Assessment of Hydrological Database for Automated Flood-alert System—Case Study: Shonai River, Kasugai

P. Limlahapun and H. Fukui
International Digital Earth Applied Science Research Center, Kasugai, Aichi, Japan,
Email: thip.limlahapun@gmail.com, fukui@isc.chubu.ac.jp

***Abstract*—This study uses database infrastructure, hydrologic models, and geospatial analysis to assess flood inundation areas and their distribution in the Shonai sub-basin, Kasugai City, in western Japan. The proposed method utilizes near-real time data; hence, efficient database processing is an important requirement for the assessment tool. The river hydrological models utilize geometric input flow characteristics and river discharge volume to generate an inundation map. Discharge volume is estimated owing to the lack of data on discharge measurements. Distributions are presented in maps of inundation-susceptibility using an interactive web-based system. The simulated results from the hydrological model indicate that the topographic characteristics (slope and elevation) of the watershed significantly affect the depth of inundation. Hydrological factors (e.g., rainfall and water level) also significantly affect changes in the rate of river discharge. The centralized geo-database can be processed on-the-fly, and it is believed that this approach is reliable and well suited to such a flood alert system. The significant points of this work are to determine a necessary but unknown parameter (discharge volume) via existing data resources, and—ultimately—to make informative mapping data available in a timely manner. The use of a near-real time system ensures that the public and relevant agencies can assess emergency information and initiate appropriate and prompt responses.**

***Index Terms*—aichi, hydrological model, geo-database, near-real time observation, flood alert system**

I. Introduction

Flooding is one of the most widely observed global natural disasters and often results in the loss of life and damage to property, and activities. Flooding can result in damage to various industrial sectors (e.g., industry, agriculture, transportation, and communication networks), and has environmental effects on water systems [1], ecological resources [2], and food security [3]. Predicting flooding event can help minimize economic losses, threats to public safety [4], potential damage, and costs of recovery [5].

In September 2000, Nagoya, Kasugai, and surrounding areas were flooded as a result of a storm unrelated to a tropical system [6]. The current rate of global changes leads to uncertainty regarding both environmental factors and appropriate risk-management strategies. Therefore, the integration of environmental data and information technology can help obtain, analyze, and disseminate information in a reliable and prompt manner. A flood assessment system considers many variable factors, such as meteorological and topographic parameters [7]. This article examines the processes executed in a near-real time system for receiving hydrological data, modeling river conditions, and issuing flood alerts. It is hoped that the proposed system will enable the local government and local communities to acquire relevant information and simultaneously respond to predicted flood events.

II. Literature Review

The consequences of flooding have become more severe over the past two decades [8]. Meanwhile, research has examined various related issues such as preparation, prevention, recovery, or response to flooding [9]. Remote sensing applications have commonly been used to indicate flood-affected areas via optical and/or radar satellite images, such as data sets from the MODIS instrument [10]. Sakamoto et al. (2007) investigated the extent of annual flooding using MODIS times-series for Cambodia and the Vietnamese Mekong Delta. The study successfully applied a wavelet-based filter to detect spatio-temporal changes in inundation areas. One positive outcome showed the strong relationship between water level and flood extent [10]. In another example of using satellite images, Auynirundronkool et al. (2012) developed near-real time detection using MODIS data to overview extensive areas and RADARSAT data to classify inundated areas of the central Thailand plain. The resulting system combined data retrieval services, flood sensor observation services (SOS), and flood detection web processing services (WPS) under a sensor web environment [11]. Other studies used artificial neural networks to estimate flooding [12]. Each approach has advantages and limitations, according to the study site and its characteristics (topography, weather conditions, and the quality of data and infrastructure).

The Hydrological Engineering Centers River Analysis System (HEC-RAS) performs hydraulic estimations for natural river networks or free surface flow (e.g., rivers and streams) [13]. The system was computerized and released

Manuscript received December 25, 2012; revised March 20, 2013.

doi: 10.12720/jiii.1.1.25-30

in 1995, and the current eighth edition (called version 4.1) was released in 2010 [14]. The HEC-RAS calculates flow parameters including depth, flow area, and velocity [13]. HEC-GeoRAS delineates floodplain mapping in pictorial form, which may draw the attention of the local community. HEC models have been widely applied in numerous hydrological analyses [15]-[17]. The proposed system then regularly retrieves new data; automatically recalculates and updates the online inundation zones, maps, and table display; and issues notifications warning.

