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Flood Disaster Mitigation System Adopting Meteorological Data and Geographic Information Systems

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Abstract. Recently climate change causes greater disaster than before, and the conventional measures especially against flood disaster are not enough at present. Integrated measures of facilities and Information systems are reinforced to cope with these situations. This study describes a solution to the issues. Flood disaster mitigation system is designed and developed to mitigate the damages caused by flood disaster adopting meteorological data and geographic information systems (GIS). In the phase of requirements analysis, system dynamics (SD) techniques, such as Iceberg Model and causal loop diagram (CLD), were applied to clarify three leverage points (precipitation data observation, river level forecast, and evacuation/alarming issuing). Precipitation information was derived from MesoScale Model (MSM) data provided by the Japan Meteorological Agency, and river level forecast was conducted based on Urban Tank Model. Swiss Cheese Model, basin hydraulic control, necessity of information (software) and facilities (hardware) were adopted into the structure of the Iceberg Model. The test site of the system is planned in the basins of the Nogawa and Tama Rivers in Tama Area, Tokyo, Japan. This study relates to the 9th “Industry, Innovation and Infrastructure” and the 13th “Climate Action” of the sustainable development goals (SDGs) proposed by the United Nation (UN).

Keywords: Flood Disaster Mitigation System, Iceberg Model, Causal Loop Diagram, Climate Change, Precipitation, River level forecast, Alarm, Evacuation

1 Introduction

In recent years, because the occurrence frequency of meteorological disasters such as typhoon, local heavy rain and heavy snow in addition to earthquake and volcanic eruption tremendously increased, it is the most important issue to adopt the effective measures for disaster prevention and reduction around the world. This research targets flood disaster, because the occurrence frequency recently increased by climate change and the amount of damages are the most expensive comparing other disasters. The final purpose of this research is to provide proper information by the integrated systems to minimize the damages by flood disasters in Tokyo metropolis, Japan. The system aims to mitigate flood disaster with a series of information processing. Specifically, the

system monitors the amount of precipitation and the water level of river to forecast the latter, and gives the alarm to urge residents living in the nearby area to evacuate to safety places at the times when flood disaster is judged to occur. The stakeholders are public organizations (the Ministry of Land, Infrastructure, Transport and Tourism, the Japan Meteorological Agency, and central and local governments) and common residents living in the nearby area.

Fig. 1 shows the relationship between this research and the sustainable development goals (SDGs) of the United Nation (UN). Among 17 goals, this research has close relationship with the 9th goal (Industry, Innovation and Infrastructure) and the 13th goal (Climate Action).

This research consists of three steps. In the first step, a feasibility study will be conducted to grasp the achievements and subject of the previous researches, and examine how the system will be design and developed with the piece of structural elements. In the second step, a requirement analysis of the system will be conducted for the basic design of the system, the development of the prototype adopting meteorological data and geographic information systems (GIS), and the evaluation. Finally, in the third step, these results will be sorted out.

