An Enhanced Meteorological Observation System for Water-Related Disaster Assessment

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***Abstract*—Floods can be predicted with some notice and their death toll is reduced compared to other disasters (i.e., earthquakes or cyclones). Nevertheless, their negative aftermath (e.g., transport limitations, agricultural damage, water pollution, disease spreading, and effects on the people's mental health) are inescapable. This paper explored the potential of meteorological observations and enhanced data manipulation to support warning systems based on a database approach. We also focused on the development of a visualization platform to support time series data properties. The investigation emphasized that database-oriented work is adequate for relational spatial data storage and active operational mechanisms.**

***Index Terms*—Database, monitoring system, rainfall, spatial data infrastructure.**

I. Introduction

The damage from natural disasters results not only from their maximum intensity but also their volume, duration, and areal extent. Over 50% of South Asian countries are highly susceptible to natural disasters [1] and fall in the top quarter of 193 countries at high climate risk [2]. In terms of population exposure to natural disaster (i.e., earthquakes, storms, floods, droughts), Japan ranks 4th on a global scale [3]. In 1990-2008, its suffered-damage involved 230,000 deaths and USD 45 billion [1]. In year 2014, the United Nations Economic and Social Commission for Asia and the Pacific (ESCAP) reported that river basin floods led to the highest economic losses (USD 26.8 billion) [4].

In recent decades, many areas around the world have suffered from severe tragedies: irregular and shifting weather patterns leading to unpredictable rainfall have affected food production, sea level rise has resulted in the contamination of coastal freshwater, while the impact of temperature on fisheries and aquatic ecosystem has been drastically intense. The frequency and incidence of such natural disasters is projected to increase [1]. On July 7, 2011, the Moderate Resolution Imaging Spectroradiometer (MODIS) from National Aeronautics and Space Administration (NASA)'s Terra Satellite observed snow shown on the hyper-arid Atacama Desert in South America, one of the driest places on earth [5]. More recently, in January, 2015, snow has fallen in the Middle East, spreading over the northern of Saudi Arabian desert [6].

Various global and local studies have focused on the variable (e.g., temperature, precipitation) and factors (e.g., frequency, intensity and duration) determining the severity of natural disasters. However, flood observation, monitoring and warning, through meteorological stations, telemetered networks, or remote sensing [7] are still active research subjects. Meteorological observations and monitoring are the main approaches to address environmental disasters like floods. Reliable historical data plays a major role in trend analysis and algorithm development, with probability distributions based on historical data representing an important step in the understanding of the processes leading to a disaster. Meanwhile, near real-time data illustrates the current situation and may be useful for precautionary measures.

Flood damage mitigation in Japan led by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) includes three main components: disaster prevention (i.e., improvement of the river network, information, forecasting, and warning systems), crisis response (i.e., damage assessment, flood warnings), and emergency and post-disaster recovery measures) [8]. However, the construction of a scientific database to support questions and simulations regarding flood damage is still complex but challenging and important. The goal of this study was to investigate the relationship between rainfall intensity and patterns and river floods. Specifically, this involved the review of the stations covering the study areas and the collection of historical water level records, the development of an automated technical system for hydrological data deployment, the analysis of the relationship between rainfall intensity records and radar images, the examination of the spatial distribution of heavy rainfall leading to warning alerts and determination of the river network flow, and the development of an approach to visualize time series data in an informative and user-friendly manner.

II. Related Work

Hydro-meteorological data has improved numerous applications in many research studies and regions. Jarvis *et al*. [9] applied geographical modelling to enhance the spatial and temporal resolution of agro-meteorological data in Britain using the internet for data distribution. The internet enabled the access to spatial information [10] relating GIS, remote sensing, and database management to support decisions on disaster responses systems [11]. Hiwasaki *et al*. stated that

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policies and actions related to disaster risk reduction can be implemented integrating scientific and local community knowledge. The combination of hydro-meteorological observations with local knowledge could enhance disaster preparedness and reduce its potential risk [12]. Another study on the relationship between soil moisture, hydro-meteorological patterns, and flood types by observing discharge time series, categorized the flood occurrence based on their processes and characteristics. Nied *et al*. categorized weather patterns (i.e., cyclones) and identified flood types (i.e., long rain floods). Although floods seemed to be moderately related (18%) to weather patterns, the physical characteristics of the soil (i.e., saturation) could not be neglected [13]. Different approaches to investigate basins were found. Supriya *et al.* applied regression analysis between the weighted maximum rainfall and the maximum stream flow for flood events in catchments in South India to investigate the catchment vulnerability and suggest flood control measures [14].

