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EFFECTIVE SENSING AND COMPUTING INLAND FLOOD PROCESSES IN A LOWLAND URBAN AREA WITH SEWER AND DRAINAGE SYSTEMS

Takashi TASHIRO[1], Aung Khaing MIN[2] and Ryota TSUBAKI[3]

[1]Member of JSCE, Designated Professor, Disaster Mitigation Research Center, Nagoya University
(#401 Disaster Mitigation Building. 1 Furo-cho, Chikusa-ku, Nagoya 464-8601, Japan)
[2]Student Member of JSCE, Graduate School of Environmental Studies, Nagoya University
(#206 Eng. Bldg. No.9, 1 Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)
[1]Member of JSCE, Associate Professor, Graduate School of Engineering, Nagoya University
(#205 Eng. Bldg. No.9, 1 Furo-cho, Chikusa-ku, Nagoya 464-8603, Japan)

Pluvial flooding has not been sufficiently characterized owing to the lack of real quantitative data and accessible simulation tools although it has become a critical concerns in lowland urban areas. The present study proposes the effective sensing and modeling of inland flooding processes in lowland cities with drainage systems. First, we develop an estimation method for local inland flooding processes in urban areas using water depth loggers and a digital elevation model, both of which are cost-effective and do not require the latest technology. The logged observation data in storm water drainage systems combined with high-resolution altitude distributions can help track the inland drainage process. We examine the effect of drainage channels in mitigating inland flooding by employing the open source, free computational modeling tool NILIM 2.0. Further, we discuss the accuracy of the model by comparing actual flooding data with spatio-temporal data collected using the new method.

Key Words : *inland flooding, lowland city, combined sewer system, drainage channel network, digital elevation model, water level logging, NILIM 2.0*

1. INTRODUCTION

Inland flooding is one of the most frequent disasters in urban areas with tropical or monsoon climates, and it can cause significant damage in developing countries because of insufficient infrastructures for preventing inundation[1), 2)]. There are a few conventional studies that have visualized and observed inland flooding processes. It is necessary to monitor practical scenarios for collecting data related to inland flooding. Moreover, reliable computational methods need to be employed to analyze the effects of storm water drainage systems in urban areas during heavy rainfall events in order to mitigate inundations and minimize damage. This study proposes an effective data collection system and applies it to an open source flood/drainage model for identifying inland flooding processes.

Only a few studies have focused on quantitative record-based inland flooding processes. Although inland flooding frequently leads to large economic loss in urban areas, such as those caused by the Tokai Flood[3)], these phenomena or processes have not been sufficiently characterized. Currently, high-resolution elevation data can be easily collected via remote sensing using satellite images on a global scale, and water depth measurements can be obtained using pressure sensors. Thus, one of the objectives of this study is to propose a cost effective and reliable sensing system for inland flooding by employing conventional data and devices. This may help develop and spread onsite monitoring systems using recently developed communication techniques such as the Internet of things (IoT)[4)].

Modeling inland flooding processes is a popular research topic not only in the fields of hydraulic and hydrology, but also in other fields such as electrical engineering and informatics. There are various approaches based on different specializations. Although new methods such as artificial intelligence (AI) and machine learning techniques have been recently applied[5)], some hydraulic researchers have developed a real-time forecasting system for urban inland flooding[6)]. However, in order to analyze urban inland floods on a global scale, most studies recommend the use of commercial software such as InfoWorks, MOUSE and XP-SWMM; however the uses of these programs have been very limited due to their high cost, with regard to developing countries where especially vulnerable to severe inland flooding[2].

Thus, to overcome these issues, researchers can use the New Integrated Lowland Inundation Model (NILIM 2.0), which is a conventional free and open source model (National Institute for Land and Infrastructure Management, Japan, http://www.nilim.go.jp/lab/rcg/newhp/seika.files/nilim/download.html)[7, 8] for inland flooding simulations. However, only a few researchers have applied the NILIM 2.0 model (Sunaguchi and Tsuchiya[9] and Tashiro and Min[10]), and thus, the software developers have not updated the program code in recent years. Hence, we also discuss the advantages and disadvantages of NILIM 2.0 by verifying its performance using originally collected data in order to develop an accurate model for inland flooding. Furthermore, to better understand inland flooding and develop effective sensing and modeling, a case study was conducted in the downtown area of Tsushima City, located in the Nobi plain, which is the western lowland area of Aichi prefecture. The study area features a storm drain system composed of a small combined sewer and drainage open-channel networks.