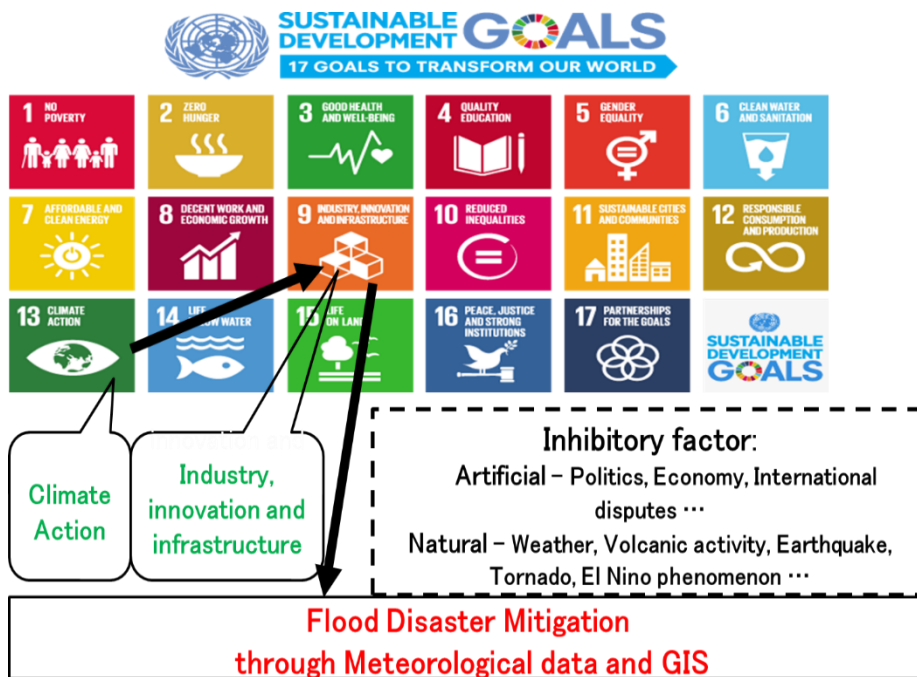


Fig. 1. Relationship between This Research and the UN' SDGs

2 Related Work

In the related academic areas with this research, the previous researches have clarified many facts until now. The results of Hirata et al. (2007) [1], Yaginuma et al. (2014) [2], Yoshimi et al. (2019) [3] and Susumu et al. (2019) [4] in the industry world showed that the experts in the academic fields of meteorological radar, power demand and public facilities collaborated to prevent and mitigate disasters. In the academic area of meteorological administration, in order to prevent and mitigate disasters, the coordination committee for weather forecast research (2011) [5], Sato (2018) [6], Uno et al. (2018) [7], Tsuboi et al. (2019) [8] showed that the necessity of collaboration with the industry world in addition to each research related to meteorological model, typhoon and flood to prevent and mitigate disasters.

In the academic area of system dynamics (SD), Medrizam et al. (2020) [9] and Pham et al. (2020) [10] conducted current analyses of the disaster measures of national and local governments, and discussed what we should do against the candidates of forecastable future results. The above previous researches adopted the causal loop diagrams (CLD) and showed important points (we call “leverage points” in this research) to show a route to solve the issues.

In the academic area of information processing, Usuta (2020) [11] and Tai (2020) [12] mentioned that though there were currently many disaster mitigation systems, governments as ordering destinations could not derive enough requirements, and the tasks were instructed to system integrator in many cases. Additionally, they also pointed out the necessity of IT education for the planning department of governments.

Rossi et al. (2017) [13] introduced the i-REACT (improving resilience to emergencies through advanced cyber technologies) provided by the United Nation International strategy for Disaster Reduction (UNISDR) that is mostly composed of European members, and the system covers a wide area of disasters including earthquake, forest fire and flood etc. It is a large-scale system that forms an eco-system, and it could conduct information processing as a data bank. It has specific database in response to three measure stages (prevention, preparedness and post action) against various kinds of disasters. However, as the system aims to provide the measures against various kinds of disasters, it had not applied to any cases yet.

Based on the result of the above previous researches, targeting flood disasters, this researches uniquely develop a flood disaster mitigation system (FDMS) adopting meteorological data and GIS. Additionally, comparing the above previous researches, the originality of this research is to develop a series of system that monitors the amount of precipitation and the water level of river to forecast the latter, and gives the alarm to urge residents living in the nearby area to evacuate to safety places at the time when flood disaster is judged to occur.

3 System Design Requirement Analysis of FDMS Using SD

3.1 Outlines of SD

Referring to Sterman(2000)[14]and Sheffield et al. (2012)[15], SD methods including Iceberg Model and causal loop diagram (CLD) etc. are applied to the system of this research. First, an analysis of the current status and the issues concerning the research target was conducted, and both visible and non-visible objects were sorted out.

Next, based on these, the relationship between various elements was clarified to propose the measures to solve the above issues and examine the feasibility. Specifically, Iceberg Model is used and element relationship was expanded in multi causal loop diagrams, deeper analysis was conducted and the leverage points are clarified.

3.2 Iceberg Model Analysis

Fig. 2 shows the Iceberg Model that were developed in response to the purpose of this research sorting out considerable elements. Iceberg Model compares to the iceberg floating in the sea water. The upper part of iceberg floating in the sea water, which is visible to us, is assigned as “event (phenomenon)”. The lower parts of iceberg, which are not visible to us, are assigned as “pattern (behavior)”, “structure” and “mental model” from top to bottom.

