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Case Report

Lesson Learned from Catastrophic Floods in Western Japan in 2018: Sustainable Perspective Analysis

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Abstract: Natural hazards have a significant impact on the sustainable development of human society. This paper reports on the catastrophic floods in western Japan in 2018. Continuous rainfall resulted in catastrophic floods, leading to 212 deaths, damage to more than 2000 houses and 619 geological disasters in 31 prefectures. The causes and contributing factors of these catastrophic floods are analyzed. The analysis of the causes of typical natural hazards provides an important lesson for hazard prevention and management. To adapt to climate change and prevent natural hazards in the future, the preliminary investigation and sustainable perspective analysis in this paper suggest the importance of the construction of a spongy city and the establishment of an early warning system with the help of information science and artificial intelligence technologies (ISAIT); we also highlight the urgent need to improve and strengthen the management of infrastructure.

Keywords: flood hazard; investigation; western Japan; early warning system; flood hazards management

1. Introduction

The climate is determined by patterns of temperature, wind, atmospheric pressure, humidity and rain over a prolonged period. Global warming, caused by both natural factors and anthropic activities [1–3], is causing immediate and direct climatic change across the planet [4–8]. Flood hazards have a great influence on humans; numerous villages and farmlands are destroyed or submerged, leading a large number of people to lose their homes or lives and reducing the crop yields. Besides, traffic and communication are interrupted or blocked, and information transfer and supplies transportation are delayed. Moreover, the living standards of people in disaster-stricken areas are greatly affected.

In July 2018, catastrophic floods occurred in western Japan. These catastrophic floods caused great economic losses and casualties, resulting in 212 deaths. damage to more than 2000 houses and 619 geological disasters in 31 prefectures [9]. The flood resulted in the most significant impacts on western Japan since 1982; furthermore, the number of rainfall observation stations receiving the highest amount of rainfall within 48 h compared to historical recordings was the highest since 1982. Investigations into catastrophic floods or other hazards can provide significant resources and guidelines to make comprehensive hazard prevention and management plans.

Predicting flood hazards accurately and implementing effective natural hazard prevention and management plans can mitigate the impacts from hazards and reduce the loss to the minimal possible extent. Thus, it is necessary to establish an early warning system (EWS). Two main issues need to be tackled in an EWS: one is data collection, and the other is data processing. Data concerning different hazards should be collected through advanced technology and equipment. The geographical information system (GIS), global positioning system (GPS) and remote sensing (RS) (simplified as 3S in the following context) can be applied in data collection; furthermore, 3S has wide applications in the field of hazard prevention [10]. For example, Hussein et al. [11] applied remote sensing data to predict the occurrence of flash floods. Detailed applications of RS technology to flood prediction can be seen in the work of Sharma et al. [12]. Zhang et al. [13] utilized sensing data to map coastal flooding from local and global perspectives. Many data can be collected from 3S technologies. Information science and artificial intelligence technologies can provide effective means of dealing with these data. Dodangeh et al. [14] utilized machine learning methods to predict flood susceptibility. Thus, the use of 3S technologies integrated with information science and artificial intelligence technologies (ISAIT) to construct an EWS can increase the accuracy of hazard occurrence prediction.

The objectives and novelties of this paper are as follows: (1) we investigate the formation and impacts of catastrophic floods in Japan; (2) we systematically analyze the causes of flood; and (3) we develop novel and sustainable suggestions for dealing with catastrophic flood hazards, which can provide lessons regarding countermeasures and guidelines for preventing and coping with natural hazards, such as spongy city construction and the establishment of an early warning system. Figure 1 presents the flowchart of this article.

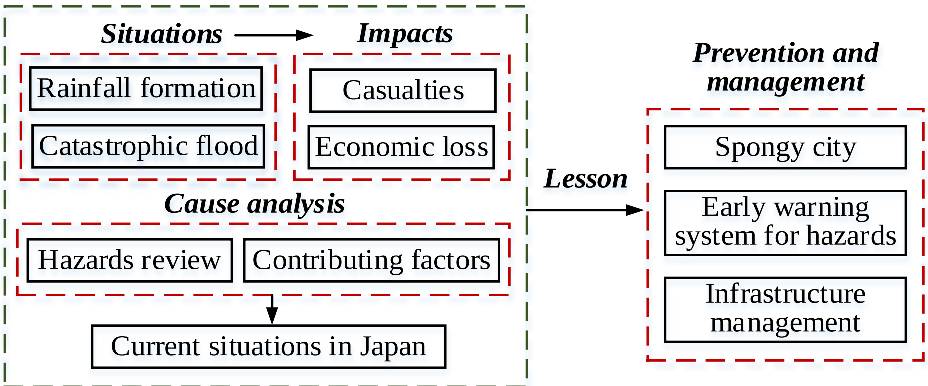

Figure 1. Flowchart of the article.