2. SENSING INLAND FLOODING

In this study, we present the estimation procedures for local inland flooding processes in the downtown area of Tsushima City using water depth loggers and a digital elevation model, both of which are cost-effective and do not require the latest technology.

(1) Materials and methods

Tsushima City (35º 10' 37’ N and 136º 44' 29’ E) has a total area of 25.09 km². In 2012 the total population was 65,118, i.e. a population density of 2,596 inhabitants per 1 km² [11]. Topographically, the city is in a low-lying area with elevations ranging from 3.6 m below to 8.2 m above mean sea level. Due to its location in the East Asian monsoon region, the city experiences a rainy season in June; annual precipitation is approximately 1,500 mm.

The typical forms of land cover have undergone rapid changes; e.g., urbanized land increased from 30% in 1976 to 51% of total area in 2009, whereas the extent of crop fields decreased from 65% in 1976 to 42% in 2009[12]. Most inundation is in the form of inland flooding; river flooding has hardly been observed in this area since the Isewan Typhoon (VERA) of 1959.

Table 1 Dimensions of observed drainage channels.

	Width (m)	Height (m)	Bed elevation (m)	Remarks
St. 1-1	2.00	1.25	-2.15	open straight type -1: upper, -2: middle, -3: lower part
St. 1-2	2.00	1.18	-2.08	
St. 1-3	2.00	0.99	-2.09	
St. 2	2.15	1.14	-2.44	open straight type
St. 3	1.20	0.65	-2.35	junction of open / closed channels
St. 4	5.00	1.28	-2.68	effluent stream

We conducted a survey with four measuring stations (Sts. 1, 2, 3, 4), including a total of six observation points (Sts. 1-1, 1-2, 1-3, 2, 3, 4) that were set up at the two drainage channel systems (Channel A: Sts. 1, 2 and Channel B: St. 3) and the effluent stream (St. 4) which receives the water drained from both these channels. The channel dimensions such as the height and width of every station were measured (**Table 1**). Self-recording depth loggers (HOBO U20L-01, Onset Computer) were installed in storm water drainage channels at these observation points. The time series data for water level elevations were obtained by adding the measured water depth to the altitude of the stations in the GSI map based on the digital elevation model acquired by airborne laser surveying with a 0.3 m altitude resolution (Geospatial Information Authority of Japan, https://maps.gsi.go.jp/).

The survey period was approximately 450 days, from October 2017 to January 2019; however, the water level was not measured in some non-flooded seasons. The overflows of water channels at the survey sites are recorded using loggers, and these results are used to describe the inundation area from the altitude distribution of the area surrounding these sites. Hourly rainfall data were available from the nearest local rain gauge station “Aisai” approximately 6 km away from our study site, published in the website of the Japan Meteorological Agency (http://www.jma.go.jp/jma/index.html) during the survey period. The 10 min rainfall intensities were also collected in Tsushima City by the River Division of Aichi Prefecture.

(2) Results and discussions

Fig. 1 shows the water level fluctuations at each station along with the rainfall hyetograph. The heaviest recorded rainfall was 32 mm/hr (23:00 on October 22, 2017) when Typhoon No. 21 (LAN) was approaching the city (**Fig. 2**), and the second heaviest rainfall was 30.5 mm / hr (21:00 on July 7, 2018) during a heavy rain event, which caused water level increases at the measuring stations. By comparing each of these water levels and channel dimensions such as heights and bed elevations (**Table 1**), the overflow from the drainage channels could be monitored if the

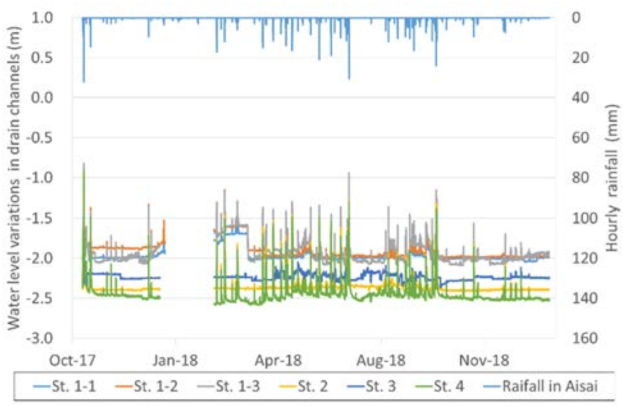

Fig. 1 Water level variations in the drainage channels and rainfall distributions in the target area during the survey period (rainfall data source: Japan Meteorological Agency).

