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Current status and challenges in operating flood early warning systems at the local level in Japan

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ABSTRACT

Flood early warning systems (FEWS) are crucial in reducing flood loss and damage, especially under increasing flood risks due to climate change. Currently, there is limited literature holistically investigating all components of FEWS, namely Risk knowledge, Monitoring and Forecasting, Warning Dissemination, and Preparedness and Response Capabilities. There is also a lack of in-depth understanding of FEWS operation at the local level where local governments play a crucial role. This study conducted a nation-wide survey targeting Japanese municipalities (n = 350) to investigate the current status and challenges of FEWS operations at the local level and the relationships between these elements. The results indicated that while progress in FEWS operation varies in municipalities, they are encountering different challenges in each element of the system. These include a lack of human resources and financial resources, difficulties in risk assessment and data acquisition, limitations of dissemination methods to reach vulnerable, and limited understanding of public perception. This study is the first to investigate all four key elements of FEWS at the local level and the relationships of its key factors, providing useful implications for policy directions to enhance FEWS implementation. All key elements of FEWS positively correlate, suggesting that improving one component can improve the whole system. Government should also strengthen progress in vulnerability assessment, particularly incorporating socio-economic changes as these have the strongest influence on preparedness and response capability of the local areas.

1. Introduction

Flood risk in urban areas has drawn extensive attention of governments and authorities worldwide due to costly damages associated with increasing extreme weather events. Floods are the most common disaster and have affected more than two billion people, causing over one million deaths and an economic loss of US$80 billion [1,2]. Flood damage has been growing exponentially due to increased flood risk induced by climate change, urbanization, and development practices. In coping with such risk, flood early warning systems (FEWS) are crucial and have been successfully implemented in numerous areas globally to prevent loss and damage from flooding, especially extreme events such as storms and heavy rainfalls.

Early warning is defined by the International Strategy for Disaster Reduction as “the provision of timely and effective information, through identified institutions, that allows individuals exposed to hazard to take action to avoid or reduce their risk and prepare for effective response” [3]. FEWS is more than just a prediction. It is an integrated system of four key elements, namely Risk Knowledge, Monitoring and Forecasting, Warning Dissemination, and Preparedness and Response Capability [4,5].

Risk knowledge refers to systematically collecting data and undertaking risk assessment, specifically the identification of flood risks and related threat, and the consolidation of such risks into hazard maps [4]. Risk assessment includes identifying exposure to

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flood risk and quantifying vulnerability such as assets and population that would be affected by floods and social-economic changes that contribute to such vulnerability. *Monitoring and Forecasting* refers to the observation and detection of hazards and the provision of forecasts and warnings, using hydrological models with observed data and hydrodynamic models [6,7]. Forecasting models must be reliable to provide timely warnings, which are the core of early warning systems [6]. Continuous and long-term observation data is crucial in improving the accuracy of forecasting models. *Warning Dissemination* refers to risk information and early warning communication to those at risk in a timely and effective manner [4–6]. Warnings must include useful information of coming hazards, be clear and easy to understand to motivate populations at risk to take proper actions to prepare and respond to risks [6]. It is important to make sure that the population at risk can receive timely warnings so that they have enough time to take required actions to keep themselves safe [8]. Consideration of vulnerable groups must be integrated as they usually have limited access or exposure to warnings [9]. The last key element of FEWS is *Preparedness and Response Capabilities*. Disaster preparedness and response plans must be created and implemented at both national and local levels to mitigate flood impacts and allow a population to respond effectively when floods occur as these plans can help the government to navigate through different response stages and ensure smooth coordination between agencies [4,7]. These plans must be well practiced and incorporate a participatory approach to include communities' perspectives to better enhance their capabilities [7,10]. Communities should be well informed of what to prepare and what actions to take in the event of disasters [6]. Strong preparedness education programs, training activities, and evacuation drills are required to build community capabilities [7,8]. Such efforts can help increase risk perception and disaster (response) awareness, informing people's actions and behaviours when receive flood early warnings.

Despite the recognized importance of FEWS, there is limited literature investigating all component of FEWS as most existing studies have investigated each element separately [11–14] or focused on the technical aspect of providing warning services (i.e., forecasting technology or technical effectiveness of the system) [15–22].

In 2005, a global survey indicated that forecasting technologies had been available for all types of hazards [4]. However, there is an unequal focus on generating and issuing warnings in existing FEWS, and the three other elements were absent or weak. Garcia and Fearnley investigated the interlinkages of the four key elements of early warning systems, highlighting the importance of all four key elements (2012). Perera et al. [9] provided insights into the current status and challenges in operating forecasting centre globally, but it overemphasized the technical aspects (Monitoring and Forecasting element of FEWS) over the community response and preparedness.

Perera et al. [7] identified the social challenges in warning dissemination and community preparedness and response through literature review and some case studies. Communication of warnings has not reached all populations at risk and warning messages are often not tailored to the needs of vulnerable groups [7]. Challenges related to preparedness and response are lack of public awareness in early warnings, limited drills and trainings, absence of political commitment, lack of financial and technical resources, lack of community engagement, and lack of transboundary planning [7].

Sufri et al. [10] specifically dived into community engagement in the four elements of early warning systems and indicated that there is inadequate community engagement across the four elements of FEWS. There is also inadequate integration of local and scientific knowledge into operation and insufficient consideration of the full range of vulnerable groups [10].

Aguirre-Ayerbe et al. [23] took a step further in assessing the key areas of the four elements of FEWS in Maldives, Sri Lanka, Myanmar, and the Philippines. The study highlighted that dissemination and communication elements are still in the first stage of development in these countries. Furthermore, there is insufficient consideration to vulnerability factors such as gender, disability, and access to infrastructure [23]. Despite the involvement of different stakeholders in this study, its scope is still limited to the national scale.

Looking at the four elements of FEWS separately, for example, in risk knowledge and assessment, there is extensive literature on advancements of understanding river flood mechanisms and methods and tools for practitioners [14,21,22]. However, the progress of flood risk assessment in practice at the local level is largely unknown. Similarly for other elements, there is limited knowledge on the progress of implementation in practice, particularly at the local level [10,11,20,24–28].

Overall, while existing studies have provided a global overview of the availability, adequacy, and various challenges of FEWS [7,9,13,29], all of them have addressed FEWS at the national level through involving national forecasting centers or high-level decisionmakers. Such studies have provided merely the surface of the FEWS implementation process. There is a shortage of in-depth understanding of FEWS operation at the local level, where local governments play a crucial role. Local governments are involved in most key elements of FEWS, particularly Risk Knowledge as they have the most understanding of the local context. Additionally, local governments directly communicate with residents and have the responsibility to implement disaster risk preparedness and response measures to ensure residents' safety [4].

Addressing this gap, this study conducted a comprehensive nation-wide survey with Japanese municipalities to assess the current progress and identify major challenges in implementing FEWS at the local level. Japan is among the countries with the highest flood risk due to its long typhoon season [30]. FEWS in Japan are among the more advanced systems available worldwide and have been implemented nation-wide [31,32]. A comprehensive assessment of all components of FEWS at the municipal level in Japan can provide valuable insights and lessons into how to enhance FEWS implementation. Furthermore, existing studies have primarily overlooked the linkages between the key components of FEWS [12,27]. Hence, this study has further investigated the relationships between key FEWS elements by using correlation and path analysis to provide crucial hints on how to improve FEWS at the local level.

In the next section, the paper provides an overview of Japanese FEWS operation as background to this study. Then, the survey design, data collection, and data analysis are described. In the Results section, current progress and challenges in implementation are discussed for each element of FEWS. Then, results on the relationships between these elements are discussed. The next section provides discussion on key findings of this study comparing to existing literature and extract insights and implications for FEWS in other areas of the planet. The paper then concludes on summarizing key findings and suggestions for future research directions.

2. Methods

2.1. Flood early warning systems in Japan

Japan is among the countries most exposed to flood risks due to its location in the East Asian Monsoon Area with high annual rainfall and long typhoon season [30]. The country has been hit by various typhoons annually and historically, and it has suffered devastating losses from such extreme events [31,33].

In the event of disaster, the national and local governments quickly collect and share disaster and damage information and secure communications to carry out effective emergency activities as rescue and medical operations [31]. Based on the disaster information, the local governments set up the Disaster Management Headquarters and related organizations (ex. local voluntary disaster prevention organizations) establish their own operation mechanisms [31]. Roles and responsibilities of national, prefectural, and municipal government are clearly defined in the Disaster Management Plans at each level [34]. How disaster management functions between national, regional, and local governments in each component of FEWS is described below.

Regarding *Risk Knowledge*, municipalities are responsible for collecting and reporting disaster damage [34,35]. They also manage disaster history data of the local areas. Exposure to hazards and aspects of vulnerability assessment should be conducted by the municipalities [35]. However, when there is limited capacity to conduct such assessments or to collect disaster damage, municipalities can request support from the prefectural government [31]. Municipalities are responsible for publishing flood hazard maps and disseminating them to residents [35]. The creation of hazard maps can be supported by private consulting services. The national and the prefectural governments determine the warning water levels and expected inundation areas, which are used by the municipalities to produce the hazard maps at the local level [35].

Regarding *Monitoring and Forecasting*, a meteorological observatory has been established since the Meiji era; however, it was not until after the devastating damage of Typhoon Muroto in 1934 that a complex system of meteorological services was established, setting a foundation for FEWS in Japan [36,37]. The law on dissemination of water level information was established in 1955 for designated “flood forecast rivers” [38]. Throughout the history of coping with various flood events, the Flood Control Act [39] was gradually revised to cover wider ranges of rivers, provide regulations on methods of warning dissemination, and require plans for disaster preparedness and response, including evacuation plans for both facilities and individuals [38]. As of Oct 2019, 80 % of the prefectural managed rivers have specified flood inundation areas corresponding to the expected maximum rainfall but there is no progress for small and medium-sized rivers that do not have water level notifications [40].

River administrators have the statutory responsibilities to manage rivers, including monitoring the water levels and implementing flood prevention measures such as pumping stations [41]. Depending on the designated class, the river administrators can be the MLIT (managing Class A river, 一級河川), prefectural government (managing Class B river, 二級河川) or the municipalities (managing small and medium rivers). While there are some general criteria for river classification, specific parameters are not determined and changing the class of a river requires opinions of the River Council and the prefectural governors concerned [41]. See supplementary information for the details of river classification in Japan. Generally, municipalities manage small and medium rivers.