2. Investigations

2.1. Rainfall Formation

This section presents the formation of a catastrophic flood. Figure 2 displays a specific rainfall formation; the area affected by catastrophic flood in Japan is also shown in the figure. The affected area accounts for nearly half of Japan's territory. In July 2018, the western regions of Japan (see the red circle in Figure 2) were severely affected by Typhoon Prapiroon. The formation of a connective airflow and the footprints of Typhoon Prapiroon are presented in the figure. Heavy rainfall started at Kyushu Island from 5 July 2018 [15,16]. The stranded plum rain front in Hokkaido then crossed Nihon-Kai from north to south on 5 July 2018 because of the weakening of the subtropical high-pressure system on Pacific Ocean. Then, the warm and moist vapor carried by Typhoon Prapiroon crossed the Pacific Ocean. The information including the wind speed, scale of wind force and the tropical storm grate of five footprints of Typhoon Prapiroon is summarized in Table 1 [15,16]. Simultaneously, the plum rain front—affected by the high pressure on the northern Okhotsk Sea and the southern Pacific Ocean—remained over the western regions of Japan, and heavy rainfall occurred in western Japan when the warm and moist vapor met with the plum rain front. The continuous rainfall resulted in the heaviest floods in Japan of the previous 30 years. The formation of the catastrophic flood provides a significant resource when designing a comprehensive hazard prevention plan.

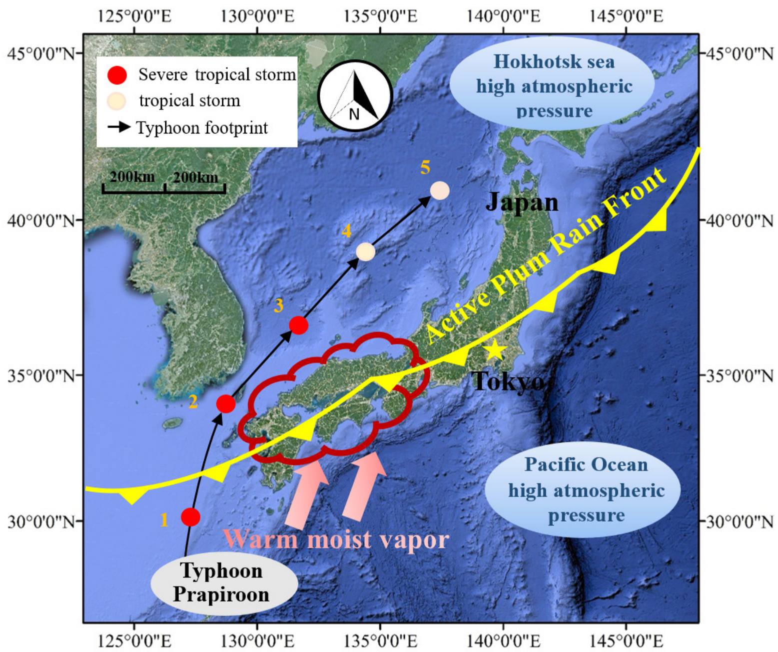

Figure 2. Factors triggering the formation of rainfall (data from [17]).

Table 1. Information for five footprints in the typhoon path.

Point	Tokyo Standard Time	Wind Speed (m/s)	Scale of Wind Force	Tropical Storm Grate
1	3 July, 7:00	30	11	Severe tropical storm
2	3 July, 19:00	28	10	Severe tropical storm
3	4 July, 7:00	25	10	Severe tropical storm
4	4 July, 19:00	23	9	Tropical storm
5	5 July, 7:00	20	8	Tropical storm

2.2. Flooding in Western Japan

The western regions of Japan experienced catastrophic flooding from 5 to 9 July 2018. Of the 1300 rainfall observation stations across Japan, precipitation at 119 stations reached its highest level within 72 h and 123 stations received the highest amount of rainfall within 48 h compared to all historical recordings [17,18]. The water depth in some areas was up to 3 m, and numerous residual houses were immersed in the flood. Figure 3 presents the flooded areas in western Japan. Kochi, Gifu, Ehime and Saga were the most seriously flooded areas in this catastrophic flood. The cumulative rainfall of these four prefectures was over 600 mm. The flooded area of Ehime Prefecture was 970 hm^2, and about 720 houses were flooded [19]. As shown in Figure 3, the maximum accumulative rainfall occurred in Malu village, Anji-gun, Kochi Prefecture, reaching 1425.12 mm in four days. The amount of rainfall in many places reached its highest level in recorded history. Residents in Okayama County reported that floodwaters arrived and immersed their houses in a very short time, leaving them without sufficient time for evacuation at midnight.

Continuous heavy rainfall was the primary reason for the flooding disasters, which were recognized as the most serious flooding disasters of the previous 30 years. The continue heavy rainfall increased the rainstorm intensity index (precipitation within the past 24 h). The rainstorm intensity index is an important parameter to analyze the flood in the return period of event. The return period of recorded maximum rainstorm intensity indices in 77 locations in Japan ranges from 0.7 to 41.8 years [20].

To evaluate the effect of precipitation on the severity of the catastrophic flooding, a rainstorm intensity index (R = rainfall within the past 24 h) is introduced [2]. Based on the standard rainfall level [2], rainfall can be classified into three different levels: (I) rainstorm (R = 50–100 mm); (II) torrential rain (R = 100–250 mm); and (III) extraordinary rainstorm (R > 250 mm). Figure 4 shows the recorded rainfall levels for 11 prefectures from 4 to 8 July 2018 (the locations of prefectures have been marked in Figure 3). These 11 prefectures (Ehime, Fukuoka, Hiroshima, Kagoshima, Kochi, Kagawa, Miyazaki, Nagasaki, Oita Shimane and Tokushima) were all flooded to different degrees by this flood.

