasures, which are clearly dependent on each other. Therefore, risk evaluation methods remain questionable. On the other hand, the Risk-Based Approach (Rosner et al., 2014), which considers nonstationary processes, positively takes into account the effects of future climate change and is a model with an aspect similar to the concept of disaster immunity. However, that approach is basically designed to curb over- and underinvestment in social disaster management infrastructure; therefore, it is very different from disaster immunity, which aims to aid preparation for the future by enhancing disaster preparedness in the broad sense by making full use of not only infrastructure but also the resilience of nature, indigenous knowledge (Nakamura et al., 2014), and so on.

In recent years, social vulnerability has been studied from a variety of perspectives. For example, one study pointed out that not all factors, including contributing to vulnerability in one situation and having the opposite impact in another, have a consistent impact, although definitions and measurement standards for social vulnerability have been partially established (Rufat et al., 2015). Other studies have discussed social vulnerability in high vulnerability and high exposure societies (Hidayati, 2012), as well as social vulnerability in low vulnerability and low exposure societies (Sihvola et al., 2018). However, this kind of social vulnerability has not been linked to an appropriate integrated disaster management index such as disaster immunity.

In this study, “rivers and coasts expenses” (RCE) and “disaster recovery expenses” (DRE) are used as main elements of disaster immunity. RCE are expenditures for river improvement, coastal protection, and so on, while DRE are those for restoring facilities damaged by natural disasters such as torrential rains, typhoons, and earthquakes, which are considered to be largely related to the disaster prevention capability of national or local governments. DRE is basically the cost of restoring facilities to their original condition. However, stronger external disaster forces will also may occur and the level of planning for next disaster will be enhanced actually, as they say build back better (Ministry of Economy, Trade and Industry, 2024). Therefore, DRE was included for disaster immunity in this study.

Ikegami (Ikegami, 2014) examined changes over time in civil engineering expenses, including rivers and coasts, and compared the fiscal structures of metropolitan and non-metropolitan areas. Takahashi (Takahashi et al., 1996) investigated the macroeconomic situation of social infrastructure development and the magnitude of municipal expenses per population, including RCE. Inoue (Inoue, 2021) investigated the relationship between national and local governments in terms of reconstruction finances, including DRE after the Great East Japan Earthquake of 2011. However, these studies have mainly been socioeconomic studies, and little research has been conducted on comparative regional characteristics in disaster prevention.

2. Target Local Governments

Figure 1 (Geospatial Information Authority of Japan, 2024, Esri Japan, 2024) shows a map of Japan, including the locations of the main prefectures examined in this study. Prefectures are larger administrative districts in Japan that include numerous cities (Council of Local Authorities for International Relations, 2020). The prefectures targeted in the present study are numbered in the figure. Saga Prefecture, located in the Kyushu region, is a lowland area where agriculture is common. Fukuoka Prefecture, located next to Saga Prefecture to the east, is the center of socioeconomic activities in the Kyushu region, and its industrial structure and economic scale differ widely from those of Saga Prefecture. Osaka and Aichi Prefectures are two of Japan's three major metropolitan areas, with the Osaka metropolitan area (Kansai) and Nagoya metropolitan area (Chubu) considered the most economically powerful local governments in Japan. Okayama Prefecture is known as the "Land of Sunshine" in Japan because it has little rainfall and it is roughly the same size as Saga Prefecture economically. Kochi Prefecture, which faces the Pacific Ocean, is one of the

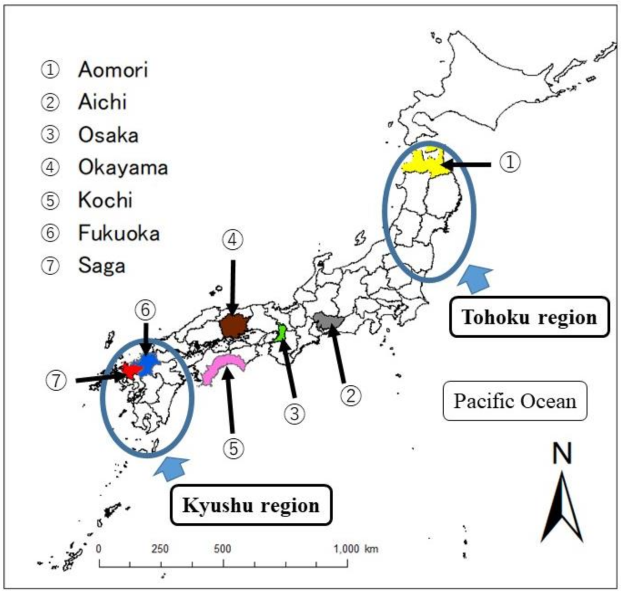

Fig. 1. Location of the target prefectures

wettest regions in Japan, and is also approximately the same size as Saga Prefecture economically. Aomori Prefecture, another agricultural prefecture located in the Tohoku region of Japan, also has low amounts of precipitation and is almost the same size as Saga Prefecture economically.

3. Differences in Disaster Immunity among Local Governments

3.1 Summary of Evaluation Methods

The relationship between disaster damage costs in a prefecture and external disaster forces in local governments was examined in terms of total precipitation from a disaster, maximum hourly precipitation in a disaster, maximum daily precipitation in a disaster, and disaster damage information. In this study, damage costs in Saga Prefecture were compared with those in Aomori Prefecture, which was chosen as a comparative target for two reasons. First, Aomori Prefecture has a markedly different climate from Saga Prefecture because the normal precipitation and temperature values for 1981–2010 were 1870 mm and 16.5°C, respectively, at an observation site in Saga Prefecture, and 1300 mm and 10.4°C, respectively, at an observation site in Aomori Prefecture (Ministry of Internal Affairs and Communications, 2021 a). Second, Saga Prefecture has a similar gross prefectural product (economic scale) and a similar industrial structure to Aomori Prefecture because both are agricultural prefectures with a high percentage of primary industry in its gross prefectural product (Aomori Prefecture, 2021 Saga Prefecture, 2021).