III. Problem Statement

This investigation is conducted for the following reasons. Flooding disasters have become more frequent in Kasugai city in recent years, in association with irregular climate. Although the local government has attempted to establish a real-time online system to monitor and publicize the water level of the Shonai River, the use of water level data may not be enough to gain local attention in the absence of corresponding visual maps of inundated areas. Second, flood assessment models use river discharge volume as one parameter in the calculation, but it is not possible to derive near-real time discharge data.

Data on the spatial distribution of flooded areas will help local government better manage the watershed and raise community awareness of flooded locations. Data will be freely disseminated and accessible to communities via the Internet. The results of the analysis will also provide immediate information to relevant local agencies via an integrated alert system. Near-real time observations can facilitate preemptive action by local agencies, which may help mitigate the effects of flooding.

IV. Framework of the Study

Natural disasters such as floods are difficult to predict accurately because there are no obvious factors as to time and locations. An efficient observation and monitoring system can supplement visual assessment because an effective supervision allows quantitative inspection of possible flooding. Observation is the first step to understand the fundamental phenomena underlying floods and their effects on the environment. Real-time monitoring and early warning systems are vital to reduce the region's vulnerability to floods. Continuous data monitoring is the key point, which support the analytical process and, to ensure that precautions are taken. The proposed system comprises two components; 1) floodplain delineation; and 2) a flood-alert system.

Flood plain delineation: The HEC hydraulic model is applied to estimate surface flow. The major physical input parameters include a Triangular Irregular Network (TIN) surface which represent a topographic condition [18] via a network of non-overlapping triangles comprising nodes and lines in three-dimensional coordinates [19]; and also river characteristics (river, banks, flow-path, and cross section). These parameters are operated by HEC-GeoRAS, which is a tool for processing geospatial data in ArcGIS [20]. Discharge serves as an input parameter required to generate the inundation map in the HEC model and is also an alert factor. The system automatically collects data every 10 minutes; however, source data is subject to a 10-minute broadcast delay (e.g., data for 13:20 is available at 13:30). Discharge is calculated once water level data is received.

A flood-alert system: Three parameters are used to trigger an alert message: water level, river discharge, and rainfall. The web-based system utilizes the geo-database in combination with PHP programming to assess water level data, which is provided by the Water Information System agency [21].

A. Study Area

The study area comprises Kasugai city, located in the Shonai sub-watershed. The Shidami hydrological observation station covers approximately 530 km^2 of the catchment area (Fig. 1). Japan Meteorological Agency (JMA) data for 1981-2010 show the average temperature of approximately 15 ℃ and an annual rainfall of 1,535 mm. [22]. The river basin has a long and narrow shape from east to west. Most of the upstream areas are mountainous, and those downstream are mostly urbanized flood plains.