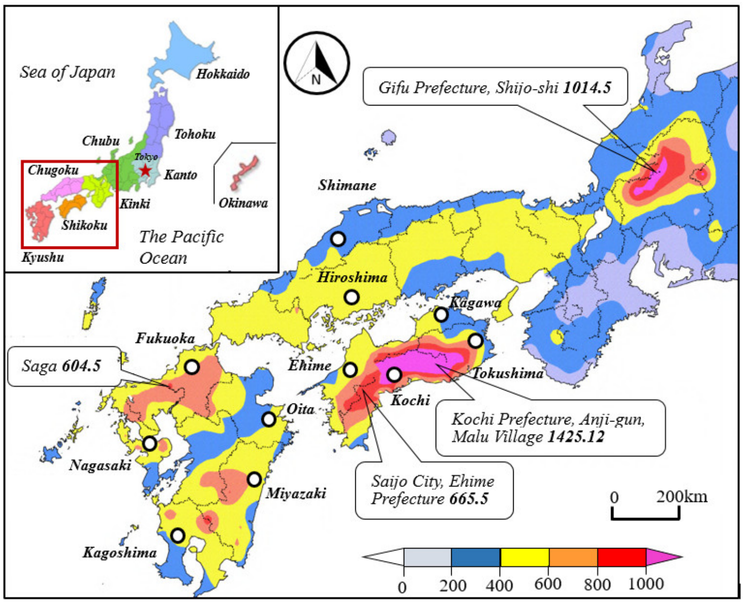

Figure 3. Cumulative rainfall distribution during 5–8 July 2018 (modified from [21]).

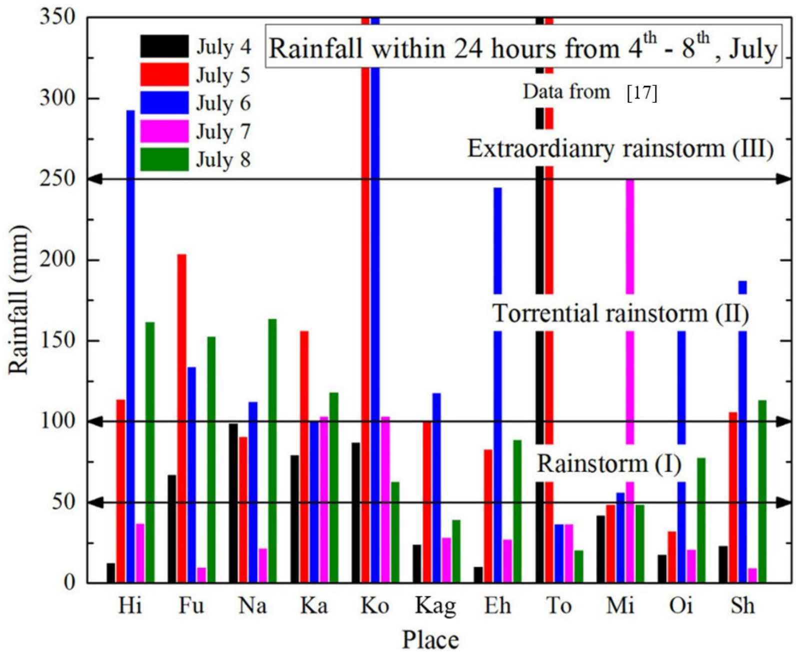

Figure 4. Summary of the rainfall measured during 4–8 July 2018.

3. Hazards and Loss Caused by Flooding

3.1. Flood Hazard

Flood, levee breaking and waterlogging were caused by heavy rainfall and further triggered secondary disasters such as landslides, mudslides and cliff collapses. Until 13 July 2018, 619 geological disasters occurred in 31 prefectures due to the heavy rainfall in western Japan. As shown in Table 2, 168 mudslides, 427 cliff collapses and 24 landslides occurred, with cliff collapse disasters accounting for more than 60% of the total number of disasters. More than 23,000 people in 17 prefectures received refuge warnings and were forced to leave their residence. More than 2000 houses were damaged and nearly 15,000 houses were immersed under water in 31 prefectures. In total, 5074 houses collapsed during this flood hazard and 2687 houses were partially damaged. The supply of clean water and electricity in the most seriously affected areas was stopped, affecting more than 250,000 households [18]. Traffic obstacles occurred due to the disturbance of the rail and road transportation system.

Table 2. Statistics of geo-disasters (data from [18]).

Item	Geological Disaster Numbers		
Geo-Disaster Types	Debris flow 168	Cliff collapsed 427	Landslides 24
Heaviest Affected Prefectures	Hiroshima 123	Ehime 59	Hyogo 51

In Kurashiki City, Okayama Prefecture, the flood water level rose rapidly, especially in low-lying areas, owing to the heavy rain. The depth of the water nearly reached the roofs of houses. Besides, in the Shinjuku-machine area of Kurashiki City, two dams on Odawa River collapsed and about 1200 ha of land were flooded [18]. Hiroshima Prefecture was most affected by this extreme natural hazard, and it suffered from the most geological disasters (see Table 2). According to the work presented in [18], the floods triggered 97 landslides and 26 cliff collapses in Hiroshima Prefecture.