For the purposes of this study, we collected data on heavy rainfall and typhoon disasters: 108 disasters (1995–2012, 2018–2019) in Saga Prefecture and 116 (1989–2019) in Aomori Prefecture. For disasters in Saga Prefecture, we grasped details of each disaster event from the Saga Shimbun (a local daily newspaper) and the Saga Prefecture Disaster Magazine (Lowland Research Association, 2005, 2015), and excluded events that recorded significant damage as a result of winds. Precipitation data from the JMA's meteorological observatory (Japan Meteorological Agency) were used.

3.2 Results and Discussion

Figures 2–4 show the relationships between total precipitation in a disaster, maximum daily precipitation in a disaster, and maximum hourly precipitation in a disaster and the disaster damage costs in both Saga and Aomori Prefectures. Costs, shown on the vertical axis, were corrected for the base year of 2015 based on a consumer price index (Ministry of Internal Affairs and Communications, 2020). The figures demonstrate that disaster damage in low-rainfall areas such as Aomori Prefecture occurs with less rainfall compared with high-rainfall areas such as Saga Prefecture.

Figure 2 shows the relationship between the total amount of precipitation in each disaster event and the amount of damage. It demonstrates that the amount of precipitation at which significant damage occurred in Saga Prefecture (high-rainfall area) was around 400 to 500 mm, however significant damage occurred even at less than 100 mm in Aomori Prefecture (low-rainfall area).

Figures 3 and 4 show that the maximum daily precipitation in a disaster event causing significant damage was about 200 mm in Saga Prefecture, compared with about 30 mm in Aomori Prefecture, and that the maximum hourly precipitation was about 50 mm in Saga Prefecture compared with about 10 mm in Aomori Prefecture, indicating a similar trend as that seen in **Fig. 2**.

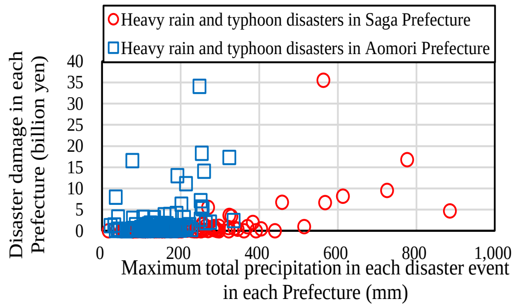

Fig. 2. Relationship between total precipitation in each disaster event and the amount of damage

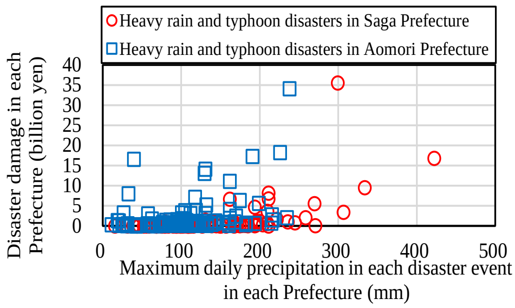

Fig. 3. Relationship between representative precipitation in each disaster event and the amount of damage

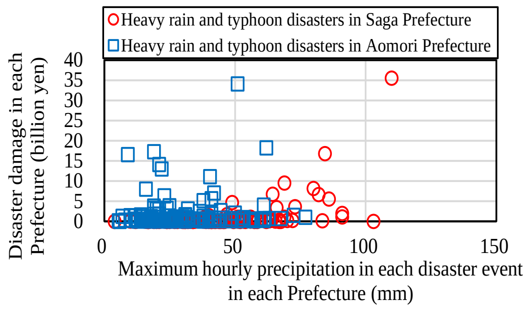

Fig. 4. Relationship between representative short term precipitation in each disaster event and the amount of damage

In other words, damage in a low-rainfall area such as Aomori Prefecture occurs with less rainfall than that in a high-rainfall area such as Saga Prefecture. This is the reason why the difference in the relationship between "precipitation" and "damage" in these high and low rainfall regions depends on "disaster immunity" cultivated to date. In a high-rainfall area such as Saga, natural conditions (e.g., geology, slope) have been affected by large external forces (i.e., hazards), and as a result of investments in disaster prevention projects, "disaster immunity" has become large. On the other hand, "disaster immunity" in a low-rainfall area such as Aomori has to be smaller than that in a high-rainfall area because its natural environment has not been subjected to large external forces, and there is less investment in disaster prevention projects compared with high-rainfall areas. That is to say, the needed level for "flood control measures" varies greatly depending on each environment (e.g., precipitation), even among local governments with a similar socioeconomic condition. Therefore, differences in not only "geophysical aspects" but also "local policies" and "historical investments" in each region are considered to cause differences in "disaster immunity" (see Figs. 2-4).

4. Differences between Past and Present Disaster Immunity

This section describes the results of an examination of temporal changes in disaster immunity using data on the relationship between precipitation and disaster damage in section 3. Although "present" degree of disaster immunity was considered in section 3, disaster immunity must change over time.

Past and recent disaster immunity were compared in Saga and Aomori Prefectures. Regression lines for past and recent heavy rainfall disasters in each prefecture in **Fig. 2** were added as **Figs. 5 and 6**, respectively, covering heavy-rainfall disasters of less than 400 mm in Saga Prefecture and less than 300 mm in Aomori Prefecture. These figures exclude remarkably heavy precipitation disasters as outliers in order to consider small and medium-sized floods occurring frequently. Both slopes of the regression line for "recent" disasters in Saga or Aomori Prefecture were gentler than those for "past" disasters. The test for difference of the regression line angle (Tomita et al., 2004) was conducted to confirm whether the difference in slopes was statistically significant. As the results, a significant difference in slope was confirmed at the 5% level in Saga or Aomori Prefecture. The amount of disaster damage in recent years was lower than that in past years, which can be understood by a general comparison of the circles and rectangles shown in **Figs. 5 and 6**. In short, the results indicate that disaster immunity has increased in each local government in recent years. Therefore, disaster immunity is expected to change in the future in accordance with climate change, economic and social conditions, and disaster experiences. It is also possible to increase disaster immunity artificially through appropriate flood control measures and emergency drills, etc.

