

## Review:

# Advances in Urban Stormwater Management in Japan: A Review

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The series of annual flood disasters that struck Japan in recent years pose challenges to urban stormwater management. Japan has been implementing nation-wide hydrometeorological observation through a dense network of rain gauges. Since the recent decade, ground radars have been deployed to observe heavy rainfall with high spatiotemporal resolution as a countermeasure. While commercial software is popular in designing stormwater drainage systems, several integrated urban flood models have been developed domestically and are applicable in stormwater management. A paradigm shift with the rise of Internet of Things (IoT) provides an inexperienced opportunity in hydrological observation, and has been implemented for monitoring sewer network conditions. Despite this broad scope of research works and technological innovations, such advancement is not internationally recognized yet. The present study aims to review the development and role of science and technology in stormwater management in Japan, focusing specifically on rainfall observation, integrated urban flood modelling, and emerging technologies for stormwater monitoring. In addition, the possible future direction of stormwater management is envisioned. Considering the series of record-breaking rainfall events that struck Japan, we will have to face more severe challenges in urban flood management alongside the impact of global climate change. As compared to structural measures, which are subject to budgetary constraints, the relative importance of non-structural measures is increasing; therefore, effective application of numerical modeling techniques is required. A common weakness of the urban flood modeling framework is the limited availability of observations in sewer networks, which can be relaxed by emerging IoT based observations. The fusion of IoT based observations with an integrated urban flood modeling technique appears to the emerging technology for stormwater management.

**Keywords:** stormwater management, rainfall observation, integrated urban flood modelling, Internet of Things

## 1. Introduction

The successive flood events associated with Northern Kyushu Heavy Rain in 2017, Western Japan Heavy Rain in 2018, and Typhoon Hagibis in 2019 that devastated wide areas of Japan have apparently increased awareness about the prevention or mitigation of flood damages and, to this effect, several research studies have been conducted to examine such flood events [1, 2]. Aside from coastal flooding, flood disasters that are particularly of concern in Japan are mainly of two types: fluvial flooding and pluvial flooding, which are known in Japanese as “Gaisui” and “Naisui,” respectively. While fluvial flooding can devastate extensive areas [3], pluvial flooding can have a strong economic impact, and a breakdown reveals that about 40% of the economic damage associated with flooding is attributed to pluvial flooding [4]. Hence, it is reasonable to assume that there have been historical research development, local practices, and technical development against stormwater management [5–13].

Despite such works that have been conducted in Japan and there exists a review in a historical development and future perspectives of run-off models and their application in urban areas [14], it appears that recognition of those developments is typically limited domestically and somewhat obfuscated internationally. This can be partly attributable to language, that is, journals and reports published in Japanese are the preferred publications in the field of stormwater management in Japan. These motivate the present authors to internationally introduce some of these contemporary sciences in stormwater management that are applied in Japan for addressing this discrepancy.

In this context, this paper intends to provide a review of some innovative science and technology in stormwater management that have been developed in Japan. Also, while reviewing emerging innovations, this study aims to present possible future directions in stormwater management, which is a worldwide concern in view of the ongoing climate change.



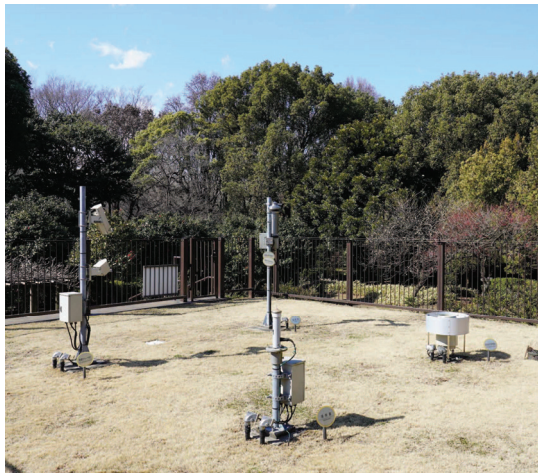


Fig. 1. AMeDAS observation in Otemachi.