3.2. Casualties and Economic Losses

Serious disasters were caused by heavy rainfall during 5–9 July 2018, leading to numerous casualties and a huge economic loss. According to the work presented in [22], the rainfall disasters resulted in 212 deaths in total, and nearly 50% of the deaths were from Hiroshima Prefecture (see Figure 5). As shown in Figure 5, the death toll in Hiroshima was the highest, at 101 within five days, followed by Okayama, where the death toll was 61. The majority of deaths were suffered by elderly people (70% of the total deaths), who were not capable of rescuing themselves. As listed in Table 3, the economic loss to agriculture related to flooding was 16.1 billion JPY, and Hiroshima Prefecture accounted for the biggest loss of 2.5 billion JPY. Besides, according to the work presented in [22], small- and medium-sized enterprises also suffered from huge economic losses, which were estimated at 473.8 billion JPY (Okayama prefecture accounted for 281 billion JPY). It is noted that the economic loss could have been greatly underestimated, because many affected areas were not accessible. The casualties, shelters and affected areas resulting from the catastrophic flood are displayed in Figure 5.

Table 3. Estimated economic loss due to the rainfall disasters during 4–9 July 2018 (Modified from [22]).

Category	Economy Loss (Billion JPY)
Agriculture	16.1
Public infrastructure	321
Small and medium enterprises	473.8
Forestry	23.13
Fishery	0.78

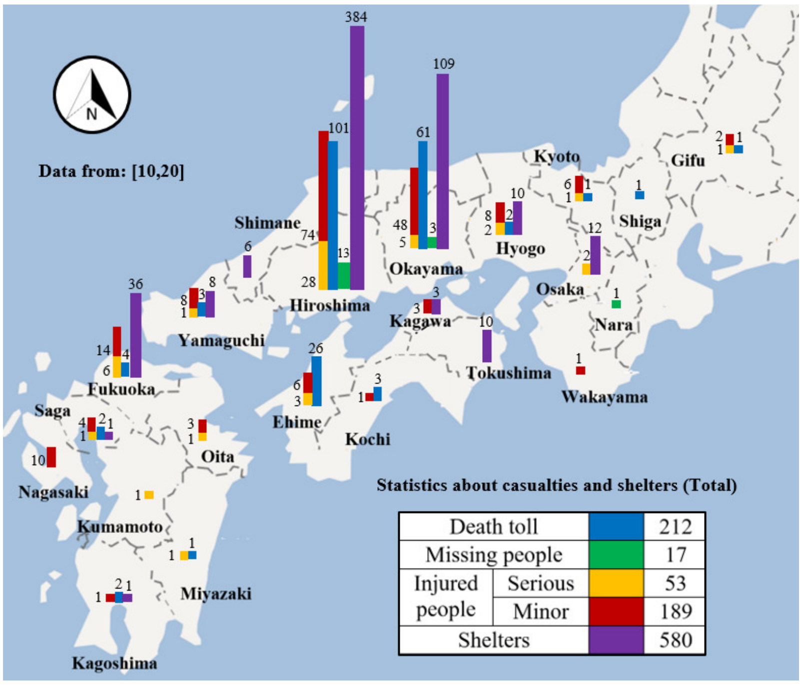

Figure 5. The distribution of casualties and shelters during 4–9 July 2018.

4. Analysis

Disasters are related to the sources of hazards and the capabilities of infrastructure to adapt to hazards [21,22]. Even though the sources of hazards are disastrous, flooding-induced hazards can be limited if the infrastructure has a strong capacity to adapt [23,24]. To create safe living environments, increasing social investment is being spent on the construction of infrastructure in urban areas, such as underground reservoirs [25–28], sewers [29–32], underground storage and drainage systems [33–36]. These underground infrastructures serve as reservoirs to store and regulate water under extreme weather conditions.

4.1. Natural Hazard Statistics over the Recent 30 Years in Japan

Typhoons, rainstorms and geological disasters caused by floods are referred to as "wind and water disasters" in Japan. Wind and water disasters are natural hazards with a strong destructive power, leading to hundreds of deaths each year. Figure 6 presents the summary of deaths due to natural hazards from 1993 to 2018 in Japan; the number of deaths caused by catastrophic floods in 2018 was the highest of all flood hazards. This indicates the insufficiency and vulnerability of the hazard prevention and management system in Japan. Besides, death comparisons are conducted for different hazards, and flood hazards should be given equal emphasis. In Figure 6, the Hanshin-Awaji earthquake in 1995 (6437 deaths) and the 2011 earthquake off the Pacific coast of Tohoku in 2011 (22, 203 deaths) are classified as "Major Disasters" in Japan. The flood in 2018 was the first time that a rainstorm disaster had been designated as a "Special Emergency Disaster" in Japanese history [37].