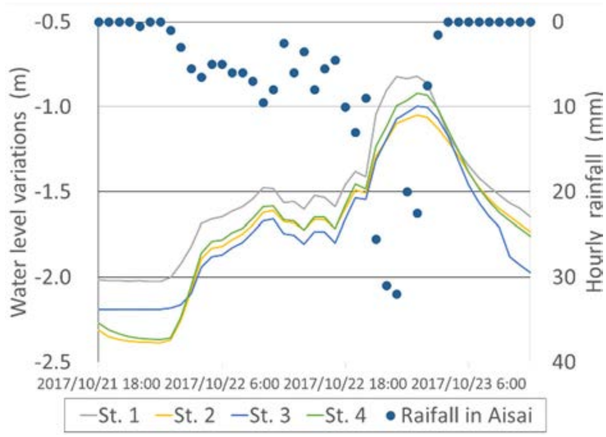

Fig. 2 Water level variations in the drainage channels and rainfall distributions in the target area as Typhoon LAN approached in October 2017 (rainfall data source: River Division of Aichi Prefecture).

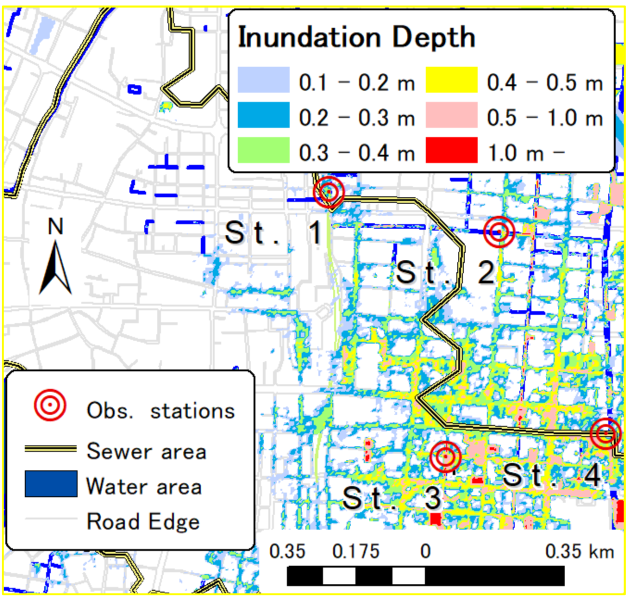

Fig. 3 Severest inundation map as Typhoon LAN approached in Oct. 2017 estimated with collected water level variations in measuring stations (Sts. 1 - 4) and digital terrain model of the GSI map, on networks of roads (gray lines) and drainage channels (blue lines) in the target area, drawn by ESRI Arc GIS 10.2.

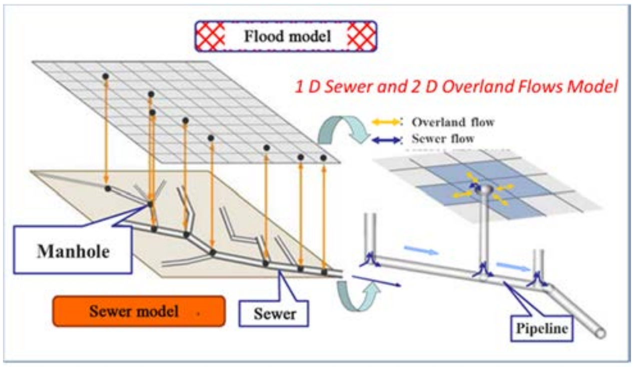

Fig. 4 Structure of the adopted NILIM model[7), 11)] with one-dimensional sewers and two-dimensional overland flows.

water levels exceeded the height of the channel top as follows: -0.9 m, -0.9 m, -1.1 m, -1.3 m, -1.7 m, and -1.4 m in Sts. 1-1, 1-2, 1-3, 2, 3, and 4, respectively. According to these conditions, overflow was observed in Sts. 1 and 2 for a total of 8 and 10 hoursrespectively, for both events (Typhoon LAN Oct. 2017 and heavy rain event July 2018). However, 11 overflow events were also observed for a total of 34 hours at St. 3 where drainages merge from three directions, and 3 overflow events for a total of a 12 hours were observed at St. 4 where drainages poured.