## 2. Rainfall Observation for Urban Flooding

Among all hydrometeorological components, rainfall is one of the most critical variables in the water cycle [15], and this is also applicable to urban hydrology. Information about rainfall is used in various ways, such as designing stormwater management infrastructure [6], preparing evacuation plans [16], or conducting numerical simulation [17]. Therefore, measurement of rainfall forms the fundamental basis in urban flood risk management.

### 2.1. Rain Gauge Networks

Organized meteorological observation commenced back in 1872 in Japan, and the observation was managed independently at the prefectural level at that time [18]. The modernized meteorological observation, so called Automated Meteorological Data Acquisition System (AMeDAS), started in 1974 by the Japan Meteorological Agency, with the intention to observe localized meteorology and to apply the information for meteorological disaster management [18]. The AMeDAS comprises densely installed observation stations, and the number of rain gauges amount to about 1,300 across Japan, having average spatial intervals of 17 km [19]. **Fig. 1** shows the observatory stations in Otemachi, Tokyo. The data on observed rainfall depth from unmanned monitoring stations are transmitted at every 10 min interval through telephonic lines, and this enables to provide near real-time rainfall information.

There is another nationwide meteorological observation service in Japan using the telemetry system operated by the Ministry of Land, Infrastructure, Transport and Tourism (MLIT), with 2,769 rain gauges currently installed as of writing the present paper [20]. The MLIT's telemetry system is similar to AMeDAS in that it is used to capture local weather condition, particularly rainfall, but the primary objective is flood risk management in rivers. Hence, telemetry stations are located not on city basis but on river basin basis to observe weather condition in each catchment area. Dense meteorological obser-

vation networks provide unique opportunities to capture spatial distribution of meteorological characteristics from the scale of small river basins to nationwide, especially compared to cases when ground observation is limited and alternative measurements such as satellite-borne information is applied in Asia [21] or in Africa [22]. Nevertheless, the number of rain gauges may not be sufficient for urban flood risk management at the city scale.

### 2.2. Radar Rainfall Observation

In July 2008, many people who were enjoying sunny weather alongside Toga River in Kobe City were suddenly swept away by flash flooding that resulted in five casualties. The Toga river is merely 1.8 km long with a basin area of 8.6 km<sup>2</sup> and the water level in the river is said to have increased to 1.34 m within 10 min, which was caused by a torrential downpour of cumulonimbus clouds [23]. As the size of cumulonimbus clouds is typically in the order of a few kilometers, which might not be captured by rain gauges, the incident highlighted the importance and necessity in detecting potentially hazardous clouds at an early stage by applying radar observations for disseminating early warnings, in the scale of less than 10 min [24].

At the time of the tragic incident, MLIT had the radar observation network for rainfall using C-band polarization radars, but the incident revealed the challenges of using the radar system in detecting downpour caused by cumulonimbus clouds, which grows rapidly. The conventional radar adopts a single horizontal polarization scheme, in which the form and direction of the precipitation particles cannot be determined from reflectivity [25]; therefore, it required calibration against ground observation for quantitative application. Although the radar observation had a horizontal resolution of 1 km and time frequency of 5 min, the time additionally required for calibration confronted real-time dissemination of observed rainfall [26].

In this circumstance, installation of an X-band multi-polarimetric radar observation site was propelled. The X-band multi-polarimetric radar has several advantages compared to a C-band single polarization radar. First, reflectivity in multi-polarimetry enabled identifying the shape of the precipitation droplet. It is known that the bigger the droplet, the flatter it becomes due to air resistance and the oblateness of raindrops can be detected from vertical and horizontal polarimetric reflectivity. Second, phase difference between vertical and horizontal polarization appears in reflectivity from the rainfall and the difference becomes pronounced, especially for intense rainfall, and the distance to the rainfall can be estimated from the phase differences between the vertical and horizontal polarizations. Third, shorter wavelength of 3 cm in X-band radars has an advantage in detailed observation as compared to the wavelength of C-band radar (5 cm), although the radar range becomes shorter. Overall, these enable rainfall observation of 250 m in space and every 1 min in time, and thereby increased spatiotemporally (**Fig. 2**). This has proven the usefulness of radar rainfall observation and is also available at the prefectural level [27].