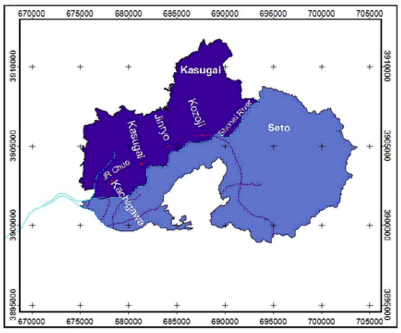


Figure 1. Study area

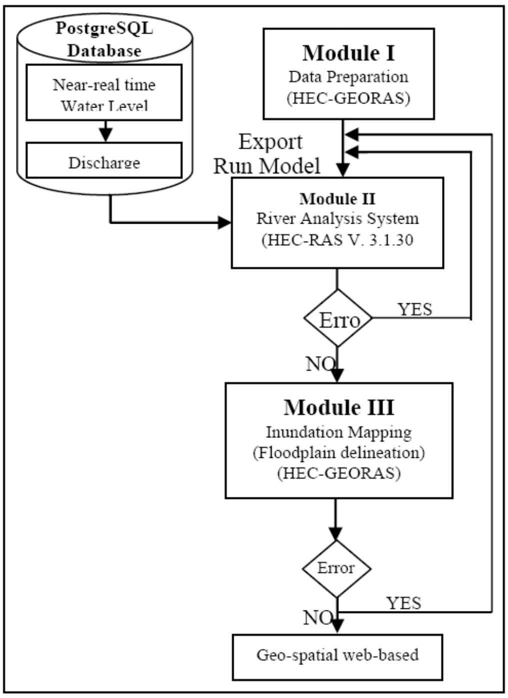


Figure 2. Framework of proposed flood-alert system

B. System Framework

The flowchart in Fig. 2 shows the structure and the various inputs/outputs of the proposed model. The model utilizes data from the year 2000, which currently represents the worst historical flooding scenario; however, similar or more extreme events could occur in the future.

V. METHODOLOGY

The flood alert system in the Shonai sub-watershed is developed under the circumstance of near-real time water level. A map of estimated flood scenarios is produced, which identifies areas at risk of inundation. Other hydrological factors (rainfall and river discharge) are derived from formulas and relationships from regression analysis based on historical records. The interactive geo-spatial web-based application is a preset function which allows members of the public to generate an inundation map at a specified water level. Other layers can be overlaid to view the affected community and infrastructure. Geo-spatial data are applied using various GIS spatial techniques in ArcGIS, as described below.

Task 1: TIN and Watershed Creation

Six scenes were downloaded from the Advanced Spaceborne Thermal Emission and Reflection Radiometer, Global Digital Elevation Map (Aster GDEM) [23] between 34-36N and 136-137E, covering the study area. The watershed was derived in ArcGIS 9.3, starting from 6 mosaics. Sinks in the raster surface were then filled to remove small defects in the DEM data [24]. The final step in watershed delineation was to complete flow direction, the direction of flow accumulation down steepest slopes to neighboring cells; and to identify river outlet cells from river and coastline layers downloaded from Japan National Land Numerical Information. A TIN was derived from the DEM elevation data, and was used as a surface layer in the HEC models.

Task 2: Water Level and River Discharge Assessment

Water level was obtained from the Water Information System, Ministry of Land, Infrastructure and Transportation [21]. The volume of river discharge is required but is not available in near-real timeframes; it is therefore derived from hydrological data, applying the regression analysis using daily average data for river discharge and water level between 2002 and 2009 (discharge data is not available after 2009). Once water level is collected in near-real time, Geo-database, PostgreSQL is used to project river discharge.

Task 3: Preparation of Geometry Data and Assessment of Inundation Map

Three modules are used, as follows.

Module I: Geometry data is prepared for the river analysis model. The dataset (stream, bank lines, flow path, bridges and cross section) is digitized and assigned topology, via an HEC-GeoRAS module compatible with ArcGIS 9.3. Important issues when deriving a cross-section layer include: 1) a cross-section line is not permitted to cross two rivers; and 2) each line must cross the left and right flow paths. All layers, including the surface (TIN), are set up before exporting for analysis in HEC-RAS (Module II).

Module II: the HEC-RAS is performed for the flow analysis, and comprises two parts: 1) geometric data (importing geometry data and assigning Manning's-n value, based on land surrounding the river network; and 2) steady flow (assigning number of flood cases and flow rate based on discharge value from Task 2). Steady flow describes conditions in which depth and velocity at a given location [25] remain constant over time [8]. After running the steady flow analysis and divide sub-section for flow distribution, the results are exported to the HEC-GeoRAS (Module III) to create the inundation and velocity distribution maps.

Module III: The result of Module II is then imported to generate a water surface and delineate the inundation map. The inundation map is displayed via a web-based application, which helps users to view the spatial distribution of flooding and identify affected areas.