The Japan Meteorological Agency (JMA), Ministry of Land, Infrastructure, Transport and Tourism (MLIT), prefectural government, and municipalities are the key stakeholders implementing FEWS in Japan. Fig. 1 shows the institutional setting for monitoring and forecasting information flow described in the Flood Control Act [39]. When there is a risk of flooding or storm surge, the JMA must inform MLIT and the public (through cooperation with the media, if necessary) (Article 10, Paragraph 1). Currently, the JMA provides risk information directly to the public through Flood Kikikuru, a real-time risk map that can send push notifications to users [42,43]. For rivers under national management, MLIT and JMA have the responsibility to inform the prefectural government of the water level and the flow rate, the area that will be flooded, and flood depth (Article 10, Paragraph 2). When the prefectural government receives such information, they must inform the municipalities (Article 10, Paragraph 3). For rivers under prefectural management, the prefectural government and the JMA (i.e., regional meteorological observatory) have the responsibility to inform municipalities of the river water level and flow rate (Article 11).

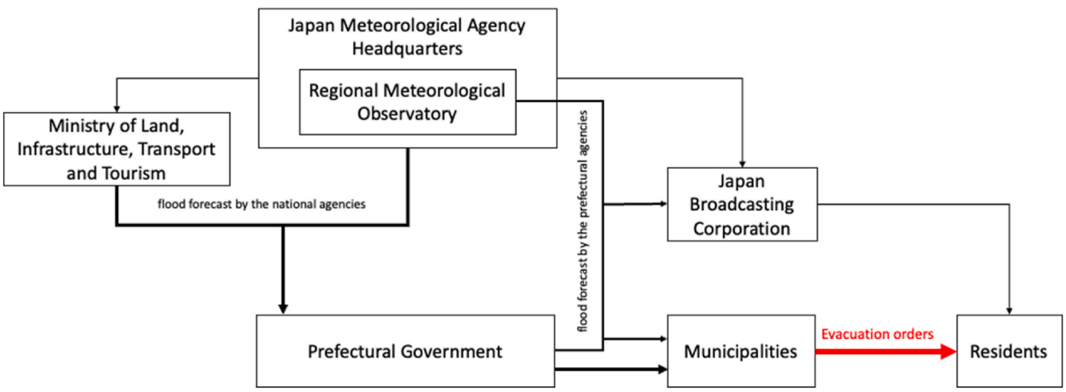

Fig. 1. Simplified institutional setting for forecast information flow (Adapted from the Flood Control Act).

JMA observes meteorological phenomena using the Automated Meteorological Data Acquisition System (AMeDAS), which includes weather radar, geostationary meteorological satellite, and coastal tide gauges [31,44]. MLIT and the prefectural government observe the rainfall and water level in the rivers they manage through mechanical observation equipment and wireless telemeter systems [31]. The three stakeholders coordinate to provide flood forecasts to the municipalities (Flood Control Act).

JMA provides monitoring and forecasting data regarding water conditions such as rainfall and snow melt for the MLIT and prefectural government [31]. MLIT and the prefectural government operate models using inputs from JMA and the water situation such as the river water levels and flow volumes to produce forecasts on river water level and expected inundation areas [35]. If the upstream and downstream of the river are under different administrators, the administrators will coordinate to inform each other of the river water level information or dam operations between upstream and downstream management.

Regarding *Warning Dissemination*, warnings and advisories issued by the JMA and the local meteorological observatory are transmitted to the prefectural government, then to the municipal offices by radio and fax [45]. Based on the level of warnings, the municipalities and other local flood prevention entities take necessary responses. Evacuation information is issued under the authority of municipal mayors [46,47]. Early warnings are communicated to the residents through various paths including official announcements from JMA, MLIT, prefectural and municipal websites, indoor and outdoor receiver systems, push notification to phones, and announcements to mass media [31,47]. Municipalities solely have the statutory responsibilities to issue evacuation orders [48]. Other stakeholders such as the media and prefectural government can disseminate such orders to residents together with the municipalities.

Regarding *Preparedness and Response Capabilities*, municipalities are the primary responders in the event of floods [31]. In the case of flooding that exceeds the response capacity of municipalities (ex., large-scale floods), municipalities can request support from the prefectural and national government in responding to floods [31]. Municipalities will establish different stages of response, in which the Disaster Response Headquarters are established, including various departments such as first responders [34]. During the disaster, prefectural governments and the national government support municipalities in terms of coordination between agencies and with requests for rescues and resources from the prefectural or national government [34]. During normal times, municipalities are responsible for promoting and supporting local voluntary organizations to promote disaster awareness programs, evacuation drills, and creation of "my timeline" for residents [48].

2.2. Survey design

A comprehensive survey was conducted with municipalities across Japan. The survey was in Japanese, focusing on understanding the current status of FEWS and challenges in operation.

The survey was designed to cover all four key elements based on the World Meteorological Organization (WMO) checklist of Multi-Hazard Early Warning Systems, Manual on Creating Hazard maps in Japan and Guidelines on Evacuation Information, which provided details on creating hazard maps, disseminating warning messages, and enhancing preparedness and response in the event of emergency at the municipality level [6,35,48]. The WMO checklist on Multi-Hazard Early Warning Systems provides series of questions on the availability of FEWS and the institutional settings for implementation (see Fig. 2 for the key questions). However, many of the questions only provide a superficial understanding of the implementation status (i.e., whether the element exists), which overlooks the actual status of implementation at the local level where each factor needs to be divided into more detailed measures. Hence, extra information from the aforementioned manual and guidelines was included to contextualize the checklist with Japanese municipalities. Most of the questions are answered on a 4-point Likert scale from 0 to 3 to indicate the level of implementation of each indicator. For example, for the question regarding understanding of flood characteristics, the municipalities can indicate whether they grasp all information (3), most information (2), part of the information (1) or nothing at all (0).

In addition to the questions about status of FEWS operation, open ended questions were asked to explore existing challenges and knowledge gaps in implementation. The survey was first consulted with Nagano prefecture before distribution to confirm the compat-

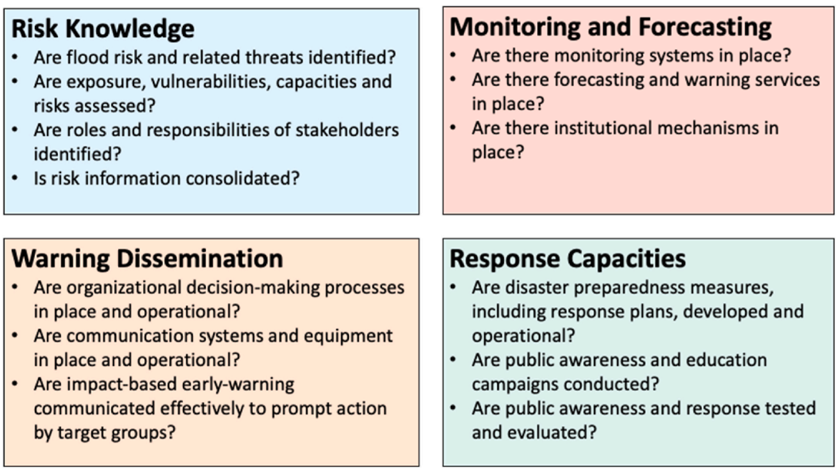

Fig. 2. Key questions on four elements of Multi-Hazard Early Warning Systems. (Source: [6])

ibility with the local government context. Officers from Nagano Prefecture checked the survey questions and provided comments and suggestions to improve the clarity of the questions.

2.3. Data collection

The questionnaire survey was distributed with the cooperation of prefectural governments, aiming to cover all municipalities in Japan. In total, there are 1724 municipalities, under 47 prefectures in Japan [49]. The authors contacted the disaster risk management department in all 47 prefectures, asking for the cooperation in distributing this questionnaire to municipalities. In total, 32 prefectures cooperated in distributing the questionnaire and as a result, 350 municipalities responded to this questionnaire, representing approximating 25 % of municipalities in Japan (95 % confidence level, margin of error smaller than 5 %). The survey respondents are officers from the municipalities. Their responses reflect the status of FEWS operations in the municipalities. The distribution of the collected responses is shown in Fig. 3.

2.4. Data analysis

The collected data is analyzed both quantitatively and qualitatively. Descriptive statistical analysis was conducted to provide an overview of implementation status for each element of FEWS. Then, qualitative analysis (thematic coding) was conducted for open ended questions (i.e., questions about challenges in operation). How the themes on challenges link to others was also analyzed to provide an in-depth understanding of challenges in FEWS operation at the municipal level in Japan.

The qualitative data analysis was conducted in MAXQDA.

Table 1 reports the descriptive statistics of the question items, including mean, standard deviation, and Cronbach's alpha. Cronbach's alpha indicates the internal consistency of factors that are measured by the question items. A Cronbach's alpha higher than 0.6 is the recommended threshold that indicate internal consistency of the factor [50]. The key factors of FEWS were computed equal to mean of the relevant items (Table 1). These factors include knowledge of flood characteristics, knowledge of social characteristics, vulnerability assessment, vulnerability assessment of social factors, monitoring system, warning dissemination, and preparedness and response capabilities.

Spearman's rank regression was conducted to explore the monotonic relationships between these factors to provide insights on their connections. Then, path analysis was conducted to test these relationships simultaneously in one model and to compare the effect size of these relationships. Path analysis is a multiple regression analysis that is used to measure directed dependencies between factors, providing insights into possible causal relationships [51]. Generally, all elements, including vulnerability assessments (considering expected damage and socio-economic changes), monitoring systems, and warning dissemination, should positively impact preparedness and response capabilities because the information from each element serves as valuable input for taking action. Similarly, vulnerability assessment and monitoring systems should positively influence the warning dissemination; knowledge of the local social characteristics should influence warning dissemination, and vulnerability assessment should influence monitoring system. Finally, knowledge of the local flood and social characteristics should provide important inputs for improving the vulnerability assessment.