5. Quantitative Estimation of Present Disaster Immunity

5.1 Summary of Evaluation Methods

The relationship between the average amount of annual precipitation and the normalized flood control cost was examined for all prefectures and some cities in Japan. The normalized flood control cost is the ratio of RCE plus DRE to the total expenses of a local government to date. The RCE (rivers and coasts expenses) are the cost for river improvement, coastal protection, and so on, while DRE (disaster restoration expenses) are those for the restoration of facilities damaged by disasters such as torrential rains and typhoons. The total expense is the sum of all expenses of a local government, including expenses unrelated to civil engineering (Ministry of Internal Affairs and Communications, 2021 b). Saga Prefecture and its cities were selected as the main target, and some representative cities in Fukuoka, Aomori, Aichi, Osaka, Okayama, and Kochi Prefectures as well as all prefectures, were used for comparison. **Table 1** lists the target cities within the target prefectures.

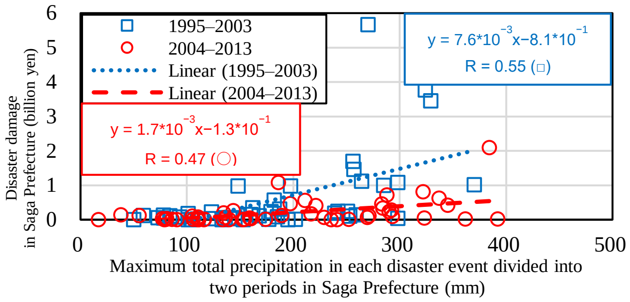

Fig. 5. Difference between past and present disaster immunity in Saga Prefecture

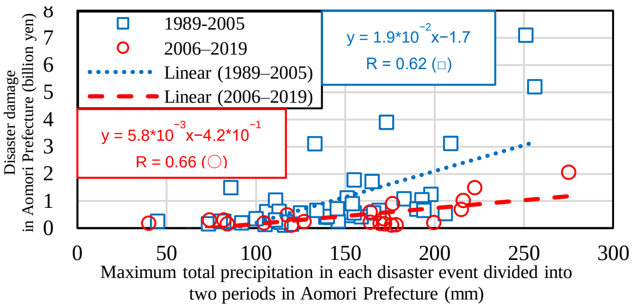

Fig. 6. Difference between past and present disaster immunity in Aomori Prefecture

The reasons why the six prefectures were chosen for comparison are described below. The reasons for Aomori Prefecture are already given in section 3. Fukuoka Prefecture was chosen for two reasons. First, it is contiguous with Saga Prefecture and has a similar climate, as normal precipitation and temperature values for 1981–2010 were 1870 mm and 16.5°C, respectively, at an observation site in Saga Prefecture, and 1612 mm and 17.0°C, respectively, at an observation site in Fukuoka Prefecture. Second, the economic scale and industrial structure in Fukuoka Prefecture are remarkably different from those in Saga Prefecture. Aichi Prefecture was selected because it has a lowland area and a relatively similar climate to Saga Prefecture, with normal precipitation and temperature values of 1535 mm and 15.8°C, respectively, at an observation site in Aichi Prefecture for 1981–2010. Osaka Prefecture was selected because it is a lowland area similar to Saga Prefecture, but its precipitation and temperature values differ significantly from those in Saga Prefecture: 1279 mm and 16.9°C, respectively, at an observation site in Osaka Prefecture for 1981–2010. Okayama Prefecture was selected because it is one of the driest areas in Japan: 1106 mm and 16.2°C at an observation site in Okayama Prefecture for 1981–2010. Kochi Prefecture was selected because it is one of the wettest regions in Japan: 2548 mm and 17.0°C at an observation site in Kochi Prefecture for 1981–2010.

Data from the Survey of Local Government Finance (Ministry of Internal Affairs and Communications, 2024) published by e-stat (a government statistics website in Japan) were used for RCE, DRE, and total expenses. Regarding RCE and DRE, the data when the impacts of

Table 1. Target cities in the target prefectures

	Target City
Saga Prefecture	Saga
	Karatsu
	Tosu
	Taku
	Imari
	Takeo
	Ogi
	Ureshino
Fukuoka Prefecture	Kitakyushu
	Fukuoka
	Omuta
	Kurume
	Iizuka
	Tagawa
	Yanagawa
Aomori Prefecture	Aomori
	Hirosaki
	Hachinohe
	Kuroishi
	Goshogawara
	Misawa
	Mutsu
Osaka Prefecture	Osaka
	Sakai
	Toyonaka
	Hirakata
	Ibaraki
	Yao
	Kawachinagano
Aichi Prefecture	Nagoya
	Toyohashi
	Okazaki
	Ichinomiya
	Toyota
	Nishio
	Gamagori
	Tokoname
	Shinjo
	Obu
Kochi Prefecture	Kochi
	Muroto
	Aki
	Nankoku
	Susaki
	Sukumo
	Tosashimizu
Okayama Prefecture	Okayama
	Kurashiki
	Tsuyama
	Tamano
	Kasaoka
	Takahashi
	Niimi

an earthquake were significant were excluded. Regarding precipitation, meteorological data from JMA stations and data from the Water Information System (Ministry of Land, Infrastructure and Transport, 2024 a) by the Ministry of Land, Infrastructure, Transport and Tourism were used.

5.2 Results and Discussion

The ratio of flood control costs to the expense of each local government is considered to represent “disaster immunity” because disaster immunity in a high-rainfall area must be larger than that in a low-rainfall area in general. **Figures 7 and 8** show the results for the prefectures and target cities regarding the relationship between normal annual precipitation (historical weather information corresponding to disaster hazards) and the costs of flood control projects (rate of flood control costs spent from 1974 to 2019) to date in each local government. The normal annual precipitation for a prefecture was calculated based on data from an observation station in each prefecture, as listed in Statistics of Japan 2021 (Ministry of Internal Affairs and Communications, 2021 a), whereas that for cities was calculated based on data from an observation station in each city. In this study, the cost of flood control projects to date was defined as the sum of the averaged RCE and the averaged DRE for each year,