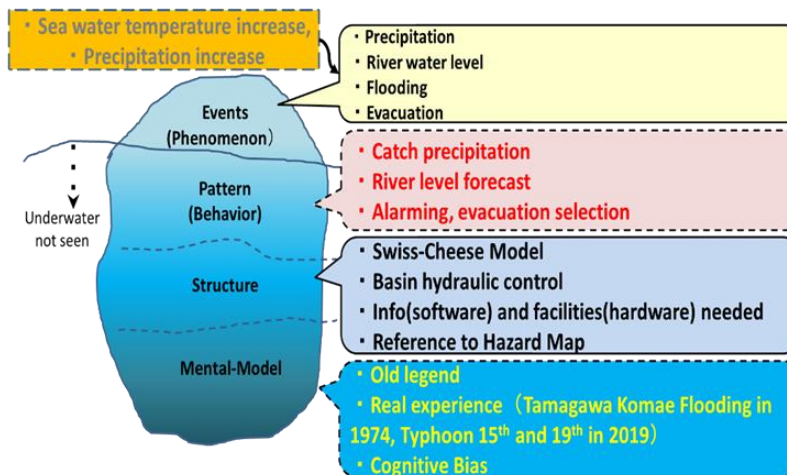


Fig.2 Iceberg Model for the FDMS Adopting Meteorological Data and GIS

Due to sea surface temperature raise and precipitation increase caused by climate change, we can observe precipitation, river level, flood disaster and evacuation as visible “event (phenomenon)”. Moreover, it is necessary for us to deeply consider the

above two issues as the “pattern (behavior)” of Iceberg Model, grasp precipitation, forecast river level, give the alarm, and select evacuation behavior. As a necessary “structure” to realize these behaviors, Swiss Cheese Model proposed by Reason (1997) [16], necessity of flood control in basins, and necessity of both information provision (software) and facilities (hardware), and reference to hazard map are proposed. “Mental model” as the lowest part of Iceberg Model includes old legend, real experience and cognitive bias. Next, the relationship between the considerable elements in multiple CLDs will be developed and analyzed in the following sections.

3.3 Causal Loop Diagram Analysis

Fig. 3 shows the CLD that denotes the relationship between the elements described as “event (phenomenon)” in the upper level of Iceberg Model in Fig. 2. According to the left part of the loop, as climate change and global warming affect sea surface temperature, increase of vapor in the air, rain cloud, rain-fall, river level. Precipitation causes river level rise, flooding and disaster. Based on the data concerning past disasters, evacuation shelter and disaster prevention database are enriched. These contribute to mitigate flood disaster caused by river level changes. Thus, this CLD is balanced feedback loop.

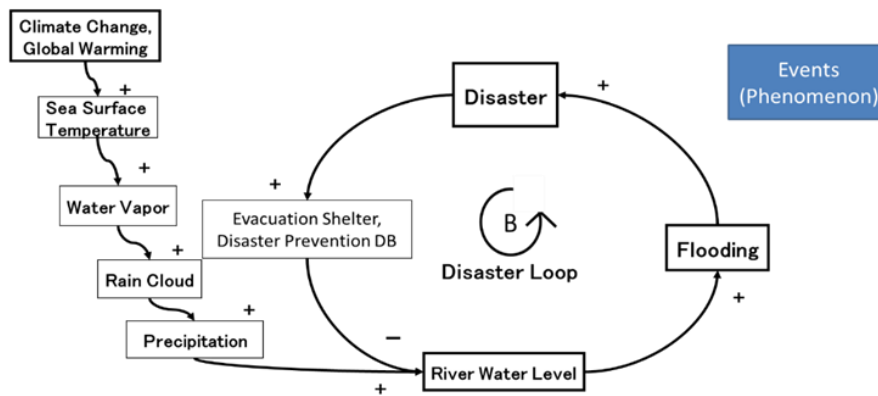


Fig. 3 CLD at Event Level

Next, the elements described in the “pattern (behavior)” and “structure” of Iceberg Model in Fig. 2 as well as those in Fig. 3 are examined. Fig. 4 shows the CLD that includes disaster mitigation loop to forecast future flood disaster occurrences added to the CLD in Fig. 3, using both current and forecast values of river level. The CLD shows the disaster mitigation status, by setting hardware of flood disaster measure facility (rain water shelter storage pond) so as to make the time delay of flood disaster and minimize the damages. The mitigation loop (B1) shows that the river level is forecasted. If the level is judged to reach the warning river level, flood disaster is mitigated by giving the alarm to residents living in the nearby area. The mitigation loop (B2) shows the smarter disaster mitigation comparing the one in B1, those are planning of disaster

mitigation, selection of the most appropriate mitigation plan from the candidates, alarming and urge of evacuation.