Statistics on population of the responded municipalities and their flood experience were also included in the Spearman's rank correlation and the path analysis to provide a more in-depth analysis of the FEWS operation situation and relationships between key factors. Population data was estimated in October 2022 [52] and flood experience data was retrieved from Portal Site of Official Statistics of Japan [53]. The statistics of disaster damage at municipalities for the period of 2016–2020 (the latest available data) indicated that 49 % of the municipalities that participated in this survey had no flood experience in the given period. Approximately 51 % of

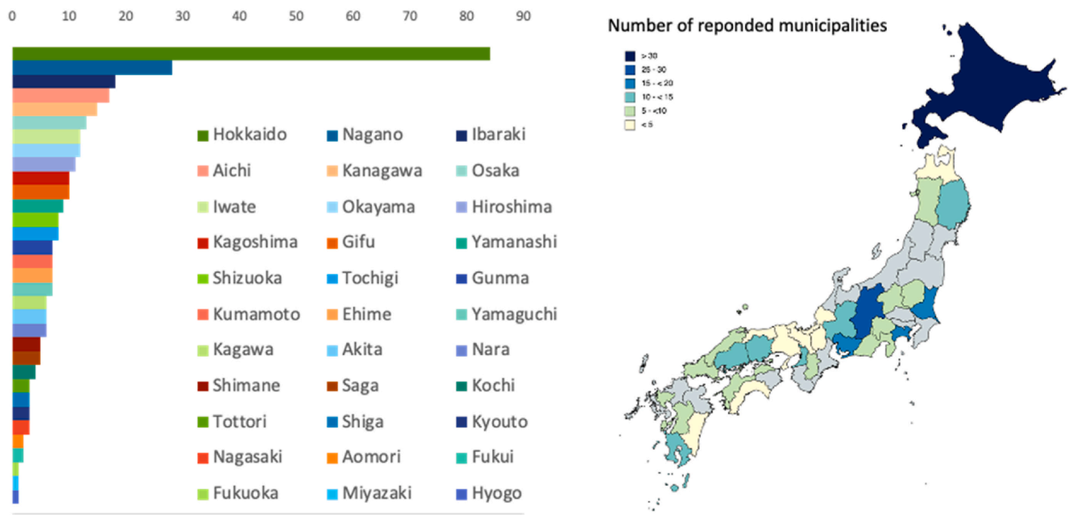

Fig. 3. Distribution of the collected responses (n = 350).

Table 1
Key factors and question items of FEWS at the local level.

Key factors	Cronbach's alpha	Items	Mean	Standard Deviation
1. Knowledge of flood characteristics	0.79	1. 1. Are you aware of the flood damage (fatalities and economic loss) in the expected inundation zone?	1.56	1.06
		1. 2. In areas with multiple rivers, do you know the scale of damage of each river?	1.74	1.00
		1. 3. Do you know the different scale of damage for each dike breach point?	1.17	1.03
		1. 4. Do you grasp the records of past flood damage (approx. 30 years)	1.85	0.73
		1. 5. Do you grasp the areas that requires early evacuation?	2.01	0.80
2. Knowledge of socio-economic characteristics	0.69	2. 1. Do you grasp the age structure of residents and the status of those in need of assistance?	1.88	0.69
		2. 2. Do you grasp the status of community-based disaster prevention organizations?	1.97	0.68
		2. 3. Do you grasp the status of underground facilities and facilities used by people requiring special care (hospitals, nursing homes, etc.)	2.48	0.65
		2. 4. Do you grasp the land use changes (topography, houses, roads, etc.) over time?	1.57	0.86
3. Vulnerability assessment	0.95	3. 1. Have you investigated the expected flood damage to general assets (households and businesses)?	0.81	0.89
		3. 2. Have you investigated the expected flood damage to agricultural products?	0.88	0.95
		3. 3. Have you investigated the expected flood damage to public facilities?	1.03	0.97
		3. 4. Have you investigated the expected casualties due to flood damage?	1.07	1.02
		3. 5. Have you investigated the expected flood damage to the vulnerable groups (the elderly and disabilities)	1.21	0.91
4. Vulnerability assessment (social factors)	0.73	4. 1. Have you designated evacuation sites and routes according to the age structure of residents and the situation of those requiring support?	1.25	0.87
		4. 2. Are past flood damage records and risk information compiled into a database?	0.93	0.90
		4. 3. Have you considered possible causes of increased flood risk, such as urbanization and land use change?	0.42	0.76
		4. 4. Have you investigated any regulations (such as laws or ordinances) that may increase flood risk?	0.30	0.66
		4. 5. Are you aware of cultural and local practices (e.g. patrolling waterways during heavy rain) that may increase flood risk?	0.86	0.88
		4. 6. Are you aware of the area's past experiences and traditions that have led to flood risk reduction?	0.98	0.78
5. Monitoring system	0.81	5. 1. Are local rivers equipped with water level observation stations (including CCTV cameras, etc.)?	1.29	0.97
		5. 2. Is data from river observation stations transmitted in real time or near real time?	1.82	1.20
		5. 3. Are the hardware and software for observations maintained periodically?	1.71	1.19
6. Warning dissemination	0.70	6. 1. Do you verify if the evacuation information was received?	0.50	0.84
		6. 2. Are backup systems and methods in place for information transmission facilities and equipment in the event of a flood?	1.47	0.99
		6. 3. Do you grasp the public's understanding of flood forecasts?	0.82	0.80
		6. 4. Do you grasp the public's understanding of evacuation information?	1.02	0.79
		6. 5. Do you grasp the needs of residents during flood disasters by age, gender, and physical characteristics?	0.68	0.73
		6. 6. Assess the status of warning dissemination at your municipality.	2.01	0.67
7. Preparedness and Response Capabilities	0.86	7. 1. Is "Local Disaster Prevention Plan" developed based on a participatory and gender-sensitive approach?	1.45	0.84
		7. 2. Do disaster preparedness and response plans consider the needs of the elderly, people in need of assistance, etc.?	1.60	0.69
		7. 3. Do you evaluate residents' evacuation capability?	0.71	0.86
		7. 4. Are you promoting disaster prevention education? (Using flood hazard maps in general studies in school education, etc., and training local disaster prevention leaders.)	1.76	0.74
		7. 5. Do you conduct evacuation drills every year?	1.77	0.95
		7. 6. Do people know or understand how alerts are sent?	0.97	0.901
		7. 7. Is public awareness and disaster prevention education tailored to specific needs due to age, gender, physical characteristics, etc.?	1.51	0.79
		7. 8. Are you learning from past event and incorporating them into disaster management planning?	1.26	0.88
		7. 9. Have you analyzed past (30 years or so) emergency and disaster events and responses and incorporated the lessons learned into your flood preparedness and planning?	1.36	0.86
		7. 10. Are public awareness plans and efforts regularly evaluated and updated as necessary?	1.02	0.89
		7. 11. Do you measure public risk perception?	0.34	0.65
		7. 12. Are residents informed of the list of items to take with them during evacuation?	2.07	0.61
		7. 13. Evaluate residents' disaster preparedness.	1.30	0.58

(*continued on next page*)

Table 1 (*continued*)

Key factors	Cronbach's alpha	Items	Mean	Standard Deviation
		7. 14. Is insurance provided for personal property (house, household goods, farm, etc.) affected by the disaster?	0.80	0.73

the responded municipalities had flood experience. The two groups were fitted with path analysis, then chi-square difference test and *t*-test were used to examine the differences between them. All the statistical analyses were conducted in STATA 18.

3. Results and discussion

3.1. Risk knowledge

Overall, 91 % of the responding municipalities have issued hazard maps of the areas that could be affected by flooding on the municipal websites or distributed them to the residents. Fig. 4 presents the descriptive data of current status in creating risk knowledge at the municipal level, including understanding of flood characteristics (left), understanding of social characteristics (right).

Most municipalities reported that they understood the flood damage characteristics of their local areas, including understanding of areas that require early evacuation, history of the past flood damage, compounding damage of multiple rivers, and overall casualties and economic loss. However, 28 % of the municipalities do not have information regarding different scales of damage at dike breach points, 19 % do not grasp knowledge of casualties and economic loss, and 13 % of do not grasp knowledge of damage from multiple rivers.

Comparing to the understanding of flood damage characteristics, more municipalities grasp knowledge of the social characteristics, including situations of land use change over time, presence of underground facilities or facilities used by the vulnerable groups, the status of voluntary disaster prevention organizations, and the status of vulnerable groups (i.e., the elder and people with disabilities). Quantitatively, more municipalities grasp the knowledge of critical facilities that are used by vulnerable groups. Most municipalities grasp the major status of local voluntary disaster prevention organizations and the status of vulnerable groups. Comparatively, fewer municipalities grasp the knowledge of land use change over time (14 % of the municipalities do not have the knowledge of land use change).

The status of vulnerability assessment at the municipal level was measured by analysis of expected damage to various aspects and analysis of social changes that might increase vulnerability (Fig. 5). Around 21 %–31 % of the responding municipalities do not evaluate the expected damage to local areas, including general assets such as households assets and business assets, damage to agriculture products, damage to public facilities, expected casualties, and damage to vulnerable groups. Around 10 %–15 % of the municipalities are uncertain about the status of vulnerability assessment in different category of expected damage. Approximately 33 %–52 % of the municipalities partly or mostly conducted vulnerability assessment. Up to 6 % of the municipalities have fully assessed the expected damage from floods.

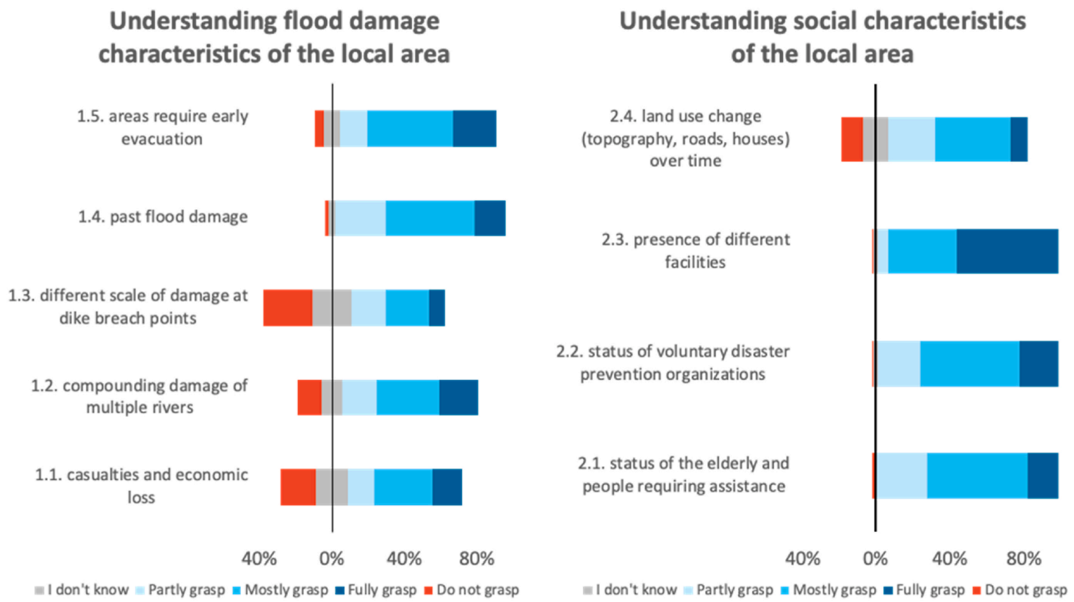

Fig. 4. Current status of knowledge about the areas at the local level.