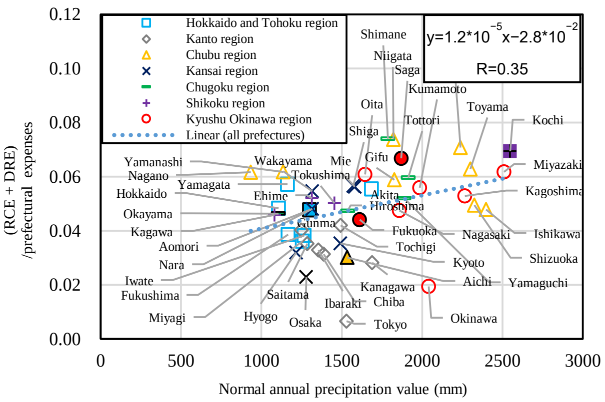

Fig. 7. Relationship between normal annual precipitation values and flood control costs for all prefectures

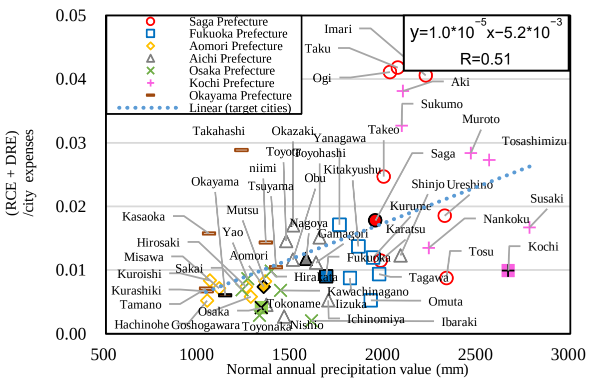

Fig. 8. Relationship between normal annual precipitation values and flood control costs for target cities

normalized by the total expenses in each local government. In **Figs. 7 and 8**, a positive relation (roughly monotonically increasing) was recognized between the ratio of flood control costs to the expenses of each local government and normal annual precipitation, although there was some dispersion. The positive relation corresponds to differences in the amount of rainfall-induced damage between prefectures, as discussed in section 3. This definition of normalized flood control costs in terms of expenses was determined as the largest correlation coefficient using trial and error by many kinds of data listed (Ministry of Internal Affairs and Communications, 2024). Then, the values for RCE, DRE, and total expenses for each local government in each year were corrected according to the consumer price index in 2020. Based on these results, if we consider the ratio of flood control costs to the expenses of each local government as “disaster immunity,” it should be smaller in low-rainfall areas and larger in high-rainfall areas because of investments in social disaster management infrastructure and disaster experience to date.

The linear correlation between the ratio of flood control costs to expenses for each local government and normal annual precipitation in a city was stronger than that in a prefecture. The results for the prefectures in **Fig. 7** show a somewhat weak positive correlation, with a correlation coefficient R=0.35. However, that for cities in **Fig. 8** shows a positive correlation (R=0.51), which is significantly higher than that for the prefectures. This is the reason why normal annual precipitation in a city is measured at an observation site in the city, as this enables an appropriate evaluation of rainfall. The results revealed that a city with less rainfall has a smaller disaster prevention capability, whereas a city with more rainfall has a larger disaster prevention capability. Literally “immunity” for precipitation was evaluated. Therefore, the ratio of flood control costs to expenses for each city should be considered “disaster immunity” given that the ratio increases due to investments in social disaster management infrastructure as well as disaster experiences to date. In particular, the ratio of flood control costs is high for cities in Saga Prefecture compared with other central and capital cities Fukuoka, which have higher economic capacity; thus, cities in Saga Prefecture have greater disaster immunity compared with cities in metropolitan areas. The regression lines in **Figs. 7 and 8** roughly indicate that the local governments located above the line have more disaster immunity, whereas those below the line have less disaster immunity. Furthermore, these findings provide standards for determining the degree of disaster immunity in local governments not included in this study by calculating only its normal annual precipitation.

Since it is a very interesting that there is a certain correlation between precipitation and flood control cost (RCE + DRE), the flood control cost is used here as a substitute for disaster immunity. However, strict disaster immunity is a disaster prevention capability that includes both physical and social factors (Oshikawa et al., 2009). Therefore, it is necessary to properly evaluate social factors (e.g. resilience to disasters and social disaster preparedness) as well in the future.

The current disaster immunities of the metropolitan cities of Osaka and Nagoya are 0.004 and 0.012, respectively, as shown in **Fig. 8**. Disaster immunity is remarkably higher in Nagoya than in Osaka City because Aichi Prefecture, where Nagoya is located, is closer to the Pacific Ocean compared with Osaka Prefecture and thus needs to expend more on river and coast management to prepare for typhoon and storm surge disasters. Indeed, Aichi Prefecture has experienced major disasters, including the Ise Bay Typhoon of 1959 (Donovan et al., 2009). Therefore, disaster immunity in cities in Aichi Prefecture such as Nagoya is higher than that in cities in Osaka Prefecture.

Some cities have relatively high disaster immunity even if the normal amount of annual precipitation is considerably small. Takahashi and other cities in Okayama Prefecture (**Fig. 8**) are rated highly for disaster immunity, even though Okayama Prefecture, which faces the Seto Inland Sea, is a low-rainfall area (see F**ig. 1**). This is largely due to the impact of DRE from the heavy rain disaster that caused extensive damage over a wide area in July 2018 (Liu et al., 2019, Nihei et al., 2019).