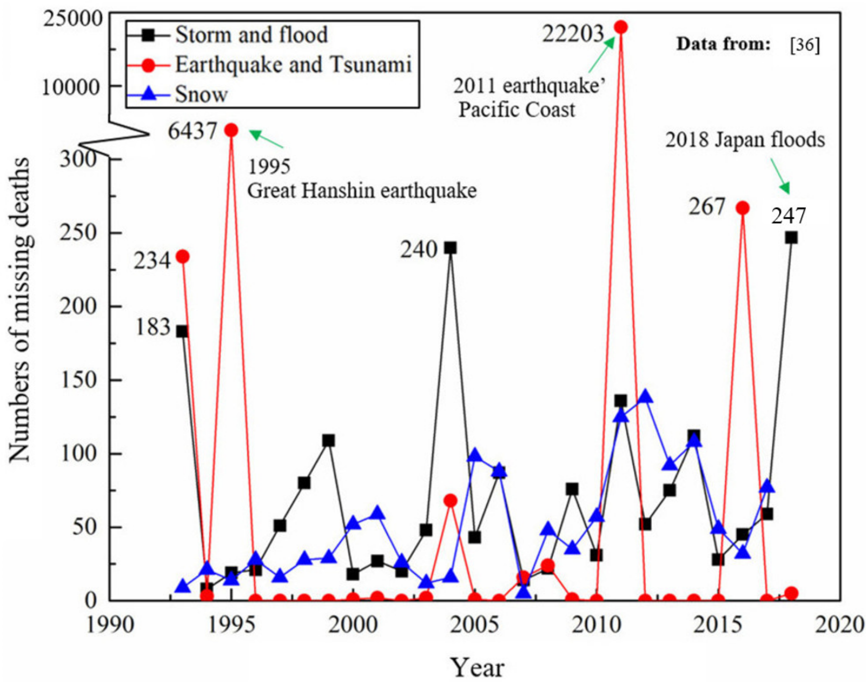

Figure 6. Summary of missing deaths due to natural hazards from 1993 to 2018 in Japan.

4.2. Cause Analysis of Flood Hazards in Japan

There are many factors that contribute to flood hazards. These factors are justified based on the preliminary investigations of catastrophic floods in western Japan and can be classified into direct and indirect factors. The extreme level of accumulated rainfall and rainfall intensity were the direct factors affecting the catastrophic flood in 2018 in western Japan. As shown in Figure 4, the rainfall in Hiroshima, Kochi, Ehime and Miyazaki reached over 250 mm (extraordinary rainstorm) in one day, and the indirect contributing factors were global warming, a fragile geological structure, aging infrastructure and issues in the hazards prevention and management system (HPMS).

Torrential rains have occurred with a high frequency in recent years in Japan, and the frequency of extreme weather conditions is increasing. In Figure 7a, the number of days with an annual maximum temperature over 30 °C per year in the last 10 years (2008–2017) was about 1.24 times greater than between 1975 and 1985. In Figure 7b, the annual number of occurrences of rainfalls of more than 50 mm/h in the last 10 years (2008–2017) was about 1.4 times that between 1976 and 1985. This indicates that global warming is a potential contributing factor to catastrophic floods in western Japan.

About two-thirds of territories in Japan are mountainous, and the fragile geological structure in the hilly territories shows a high liability for landslides and mudslides. Japan is a mountainous island country; mountains and hills account for 71% of the territory. Japanese residences are often built on slopes that are easily flooded [38]. Besides this, most houses in Japan have a wooden structure, which has a better resistance to earthquakes but is more easily damaged by either flooding or landslides. Slopes and fragile geological structures are located near residents without proper management before extreme heavy rain; this will easily trigger secondary disasters under the influence of heavy rain. Concerning catastrophic flood hazard-affected areas, Hiroshima Prefecture suffered the most victims. In Hiroshima, massive landslides and mudslides caused by rainstorms and flooding destroyed or even buried numerous residential houses. Traffic was paralyzed in areas with serious secondary geological disasters (such as soil collapse and debris flow), which caused difficulties for transporting large rescue machinery to the affected areas to save lives within the vital window of the first 72 h.

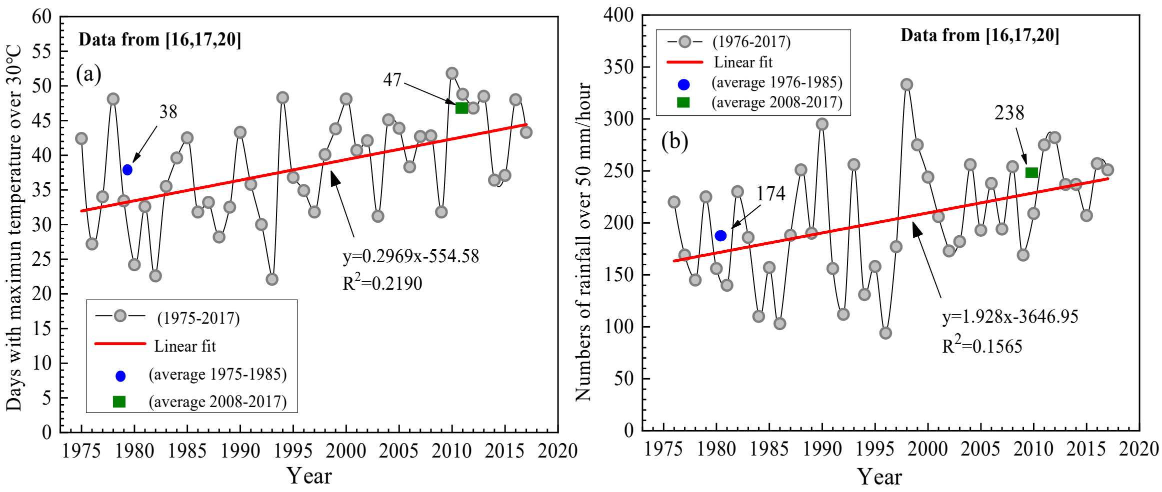

Figure 7. (**a**) Days with a maximum temperature over 30 °C per year (**b**) numbers of rainfall events over 50 mm/h annually during the period 1975–2017 in Japan.