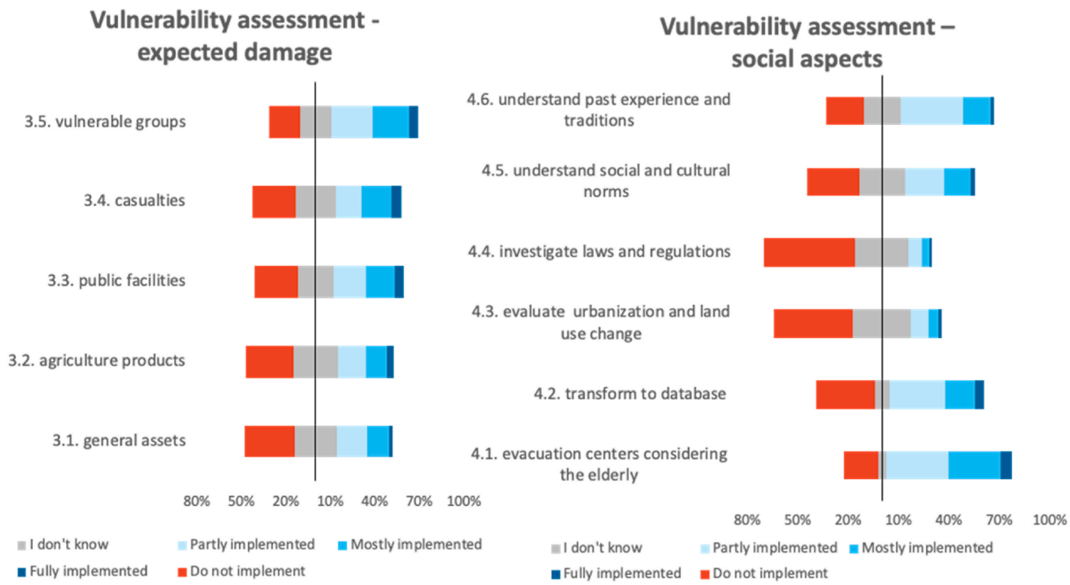

Fig. 5. Current status of vulnerability assessment at the local level.

Investigation of social factors that influence local vulnerability varies. Most municipalities have reviewed hazard maps periodically and identified evacuation centers and routes that take the vulerable groups into account. Many municipalities have partly integrated risk knowledge (past events or flood risk related knowledge) into a database but 35 % of the municipalities have not started yet. A large number of municipalities do not evaluate the impacts of urbanization and land use change on flood risks (47 %) and more than half of the municipalities do not examine laws or regulations that might increase vulnerabilities of the local areas. Around 13 %–16 % partly or mostly investigated the impacts of land use change and laws or regulations on flood risks. Only 1 % of the municipalities have fully investigated these factors. Around a third of the municipalities do not investigate social and cultural norms and 22 % of the responded municipalities did not grasp past experience and traditions that can reduce flood risk. Overall, social factors that can influence vulnerabilities were not well considered by the municipalities.

Around 41 % of the municipalities indicated the challenges that they are encountering in relation to Risk Knowledge (n = 145). Fig. 6 shows the results from qualitative analysis of open-ended questions, indicating the frequency of challenges mentioned by the municipalities. In *Risk Knowledge*, the biggest challenges identified by the municipalities are a lack of human resources (29 %), difficulties in conducting risk assessment (24 %) and data acquisition (21 %).

Fig. 6. Frequencies of challenges in creating risk knowledge at the local level.

Fig. 7 indicates a more detailed understanding of the relationships between these challenges as described in the open-ended question. The most common challenge among municipalities is lack of human resource for creating risk knowledge. Some municipalities further specified that they lack people with expertise in disaster risk or have the technical know-how and specialized skills, lack personnel for managing risk information, lack staffs that are experienced with previous disasters and have knowledge of past flood events. In some cases, the staff rotations led to experienced staff leaving and time-consuming takeovers. See the supplementary information for supporting quotes from the responding municipalities.

Another major challenges that the municipalities have to overcome is difficulties in assessing risk, including estimating the expected damage and evaluating factors related to vulnerability. Risk assessment connects with many other challenges such as data acquisition, lack of specialized knowledge, and difficulties in coordination with other governmental agencies as data was scattered in different departments. Regarding the estimation of expected damage from floods, there is significant confusion on how to estimate, to what extent estimation should be done, and which relevant data needs to be provided by the prefectural government (ex. past damage data was summarized in prefectural unit). In some cases, expected damage needs to be estimated by the prefectural government, which has been slowed or not yet finished, which leads to delay in understanding risk at the municipal government and the process of creating hazard maps. The expected damage estimation also needs to consider the changes in flood magnitude based on previous flood events. However, information on past damage is inconsistent in terms of damage categories and content.

Regarding vulnerability assessment, municipalities indicated difficulties in grasping the change in land use, development and growing population in hazardous areas, and social factors such as incorporating vulnerable groups. Changing exposure further complicates the risk assessment.

Data acquisition is the next major challenge in creating risk knowledge at the municipal level. It refers to the lack of data, mostly regarding risk assessment and damage from past flood events. This is because data is distributed in various government agencies. In the case that primary data needs to be collected, municipalities lack specialized knowledge and methods to do so. This is also partly because of limited experience with disasters in some cases.

Another challenge related to risk knowledge is how to communicate risk information to residents, including to the vulnerable groups to increase risk perception as risk assessment itself is not yet clearly achieved. Risk assessment is also complex, making it difficult to communicate information in an easy-to-understand manner.

Overall, beside the lack of human resources, challenges related to risk information, regarding whether past damage or expected damage due to flood risks, is the next major challenge that municipalities must face. This is due to the lack of data, limited experience, and limited expertise at the municipal level on how to collect and manage the data and conduct risk assessment.

3.2. Monitoring and forecasting

Regarding Monitoring and Forecasting, since the municipalities only manage small rivers in the areas (if any), the survey results provide the status of monitoring systems at these municipalities. A majority of rivers at the responding municipalities are at least partly to fully equipped with water-level monitoring equipment. Around 20 % of the municipalities do not monitor the water-level at their rivers. Most municipalities transmit the monitoring data in real-time or near real-time. However, 46 % of the municipalities are

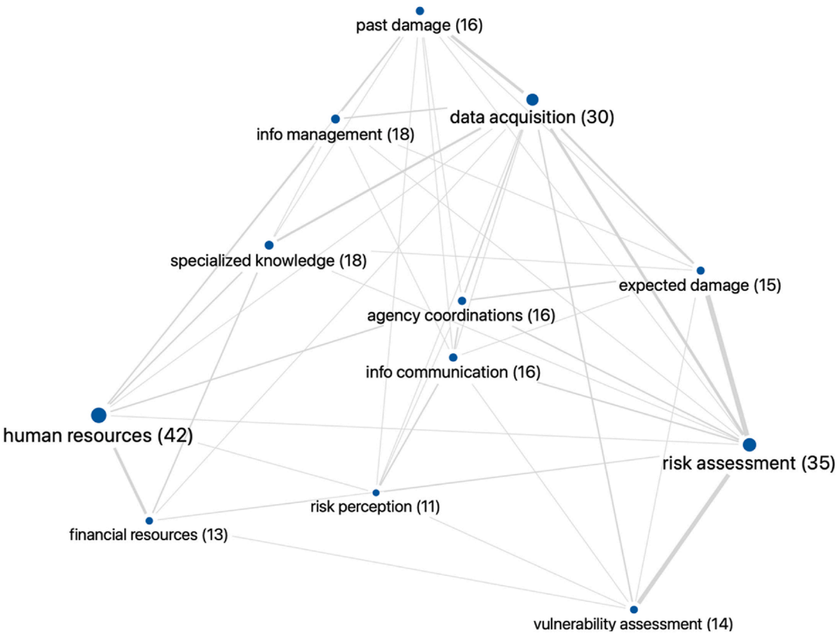

Fig. 7. Connection between major challenges (frequencies higher than 10) in creating risk knowledge at the local level. The number indicates frequencies of each challenge (how many municipalities mentioned such challenge). The line indicates the co-occurrence of challenges mentioned by the municipalities. The line thickness indicate higher frequencies of co-occurrence.Only co-occurrences higher than 2 is shown.

unclear about the situation regarding periodic maintenance of the monitoring equipment. This might be because the rivers are under management of the national or prefectural government (24 %). The main reason why rivers at the local areas are not yet equipped with monitoring systems is the lack of financial resources (63 % of the municipalities). Other reasons include a lack of equipment suitable for the local characteristics (20 %), lack of technical expertise (18 %), and low priority compared to other responsibilities at the local government (5 %) (Fig. 8).

3.3. Warning dissemination

Warning information is disseminated to residents mostly through mass media (TV and radio, in 62 % of municipalities), area mail, and the J-alert system (63 % of municipalities). Around 23 % of the municipalities distribute warning information through an administrative wireless system. Other methods of warning distributions include SNS, subscription mail, municipal homepages, disaster prevention applications, etc.

Evacuation orders are disseminated through a variety of methods including area mail (78 %), an administrative wireless system (74 %), mass media (67 %), public relation vehicles (61 %), SNS (59 %), safety mail subscription (41 %), and telephone and FAX (33 %). Other methods include evacuation staff (21 %), siren (17 %), automatic disaster prevention radio (14 %), municipal homepage (12 %), and disaster prevention applications (9 %), etc.

In the event of floods, residents can proactively seek out information as well, through the municipal homepage (82 % of municipalities). Other ways of receiving information include digital terrestrial broadcasting (61 %), SNS (60 %), safety mail subscription (48 %), and CATV (32 %), etc.