Fig. 3 shows the inundation area at the peak of flooding as Typhoon LAN was approaching in October 2017 (see **Fig. 2**) when the water levels reached -0.9 m in altitude (higher than each of the channel tops), estimated from the collected water level at each of the stations and the terrain altitude distribution of the surrounding area by the GSI map. It was clarified that the inundation expanded along drainage channels and roads at relatively lower areas in the eastern part of the downtown (see **Fig. 3**). Because Typhon LAN caused inland flooding in this area between 21:00 to 5:00, it could not seriously damage public/private properties at that time, owing to the less traffic in this area. These processes are important, because thus far, the inland drainage process during heavy rainfall in urban areas has hardly been analyzed empirically.

3. COMPUTING INLAND FLOODING

To model the entire process of inland flooding using an open source program, we selected the NILIM 2.0 model[7)]. In Tsushima City, the combined type of sewer system has been used in the downtown area since 1964[11)]. This system comprises sewer pipes, manholes, regulators and pumping stations, and the drainage channel networks that help drain storm water. Data on the position of each component, including the slope, shape, and diameter of pipes, were obtained from Tsushima City authorities. The drainage infrastructure of the sewer system encompasses 796 manholes, 28 km of sewer pipes, and 3,159 flow regulators.

(1) Simulation model

The NILIM 2.0[7)] model is an integrated flood model that combines three separate modules: a one-dimensional unsteady river flow model, a sewerage network model, and an urban floodplain overland flow mesh model. An overview of the NILIM model is shown in **Fig. 4**. The model can analyze complex hydraulic interactions between the surcharging flow from sewer pipes and the flow of overland surface flooding by considering detailed conditions of the surface topography and the features of the underground sewer network. In the sewer system, two flow conditions are considered: open channel state and pressure state. The open channel state is considered when the water level is lower than the pipe crown and the pressure state is considered when the water level is higher than the pipe crown. The selection of basic equations for the simulations depends on this situation. For floodplain surface conditions, a variety of structures and drainage facilities can be specified on the mesh and regarded as the roughness or boundaries of the surface water calculation.

(2) Setup for the computation environment

a) Computational domain

The computational domain was selected considering the distribution of the combined sewer system and the drain channel networks by reviewing flood data from the Tsushima City authorities to cover the areas that frequently experience inland flooding. This domain includes the Tsushima station and some parts of the core downtown areas, involving a total area of 202.59 ha. A two-dimensional surface model (30 m × 30 m) was established using the digital elevation model (DEM) of LiDAR data (5 m resolutions) with a vertical resolution of 0.1 m, and the actual building distribution in the period 2014–2015. Both datasets were part of the basic geographic data for Japan provided by MLIT's Geospatial Information Authority (http://www.gsi.go.jp/kiban/).

Fig. 5 shows the computational domain with modeled sewer systems and drainage channel networks. We described 122 manholes and 6.6 km of pipes (larger than 0.6 m in width) in total for the modeled sewer system, and 115 channels (larger than 1.2 m in width) with a total length of 7.2 km in the computational domain. These settings were given based on the information provided by the water and sewage department of Tsushima City.

In this computational domain, each manhole was modeled to be combined with its drainage area, and