6. Relationship between flood control costs and disaster damage in each period

6.1 Summary of Evaluation Methods

In this chapter, we examined whether flood control costs (RCE + DRE) had reduced disaster damage to ensure the appropriateness of the evaluation method for disaster immunity. The relationship between the amount of disaster damage and the flood control costs (RCE + DRE) in a period was evaluated in some region. First, the data on disaster damage in Chapter 3 and the data on flood control costs in Chapter 5 were divided into three periods so that the number of disasters was roughly evenly distributed. Next, the relationship between total flood control costs and the amount of disaster damage was examined in each period. However, extremely large disaster events were excluded, for example, "Northern Kyushu heavy rainfall in 2012" in Fukuoka Prefecture (Asahiro et al., 2015, Hashimoto et al., 2014) which was a flood event beyond the designed level. Therefore, each evaluation covers the period up to the previous year of an extremely large disaster event. **Figures 9-11** show the results for Saga, Fukuoka, and Aomori prefectures. For example, regarding the horizontal axis (total flood control costs) for Saga Prefecture in **Fig. 9**, the value on the horizontal axis for 1995-2000 is the flood control costs for 1995-2000, while the value on the horizontal axis for 2001-2007 is the flood control costs for 1995-2007. For Saga Prefecture, the number of disaster events for each period is 33 for 1995-2000, 37 for 2001-2007, and 36 for 2008-2013. For Aomori Prefecture in **Fig.10**, that is 49 in 1989-1998, 41 in 1999-2008, and 26 in 2009-2018. For Fukuoka Prefecture in **Fig.11**, that is 37 in 1999-2003, 18 in 2004-2007, and 13 in 2008-2011. These figures mean the efficiency of flood control cost because slopes connecting two points corresponds to decreasing magnitude of disaster damage for investment.

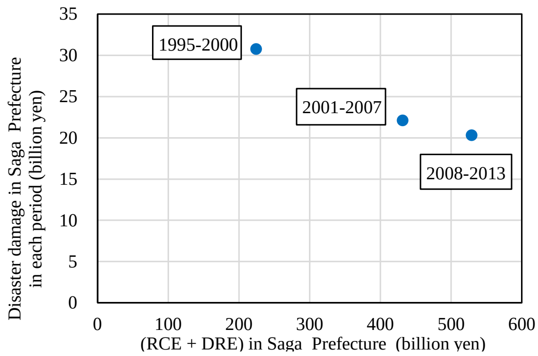

Fig. 9. Relationship between flood control costs and disaster damage in Saga Prefecture in each period

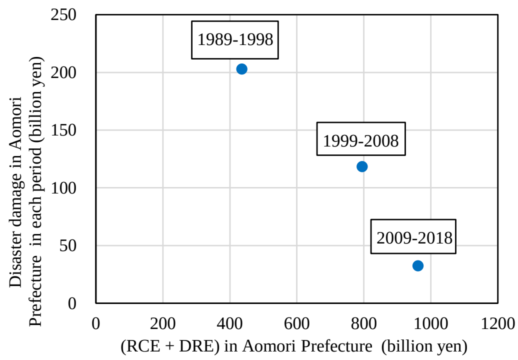

Fig. 10. Relationship between flood control costs and disaster damage in Aomori Prefecture in each period

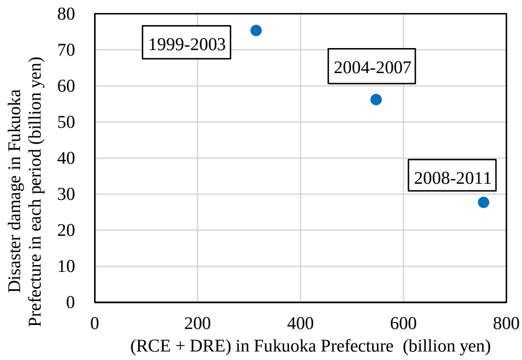

Fig. 11. Relationship between flood control costs and disaster damage in Fukuoka Prefecture in each period

6.2 Results and Discussion

It is reasonable to use the total flood control costs collected relatively easily as an indicator to evaluate the time-varying disaster immunity corresponding to disaster prevention capability in a broad sense. The results for Saga, Aomori, and Fukuoka Prefectures shown in **Figs. 9-11** indicate that the amount of disaster damage decreases monotonically as flood control costs (RCE + DRE) increase. In other words, the flood control costs increase disaster prevention capability. Time-varying disaster prevention capability depends on the costs of disaster prevention in advance (RCE) although it is also affected by disaster experience and post-disaster recovery costs (DRE). Therefore, total flood control costs (RCE + DRE) are useful for evaluating disaster immunity.

7. Estimation of Future Disaster Immunity and Regional Characteristics of Disaster Prevention Capability

7.1 Summary of Evaluation Methods

"Future" disaster immunity is estimated by using the normalized flood control costs. In section 5, the "current" disaster immunity in each local government in regard to flood disasters was estimated by Equation (1) shown below. In this study, future disaster immunity in regard to flood disasters is defined by Equations (1)–(3) below, where "current" disaster immunity is corrected using a modified rate. Here, the modified rate is estimated by multiplying some dimensionless correction factors, where correction factors on the impacts of social change and climate change are considered for simplicity. Especially, changes in economic conditions and aging infrastructure are used in regard to social impact, and changes in precipitation in regard to the impact of climate change. If another effect (impact) needs to be considered to achieve more accurate disaster immunity, it can easily be added as another multiplying coefficient. Therefore, temporal disaster immunity is evaluated as follows, taking future conditions into account:

$$\textbf{"Current" disaster immunity} = \frac{\text{"rivers and coasts expenses"} + \text{"disaster recovery expenses"}}{\text{total cost}} \qquad [1]$$

$$\textbf{"Future" disaster immunity} = \textbf{"current" disaster immunity} \times \text{modified rate} \qquad [2]$$

$$\textbf{Modified rate} = \text{social correction factor} \times \text{correction factor of the impact of climate change} \qquad [3]$$

For the social impact, in this study, population and economic status projections based on shared socioeconomic pathway (SSP) scenarios (National Institute for Environmental Studies, 2017) were used. The SSP scenarios have been numbered from SSP1 to SSP5 according to the difficulty of climate change mitigation and adaptation measures. The future population of each local government in Japan was projected for each SSP in the Japanese SSP scenario (Climate Change Adaptation Information Platform, 2021). **Table 2** shows the population of each capital city in the targeting prefectures in 2020 and 2100, and **Figure 12** shows Japan's projected future GDP per million (International Institute for Applied Systems Analysis, 2018). The future economic situation in each city was estimated by multiplying the population by GDP per capita in these target cities. As effects of aging infrastructure, the percentage of river management facilities including check dams that were 50 years old or more was estimated based on the "Current Status and Future of Aging Infrastructure" by the Ministry of Land, Infrastructure, Transport and Tourism (Ministry of Land, Infrastructure and Transport, 2024 b) because in Japan, the service life of a concrete structure is usually considered to be 50 years. **Table 3** shows the aging ratio of the river management facilities.