Evacuation orders disseminated from municipalities include names of target areas (89 %), information on the disaster situation (85 %), and actions that residents should take (84 %). Around half of the municipalities include details of the disaster situation. Around 22 % of municipalities include information on situations of road closures. Only 7 % of the municipalities include information on the opening of evacuation centers and 6 % of the municipalities provide information on evacuation routes in warning information.

Fig. 9 indicates the current status of warning dissemination at the municipal level. Around half of the municipalities do not implement confirmations of warning receivals. Only 14 % of the municipalities partly implemented and 7 % of the municipalities have fully implemented confirmation methods. Among these, the common warning receival confirmation methods are subscription mail, SNS, or disaster prevention applications. Around 15 % of the municipalities indicated a receival rate of 80 %–100 %, and 7 % of the municipalities have a warning receival rate fewer than 80 % through such confirmation methods.

Many municipalities have backup systems and methods for dissemination and partly grasp public understanding of the warning information. However, fewer municipalities grasp public understanding of the weather forecast and there lacks understanding of the needs of different groups (37 %). The common methods to grasp public understanding were through on-site seminars, hazard maps briefing sessions, or evacuation training by the voluntary disaster organizations. A few municipalities conducted surveys to better grasp residents' understanding of flood forecasts and warning information. Some municipalities indicated that residents in areas with flood experience or nearby the river generally have some understanding of flood forecasts and warning information.

Fig. 10 shows the results of qualitative data analysis, indicating the frequencies of challenges in warning dissemination at the local level and Fig. 11 presents the connections between those challenges. The results indicate the biggest challenges in warning dissemination to be the limitation of the dissemination means (35 % of municipalities), particularly challenges in disseminating infor-

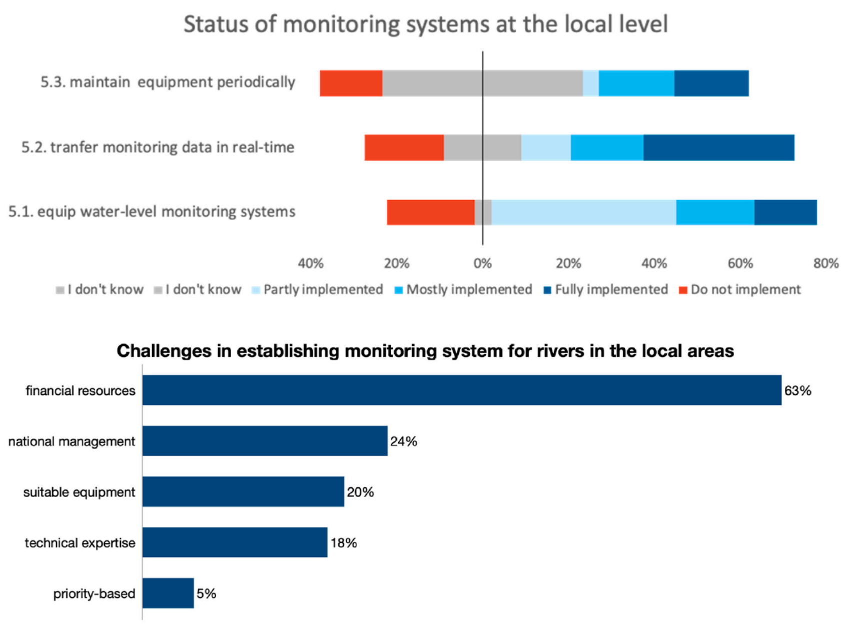

Fig. 8. Current status (top) and challenges in implementation (bottom) of monitoring system at the local level.

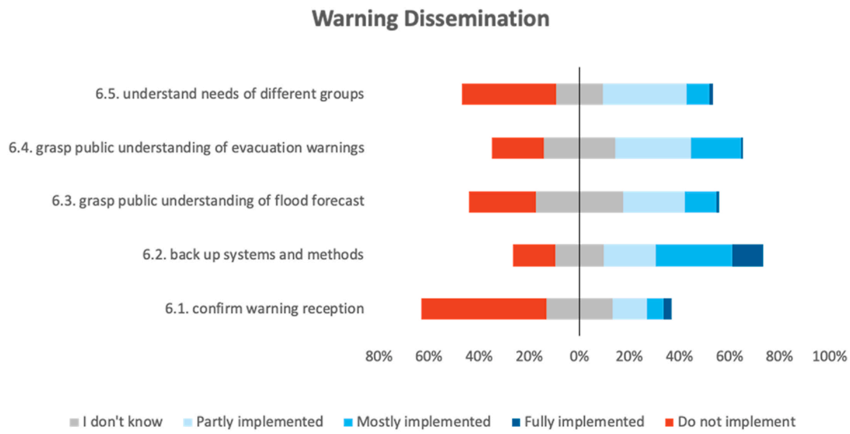

Fig. 9. Current status of warning dissemination at the local level.

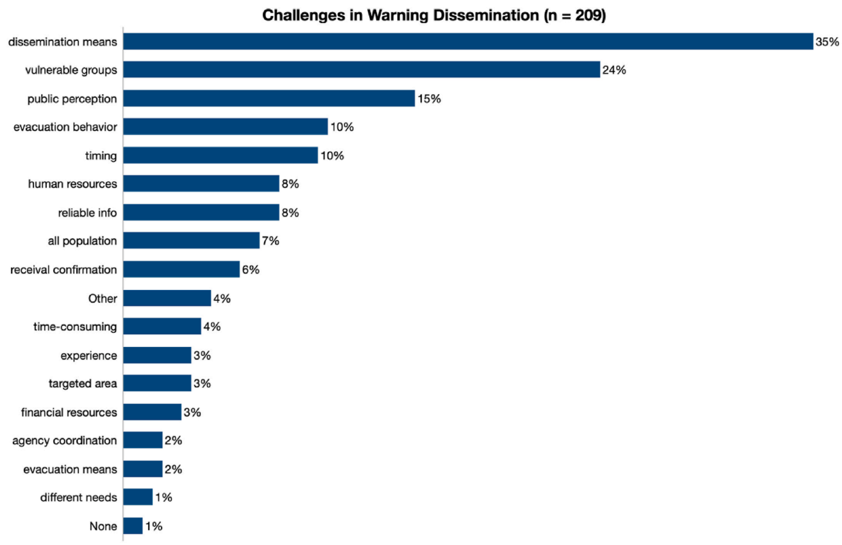

Fig. 10. Frequencies of challenges in warning dissemination at the local level.

mation to the vulnerable groups. Some methods such as outdoor speakers or the wireless communication system are hard to hear during heavy rains. Dissemination methods are also getting more diverse, and it takes time to disseminate warnings through such means. In many municipalities, there are insufficient communication means, particularly to reach vulnerable groups in remote areas where wireless radio cannot reach. See supplementary information for supporting quotes from the responding municipalities.

Dissemination to vulnerable groups remains a major challenge for municipalities (24 % of the municipalities), including the elderly, people with disabilities, or people who have limited access to warning information (ex. living in remote areas, no access to smartphones). The elder population is growing, making it difficult for the government to understand their situation. For people with disabilities, the village officers or care managers will visit the site to communicate the information, which takes time, and there are insufficient human resources. Another challenge in warning dissemination is understanding and increasing public perception, including public understanding of warning information, risk perception, and disaster response perception. Understanding evacuation behaviors and how to motivate people to take actions when needed is also a challenge for the municipalities, as in some cases, people have the normalcy bias and do not evacuate even when the evacuation orders were issued.

Public perception was also linked to the challenge of communicating reliable information at the right timing to the targeted areas. Many municipalities indicated that there are insufficient communication means, particularly to reach vulnerable groups and remote areas, which cannot be reached by wireless radio. While in other municipalities, methods of communication are getting more diverse, requiring extra steps in the communication process, which might lead to a time lag in receiving such information. In some cases, there are information discrepancies between agencies, creating difficulties for municipalities to select information to communicate. Finally, similar to the results from quantitative analysis, many municipalities do not have methods to confirm whether residents have received warning information and how much information was perceived and understood.

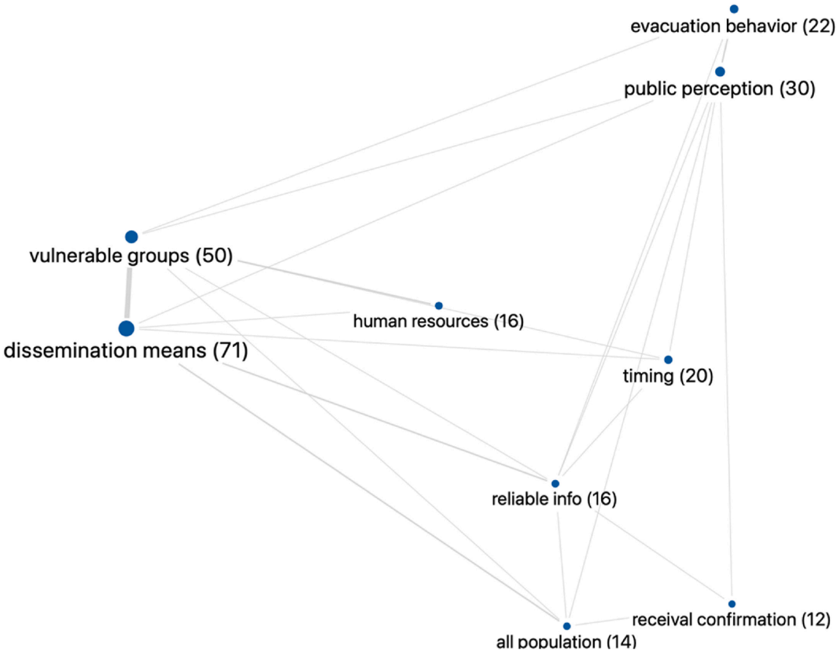

Fig. 11. Connection between major challenges (frequencies higher than 10) in warning dissemination at the local level. The number indicates frequencies of each challenge (how many municipalities mentioned such challenge). The line indicates the co-occurrence of challenges mentioned by the municipalities. The line thickness indicate higher frequencies of co-occurrence.Only co-occurrences higher than 2 is shown.

3.4. Preparedness and response capabilities

Overall, several factors regarding preparedness and response capabilities are being implemented relatively well at the municipal level (see Fig. 12). These factors include developing disaster response plans with a participatory and gender sensitive approach (79 %), considering the needs of vulnerable groups (90 %), incorporating disaster risk reduction into education (94 %), disaster risk education targeting needs of different groups (73 %), implementing regular evacuation drills (83 %), and learning from past flood events and incorporating them into disaster preparedness (71 %). Municipalities are doing particularly well at informing residents with a list of things to bring during evacuation (97 %).