A large amount of infrastructure was damaged and collapsed in this catastrophic flood, including bridges and dams. This indicates that public infrastructure is incapable of adapting to major natural hazards. Moreover, numerous bridges, reservoirs, dams and tunnels were constructed more than half a century ago in Japan; most roads in Japan were built around the 1920s. Some bridges (about 14,000) and tunnels (about 600) were even built earlier [38] and are still in service today. At the same time, with the development of construction technology, the geographical environment around these bridges and tunnels has been affected by human activities, making the historical infrastructure fragile to disasters. Problems such as aging decay are currently reducing the resilience of the infrastructure, which needs to be renovated and updated. According to the survey results released by the Japanese Ministry of Land and Communications in the summer of 2017, 398 bridges and 27 tunnels, footbridges and other ancillary facilities were assessed as "urgent measures to be taken" between 2014 and 2016—the most serious level in the four-level assessment [38,39]. Since 1995, the performance of main structures, such as bridges, has been improved to better adapt to natural hazards. The ability—termed resilience—to withstand and recover from hazards is important for a city. To strengthen the resilience of Kobe city, a large amount of work has been done, such as upgrading the hazard prevention and mitigation performance of facilities and increasing publicity regarding disaster prevention knowledge. However, these tasks are not well implemented in remote areas and underdeveloped cities [40,41]. Many houses and villages near slopes or fragile geological structures have been damaged or submerged by catastrophic floods.

Considering the massive flood disasters in Japan, the early warning and disaster-relief mechanisms in Japan have been questioned. The Japanese government has focused on earthquake prevention, which has meant that they have failed to implement sufficient countermeasures and plans for other types of disasters, such as floods. As shown in Figure 6, which presents the deaths caused by different hazards, the Japanese government has emphasized earthquake prevention but omitted other events, which leads to high risks and insufficient countermeasures for other types of disasters, such as rainstorms and flooding. The public is less aware of the methods of prevention of rainstorm disasters and lacks an understanding of the criteria for special rainstorm warnings. Besides, more serious debris flows, landslides and other disasters have occurred than the government and population expected. The rainstorm in 2018 covered a wide area and lasted for a long time, and the past practices, which relied partly on the adjacent areas to provide disaster relief, were ineffective, meaning that not all localities were able to take care of themselves. HPMS have been established in Japan for a long time; however, the catastrophic flood which occurred in western Japan indicated that improvements should be made to HPMS in Japan.

5. Suggestions

5.1. Strengthen River Management and Construct Sponge Cities

A spongy city is an effective method to adapt to flood hazards. In 1980, the Ministry of Construction (MOC) in Japan formulated a set of low-impact urban rainwater management systems simulating natural drainage, aiming at solving the prominent problems in the process of urbanization, such as frequent waterlogging, aggravated runoff pollution, water resource loss and the deterioration of the water ecological environment. The comprehensive management of rainwater resources was carried out by promoting the "Rainwater Storage and Infiltration Plan". In 1992, the MOC in Japan promulgated the "Second Generation Urban Sewerage Master Plan". In 2002, Japan launched the "Comprehensive Rainwater Policy-related Action Plan", aiming to reduce urban floods, ensure a good water cycle in the basin, alleviate the phenomenon of "heat islands" in the urban circle and guide the formation of the "natural" circulation of rainwater [42,43]. In recent years, the comprehensive rainwater planning measures—named the spongy city scheme—have been employed, as shown in Figure 8 [44–47]. The scheme related to a spongy city has improved flexibility in terms of adapting to environmental changes and responding to natural hazards caused by rain. Strengthened river management is a critical way to store and drain water in flood hazards and to irrigate and replenish water in drought periods.

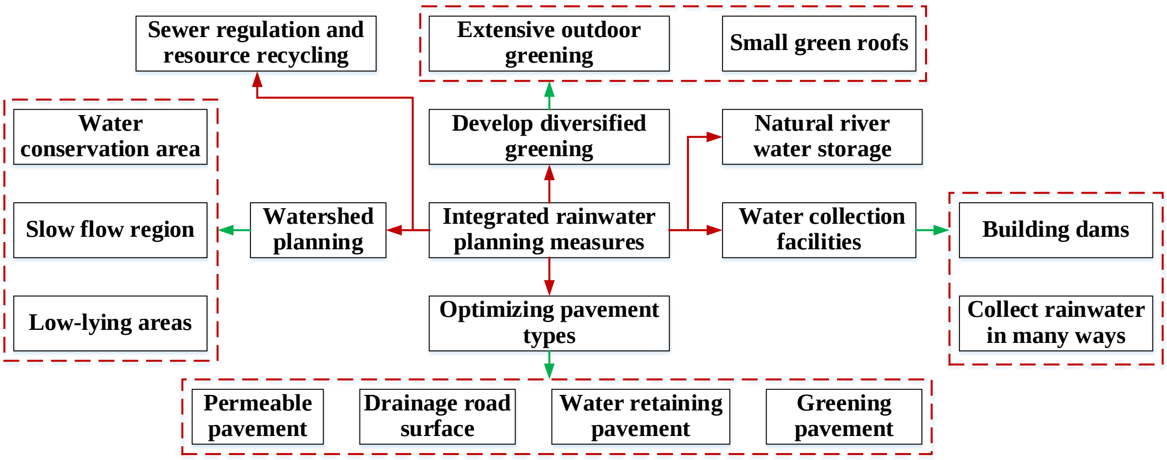

Figure 8. Comprehensive rainwater planning measures.