Disaster information support systems require international collaboration or evidence and most information service providers deliver news and forecasts at a national and global level (e.g., Sentinel Asia, which provides disaster information for the Asian Pacific region). Regarding remote sensing and web-GIS information, the cooperation among regional space and disaster management agencies could lead to improved disaster information support systems benefiting multiple agencies and users [15]. Ancona *et al*. (2014) developed a system involving internet technology and sensors to compute potential flood areas and issue alerts [16]. Early flood warnings allow flood prevention [17], since a quick response from local communities [18] is one of the largest challenges [17].

Based on our review, the observation of historical records and investigation of past events are a prerequisite for trend analysis. The use of meteorological data to determine rainfall and flood patterns, the improvement of real-time monitoring by seamless data assemblies, and the efficient dissemination of disaster information for a rapid response remain inspiring lines of research.

III. Framework of the Study

A. Study Area

Japan is a country composed of islands and located in the Pacific Ocean belt. Its weather is influenced by the South Pacific seasonal summer wind, and the Siberian weather system, with its winter wind. Typhoons, with strong wind and heavy rain, often occur in May-October [19].

The study area (34°-38° N, 136°-139° E) covered approximately 76,000 km^2 and included 11 prefectures: Aichi, Fukui, Gifu, Ishikawa, Mie, Nagano, Niigata, Shiga, Shizuoka, Toyama, and Yamanashi (Fig. 1). Flood historical records from 1995-2010 for the study region were collected from the Center for Research on Epidemiology of Disasters (CRED) global database: the Emergency Events database EM-DAT. The EM-DAT was initially created in 1988 by the World Health Organization (WHO) and the Belgian Government, but worldwide collaborations have increased it until present [20]. The flood events were selected based on the following criteria: >=10 death, >=100 people affected, declaration of state of emergency, or call for international assistance. Table I shows the flood start and end dates, locations, and induced mortality and injuries.

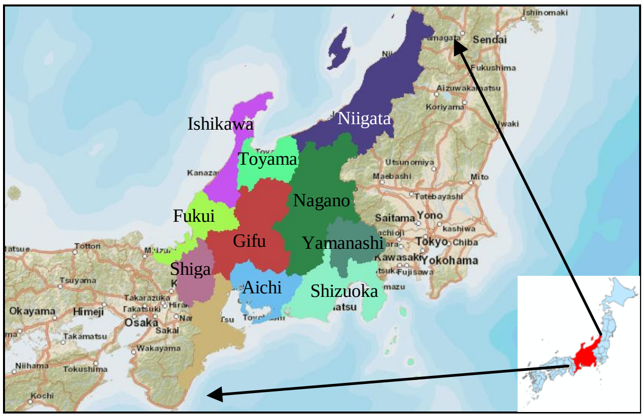


Fig. 1. Study area. Source: Open street map as a background map.

TABLE I: Flood Historical Record Information

Start	End	Location	Total deaths	Total affected
07-1995 (unidentified date)	07-1995 (unidentified date)	Niigata, Toyama, and Nagano,	-	12,000
10-09-2000	17-09-2000	Aichi, Shizuoka, Mie, and Gifu	18	360,110
12-07-2004	14-07-2004	Niigata, Fukushima	21	25,807
11-11-2004	12-11-2004	Shizuoka	1	2,290
28-06-2005	28-06-2005	Niigata	-	900
18-07-2010	18-07-2010	Gifu, Shimane, and Hiroshima	10	N/A

Source: EM-DAT, 2012 [20]

B. Approach

Four main components were involved in the support, operation, management, and representation of various types of data: spatial (i.e., rivers, roads, administrative boundaries) and non-spatial (i.e., historical and near real-time data) database management and rainfall image processing systems, the development of web infrastructures for times-series.