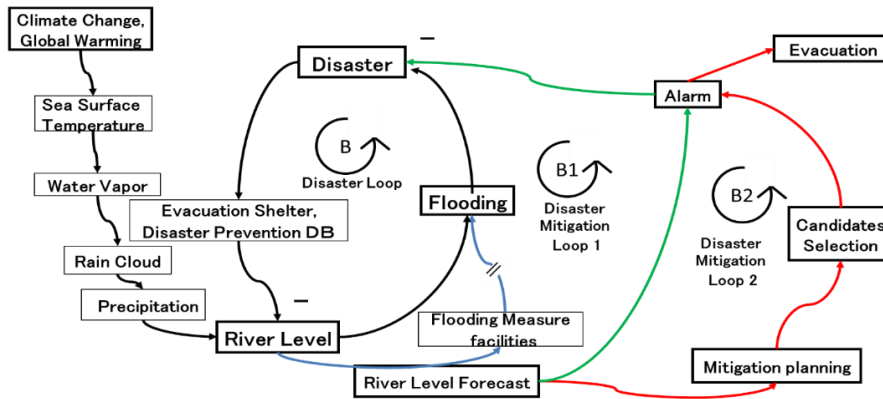


Fig. 4 CLD at Event Level Adding Disaster Mitigation Loops (B1 and B2)

3.4 Leverage Points

In order to realize these relationships, it is essential to examine what the leverage points are. Fig. 5 shows the CLD at pattern level. This CLD shows three leverage points. First one is to grasp the amount of real-time precipitation, second one is to grasp the actual situation and forecasted simulation of river level, and third one is planning of disaster mitigation.

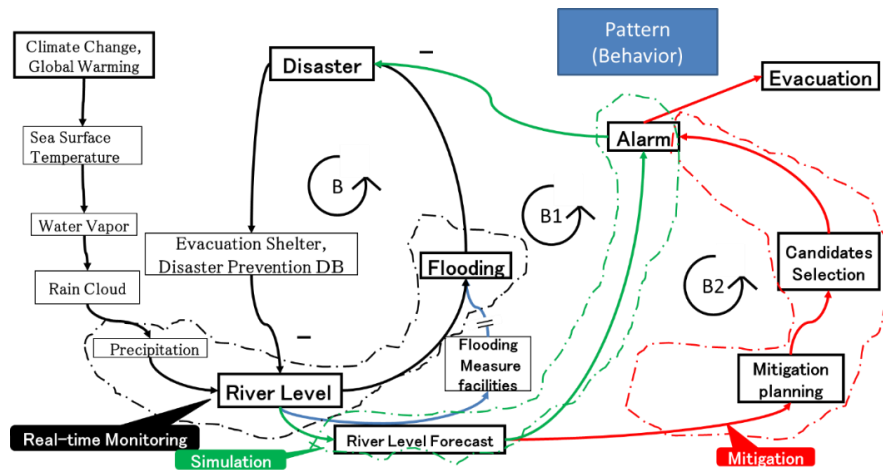


Fig. 5 Pattern level CLD

3.5 Observed Data Examples at River

Fig. 6 shows the observed data examples concerning actual river. If the river flows from right side to left side, the river level meter is set at the important point to measure the current river level. The amount of current precipitation is measured by precipitation meter. In order to adjust the appropriate river level, the rain water shelter storage pond has the special function that is set to intake the river water into it, when the river level is going to reach the dangerous water level so as to delay the increasing river level in lower basin. Also, in order to visualize the river level that is dangerous to residents living in the nearby area, the digital display of river level and arrowed marking to show dangerous river level in visual confirmation.

Thus, the FDMS developed in this research is composed of two elements, one is observed data (digital data) measured by online software, and the other is flood disaster prevention facilities (hardware). The system gives the first-responders the alarm to clearly understand what is going to happen. Thus, integrating and managing multiple systems into single system, it enables to mitigate flood disaster and minimize the damages.