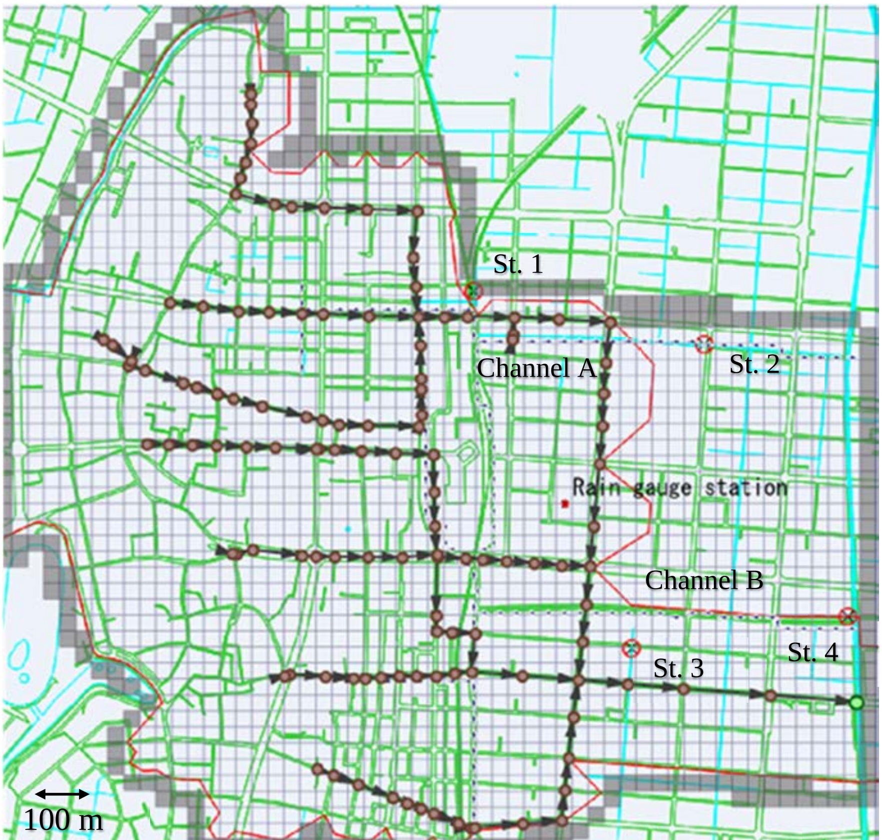

Fig. 5 Computational domain and measuring stations (Sts. 1 to 4 and rain gauge) in the map of railway, road and water location (green and light-blue lines) with a 30 m square mesh configuration, icluding modeled sewer manholes and pipes (arrows and plots) and drainage channels (broken lines, Channels A and B).

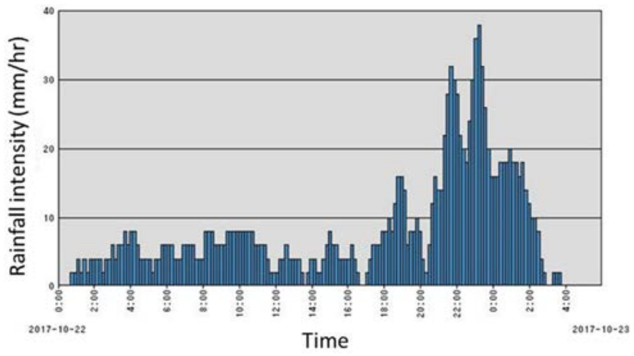

Fig. 6 Hyetograph used for the inland flooding computation, made from the rainfall data in every 10 min (data source: River Division of Aichi Prefecture).

it was to be treated as an interfaces for the 2D surface and 1D sewer flow[7), 8)]. An infiltration rate of 10 mm/hr was selected as the condition for the area without buildings according to the NILIM 2.0 manual[8)].

b) Computational condition

The rainfall event considered in this simulation is the 29-hour rainfall from 00:00 on October 22 to 05:00 on October 23 when the 2017 Typhoon No.21 was approaching. This is the period when the study area was most recently inundated by severe inland flooding (**Figs. 1-3**). A hyetograph was plotted from the data recorded at the regional prefectural office near the study location (**Fig. 6**). These data were collected in the “Rain gauge station” as shown in **Fig. 5** and it was provided by the River Division of Aichi Prefecture.

For the roughness condition (given as the Manning’s *n* values) in the domain, the building occupation ratio in each of the meshes was reflected in the 2D overland flow calculation, whereas common values such as 0.015 were used for sewer pipes and 0.013 for drainage channels for the 1D sewer and drainage flow calculations. As boundary conditions, the base flow discharges were provided based on estimates using the watershed area and the specific discharge (0.015 $m^3/s/m^2$) for each of the manholes, whereas the water level data monitored in St. 4 were at the downstream end of pipe. These default values are inputted as per the NILIM 2.0 manual[8)].

Moreover, because the NILIM model can reflect the inundation phenomenon with drainage channel networks as its optional function, both cases with and without these channel networks were simulated.