C. Module 1: Water Level and River Monitoring

The MLIT of Japan established rainfall and water stations throughout the country, with rainfall and water level records provided by the Water Information System (WIS) website (http://www1.river.go.jp/), with historical and 10 minute interval near real-time data for different stations. In this research, web programming and databases were mainly used to manage large quantities of information for relevant spatial locations. Hourly water levels from January 2005-March 2015 were collected by 301 stations covering 11 prefectures. The stations locations were marked and the data fixed for errors (e.g., missing or incorrectly introduced values, different formats) and to ensure a uniform pattern. After a certain pattern and readable format were obtained, the data were uploaded to the PostgreSQL database with the updated station IDs as an index. Another table including station details (i.e., ID, name, prefecture, latitude/longitude, and WIS-recommended warning, evacuation and flood values) was created (Fig. 2).

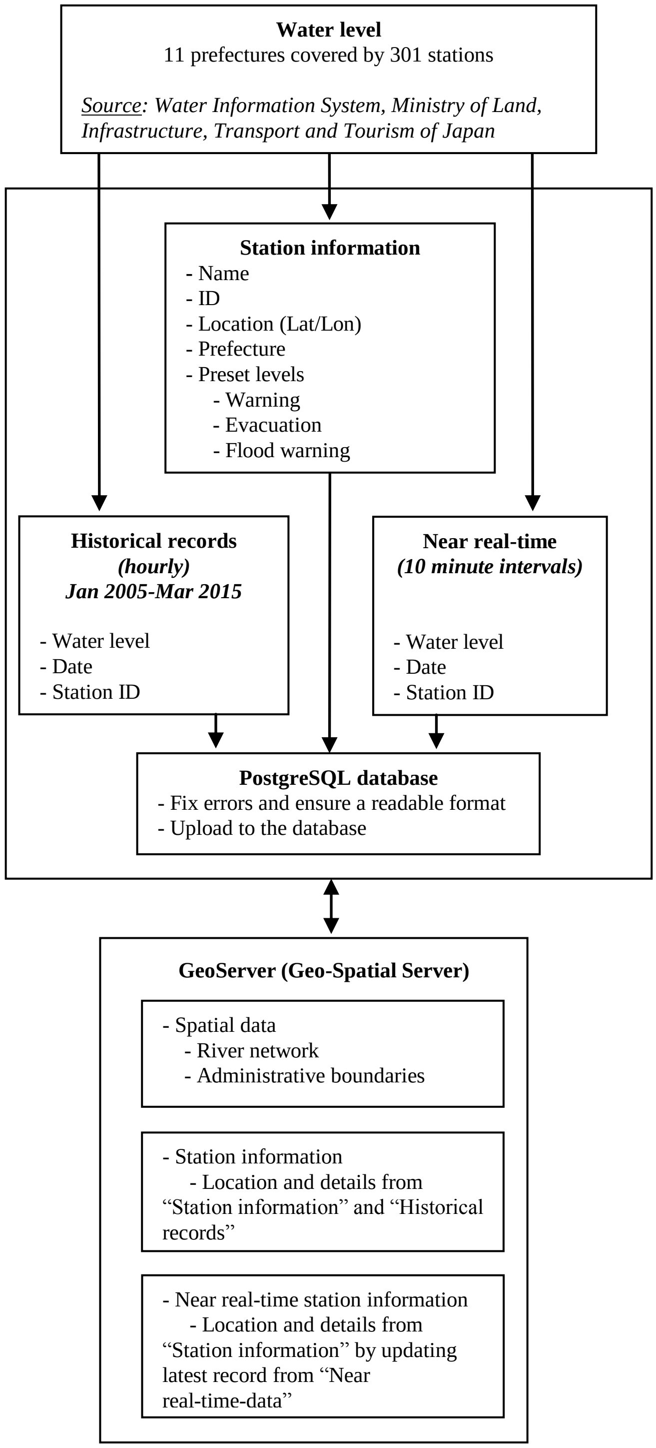


Fig. 2. Diagram for the water level and river monitoring.