Regarding the number of participants in annual evacuation drills, 67 % (n = 234) of the municipalities indicated their records on participants. The number of participants varies greatly. More than 45 % of the municipalities have 100–1000 participants per year. Around 24 % of the municipalities have fewer than 100 participants every year. Around 18 % of the municipalities have 1000–10,000 people participating in the evacuation drills and more than 4 % of the municipalities have more than 10,000 participants annually.

However, more than a third of municipalities do not evaluate public response capability and 29 % of the municipalities do not grasp public awareness of warning dissemination methods. Around 29 % of the municipalities at least partly evaluate residents' evac-

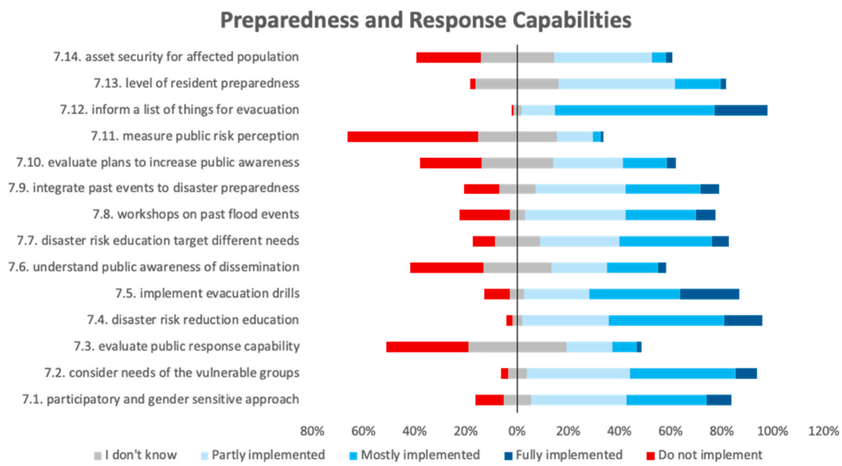

Fig. 12. Current status and knowledge gap in preparedness and response capabilities at the local level.

uation capabilities through creating a list of people who need support during evacuation, individual evacuation plans, evacuation drills, or through assessment from the voluntary disaster prevention organizations.

Among these municipalities, more than half of which indicated that residents have some evacuation capabilities and more than a third of the municipalities indicated relatively high coping capabilities in residents.

Municipalities were also asked about the evacuation rate of the residents if evacuation orders (or advisories) were issued in recent years (n = 155). Among these, around a third of the municipalities are unclear about the evacuation rate. More than half of the municipalities indicated the evacuation rate was smaller than 10 %. Concerningly, around 23 % of the municipalities indicated the evacuation rate was less than 1 % of the target population.

There have been efforts to increase public awareness, but many municipalities do not evaluate their effectiveness (24 % of the municipalities). There is a significant knowledge gap of public risk perception in more than half of the municipalities. And a quarter of the responded municipalities do not provide asset security for people who have to evacuate.

3.5. Relationships between factors

Table 2 shows the spearman correlation results between elements of FEWS. Most elements positively correlated with each other, suggesting improving one factor of FEWS can improve the whole system. The relationships between municipality size (i.e., population) and these factors are also shown in Table 2. The results indicate that municipalities with smaller populations have slightly better progress in vulnerability assessment. This is understandable as larger municipalities usually have more facilities and it is more difficult and takes more time to quantify these assets and population characteristics for vulnerability assessment. On the other hand, municipalities with larger population have slightly better progresses with monitoring systems and preparedness and response. This might be because they have more human and financial resources or larger rivers that are under prefectural or national management.

Based on the spearman correlation, a path analysis on the relationships of FEWS factors were tested with a structural equation model to simultaneously test the relationships and compare effects of factors on preparedness and response capabilities. Fig. 13 shows the standardized solutions of the path analysis and Table 3 shows the comparisons of total effects of factors on preparedness and response capabilities. The path analysis shows a good fit and provides a baseline for understanding relationships between factors of FEWS (RMSEA = 0.053, pclose = 0.395, CFI = 0.989, TLI = 0.962, SRMR = 0.035), explaining 39 % of the variance of preparedness and response capabilities (r^2 = 0.39). Other models with different path directions were also tested and showed a worse fit compared to the model in this study.

Interestingly, the analysis results indicated that vulnerability assessment of socio-economic factors has the strongest effect on preparedness and response capability, highlighting the significance of understanding impacts of land use change, social cultural norms, regulations, and traditional knowledge in improving FEWS, particularly when many municipalities have not considered such evaluations. Socio-economic vulnerability assessment also plays an important role in progress of warning dissemination as it can improve understanding of public needs and perceptions of warning information.

Warning dissemination is significant for improving preparedness and response capabilities. The better the municipalities are doing at communicating warning information to the residents, the better their preparedness and response to disaster. Risk knowledge of the local areas and risk assessment also can help to improve warning dissemination, particularly vulnerability assessment of the socio-economic factors and knowledge of the local social characteristics. The more the municipalities understand the situation of vulnerable groups, critical facilities, and voluntary disaster prevention organizations in local areas, the better they can disseminate warning information to residents, including vulnerable groups.

Table 2
Spearman correlations between key factors of FEWS.

	Knowledge of flood characteristics	Knowledge of social characteristics	Vulnerability assessment	Vulnerability assessment (social)	Monitoring system	Warning dissemination	Prepared and response	population
Knowledge of flood characteristics	1							
Knowledge of social characteristics	0.34***	1						
Vulnerability assessment	0.40***	0.23***	1					
Vulnerability assessment (social)	0.49***	0.32***	0.48***	1				
Monitoring system	0.13*	0.11	0.15*	0.17**	1			
Warning dissemination	0.28***	0.36***	0.31***	0.47***	0.18**	1		
Prepared and response	0.32***	0.35***	0.34***	0.50***	0.20**	0.52***	1	
population	−0.10	−0.10	−0.14*	−0.05	0.14*	−0.06	0.14*	1

* $p < .05$.
** $p < .01$.
*** $p < .001$.

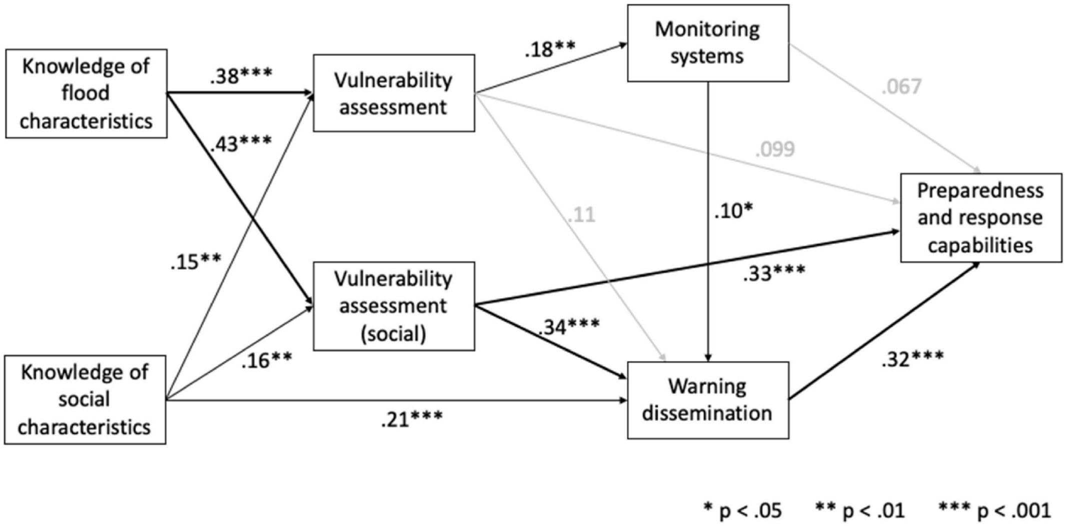

Fig. 13. Standardized solution of path analysis for relationships between key factors of FEWS at the local level. Grey arrows indicate statistically insignificant paths. The path thicknesses indicates relative size of path coefficients.

Table 3
Total effects of factors on preparedness and response capabilities.

Key factors influencing preparedness and response capabilities	Standardized coefficient	z value
Knowledge of flood characteristics	0.25***	6.72
Knowledge of social characteristics	0.16***	4.50
Vulnerability assessment	0.15**	2.65
Vulnerability assessment (social)	0.44***	7.70
Monitoring systems	0.10*	1.98
Warning dissemination	0.32***	5.84

* $p < .05$.
** $p < .01$.
*** $p < .001$.

Monitoring systems at the local level have small positive correlations with other factors. This can be because of the limited roles of the municipalities in the monitoring and forecasting. Flood forecasts are typically conducted by the JMA, and major rivers are managed by national or prefectural government.

Finally, knowledge of flood characteristics is crucial in improving progress in vulnerability assessment both regarding expected damage and socio-economic factors while knowledge of local social characteristics have small positive correlations with vulnerability assessment. Both factors have small positive effects on improving monitoring systems, warning dissemination, and preparedness and response capabilities through improving vulnerability assessment.

The path analysis was also fitted with two groups of municipalities, with and without flood experience, to explore their differences. The Chi-square difference test of the unconstrained model and the model with path-coefficient constraints indicated chi-square (13) = 9.24 and $p = .755$. As a result, the chi-square difference is statistically insignificant, suggesting that the two groups are not different at the model level, though they may be different at path level.

The *t*-test for group difference in parameters indicated significant differences in knowledge of flood and social characteristics between municipalities with and without flood experience (see Supplementary Material, Table S - 1 and Table S - 2). Municipalities with no flood experience showed more knowledge of both local flood and social characteristics. This might be because the municipalities without flood experience are more confident and indicated a higher level of knowledge (self-assessed).

Looking at the path-level difference, vulnerability assessment that includes socio-economic factors is significantly more important to preparedness and response in municipalities with experience. The path model can better explain relationships between factors in municipalities with flood experience (51 % of variance) than those with no experience (33 % of variance). See supplementary information Table S - 3, 4, and 5 for detailed results of group analysis.