(3) Results and discussions

The simulations provided information on the overland flooding processes and the performance of the existing drainage network. We identified that inland flooding firstly occurred around at 21:00 October 22, 2017 when the city had heavy rains with an intensity more than 30 mm/hr (**Fig. 6**) which continued up to the end of the simulation duration in both NILIM modeling cases. They were caused by water overflowing from the manholes due to the sewer system saturations, and the total volume of inundating water reached around 29,000 m^3 and 65,000 m^3 with and without drainage channels at 3:00 October 23, respectively. **Fig. 7** shows the two cases of computed inundations with (left) and without (right) the drainage channel network at 03:00 on October 23, 2017 when Typhoon LAN was approaching. We identified that the storm water was collected by the sewer network, leading to inundations at lower elevations in the south or east flatlands. Furthermore, these simulation figures show that the channel networks practically drained the storm water to decrease not only the

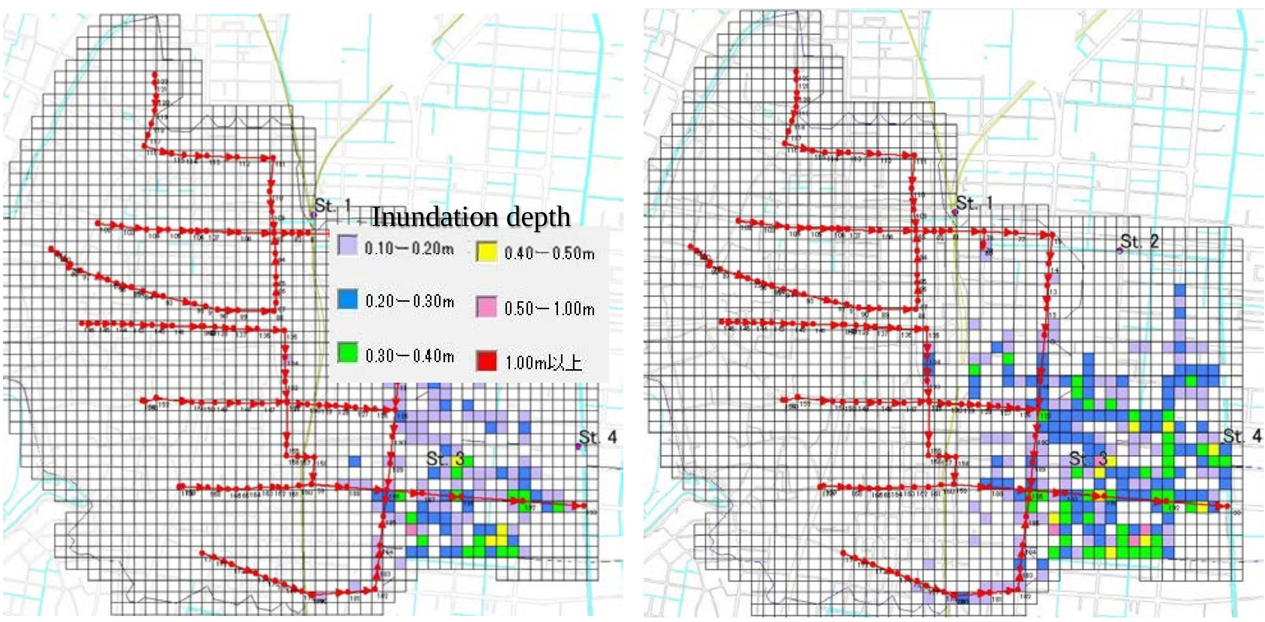

Fig. 7 Computed inundation depth distributions with (left) and without (right) the drainage channel network with the sewer system network (red arrows and plots), at 3 am October 23, 2017 in the severest situation.

area, but also the depth of inundation. Moreover, the computed inundation distribution without drainage channels is closer to the observed one (**Fig. 3**).

We could simulate and describe the spatiotemporal processes of detailed inundations (in 30 m meshes with 10 min intervals) in the case of urban flooding due to heavy rainfall. However, by comparing the temporal processes, although both of the starting times of inundations are equally around 21:00 October 22, the severest times were quite different. Severe inundation actually occurred around 01:00 (**Fig. 2**) but was computationally predicted around 03:00 October 23 (**Fig. 7**). Moreover, the depths and locations of computed inundations (**Fig. 7)** were under-estimated in both of the computational cases compared to the actual situation (**Fig. 3)**. The computed results could be improved by tuning (but would not be so meaningful under the anomalous conditions), if we change the setting of the pipe and channel conditions such as roughness coefficient and so on. However, we consider that the drainage functions might be deteriorated by clogging due to sediments or garbage from upstream drainage areas as described in official reports[13)] and as observed in the field. There are few studies which focused on these clogging effects on drainage capacities, although there have been several studies that reported on enlarging sewer pipes[9)] or raising the infiltration rate of the surface area[10)] to mitigate inland flooding using conventional software. Solid wastes and sediments are more crucial issues in effective maintenance and the development of drainage systems not only for sanitation improvements but also for flood mitigations in (sub) urban areas.