Task 4: Acquiring Rainfall Data using Inverse Distance Weight (IDW)

Rainfall is a major factor in hydrological river analysis, as it directly anticipates water level and river discharge. There is no rainfall monitoring station within the study location, so the analysis uses interpolation techniques. Using the Inverse Distance Weight Method, rainfall values from four rainfall monitoring stations in the region surrounding the study area (Kozoji, Seto, Yazako, and Nagoya) were used to calculate rainfall (Equation 1) at the location (variable *i*) where water level is recorded (Fig. 3).

$$P_i = \frac{\sum_{j=1}^{G} P_j / D_{ij}^{\,n}}{\sum_{j=1}^{G} 1 / D_{ij}^{\,n}} \qquad (1)$$

where

P_i = Rainfall value at location i
P_j = Rainfall value at location j
D_{ij}= Distance between i and j
G = Number of locations
n = 2 (interpolating rainfall used by NOAA [26]

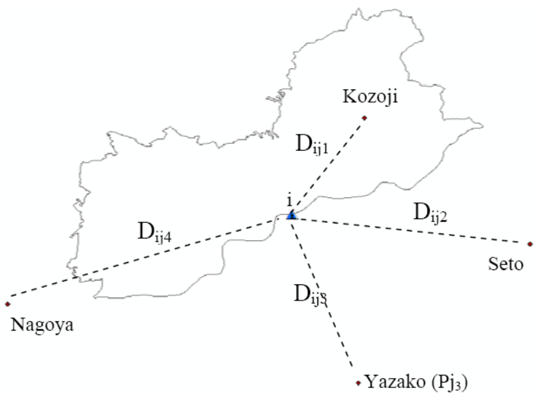


Figure 3. Rainfall data using IDW equation

Task 5: Criteria for Flood-Alert System

A system was developed to issue alerts via e-mail, according to observed water level and estimated discharge and rainfall. The alert criteria are shown in Fig. 4.

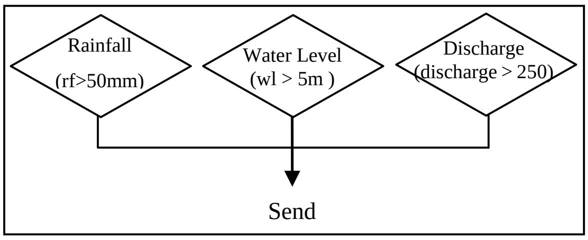


Figure 4. Criteria for issuing flood-alert

VI. Results

The results, derived from each measure, are summarized below.

A. Topographic Surface

The topography of the central part of the study area resembles a pan shape, where two rivers (Utsutsu River and Shonai River) meet; therefore, water level is likely to show greater increase than in other areas (Fig. 5) and the floodplain may be submerged for longer periods for a given flood event.

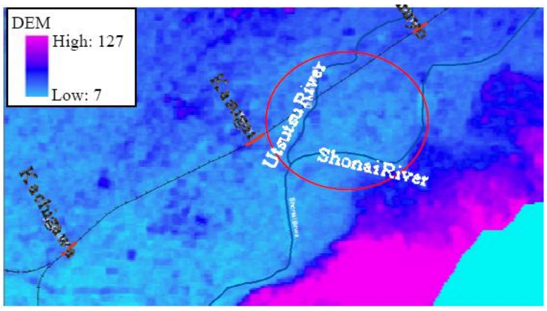


Figure 5. DEM (case of upstream flow 2,500 m^3/s, and downstream 3,500 m^3/s)

Reference flow in Shonai River in September 2000 during heavy rain [6]

B. Discharge Estimation

The daily historical water-level and discharge records were obtained for 2002-2009. The use of regression analysis is applied to investigate the relationship between these two parameters. Regression analysis showed that a second-order polynomial (R^2 = 0.97) best describes the relationship between historical daily water level and river discharge volume (Equation 2 and Fig. 6), whereas simple linear regression gave a lower R^2 of 0.86. In comparison with linear regression, projected discharge volumes were less than actual discharge significantly when the water level exceeded 2.5 m. (Fig. 7). Therefore, the regression (Equation 2) is used in the flood alert system to calculate discharge volume. Fig. 8 shows estimated discharge for one week (between 18 Jan. 2013 and 24 Jan. 2013). The original on-site data is credible for monitoring the current stream pattern (e.g., water level and discharge volume). Constructing features and events are more convincing in the analyzing process, when information is available. The Fig. 9 shows the historical water level records from December, 2012 to present.