An initial trial to display all stations from the data records on the map was very slow because of the amount of data. Therefore, the tables were adjusted to reduce the handling time by removing the stations with water level records below the warning threshold. Only 184 stations remained, as 80 stations always had water levels below the warning threshold and 37 stations had no warning value set. Meanwhile, 116 stations had set flood warning values (Table II).

The water level records for all 238 stations for 10 years were kept in the database to observe the level changes over time. The database was functional and designed to provide detailed information as a non-spatial database. A GeoServer was implemented to handle it as a spatial database including the administrative boundaries and river network. Using an overlay technique, the data were combined to identify, for example, when and which stations exceeded the warning value and for which river and to assess the river flow direction by temporally analyzing the water levels.

TABLE II: NUMBER AND CHARACTERISTICS OF THE STATION USED IN THIS STUDY

Number of stations					
Warning threshold		Evacuation threshold		Flood threshold	
Total	Exceed	Total	Exceed	Total	Exceed
264	184	154	77	116	36

D. Module 2: Rainfall Radar Imagery

The Japan Meteorological Agency (JMA) is one of the main organizations providing meteorological data, with the daily broadcasted weather information and forecasting mostly relying on it. Rainfall radar images are launched and updated every hour for 19 north-south zones covering Japan and including Okinawa and other islands represented by one image for each zone.

Since November 4, 2013, two zone images (Hokuriku East and Hokuriku West) were collected and provided as non-registered Portable Network Graphic (PNG). To apply them to other maps (i.e., Google), these images must be registered and transferred to a known coordinate system (i.e., geographic latitude/longitude). Initially, the non-geographically referenced image was located and registered in a coordinate system using Exelis Visual Information Solution (ENVI) image software from Chubu University. An image property text file storing the x and y pixel sizes, coordinate, and rotational information was created. Subsequently, this file was applied to other images from the same location. The GDAL library function was used to transform the non-geographically referenced image from its geographical information. The output image was produced as a geographic raster image to be displayed in any GIS tool. All raster images were stored in the GeoServer with the files location identified in the PostgreSQL database (Fig. 3).

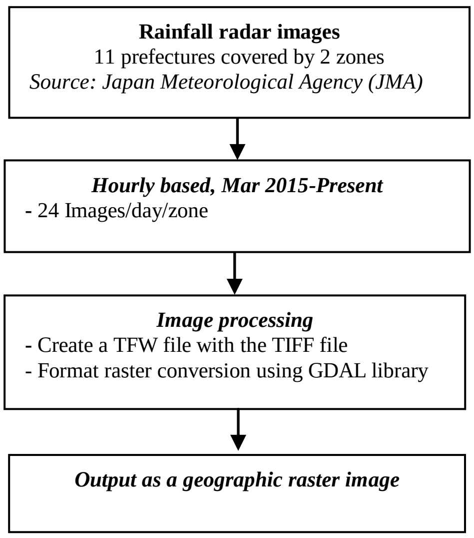


Fig. 3 Procedure for processing the rainfall radar imagery.

E. Module 3: River Network and Alert System Analysis

The watershed, river delineation, and alert period were investigated. The creation of the watershed model required a Digital Elevation Model (DEM) to process the flow movement, with rivers and coastal lines used to identify the outlet locations. A 15 meter spatial resolution DEM was obtained from the Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (Aster GDEM) from the Japan Space System [21] and processed as shown in Fig. 4. The flow direction was computed for each cell where water would flow through. The outcome of the flow network was used as a reference to identify the river flow respectively to the stations' locations.