A suitable regional sponge city construction plan has been proposed based on local rainfall, urban residential density and population density. The major benefits obtained from spongy city construction include the reduced possibility of urban inundation, the alleviation of urban waterlogging and the replenishment of groundwater. The numerous drainage and storage systems improve the drainage and storage capacity of spongy cities, which could prevent some small-scale floods. Regarding a super flood, although the amount of water might exceed the storage capacity of the spongy city, the spongy city could still delay the flood at the initial stage; this would increase the time not only for citizens to transfer to a safe place but also for the government to take countermeasures. This is thus beneficial to alleviate the hazardous results of floods. A high drainage capacity would also improve the recovery time of cities from the flood. Besides, the silt in rivers should be cleaned up in time to increase the volume of water storage during flood hazards. Since the implementation of the spongy city in 2002 in Tokyo, flooded areas and houses displayed a descending trend from 1.37 to 0.33 km^2 in 2002, 2004 and 2006, when the annual rainfall was 160, 199 and 172 mm, respectively [48]. In Japan, taking the Tokyo Sky Tree (Japan's tallest tower) as an example, which is an important section of the drainage and storage system, the system can store 7000 tons of rainwater. Moreover, an underground reservoir of 4000 tons has been built at Shibuya Station (transportation hub of Tokyo). When the rainfall exceeds 50 mm per hour, it can store the rainwater in the surrounding area. At the same time, it is connected with Tokyo's huge underground drainage system to discharge rainwater after the peak of heavy rain. Under this condition, the spongy city represents a preferred way to cope with flood events. In China, many spongy cities have been applied in coastal cities, such as Shanghai, Xiamen, Ningbo and Shenzhen.

5.2. Establishment of an Early Warning System for Flood-Hazards

An early warning system for flood hazards based on information science and artificial intelligence technology should be established. The prediction of hazards is a complicated systematic process because it involves many fields, such as nature, society and the economy. The different range and degree of the selected index factors for natural hazards prediction can interact with each other on the spatial scale, which results in the increased complexity of natural hazard prediction.

Under these conditions, this paper develops a framework of a flood hazard early warning system. Figure 9 shows the framework of an early warning system for flood hazards. This system includes four sub-systems: a monitoring and data collection system, data processing system, dynamic disaster early warning system and management system. It could be established through the Japan Meteorological Agency (JMA). In the monitoring and data collection system, the data are collected using advanced technologies: remote sensing (RS), geographic information system (GIS) and global positioning system (GPS). The collected data in the monitoring and data collection system include temperature, wind speed, rainstorm intensity index, atmospheric pressure, relative humidity and total cloud cover. The dynamic early warning system utilized these collected data to predict the precipitation. The predicted precipitation within 24 h (aforementioned rainstorm intensity index) works as the warning index for a flood hazard. The warning (hydrological) threshold is the maximum rainstorm intensity index that one city could sustain. The assigned hydrological threshold could be empirically obtained from the local return period of flood events or estimated using the capacities of local drainage and storage systems. A warning will be released when the predicted precipitation should be over the hydrological threshold. Apparently, the hydrological thresholds are distinguished for different cities, which have different drainage and storage systems. For instance, Tokyo should be assigned with a higher hydrological threshold owing to the advanced drainage and storage systems of sponge city than other cities such as saga. The data are collected by 3S technologies in a huge volume. Thus, artificial intelligence technologies (machine learning algorithms and deep learning algorithms) and big data technologies are applied to deal with data processing issues [12–14]. These new technologies have the ability to deal with data with a high non-linear correlation. For example, the multiple influential variables, such as temperature, wind speed, atmospheric pressure, relative humidity and total cloud cover are input to the system. Precipitation is a predicted variable through the early warning system as the warning index. The predicted result can provide the guideline to design the drainage and storage systems on improving the storage capacity of spongy cities. For instance, if the early warning system of one city frequently releases warnings, it implies that the warning threshold is too low. The existing drainage and storage system also could not afford the coming precipitation. One city should then improve the drainage and storage system to increase the warning threshold in the future. Besides, the flood risk can be mapped using the prediction result to provide guidelines on how to escape from the flooded area. According to the results from dynamic disaster early warning systems, the government can present a disaster prevention plan, relief plan and guidelines for the construction of infrastructure. The established warning system can be used to predict future disasters, provide relevant design principles for infrastructure construction and reinforce and transform aging infrastructure in a timely manner. It will also provide scientific decision-making support for comprehensive natural hazards risk management and emergency plans for disaster prevention [14,49–53]. For example, seasonal European early warning systems have been developed and have been running in a preoperational mode since mid-2018 under the EU-funded Enhancing Emergency Management and Response to Extreme Weather and Climate Events project [48].