Regarding the impact of climate change, "Bias-Corrected Climate Scenario Data for the Japan Region" by the National Institute for Environmental Studies (NIES2019 data) (Ishizaki, 2019) published on A-PLAT (Adaptation Information Platform for Climate Change) was

Table 2 Examples of population projections for each SSP scenario

Unit (population)	2020	2100				
	-	SSP1	SSP2	SSP3	SSP4	SSP5
Aomori City	275,192	53,015	47,150	31,777	30,946	52,607
Nagoya	2,332,176	1,780,196	1,384,576	865,076	976,202	2,002,207
Osaka City	2,752,412	1,694,147	1,339,675	853,574	942,400	1,920,776
Okayama City	724,691	616,097	461,162	282,638	327,722	603,958
Kochi City	326,545	173,042	135,243	86,250	95,732	170,665
Fukuoka City	1,612,392	1,624,488	1,165,970	722,369	874,639	1,598,430
Saga City	233,301	179,714	136,867	83,064	95,259	175,442

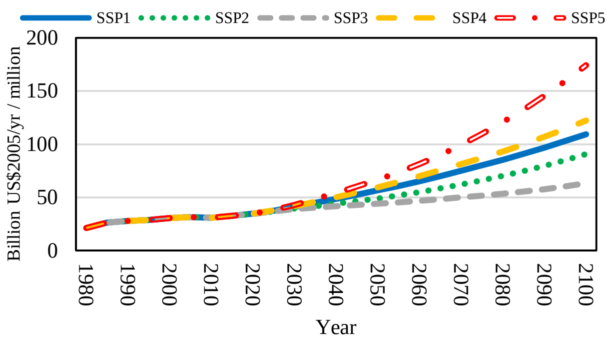

Fig. 12. Future projections of Japan's GDP per million population

Table 3 Percentage of aging river management facilities

	2020	2025	2030	2035	2040	2045	2050	2055	2060	2065	～	2100
(%)	35.7	44.7	55.7	66.6	75.7	82.7	90.1	95.8	99.7	100	～	100

used for future rainfall projection data. **Table 4** provides the ratios of average annual predicting rainfall of 2091–2100 relative to the base period of 2011–2020 for Representative Concentration Pathway (RCP) 2.6 and RCP8.5 in the target prefectures, including the target cities, in addition to the national mean value of Japan. In this study, to evaluate disaster immunity, RCP2.6 was used for the SSP1 and SSP2 scenarios, and RCP8.5 for the SSP3 to SSP5 scenarios.

To estimate “future” disaster immunity, ratios of the decadal average of these factors to each former decadal one were calculated from 2020 to 2100 for every 10 years. Regarding the economic situation, correction factors (≈ ratio) are greater than 1 if an economic situation is improved compared with 10 years ago, and less than 1 if an economic situation is worsened. Therefore, disaster immunity in 2030 could be predicted by multiplying disaster immunity in 2020 and the ratios of each factor for the period 2020–2030.

Next, we validated the evaluation method for future disaster immunity, which was based on the assumption that the “social impact” significantly affecting disaster immunity in each local government constituting the economic situation of that local government and the current state of its infrastructure. **Table 5** provides the validation results regarding future disaster immunity for two cities in Saga Prefecture. The period 1974–2020, for which flood control cost data exist, was divided into two periods (before and after 2000), and disaster immunity (the flood control cost ratio) was calculated for the first half of the period as disaster immunity at the year 2000. Then, disaster immunity was estimated by applying data on the actual population, economic conditions, aging infrastructure, and precipitation in the second half of the period to the equations for future disaster immunity, based on disaster immunity at the year 2000. In addition, disaster immunity at 2020 was calculated based on 1974–2020 data, such as the current disaster immunity in section 5. Finally, the estimated disaster immunity at the year 2020 based on that of 2000 was compared with disaster immunity at the year 2020.

The evaluation method for future disaster immunity in this study, as shown in **Table 5**, is considered suitable because the estimated disaster immunity at the year 2020 based on that of 2000 is almost same as disaster immunity at the year 2020 in Saga City and Karatsu. Therefore, disaster immunity in the future can be estimated by taking into account population, economic conditions, aging infrastructure, and precipitation, even though the evaluation equations for future disaster immunity are fairly simple.

7.2 Results and Discussion

Two representative scenarios regarding future temporal changes of disaster immunity in each prefectural capital in the target prefectures (see **Fig. 1**) are shown: SSP1 (the ideal scenario) in **Figure 13** and SSP3 (the most severe scenario) in **Figure 14**. The results indicate that the disaster immunity of cities that are currently comparable in terms of population and economic size may differ markedly in the future because of the influence of neighboring metropolitan areas. **Fig. 13** (SSP1) shows that Aomori City’s disaster immunity in 2100 is estimated to be 87% lower than that in 2020. On the other hand, because the populations of Nagoya, Osaka, and Fukuoka cities (metropolitan areas) will continue to increase until about 2050, their disaster immunities in 2100 are expected to be 41%, 51%, and 24% lower than those in 2020, respectively, indicating no extreme decrease. Okayama City shows a 39% decrease, followed by Kochi City with a 60% decrease. Saga City shows a 41% decrease, which is not as extreme as Aomori City, but about the same as Osaka City, Nagoya, and Fukuoka City, even though in 2020, Aomori City and Saga City had almost the same population (275,192 in Aomori City vs. 233,301 in Saga City) and economic size (156.0 billion yen in expenses for Aomori City vs. 131.0 billion yen in expenses for Saga City) (Ministry of Internal Affairs and Communications,

Table 4 Example of ratio on annual precipitation

	Japan	Aomori	Osaka	Aichi	Okayama	Kochi	Fukuoka	Saga
2091-2100 (RCP2.6)	1.06	1.16	0.99	1.00	1.08	1.02	1.03	1.00
2091-2100 (RCP8.5)	1.12	1.22	1.09	1.08	1.08	1.06	1.05	1.03

Table 5 Validation of estimation of disaster immunity

	Disaster immunity at the year 2000	Disaster immunity at the year 2020	Estimated disaster immunity at the year 2020 based on that of 2000
Saga City	0.024	0.018	0.017
Karatsu	0.018	0.011	0.011

2024), as shown in **Table 2**. The population of Saga City is not expected to decline as much as that of Aomori City by 2100 (SSP1) because Saga Prefecture is adjacent to Fukuoka Prefecture and Fukuoka City (metropolitan area). Therefore, even local governments with a similar population and economic size may have significantly different future disaster immunity because of the influence of their neighboring metropolitan areas.