3.6. Discussion and implications for policy

While existing surveys cover all four key elements, providing an overview on availability and adequacy of FEWS globally at the national level, this study is the first to provide an in-depth understanding of progress in FEWS implementation at the local level through a nationwide survey targeting municipalities in Japan. Overall, Japanese municipalities are doing better at obtaining knowledge of local flood characteristics and social characteristics rather than vulnerability assessment, particularly regarding socio-economic vulnerability. While there are insufficient considerations of socio-economic factors such as land use changes, social cultural norms, and laws and regulations in vulnerability assessment at the national-level FEWS in other Asian countries [23], this study indicates that it has been implemented to a certain extent at the local level in Japan but still needs further progress.

Regarding challenges in creating and managing risk knowledge, the biggest issues are the lack of human resources, difficulties in risk assessment, and data acquisition. The municipalities indicated in the survey that the local governments usually have one or two people in charge of disaster prevention. While national guidelines and regulations are constantly changing, disaster related systems are scattered in different agencies in each ministry, making it difficult for the municipalities to collect and utilize information. Comparing to existing surveys on FEWS operation at the national level [9], the lack of human resources and technical expertise remains one of the major challenges globally. Such challenges were also found in risk assessment at municipalities in Sweden [54]. National to local governments should invest in training staff and building sustainable personnel for creating and manage risk related information. Furthermore, national governments, NGOs, or enterprises should work closely with local governments to tackle the lack of human resources and provide supports in risk assessment, particularly to understand social characteristics and social vulnerability for integration into the system.

The monitoring system that provides observation of hazards (ex. water levels) in Japan is among the more advanced systems globally [9] and is managed by the national or prefectural government. While many areas around the planet have limited monitoring systems and historical data [9,18], almost 80 % of the responded municipalities have their rivers equipped with monitoring systems to some extent and in most cases, transmit monitoring data in real-time or near real-time. In many other countries, financial resources are important to sustain the operation of early warning systems as they are project based [9,23]. Differently, in Japanese municipalities, financial resources play an important role in equipping the local rivers with monitoring system.

Regarding warning dissemination, there is a big knowledge gap in confirming warning receival, understanding needs of different groups and public understanding of flood forecasts and warnings. Lack of warning receival confirmation remains one of the consistent gaps in warning dissemination at the national level in many countries [7,23]. In this study, the responded municipalities provided some insights into ways to confirm warning receival such as subscription-based email, SNS, and disaster prevention applications. Clearly, these methods can only target people who have access to smartphones and internet. Warning receival confirmation to the vulnerable groups still needs further development. While vulnerable groups are largely overlooked in warning dissemination [7,10], more than a third of the responding municipalities in this study have implemented methods to communicate to them through radio service targeting people with disabilities, FAX, telephones, text transmission using SMS, and personnel visiting the residents. These methods need to be further enhanced as communicating to vulnerable groups remains the biggest challenge in warning dissemination, especially under adverse weather conditions.

Another major challenge in warning dissemination is how to understand and raise public perception of warning and response. Public risk perception and human behavior have been studied extensively in the literature [55–58] but such knowledge has not been widely integrated into preparedness and response at the local government level in this case. Since human resources at the local level are already limited, it is recommended that national and prefectural government conduct national level surveys on public risk and response perception, and evaluate the effectiveness of dissemination methods and impacts of warning on evacuation behaviors, which can provide valuable insights for local governments implementing efforts to improve communication with the public that ensure behavioral changes.

While there still lacks effort in enhancing disaster preparedness and response in other countries [7], at the municipal level in Japan, efforts in implementing disaster risk education, evacuation drills, incorporating vulnerable groups, and participatory approaches have relatively good progress. Needs of vulnerable groups are also integrated in preparedness and response plans at the municipalities in this study through creating a list of people requiring support during evacuation. However, there remain knowledge gaps of understanding public risk perception and awareness, response capability, and evaluations of communication and education programs. Moreover, the evacuation rate in many municipalities is extremely low (less than 1 % in many cases). Such challenges persist in many other areas of the planet as well. This study provides some hints on methods that can affect public perception, enhance response capabilities including on-site lectures and briefings of hazard maps and surveys conducted by local governments, and assessment by voluntary disaster prevention organizations.

The key elements of FEWS were shown to positively correlate with each other, suggesting that strong integrations of these four key elements can enhance FEWS towards a people-centred system that motivates people and communities at risk to take timely and proper actions to protect their lives and livelihoods, and build resilience to disasters in long-term. While existing studies have touched on strategies to enhance the connections of these factors [12,27], this study is the first to provide a quantitative assessment and comparison on their relationships to extracts insights on how to improve FEWS effectively and systematically. The results revealed the importance of vulnerability assessment that integrates socio-economic changes, and warning dissemination in improving preparedness and response capabilities. Hence, it is recommended that local government should prioritize making progress in these elements.

4. Concluding remarks

This study provided a detailed picture of current status and challenges in implementing FEWS at the local level through a comprehensive survey targeting Japanese municipalities (n = 350). While progress in FEWS operation varies in municipalities, they are encountering different challenges in each element of the system. The key challenges in risk knowledge were identified to be lack of human resources (with technical expertise) and difficulties in risk assessment and data acquisition. Differently, the main challenge in monitoring systems appears to be lack of financial resources. The biggest challenges in warning dissemination are limitations of dissemination means to reach vulnerable groups in adverse weather conditions and how to understand and raise public perception. The government should prioritize focusing on overcoming the identified major challenges, which can help to improve FEWS operation in many local areas in Japan. While many efforts to enhance public preparedness and response capabilities are being widely implemented at the municipal level, evaluations of their effectiveness, understanding of public perception, and response capabilities are still lacking. The local government should collaborate with other stakeholders such as academic experts, private enterprises, or voluntary organizations to deepen their understanding of public perception and response capabilities. Efforts on evaluating the effectiveness of awareness campaigns, evacuation drills, and disaster education should be made.

This study is the first to quantitatively investigate the relationships between the key factors of FEWS, including knowledge of flood characteristics, knowledge of social characteristics, vulnerability assessment covering expected damage and socio-economic changes, monitoring system, warning dissemination, and preparedness and response capabilities. The spearman rank correlation results indicated that all factors positively correlate with each other, providing quantitative evidence on connections of elements of FEWS. Improving one element can enhance operation and progress of the whole system.

Through path analysis, the study explored the effects of key factors for improving preparedness and response capabilities. The results highlight the role of vulnerability assessment that incorporating socio-economic changes to be the strongest predictors influencing progress in preparedness and response at the local level. Municipalities should make further efforts to incorporate socio-economic changes into vulnerability assessment. The other important predictor of preparedness and response capabilities is warning dissemination, highlighting the role of timely and accurate early warnings.

Japan is among the countries with the most advanced FEWS as it is highly exposed to disaster and has experienced numerous flood events. FEWS have been implemented on various scales from national to local levels, where roles and responsibilities of stakeholders have been clearly defined. Although FEWS operation in other countries might not be at the same progress, local government in other contexts might be encountering similar challenges. Future research should examine FEWS operation at the local level in other contexts to identify the most pressing challenges. The survey used in this study can be generalized to other contexts and modified if necessary to evaluate the current progress of FEWS implementation at the local level. Understanding current progress and challenges at the local level is crucial to provide insights into tailored recommendations to enhance FEWS implementation, particularly public preparedness and response.

The questionnaire survey in this study was answered by government officials, which can be influenced by subjective judgment from the government's perspective. As suggested by the group comparison results, municipalities that have no flood experience might overestimate their knowledge of the local flood and social characteristics. Therefore, future research should also incorporate the perspectives of different stakeholders such as the local disaster prevention voluntary organizations, NGOs, and residents to provide a comprehensive assessment of the progress of FEWS operation in the local areas.

CRediT authorship contribution statement

Anh Cao: Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Shinichiro Nakamura:** Writing – review & editing, Project administration, Conceptualization. **Kensuke Otsuyama:** Writing – review & editing, Conceptualization. **Miki Namba:** Writing – review & editing, Conceptualization. **Kei Yoshimura:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ijdrr.2024.104802.

References

[1] World Health Organization, Floods, Retrieved from. https://www.who.int/health-topics/floods#tab=tab_1, 2021.
[2] World Meteorological Organization, Floods, Retrieved from: https://wmo.int/about-us/world-meteorological-day/wmd-2020/floods, 2021.
[3] UNISDR. Terminology: Basic terms of disaster risk reduction. Retrieved from: https://www.unisdr.org/files/7817_7819isdrterminology11.pdf.
[4] UNISDR, Global survey of early warning systems, Retrieved from. https://www.unisdr.org/2006/ppew/info-resources/ewc3/Global-Survey-of-Early-Warning-Systems.pdf, 2006.