6. CONCLUSIONS

We presented procedure for estimating local pluvial flooding processes in an urban area using water depth loggers and a digital elevation model, which are cost-effective and do not require the latest technology. The recorded water depths in storm water drainage systems could be utilized for tracking the inland drainage process by combining it with high-resolution altitude distribution.

Further, we demonstrated that the NILIM 2.0 model could describe the spatiotemporal processes of detailed inundations and could identify the effect of drainage channel networks on mitigating inundation depth and reducing the inundation area in our study area. However, there are some gaps between observed and computed processes of the flooding. We therefore suggest studying the effect of clogging of drainage systems by solid wastes and garbage to flood mitigation in urban areas.

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REFERENCES

1) Kundzewicz, Z.W. and Takeuchi, K.: Flood protection and management: quo vadimus?, *Hydro. Sci. J.*, Vol.44, pp.417-432, 1999.
2) Balk, D., Montgomery, M. R. and Liu, Z.: Urbanization and Climate Change Hazards in Asia, *Population Association of America 2013 Annual Meeting Program*, New Orleans, LA, April 11-13, 20p, 2013.
3) Sato, T. : Fundamental Characteristics of Flood Risk in Japan's Urban Areas: *A better integrated management of disaster risks: Toward resilient society to emerging disaster risks in mega-cities*, Eds., S. Ikeda, T. Fukuzono, and T. Sato, TERRAPUB and NIED, pp.23-40, 2006.
4) Hiroi, K. and Kawaguchi, N.: FloodEye: Real-time Flash Flood Prediction System for Urban Complex Water Flow, *Proc. of the IEEE Sensors 2016 Conference*, 2016.
5) Wada, K. and Kojiri, T.: A study on flood forecasting system by using Topological Case-Build Model, *J. Japan Soc. Hydrol. And Water Resour.*, Vol.23, pp.201-215, 2010.
6) Sekine, M.: Highly accurate prediction system of urban inundation and inundation phenomenon in Tokyo, *Nagare, The Japan Society of Fluid Mechanics*, Vol.37, pp.11-18, 2018 (in Japanese).
7) Nakamura, T., Sasaki, Y. and Mizukusa, K.: A guideline of application for flood analysis models in the urban areas, *Technical Note of National Institute for Land and Infrastructure Management*, No.202, 34p., 2004.
8) Flood Disaster Prevention Division, River Department, National Institute for Land and Infrastructure Management, Ministry of Land, Infrastructure, Transportation and Tourism: *Manual of NILIM 2.0*, 2012 (in Japanese).
9) Sunaguchi, M. and Tsuchiya, M.: Study on the simulation of an inner water inundation and reduction measures of the water disaster for the drainage basin of storm water in an urban area, *J. Japan Soc. Civil Engineers*, Ser. B, Vol.64, No.4, pp.240-250, 2008 (in Japanese with English abstract).
10) Tashiro, T. and Min, A.K.: Flood risks and their management in Urban Japan - modeling inner flooding in Tsushima City, Tokai Region, *Towards the Implementation of the New Urban Agenda – Contributions from Japan and Germany to Make Cities More Environmentally Sustainable*, Eds., B. Müller, and H. Shimizu, Springer, 2017, pp.117-126.
11) Tsushima City: Tsushima City Guide 2013, https://www.city.tsushima.lg.jp/smph/shokai/tsushimashiprofile/shiseisyoukai/2013shisei.html.
12) Min, A.K.: *Inundation management in urban drainage area with combined sewer system: A case study in downtown area of Tsushima City, Japan*, Master thesis, Graduate School of Environmental Studies, Nagoya Univ., 2015.
13) Lamond, J., Bhattacharya, N. and Bloch, R.: The role of solid waste management as a response to urban flood risk in developing countries, a case study analysis, *WIT Transactions on Ecology and The Environment*, Vol.159, pp193-214, 2012.

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