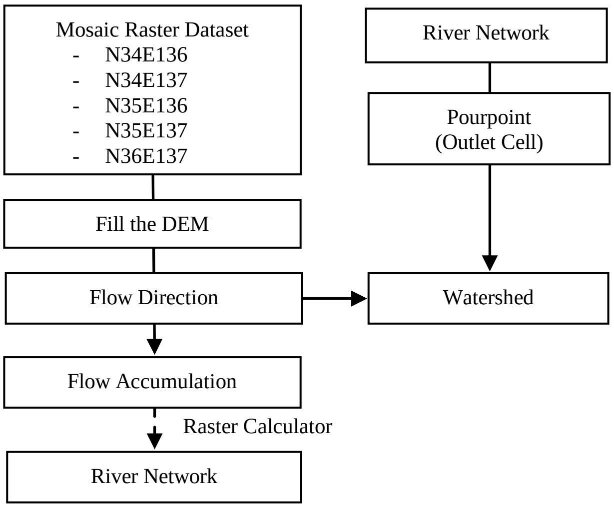


Fig. 4. Watershed analysis procedure.

The 301 monitoring stations for the 32 river systems for which an alert should have been issued were selected. Database inquiries and time-based calculations were performed manually only for stations with three warning values above the threshold.

F. Module 4: River Meteorological Data Integration and Visualization

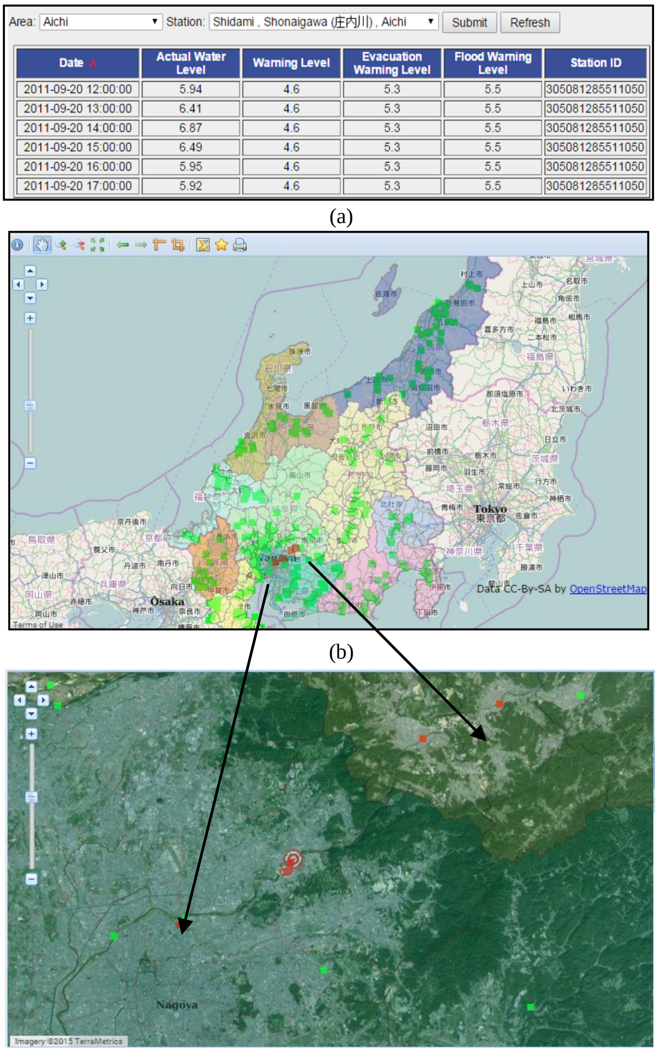
The data was related in several dimensions (i.e., spatially and temporally). Over 80,000 water level records for each station were collected. Regarding rainfall, 48 images were gathered per day covered by 2 zones since November 2013. For data presentation, a spatial web-based display for the time series records was developed, possibilitating not only the presentation of a large amount of information but also facilitating the analysis of the relationships among the data (e.g., warning station collation along a river system or identification of river overflow and land submersion after heavy rainfall). In addition to the main functions (i.e., pan/zoom facilities, toggle on/off layers), the system was also configured to support query functions by area, stations/river systems, and time series appearance (hourly rainfall radar images or water level records) on the web.

IV. Results

Intense and continued rainfall may cause flooding when the capacity of a river channel is exceeded. Above we described the obtention of meteorological observations and their visualization and analysis, ensuring that historical data provided an informative scenario. Rainfall imagery presented on a map allowed a better visualization for public users impacted by floods. In addition, the collection of continuous rainfall data ensures the monitoring of future flood risk.