$$Y = 55.441X^2 - 51.53X + 10.24 \qquad (2)$$

where
Y= discharge (m^3/s);
X = water level (m.);
R^2 = 0.9762

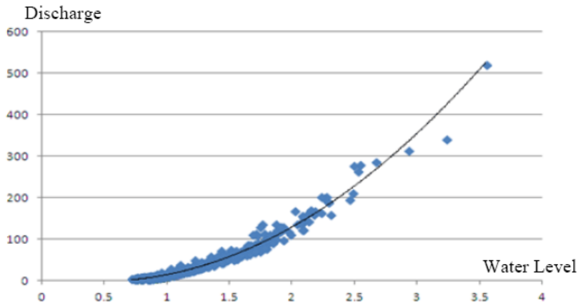


Figure 6. Water level and discharge from a second-order polynomial regression, historical observations (2002-2009)

C. Inundation Areas Along the Shonai River

Following watershed preparation, water level, discharge assessment, and preparation of geometrical data were done, a floodplain can be delineated on the terrain model, as well as inundated distribution and velocity map.

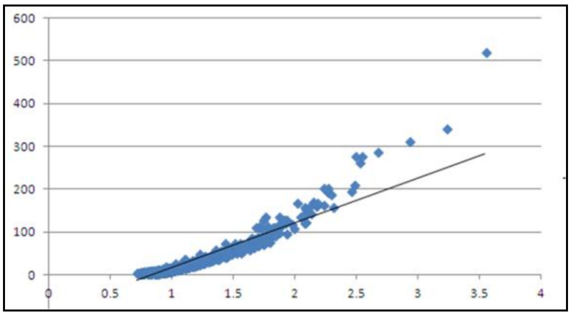
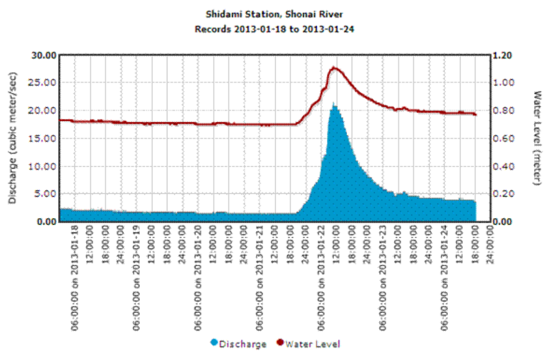


Figure 7. Water level and discharge from a linear regression, historical observations (2002-2009)



Remark: Observation record shows 10-min data-transmission delay relative to actual time

Figure 8. Near-real time water level and river discharge estimation at Shidami station, Shonai River (13 Dec. 2012 - 27 Mar.2013)

Fig. 10 shows the map generated from the worst case of flooding, during the year 2000. The inundated area overlays the image obtained from Google data. Fig. 11 shows the flooding distribution data is overlaid on the "3D-buildings" layer provided by Google Earth, which enhances the capacity for visualization. Fig. 12 shows the velocity map, indicating flood conditions in which people or property are likely to be overwhelmed during a flood [27].

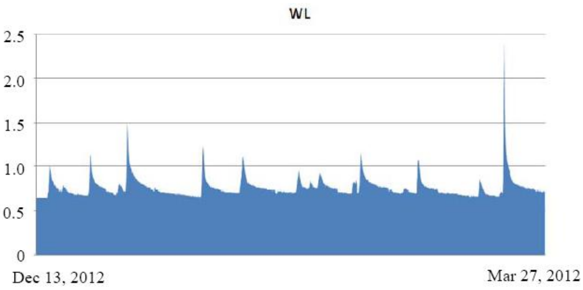


Figure 9. Water Level records (13 Dec. 2012 - 27 Mar.2013)