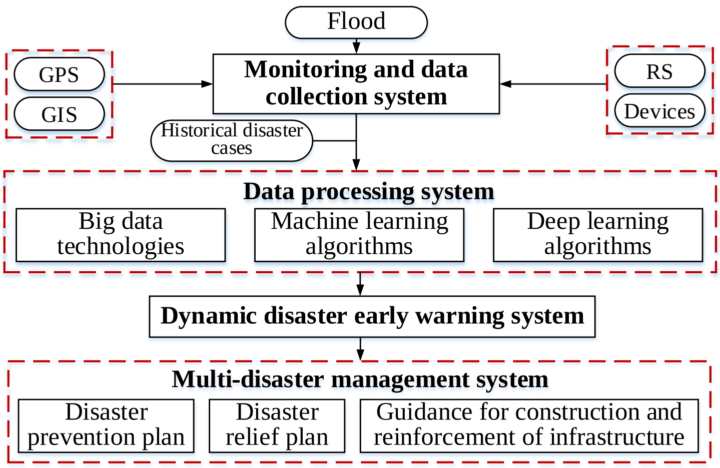

Figure 9. Multi disaster collaborative early warning system. GPS, global positioning system; GIS, geographical information system; RS, remote sensing.

5.3. Management of Infrastructure

In the flood disaster in 2018, a great deal of infrastructure, such as small reservoirs and dams in Hiroshima, Yamaguchi, Okayama and Ehime, collapsed due to aging. Most of these facilities were built in the 1970s and 1980s, and they were not able to resist the impact of large-scale mountain torrents and high water levels. Besides, these infrastructure projects were designed and built based on the highest water level of the historical records at that time; as seen in Figure 7, the numbers of rainfall events over 50 mm/h show an upward trend. The frequent heavy rainfall results in a continuous increase of the water level in the reservoirs. In the catastrophic flood in 2018, 119 stations reached their highest level within 72 h and 123 stations received their highest amount of rainfall within 48 h compared to all historical recordings. The water level continuously exceeds historical recordings. The continuous rainfall and record-breaking water levels not only overloaded the dams, which increased the risks of infrastructure collapse but exceeded the designed standard of water levels. The infrastructure then had to release flood waters and thus failed to protect cities from flood. Therefore, the management and maintenance of existing infrastructure should be strengthened, and the engineering design standards for new infrastructure in Japan should be improved. Figure 10 presents the concept of infrastructure management from a sustainable perspective. This framework of three stages of infrastructure: the design stage, construction stage and operational stage. In the initial design stage, the infrastructure is designed based on a sustainable and hazard-resistant perspective. This should lower the environmental impact during the construction stage. The operational stage is the most significant stage; it is composed of three systems (monitoring, evaluation and maintenance and repair systems) to ensure the operation of the infrastructure.

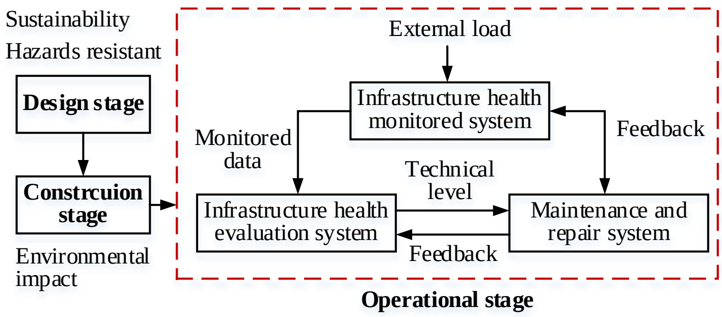

Figure 10. Management of infrastructure based on a sustainable view.

5.4. Other Recommendations

Apart from the suggestions mentioned above, flood hazard awareness should be increased. For example, the population should stay away from dangerous areas (riverbeds, reservoirs and channels and culverts). The people (in dangerous areas) should leave after receiving early warning of flood hazards. Besides, additional technical flood protection measures are also important. Infrastructure, such as dams, dikes and reservoirs, should be built and maintained in time to mitigate the impacts of flood hazards. Furthermore, houses should be built with improved engineering standards, which can give houses a better adaptive ability during flood hazards.

6. Conclusions

This paper analyzes the extreme flooding hazard that occurred during 5–9 July 2018 in western Japan. According to the preliminary investigation and analysis of flooding hazards, concluding remarks from a sustainable perspective are presented below.

(1) The catastrophic flood that occurred in western Japan in July 2018 led to 212 deaths. This flood hazard also led to more than 2000 houses being damaged/destroyed and 619 geological disasters in 31 prefectures. The impacts of the catastrophic flooding hazard in western Japan revealed the vulnerabilities of hazard prevention and management systems in Japan. The causes of and contributing factors to the catastrophic flood are illustrated. The analysis of the catastrophic flood in Japan provides a valuable lesson for flood hazard prediction, prevention, and management.

(2) Some countermeasures are presented to better prevent and cope with flood hazards in the future. A spongy city should be constructed to enhance the resilience to adapt to extreme rainfall events. In addition, a framework for a flood hazard early warning system is proposed. A collaborative early warning system is established based on information science and artificial intelligence technologies. Finally, the importance of maintaining and updating infrastructure in time is highlighted.

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Nomenclature

Items	**Abbreviation**
Carbon dioxide	CO_2
Ehime	Eh
Fukuoka	Fu
Geographical information system	GIS
Global positioning system	GPS
Hiroshima	Hi
Japanese Yen	JPY
Hazards prevention and management system	HPMS
Information science and artificial intelligence technologies	ISAIT
Kagoshima	Ka
Kochi	Ko

Items	**Abbreviation**
Kagawa	Kag
Ministry of Construction	MOC
Miyazaki	Mi
Early warning system	EWS
Nagasaki	Na
Oita	Oi
Remote sensing	RS
Shimane	Sh
Tokushima	To

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