A. Water Level and River Monitoring

A database was created to manage the 1995-2015 records, with three threshold warning values used for comparison with actual water levels. The information could be obtained by selecting an area and station (Fig. 5).



Date	Actual Water Level	Warning Level	Evacuation Warning Level	Flood Warning Level	Station ID
2011-09-20 12:00:00	5.94	4.6	5.3	5.5	305081285511050
2011-09-20 13:00:00	6.41	4.6	5.3	5.5	305081285511050
2011-09-20 14:00:00	6.87	4.6	5.3	5.5	305081285511050
2011-09-20 15:00:00	6.49	4.6	5.3	5.5	305081285511050
2011-09-20 16:00:00	5.95	4.6	5.3	5.5	305081285511050
2011-09-20 17:00:00	5.92	4.6	5.3	5.5	305081285511050

(a)

(b)

(c)

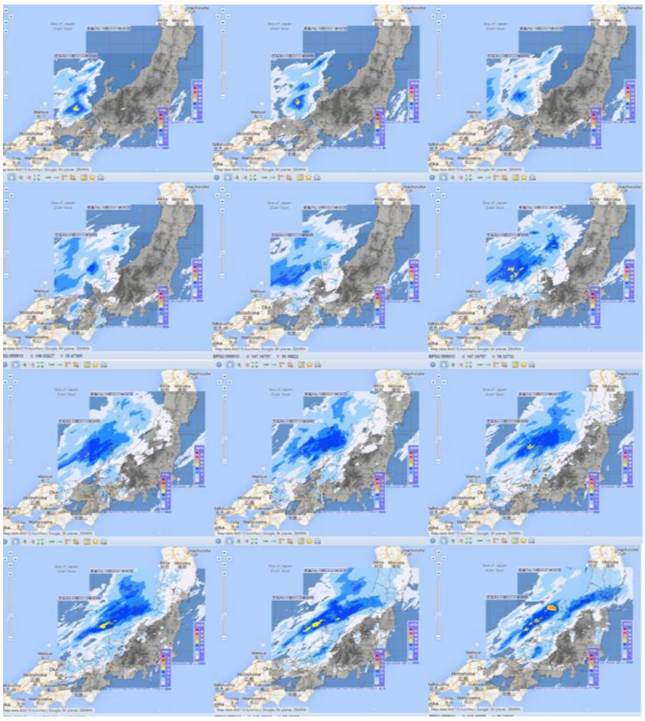
Source: Google map as a background map.

Fig. 5. Flood event as seen from the database: (a) query for the flood alert, (b) map with the location for September 20, 2011 at 11 a.m., and (c) alert message from the web browser for September 20, 2011 at 12-5 p.m.

The interface shows the actual water and setting levels for each stage (warning, evacuation, and flood) and, together with text information, the location can be seen in another web map browser. Since the data were based on the date (year) and time (hour), an additional function was implemented for the user to access it using a drop-down or slider tool that respected the dataset properties.

B. Outcome of the Rainfall Imagery

Radar rainfall images, in a non-geographic format, were registered programmatically and previewed in association with other information (i.e., settlements, roads, rivers, or meteorological stations). Spatially and temporally spreading rainfall patterns could be visualized (Fig. 6).



Source: The original data are provided by JMA as shown in the website and © JMA.
Fig. 6. Rainfall radar images from October 2 (12 p.m.) to October 3 (3 a.m.), 2014.

C. Watershed, River Delineation, and Alerting System

The watershed and river delineation were derived from the GDEM dataset (Fig. 7 and Fig. 8).