Future population projection for local governments with a currently small population can cause an extreme result in regard to disaster immunity. Okayama City had a population of 724,691 in 2020, which was much larger than that of Aomori City, so the population of Okayama City will be maintained to a certain degree, and the decrease in disaster immunity in 2100 will be small. However, Kochi City had a population of 326,545 in 2020, which was comparable to that in Aomori City, and the decrease in disaster immunity in 2100 will be also small because the population decrease will not be so remarkable in 2100. This may be the reason why Okayama and Kochi (City and Prefecture) are both close to the Osaka (Kansai) Metropolitan area. Aomori City should experience a severe decrease in disaster immunity because of extreme population decline, whereas Okayama City and Kochi City should not.

The SSP3 scenario predicts a considerable decrease in all cities, as shown in **Fig. 14**, because it is a “regional rivalry” scenario with declining populations due to the devastation of both urban and non-urban areas, as well as a large increase in future precipitation amounts. In addition, the disaster immunity for SSP3 in Saga City and Fukuoka City in 2030–2040 is expected to be larger than that for SSP1 because the annual precipitation according to RCP8.5 will be remarkably smaller than that of RCP2.6 during that period (Ishizaki, 2019).

Regarding the SSP2, SSP4, and SSP5 scenarios, **Figures 15–17** demonstrate future temporal changes in disaster immunity for each scenario in Aomori City, Fukuoka City, and Saga City, respectively. These figures allow us to understand the relationships among each scenario. The results regarding SSP2 are largely in between the ideal SSP1 and the most severe SSP3 in **Figs. 15–17** because the SSP2 scenario is maintaing the status quo (moderate), so the population and economic situations for SSP2 are between those for SSP1 and SSP3. Disaster immunity in Aomori City for the SSP4 scenario has decreased to same level as the most severe SSP3 scenario. On the other hand, disaster immunity in Fukuoka City and Saga City for the SSP4 scenario is significantly

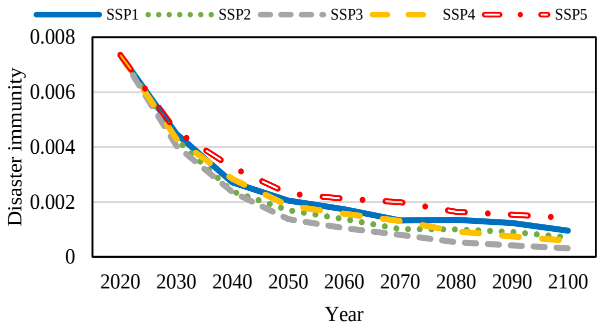

Fig. 15. Temporal changes in disaster immunity for each scenario in Aomori City

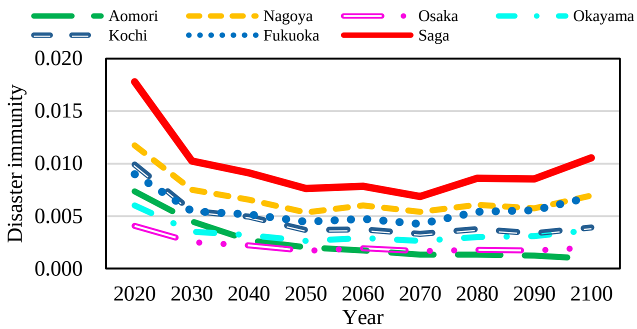

Fig. 13. Temporal changes in disaster immunity of target cities in SSP1

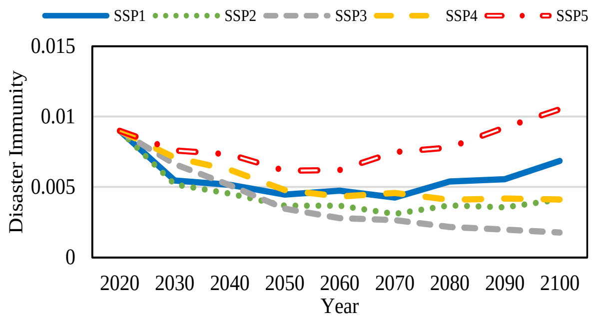

Fig. 16. Temporal changes in disaster immunity for each scenario in Fukuoka City

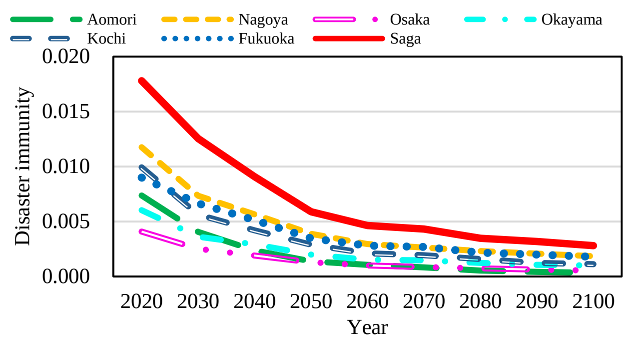

Fig. 14 Temporal changes in disaster immunity of target cities in SSP3

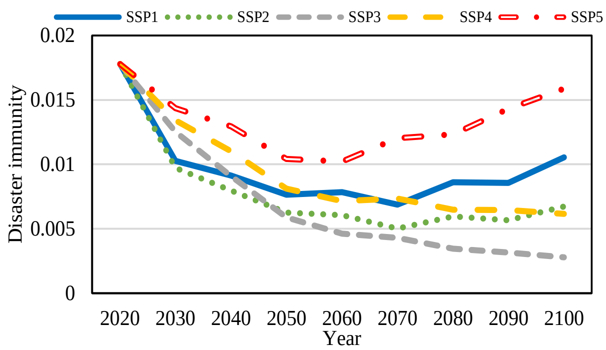

Fig. 17. Temporal changes in disaster immunity for each scenario in Saga City

larger than that for the SSP3 scenario because the SSP4 scenario involves a regional disparity where the population and economic situations deteriorate in rural areas, even though the areas surrounding metropolitan areas develop to some extent.