[5] United Nations Office for Disaster Risk Reduction and World Meteorological Organization, Global Status of Multi-Hazard Early Warning Systems, 2023 Geneva, Switzerland. Retrieved from. https://www.undrr.org/media/91954/download?startDownload=20240802.
[6] World Meteorological Organization, Multii-hazard early warning system: a checklist, Retrieved from. https://ane4bf-datap1.s3-eu-west-1.amazonaws.com/wmocms/s3fs-public/ckeditor/files/Multi-hazard_Early_Warning_Systems_A_Checklist.pdf?fVgoQYM7LhPb3oR0V97j2.Qkjs3Wc5Rq, 2018.
[7] D. Perera, J. Agnihotri, O. Seidou, R. Djalante, Identifying societal challenges in flood early warning systems, Int. J. Disaster Risk Reduc. 51 (2020) 101794.
[8] E.C. De Perez, K.B. Berse, L.A.C. Depante, E. Easton-Calabria, E.P.R. Evidente, T. Ezike, C. Van Sant, Learning from the past in moving to the future: invest in communication and response to weather early warnings to reduce death and damage, Climate Risk Management 38 (2022) 100461.
[9] D. Perera, O. Seidou, J. Agnihotri, M. Rasmy, V. Smakhtin, P. Coulibaly, H. Mehmood, Flood Early Warning Systems: a Review of Benefits, Challenges and Prospects, UNU-INWEH, Hamilton, 2019.
[10] S. Sufri, F. Dwirahmadi, D. Phung, S. Rutherford, A systematic review of community engagement (CE) in disaster early warning systems (EWSs), Progress in Disaster Science 5 (2020) 100058.
[11] D. Demeritt, S. Nobert, Models of best practice in flood risk communication and management, Environ. Hazards 13 (4) (2014) 313–328.
[12] C. Garcia, C.J. Fearnley, Evaluating critical links in early warning systems for natural hazards, Environ. Harzar. 11 (2) (2012) 123–137.
[13] O. Neußner, Early warning alerts for extreme natural hazard events: a review of worldwide practices, Int. J. Disaster Risk Reduc. 60 (2021) 102295.
[14] N.S. Grigg, Comprehensive flood risk assessment: state of the practice, Hydrology 10 (2) (2023) 46.
[15] K. Schröter, C. Velasco, H.P. Nachtnebel, H. Bianca, M. Beyene, C. Rubin, M. Gocht, Effectiveness and Efficiency of Early Warning Systems for Flash-Floods (EWASE), 2008 (London, UK).
[16] D. Rogers, V. Tsirkunov, Costs and benefits of early warning systems, Global assessment rep (2011).
[17] L. Alfieri, P. Salamon, F. Pappenberger, F. Wetterhall, J. Thielen, Operational early warning systems for water-related hazards in Europe, Environ. Sci. Pol. 21 (2012) 35–49.
[18] J. Cools, D. Innocenti, S. O'Brien, Lessons from flood early warning systems, Environ. Sci. Pol. 58 (2016) 117–122.
[19] M. Sättele, M. Bründl, D. Straub, Quantifying the effectiveness of early warning systems for natural hazards, Nat. Hazards Earth Syst. Sci. 16 (1) (2016) 149–166.
[20] S.K. Jain, P. Mani, S.K. Jain, P. Prakash, V.P. Singh, D. Tullos, A.P. Dimri, A Brief review of flood forecasting techniques and their applications, Int. J. River Basin Manag. 16 (3) (2018) 329–344.
[21] C. Liu, L. Guo, L. Ye, S. Zhang, Y. Zhao, T. Song, A review of advances in China's flash flood early-warning system, Nat. Hazards 92 (2018) 619–634.
[22] A.M. Salman, Y. Li, Flood risk assessment, future trend modeling, and risk communication: a review of ongoing research, Nat. Hazards Rev. 19 (3) (2018) 04018011.
[23] I. Aguirre-Ayerbe, M. Merino, S.L. Aye, R. Dissanayake, F. Shadiya, C.M. Lopez, An evaluation of availability and adequacy of Multi-Hazard Early Warning Systems in Asian countries: a baseline study, Int. J. Disaster Risk Reduc. 49 (2020) 101749.
[24] S. Drobot, D.J. Parker, Advances and challenges in flash flood warnings, Environ. Hazards 7 (3) (2007) 173–178.
[25] J.E. Quansah, B. Engel, G.L. Rochon, Early warning systems: a review, Journal of Terrestrial Observation 2 (2) (2010) 5.
[26] R.E. Emerton, E.M. Stephens, F. Pappenberger, T.C. Pagano, A.H. Weerts, A.W. Wood, H.L. Cloke, Continental and global scale flood forecasting systems, Wiley Interdisciplinary Reviews: Water 3 (3) (2016) 391–418.
[27] V. Sukhwani, B.A. Gyamfi, R. Zhang, A.M. AlHinai, R. Shaw, Understanding the barriers restraining effective operation of flood early warning systems, International Journal of Disaster Risk Management 1 (2) (2019) 1–19.
[28] M. Kuller, K. Schoenholzer, J. Lienert, Creating effective flood warnings: a framework from a critical review, Journal of hydrology 602 (2021) 126708.
[29] M. Macherera, M.J. Chimbari, A review of studies on community based early warning systems, Jàmbá: journal of disaster risk studies 8 (1) (2016).
[30] UNDRR, Predicting and managing flood risks from extreme rain events in Japan, Retrieved from. https://www.preventionweb.net/news/predicting-and-managing-flood-risks-extreme-rain-events-japan, 2023.
[31] Cabinet Office, Government of Japan, Disaster management in Japan, Retrieved from. https://www.bousai.go.jp/1info/pdf/saigaipamphlet_je.pdf, 2021.
[32] GFDRR, Learning from Japan's experience in early warning for natural hazards, Retrieved from. https://www.gfdrr.org/en/feature-story/learning-japans-experience-early-warning-natural-hazards, 2022.
[33] Cabinet Office, Government of Japan, White paper on disaster management 2022, Retrieved from. https://www.bousai.go.jp/en/documentation/white_paper/pdf/2022/R4_hakusho_english.pdf, 2022.
[34] Basic Act on Disaster Management, Act No. 223 of 1961 (revised, https://www.japaneselawtranslation.go.jp/en/laws/view/4171, 2021.
[35] MLIT, Suigai hazādomappu sakusei no tebiki [manual on flood hazard maps creation], Retrieved from. https://www.mlit.go.jp/river/basic_info/jigyo_keikaku/saigai/tisiki/hazardmap/pdf/suigai_hazardmap_tebiki_202305.pdf, 2021 (in Japanese).
[36] T. Furukawa, Kishōchō monogatari – tenkeyohō kara jishin tsunami kazan ma de [Meteorological Agency stories - from weather forecasts to earthquakes, tsunamis, and volcanoes, Chuokoron-Shinsha (2015) (in Japanese).
[37] M. Kawanishi, Bōsai kishō jōhō shisutemu no genten wa dō hōji rareta ka - 1934-nen Muroto taifū hōdō no naiyō bunseki [How was the origin of the disaster prevention weather information system reported? -A content analysis of the 1934 Muroto typhoon coverage-], Disaster Information (2023) *No.21-2*. (in Japanese).
[38] MLIT, Kentō no haikei oyobi kadai [Bachground and Issue of the study], Retrieved from. https://www.mlit.go.jp/river/shinngikai_blog/tyusyokasen/pdf/2_haikei_kadai_ver3.pdf, 2008 (in Japanese).
[39] Flood Control Act, Suibō-hō] 水防法, 2023. https://laws.e-gov.go.jp/law/324AC0000000193. in Japanese).
[40] MLIT, Kōzui yohō kasen to wa (suibō-hō) [What is the flood forecast river? (Flood Prevention Act)], Retrieved from. https://www.mlit.go.jp/river/bousai/main/saigai/tisiki/syozaiti/pdf/yohousyuutikasen.pdf, 2008 (in Japanese).
[41] Japan River Law, http://www.idi.or.jp/wp/wp-content/uploads/2018/05/RIVERE.pdf, 1999.
[42] Japan Meteorological Agency (JMA), Risk maps, Retrieved from. https://www.jma.go.jp/bosai/en_risk/#elements:flood/zoom:7/lat:35.692995/lon:136.873169/colordepth:normal, 2020.
[43] Hachioji City, Hachioji city general disaster prevention guidebook: the fundamentals of disaster prevention, Retrieved from. https://www.city.hachioji.tokyo.jp/kurashi/shimin/004/004/gaikokujinnbousaitaisaku/p027353_d/fil/2.pdf, 2023.
[44] Y. Usuda, Bōsai-gen wazawai no tame no jōhō tsūshin shisutemu no sōgo un'yō [Interoperation of Information and Communication Systems for Disaster Prevention and Mitigation], Science and Technology Trends, February 2008 (2008) (in Japanese).
[45] H. Hironaka, Jichitai ni yoru chiiki bōsai to bōsai kishō jōhō [Regional disaster prevention and disaster prevention weather information by local governments], Disaster Information 12 (2014) 30–34 (in Japanese).
[46] M. Ushiyama, tokushū saigai-ji no hinan' o kangaeru: puro Rō̄gu hinan kankoku-tō gaidorain no hensen' [Special feature: thinking about evacuation during disasters: prologue: Changes in guidelines such as evacuation recommendations], Disaster Information 18 (2020) 115–130 (in Japanese).
[47] S. Nagamatsu, M. Ushiyama, N. Sekiya, S. Suzuki, Hinan jōhō wa jinteki higai o keigen shita ka — heisei 30-nen 7 tsuki gōu-rei wa gan'nen Higashinihon taifū no jisshō bunseki [Did evacuation information reduce human damage? - empirical analysis of July 2018 heavy rains and 2019 East Japan typhoon], Disaster Information, No. 20-1 (2022) (in Japanese).
[48] Cabinet Office, Government of Japan, Hinan jōhō ni kansuru gaidorain [Guidelines for evacuation information], Retrieved from. https://www.bousai.go.jp/oukyu/hinanjouhou/r3_hinanjouhou_guideline/pdf/hinan_guideline.pdf, 2022 (in Japanese).
[49] Portal Site of Official Statistics of Japan. Shiku chōson-sū o shiraberu [Check the number of cities, wards, towns, and villages]. (n.d.). Retrieved from: https://www.e-stat.go.jp/municipalities/number-of-municipalities (in Japanese).
[50] J.M. Cortina, What is coefficient alpha? An examination of theory and applications, J. Appl. Psychol. 78 (1) (1993) 98.
[51] C. Lleras, Path analysis, Encyclopedia of social measurement 3 (1) (2005) 25–30.
[52] M. Higashide, Zenkoku no shiku chōson jinkō menseki jinkō mitsudo rankingu [Ranking of population, area, and population density of cities, wards, towns and villages nationwide]. https://uub.jp/rnk/rnk.cgi?T=cktv&S=j&B=20221001, 2022 (in Japanese).
[53] Portal Site of Official Statistics of Japan, Suigai tōkei chōsa [Flood damage statistical survey], Retrieved from. https://www.e-stat.go.jp/stat-search/files?page=

1&toukei=00600590&result_page=1, 2023 (in Japanese).
[54] V. Norén, B. Hedelin, L. Nyberg, K. Bishop, Flood risk assessment–practices in flood prone Swedish municipalities, Int. J. Disaster Risk Reduc. 18 (2016) 206–217.
[55] N. Dash, H. Gladwin, Evacuation decision making and behavioral responses: individual and household, Nat. Hazards Rev. 8 (3) (2007) 69–77.
[56] J.S. Becker, H.L. Taylor, B.J. Doody, K.C. Wright, E. Gruntfest, D. Webber, A review of people's behavior in and around floodwater, Weather, Climate, and Society 7 (4) (2015) 321–332.
[57] R.R. Thompson, D.R. Garfin, R.C. Silver, Evacuation from natural disasters: a systematic review of the literature, Risk Anal. 37 (4) (2017) 812–839.
[58] K. Hamilton, D. Demant, A.E. Peden, M.S. Hagger, A systematic review of human behaviour in and around floodwater, Int. J. Disaster Risk Reduc. 47 (2020) 101561.