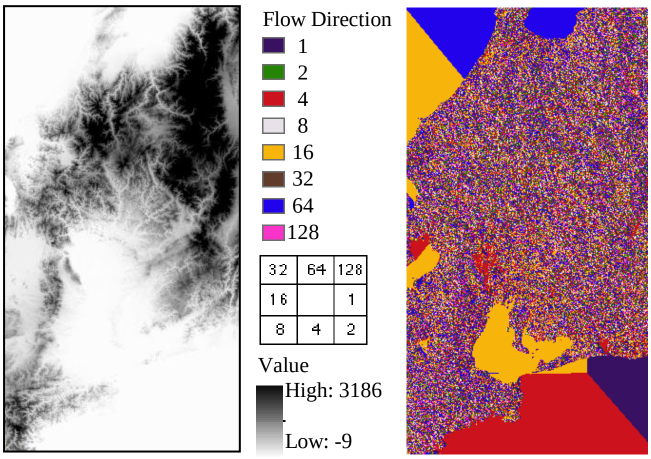


Fig. 7. Watershed analysis: (a) digital elevation model (DEM), (b) flow direction map.

The three classification (warning, evacuation, and flood level) of the alert system were set and time lapse between them was inspected through database queries. Our records showed an approximately 1-2 hours gap between the warning and evacuation and flood alerts, with the evacuation normally set too close to the flood level. If information is properly spread among the population, it may provide enough time for preparedness. Stations on the west coast (GIFU, Ishikawa) had a clearly longer period between the warning, evacuation, and flood levels compared to the other prefectures. Consequently, the warning periods were repeated and longer.

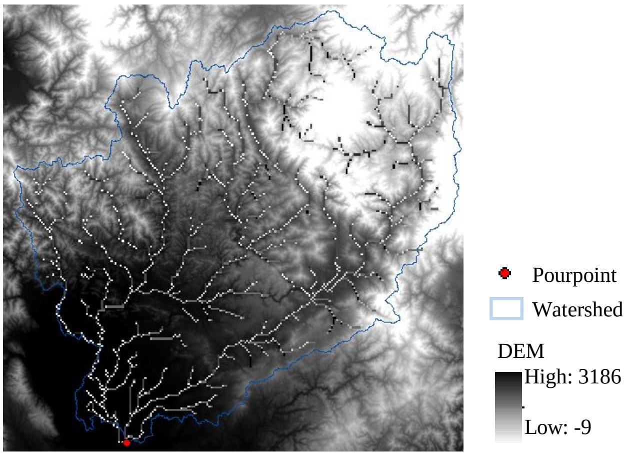


Fig. 8. Sub-basin boundaries.

D. Assessment of the Meteorological Data Visualization

An approach to increase the public understanding and awareness is the use of images for communication. The animated system developed to present the time series data in a graphical format is potentially important for effective communication and decision making (Fig. 9). The goal was to facilitate the dissemination of updated information regarding changes in rainfall scenarios and make historical records available for the general public. Additionally, good records and management could help the historical analysis and facilitate the design of efficient and effective practices.

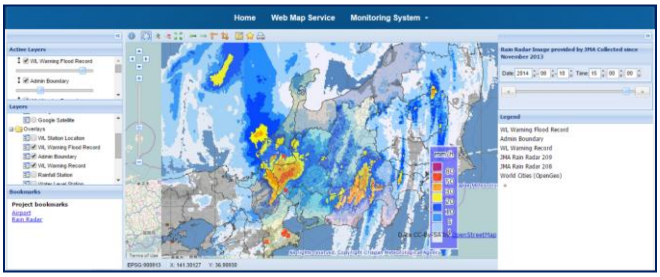


Fig. 9. Developed visualization platform.

V. Conclusion

Without discussing the advantages of receiving and disseminating information through the internet, this paper shows a well-designed database that allows the analysis of hydrological data and its corresponding map visualization more effectively than for individual data. In addition, the maintenance of archive records serves the public for educational and historical purposes. The programming and computerization allowed the generation and organization of large volumes of data that were not regularly available otherwise. Increasing the envision capability of existing rainfall radar images from reliable agencies, such as the JMA, will benefit viewers and may improve the understanding of the causes and characteristics of floods. The observation and monitorization of meteorological data was then improved for future flood watching.

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REFERENCES

[1] The International Bank for Reconstruction and Development, The World Bank, "South Asia: Shared views on development and climate change," South Asia Region Sustainable Development, Washington D.C., USA, pp. 1-213, 2009.

[2] P. Mucke, "World risk report 2012," United Nations University, Institute for Environment and Human Security (UNU-EHS), and the Nature Conservancy, Alliance Development Works, 2012.