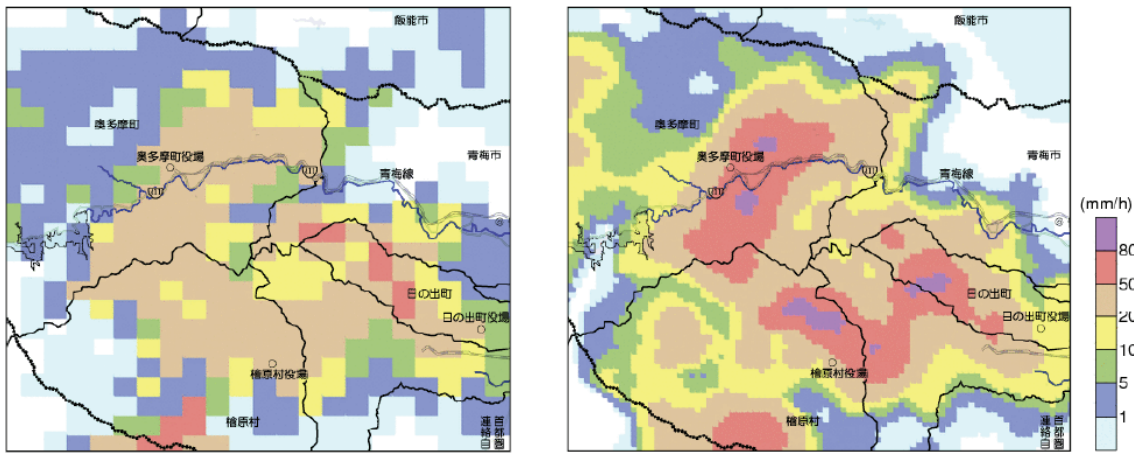


Fig. 2. Comparison of spatial resolution between C-band radar (left) and X-band radar (right).



Fig. 3. Location of radar observation by MLIT. Dashed and solid circles indicate C-band and X-band radars, respectively.

By integrating and compositing spatial coverages of C-band and X-band radars, the overall system is now called eXtended RAdar Information Network (XRAIN), which nearly covers the whole of Japan. Presently, Japan has a nationwide network of 65 radar observatories with 26 using C-band and 39 using X-band for frequency (Fig. 3).

### 2.3. Satellite-Borne Precipitation Observation

There have been extensive researches in the application of satellite-borne observations of rainfall, such as the Tropical Rainfall Measuring Mission (TRMM) [28] or Global Satellite Mapping of Precipitation (GSMaP) [29]. While satellite-borne precipitation products typically have wide observation ranges from the Southern Hemisphere to the Northern Hemisphere, the weak point of the

product is that there exists discrepancy between ground-based observation and satellite-borne rainfall [30], and the biases must be corrected to apply quantitative analysis. Mastrantonas et al. [31] performed inter-comparison of contemporary satellite-borne precipitation products against the typhoon event in 2015 and demonstrated that estimation of the typhoon induced rainfall event is challenging even for decent satellite-borne precipitation products. Therefore, bias correction using ground observation is a necessary procedure. As explained earlier, Japan has a dense observation networks of rain gauges and radars, and application of satellite-borne rainfall products are not common in urban flood risk management. Nevertheless, a combination of satellite products with rain gauges has the potential for risk management, particularly fluvial flooding [32] or identifying surface water body, including flooded areas [33, 34].