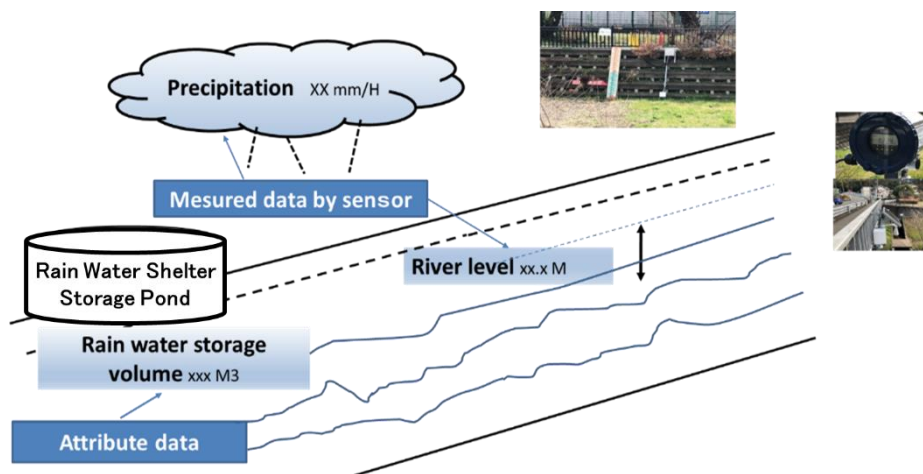


Fig. 6 Observed Data Examples Concerning Actual River

3.6 System Concept

Fig. 7 shows the system concept of the FDMS. Necessary data are saved into the database using data collection logic and the decision logic including human decision. As the result of information processing is displayed on the digital map of GIS, the FDMS can provide necessary information for the stakeholders (first-responders and residents living in the nearby area) in easy-to-understand manner.

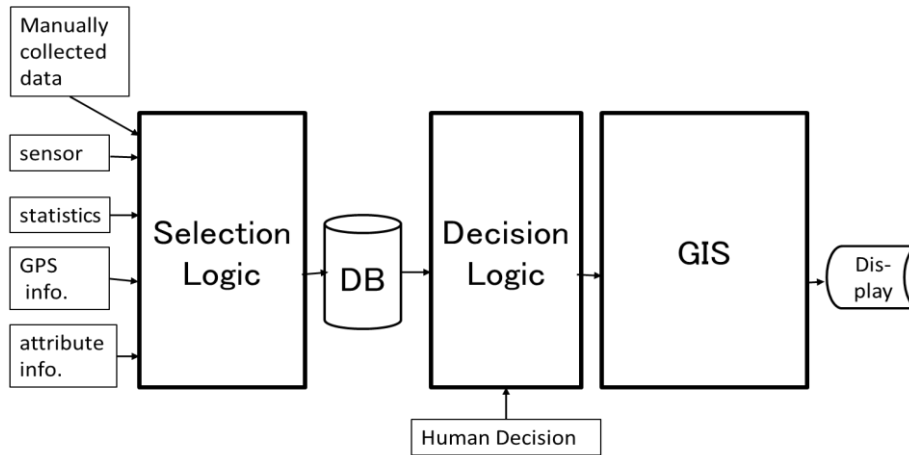


Fig. 7 System Concept

4 Basic Design and Integration of System

4.1 Basic Design of System

According to the Iceberg Model, the whole of basin is considered as one system. Using precipitation data, the river level is forecasted taking river level and rain water shelter storage pond into consideration. If the forecasted river level seems to be abnormal, the alarm is given to the stakeholders. Online data is collected and displayed on the digital map of Web-GIS. Applying the location information of global positioning system (GPS), current position that shows the abnormal status is shown on the digital map.

If stakeholder (first responder and residents living in the nearby area) ask for information about something by means of smartphones, the FDMS displays the evacuation site candidates that are the nearest to the questioner's current location and the shortest route to these. In response to this, it is necessary to refer to the hazard maps and adopt 70m/min as the walking speed for older people, not 80m/min for normal adults.

4.2 Integration of System

4.2.1 Real-Time Monitoring

For the real-time monitoring, the amount of precipitation in the unit of mesh is decided. For the purpose, wgrib2 module, which is provided by the National Oceanic and Atmospheric Administration (NOAA) in the U.S. and adopted in the Japan Meteorological Agency, is used. Additionally, MesoScale Model (MSM) and the data provided by the real-time precipitation monitoring system of Japan and called AMEDAS are also applied. The current river level is measured by a water level gauge sensor. These data are displayed on the digital map of GIS included into the FDMS.

4.2.2 Simulation

Using Urban Tank Model, the river level is forecasted based on the amount of precipitation and current river level. If the forecasted river level is going to exceed the warning water-level, the alarm will be given to the first-responders and the residents living in the nearby area.

4.2.3 Proposal for the Flood Disaster Mitigation Measure

With the operation of the system, the flood disaster mitigation measure is proposed. From the precipitation monitoring to give the alarm when flood disaster occurs, the system can collect and process data, notice the importance of the alarm, and respond to the tense situation considering residents' personal conditions.