The SSP5 scenario gives the highest disaster immunity for all cities because it emphasizes immediate economic conditions. The SSP5 scenario is a fossil fuel-dependent development scenario in which the environment must have been severely degraded over time, even though both rural and urban areas are developing economically. Therefore, disaster immunity may worsen significantly after 2100 because the evaluation method of disaster immunity in this study can only consider environmental degradation as a future increase in precipitation based on RCP8.5. To evaluate future disaster immunity appropriately with respect to SSP5, it is necessary to add more environmental factors or establish a more accurate alternate index for disaster immunity that responds sensitively to environmental change.

Finally, **Figs. 18 and 19** illustrate disaster immunity in the target cities in 2100 based on the SSP1 and SSP3 scenarios, respectively. In both figures, cities in Saga Prefecture maintain larger disaster immunity compared with those in other prefectures. Especially, the cities of Ogi and Imari in Saga Prefecture have high disaster immunity. This is due to the current large disaster immunity shown in **Fig. 8** and the low level of population decline because of the neighboring metropolitan Fukuoka as mentioned earlier. Ogi is located in a lowland area, whereas Imari is located in a partially mountainous area. Therefore, it can be concluded that disaster immunity is highly dependent on regional characteristics, and that cities in Saga Prefecture will maintain a certain level of disaster immunity in the future.

The equation for predicting future disaster immunity is very simple and has much room for improvement. Note that the present results are affected by the uncertainty of social changes based on SSP scenarios and rainfall forecasts.

8. Conclusion

In this study, we evaluated current and future disaster immunity in Japanese local governments. Normalized flood control costs, which is the ratio of RCE plus DRE to the total expense of local governments to date should be considered "current" disaster immunity because a positive correlation was recognized between the normalized flood control costs and normal annual precipitation. The current disaster immunity of high-rainfall areas is greater than that of low-rainfall areas. In other words, "immunity" for precipitation was evaluated. In particular, cities in Saga Prefecture located in a lowland area were found to have relatively higher current and future disaster immunity than were cities in other prefectures. Especially, Ogi and Imari in Saga Prefecture had high "current" disaster immunity because of their extremely large proportion of DRE. In addition, these cities are expected to have high disaster immunity in the future because their population decline is not projected to be as great as that of other local governments. Disaster immunity in cities with the same current population and economic size will differ greatly in the future because of the effects of neighboring metropolitan areas and other factors.

It should be noted that although local governments in Saga Prefecture had high disaster immunity in this study, the risk of a flood disaster in Saga Prefecture is not necessarily low. Actually, it can be said that the risk of disasters is high in lowland area like Saga, where surface water tends to collect in precipitation. This study focused on estimations of disaster immunity corresponding to "exposure" and "vulnerability." However, natural disaster risk is generally determined by relations among hazards, vulnerability, and exposure. In future studies, risk

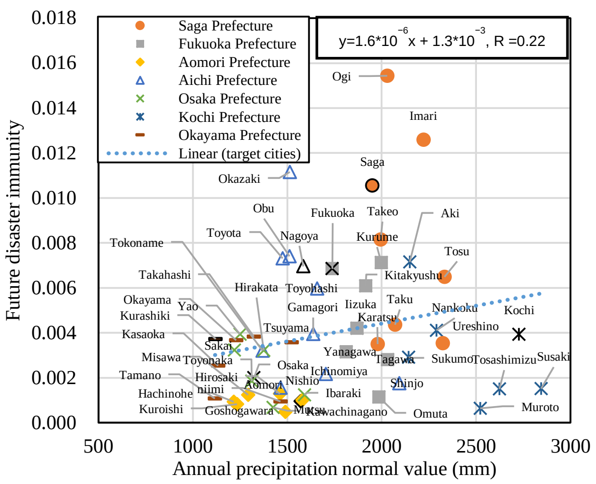

Fig. 18. Disaster immunity in the target cities in 2100 in SSP1

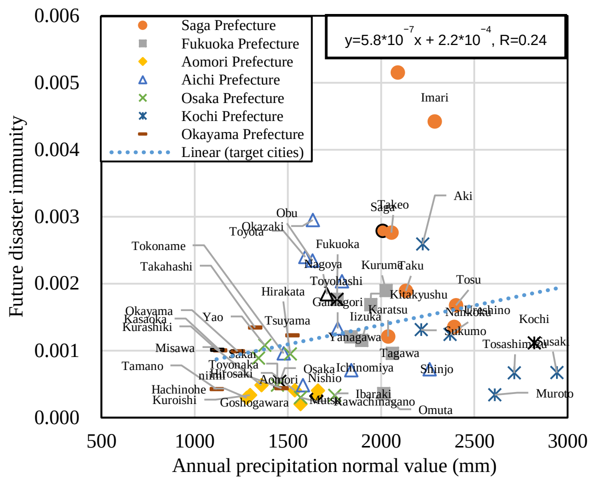

Fig. 19. Disaster immunity in the target cities in 2100 in SSP3

assessment considering disaster immunity could be expected to enable the estimation of natural disaster risk in each region such as lowland areas and other areas. In addition, although this study attempted to evaluate disaster immunity for flood disasters, the same approach can easily be extended to other disasters, such as landslide disasters.

In this study, we sought a simple evaluation method for disaster immunity from a macro perspective. More precise and realistic assessments of current disaster immunity could be made by taking other social factors (e.g. resilience to disasters and social disaster preparedness) and scientific factors (e.g. degree of urbanization, river basin area) into account. Also this study estimated future disaster immunity by multiplying current disaster immunity by several correction factors. The estimation method for “future disaster immunity” can be improved by adding other correction factors or modifying the equations.

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Symbols and abbreviations

RCE	Rivers and coasts expenses
DRE	Disaster restoration expenses