[3] P. Mucke, "World risk report 2014," United Nations University, Institute for Environment and Human Security (UNU-EHS), and the Nature Conservancy, Alliance Development Works, 2014.

[4] The United Nations, Economic and Social Commission for Asia and the Pacific (UNESCAP). Disasters in Asia and the Pacific: 2014 year in review. [Online]. pp. 1-15. Available: http://www.unescap.org/sites/default/files/Year%20In%20Review_Final_FullVersion.pdf

[5] National Aeronautics and Space Administration. [Online]. Available: http://visibleearth.nasa.gov/view.php?id=51312

[6] The Weather Network. [Online]. Available: http://www.theweathernetwork.com/uk/news/articles/rare-desert-snow-in-saudi-arabia/43466/

[7] J. G. Pintado, D. C. Mason, S. L. Dance, H. L. Cloke, J. C. Neal, J. Freer, and P. D. Bates, "Satellite-supported flood forecasting in river networks: A real case study," *Journal of Hydrology*, vol. 523, pp. 706-724, February 2015.

[8] T. Adachi, "Flood damage mitigation efforts in Japan," presented at Fifth US-Japan Conference on Flood Control and Water Resources Management, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), January 2009.

[9] C. H. Jarvis, N. Stuart, and M. J. Hims, "Towards a British framework for enhancing the availability and value of agro-meteorological data," *Applied Geography*, vol. 25, issue 2, pp. 157-174, April 2002.

[10] D. Howard, "Geographic information technologies and community planning: spatial empowerment and public participation," *The Project Varenius Specialist Meeting on Empowerment, Marginalization, and Public Participation GIS*, Department of Geography, State University of New York at Buffalo, October 1998.

[11] J. Tian, Q. Zou, S. Cheng, and K. Wang, "A framework of task-oriented decision support system in disaster emergency response," *Communications in Computer and Information Science*, vol. 35, pp. 333-336, June 2009.

[12] L. Hiwasaki, E. Luna, Syamsidik, and R. Shaw, "Process for integrating local and indigeneous knowledge with science for hydro-meteorological disaster risk reduction and climate change adaptation in coastal and small island communities," *International Journal of Disaster Risk Reduction*, vol. 10, pp. 15-27, December 2014.

[13] M. Nied, T. Pardowitz, K. Nissen, U. Ulbrich, Y. Hundecha, and B. Merz, "On the relationship between hydro-meteorological patterns and flood types," *Journal of Hydrology*, vol. 519, pp. 3249-3262, November 2014.

[14] P. Supriya, M. Krishnaveni, and M. Subbulakshmi, "Regression analysis of annual maximum daily rainfall and stream flow for flood forecasting in Vellar River Basin," *Aquatic Procedia*, vol. 4, pp. 957-963, March 2015.

[15] K. Kaku and A. Held, "Sentinel Asia: A space-based disaster management support system in the Asia-Pacific region," *International Journal of Disaster Risk Reduction*, vol. 6, pp. 1-17, December 2013.

[16] M. Ancona, N. Corradi *et al*., "On the design of an intelligent sensor network for flash flood monitoring, diagnosis and management in urban areas position paper," *Procedia Computer Science*, vol. 32, pp. 941-946, May 2014.

[17] V. V. Krzhizhanovskaya *et al*., "Flood early warning system: design, implementation and computational modules," *Procedia Computer Science*, vol. 4, pp. 106-115, April 2011.

[18] International Strategy for Disaster Reduction (ISDR), "Developing early warning systems: a checklist," presented at Third International Conference on Early Warning (EWC III) from Concept to Action, March 27-29, 2006, Bonn, Germany.

[19] Japan Meteorological Agency (JMA), Climate Change Monitoring Report, 2006, pp. 1-87, November 2007.

[20] The International Disaster Database, Center for Research on the Epidemiology of Disasters (CRED). [Online]. Available: http://www.emdat.be/disaster_list

[21] Japan Space System, Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (Aster GDEM). [Online]. Available: http://www.jspacesystems.or.jp/ersdac/GDEM/E/1.html

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