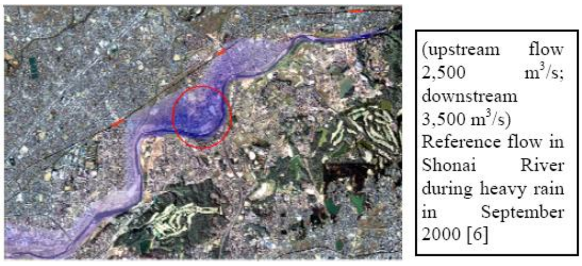


Figure 10. Water inundation within floodplain area

Figure 11. Downstream inundation area

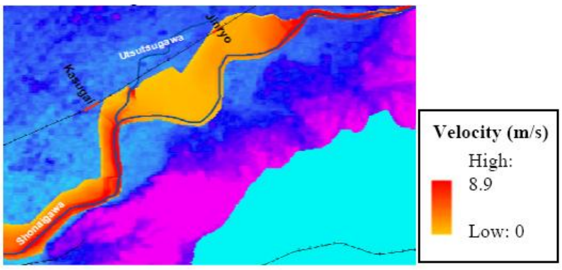


Figure 12. Velocity inundation area

D. Interactive Web-based Application

The alert criteria are used to send an e-mail alert to registered users once a threshold value is exceeded (e.g., rainfall > 50mm). Threshold values correspond with recommendations of the Water Information Center.

VII. Conclusion

In conclusion, the findings showed that the proposed method could be used to generate interactive inundation maps from historical data; to provide near-real time updates in an online setting; and to automatically e-mail flood-risk alerts based on specified hydrological thresholds. The use of such integrated flood-warning systems can rapidly disseminate information to local inhabitants and agencies; and can provide advance warning of necessary flood preparations, thereby potentially mitigating the effects of flooding within local communities.

References

[1] *The Disaster Handbook*, National edition, Coorperative Extenstion Service, Institute of Food and Agricultural Sciences, University of Florida, 1998, Chapter 6, pp. 1-12.

[2] M. Haq, M. Akhtar, S. Muhammed, S. Paras, and J. Rahmatullah, "Techniques of remote sensing and GIS for flood monitoring and damage assessment: A case study of Sindh province, Pakistan," *Egyptian Journal of Remote Sensing and Space Sciences*, vol. 15, no. 2, pp. 135-141, 2012.

[3] *Nigeria Food Security Outlook*, Widespread flooding across the country reduces crop production levels, Famine Early Warning Systems Network, October 2012 – March 2013.

[4] *Flood Damage Reduction Strategies and Tools*, Emergency *Management* Institute, Federal Emergency Management Agency, 2012, pp. 1-17.

[5] *Flood: The Awesome Power*, National Oceanic and Atmospheric Administration, National Weather Service, U.S. Department of Commerce, 2005, pp. 1-16.

[6] *Integrated Flood Management*, Case Study, Japan: Tokai Heavy Rain (September 2000), Ministry of Land, Infrastructure and Transport, Japan, World Meteorological Organization//Global Water Partnership (WMO/GWP), Associated Program on Flood Management, 2004, pp. 1-47.

[7] K. Thirumalaiah and M. C. Deo, "Real-Time flood forecasting using neural network," *Computer-Aided Civil and Infrastructure Engineering*, vol. 13, no. 2, pp. 101-111, March 1998.

[8] P. Begkhuntod, "Application of Satellite information for flood risk reduction in Mekong river basin," presented at the Regional Workshop on Innovative Approaches to Flood Risk Reductionin the Mekong Basin, October 17-19, Khon Kaen, Thailand, 2007.

[9] Disaster Planning, Safeguarding, (January 15, 2013). The United Nations Educational, Scientific and Cultural Organization (UNESCO). [Online]. Available: http://webworld.unesco.org/safeguarding/

[10] T. Sakamoto, N. V. Nguyen, A. Kotera, H. Ohno, N. Ishitsuka, and M. Yokozawa, "Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong delta from MODIS time-series imagery," *Remote Sensing of Environment*, vol. 109, no. 3, pp. 295-313, August 2007.

[11] K. Auynirundronkool, N. Chen, C. Peng, C. Yang, J. Gong, and C. Silapathong, "Flood detection and mapping of the Thailand central plain using RADARSAT and MODIS under a sensor web environment," *International Journal of Applied Earth Observation and Geoinformation*, vol. 14, no. 1, pp. 245-255, February 2012.