5 System Verification

The targets of the verification for the system are planned in the suburb of Tokyo Metropolitan area in Japan. Figure 8 shows the relationship of Japan, Tokyo Metropolitan area, and its suburb named Tama District.

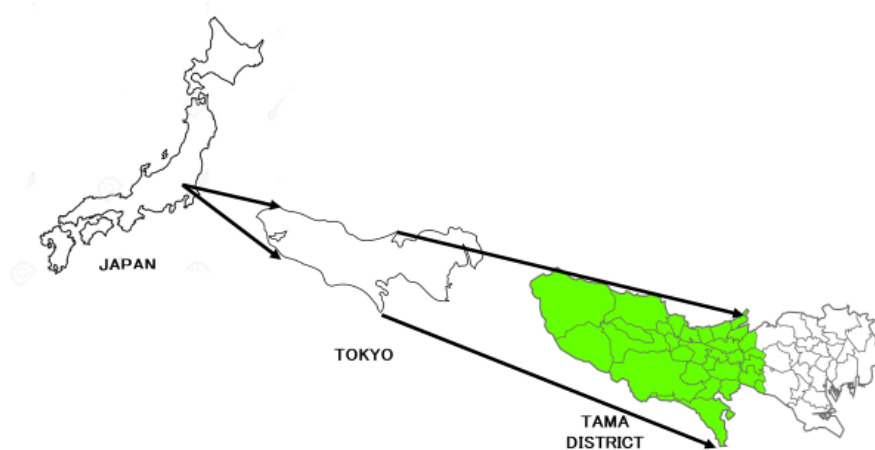


Fig. 8 Map of Verification Area

The reasons why the Nogawa River and Tama River are selected as the first and second verification target are denoted in Table 1. The Nogawa River is one of the branches of the Tama River. In the case of the Nogawa River and Tama River, if a flood disaster occurs seriously, its basin suffered damage.

Table 1. Details of Verification Target River

Name of River	River Class	Channel length (KM)	Managed by	Managed as
Nogawa	First	20.2	Tokyo Metropolitan Government	Flood Disaster Forecasted River
Tama River	First	183	Ministry of Land, Infrastructure, Transport and Tourism	Flood Disaster Forecasted River

Tokyo Metropolitan Government formulated the “Flood Control Plan” [17], the “Improvement Plan in the Nogawa River Basin” [18], and the “Countermeasures Plan against Heavy Rain in the Nogawa River Basin” [19]. The Nogawa River is regarded as one of the most important rivers. A large-scale expansion of rain water shelter storage pond near Oosawa-Ikegami Area of Nogawa is under construction at present, and have double capability in November, 2021.

Fig. 9 shows the actual situation concerning the basin of the Nogawa River when the alarm at level 3 was given. The river gauges are set in parallel in left position for human-recognizable one and in right position for digital device so as to collect river level automatically.

**Fig. 9** Nogawa under level 3 alarm

Fig.10 shows the current situation of large-scale expansion of rain water shelter storage pond. This corresponds to the hardware of flood disaster measure facility in the CLD shown in Fig. 4.



Fig. 10 Rainwater Shelter Storage Pond under expanding construction

Fig. 11 shows the middle basin of the Tama River near Komae City. Around this part, a large-scale flooding over the levee occurred and many houses were washed away in 1974. After this flooding, the measures against flood disasters had been proposed and executed in the basin of the Tama River.



Fig. 11 Tama River near Komae City

6 Conclusion

In this research, a flood disaster mitigation system (FDMS) is uniquely developed and designed. The system is composed of the observed data, forecast data, personal position data (software), and the flood disaster prevention facilities (hardware). The system gives the first-responders the alarm to clearly understand what is going to happen in proper timing. Thus, integrating and managing multiple systems into single system, it enables to mitigate flood disaster and minimize the damages. Additionally, in this research, SD method is applied to the phase of system design requirement analysis. The requirements were clearly expressed as three leverage points and integrated into the functions so as to alarm issuing toward the flooding via river water level forecast. Therefore, the FDMS is an advanced system rather than the ones that just monitor the present status.

This research described a part of example situation when flood disasters occurred in Tokyo Metropolis. However, we confirmed many patterns of flooding, as Swiss Cheese Model explains. Accordingly, it is necessary to cover various cases of flood disasters to raise the usability of the FDMS.

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