[12] C. W. Dawson, R. J. Abrahart, A. Y. Shamseldin, and R. L. Wilby, "Flood estimation of ungauged sites using artificial neural networks," *Journal of Hydrology*, vol. 319, no. 1-4, pp. 391-409, March 2006.

[13] R. Walton, "HEC-RAS for managers," presented at the Mississippi State University, Department of Engineering, 2011.

[14] G. W. Brunner, *HEC-RAS River Analysis System*, U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2010, pp. 1-790.

[15] A. Cook and V. Merwade, "Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping," *Journal of Hydrology*, vol. 377, no. 1-2, pp. 131-142, October 2009.

[16] E. C. Carson, "Hydrologic modeling of flood conveyance and impacts of historic overbank sedimentation on West Fork Black's

Fork, Uinta Mountains, northeastern Utah, USA," *Geomorphology*, vol. 75, no. 3-4, pp. 368-383, May 2006..
[17] M. S. Horritt and P. D. Bates, "Evaluation of 1D and 2D numerical models for predicting river flood inundation," *Journal of Hydrology*, vol. 268, no. 1-4, pp. 87-99, November 2002.
[18] S. M. Ervin and H. H. Hasbrouck, *Landscape Modeling: Digital Techniques for Landscape Visualization*, McGraw-Hill, 2001, pp. 64-66.
[19] G. Quaro and F. Koch, *ArcGIS Report*, Hydro Asia, 2010.
[20] C. T. Ackerman, *HEC-GeoRAS GIS tools for Support of HEC-RAS using ArcGIS*, U.S. Army Corps of Engineers, Hydrologic Engineering Center, 2009, pp. 1-246.
[21] Water Information System. (January 9, 2013). Ministry of Land, Infrastructure and Transport, Japan. [Online]. Available: http://www1.river.go.jp/
[22] Japan Meteorological Agency. (January 17, 2013). [Online]. Available: http://www.jma.go.jp/jma/index.html
[23] Advanced Spaceborne Themal Emission and Reflection Radiometer (December 4, 2012). Global Digital Elevation Model. [Online]. Available: http://gdem.ersdac.jspacesystems.or.jp
[24] Forestry Hydrology GIS Watershed Delineation. (February 2012). Scholars' Lab, University of Virginia Library. [Online]. Available: http://www.lib.virginia.edu/scholarslab/resources/class/foresthydro/foresthydroexercise.pdf/
[25] E. Tate, *Introduction to HEC-RAS*, Center for Research in Water Resources, 1999.
[26] R. Cooke, *Interpolation, Drainage and Water Management*, Agricultural Engineering Science, University of Illinois at Urbana-Champaign, 2008.
[27] H. R. Wallingford, *R&D Outputs: Flood Risks to People, Phase 2*, Flood Hazard Research Centre, Middlesex University, Rish and Policy Analysts, 2006, pp. 1-91.

Ponthip L. She obtained her B.S. degree from Thammasat University, Bangkok, Thailand in 1994. She received the Master of Arts in Geography at the Wertern Michigan University in 2002. She received the Doctor of Philosophy degree in Media and Governance from Keio University in 2011.
In 2002-2007, she worked at the Geoinformatics Center, Asian Institute of Technology, Thailand as a researcher in the field of an Interactive GIS and Database Management. At present, she is a research fellow of International Digital Earth Applied Science Research Center at Chubu University.

Hiromichi F. He graduated from Nagoya University in 1980. He received the Doctor of Science degree in Earth Sciences from Nagoya University in 1987. He is a professor of Chubu University and serves as the Director of International Digital Earth Applied Science Research Center (IDEAS) of Chubu Institute for Advanced Studies in natural disasters from April, 2011. Before joining Chubu University, he was as a Professor of the Faculty of Policy Management of Keio University.
His current research interests include regional planning, ecological development, global environment issues and education for sustainable development from the view point of spatial information sciences.
He has served on secretary general of GIS Association Japan, on Board of Directors in International Society for Digital Earth, Center for Environment Information Sciences, and as an adjunct professor of Chinese Academy of Sciences.