## 3. Numerical Models for Urban Flooding

### 3.1. Classical Approaches and Integrated Modelling

Traditionally, the rational formula, such as [35], and empirical formulae, for instance, the Bürkli–Ziegler equation, are popular methods to estimate the peak discharge of stormwater designs that are widely applied worldwide and in Japan. The rational formula assumes a linear relation between rainfall and storm runoff, and it can estimate the peak discharge when the average rainfall intensity over the time of concentration of the storm runoff is given. The empirical formula differentiates from the rational formula in that it explicitly considers the basin slope [36]. Notwithstanding its simplicity in the physical expression of the rainfall-runoff process, this methodology has demonstrated that it can express river discharges in urbanized areas, for instance, by splitting the basin into sub-catchments and overlaying their hydrographs [37].

Under the remarkable advances in computational technology during the 1990s, modernized hydrological and

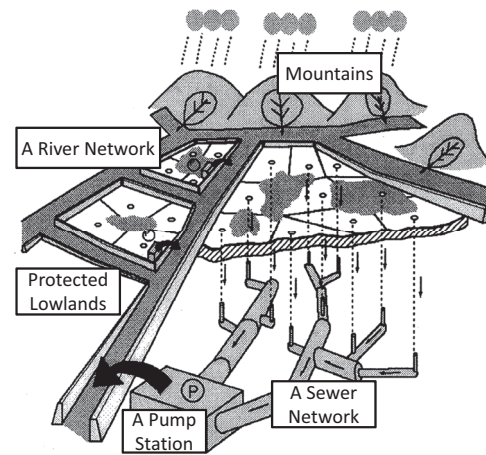
hydraulic models have been developed in Europe and the United States (U.S.) that allow an integrated computation of the rainfall-runoff process and hydraulics in channel flows. To apply those modern models to sewer network management in Japan, especially in the field of rainfall drainage systems and pollutant load, a comparative survey was conducted [38]. At the time of survey, five models were compared, namely HYDROWORKS in the United Kingdom (UK), HYSTEM-EXTRAN in Germany, MOUSE in Denmark, Storm Water Management Model (SWMM) in the U.S., and LHU in France. After considering the availability of these models in the market and the development status of pollutant load models, HYDROWORKS, MOUSE, and SWMM were nominated further for consideration in sewer network management in Japan. These models were listed in the recommended software in the “Runoff Analysis Model Application Manual” [39] and formed the basis for the most popular and wide application of commercial software, currently known as InfoWorks ICM, MIKE URBAN, and XP-SWMM in the management of sewer networks in Japan.

Since the enforcement of the act on countermeasures against flood damage of specified rivers running across cities in Japan in 2003, the anticipated inundation areas by pluvial flooding must be designated and thereby urban flood modelling needs to be applied with the corresponding designed rainfall for each city. This has likely accelerated the application of the commercial software for the urban flood model as it can perform integrated analysis of the rainfall runoff process and the dynamics of sewer network flows. These models are categorized into the so called “integrated model” as they typically consist of multiple model components [40]. The common hydraulic processes in the integrated models include the interaction of a one-dimensional pipe flow in sewer networks and a two-dimensional flow process on the ground surfaces, which is essential in relation to enforcing the aforementioned act.

### 3.2. Integrated Urban Flood Modeling in Japan

Domestically, a New Integrated Lowland Inundation Model (NILIM2.0) [41] was developed by the National Institute for Land and Infrastructure Management in Japan. The NILIM2.0 is a physically based model, and it consists of four numerical components that simulate the surface runoff process, sewer pipe flow, in- and out-flow through manholes, and horizontal flow on the ground surfaces. While the model was developed domestically, its application has been mainly in the field of research studies, such as the prediction of pluvial flooding [42], risk assessment of pluvial and fluvial flooding [43], or further including the tidal effect [44], and it is not commonly applied by local authorities. This is likely because commercial software has an advantage in the long history of an integrated development environment (IDE), for instance, integrated use and affinity with essential functions such as GIS, thereby enabling to build models with relative ease.

Nonetheless, development of integrated urban flood models has been active in Japan, and several flood models



**Fig. 4.** An integrated urban flood model, modified after Kawaike et al. [45].

have emerged and have been applied in various research fields. To our best knowledge, one of the earliest research works focusing on urban flooding by the integrated model in Japan was developed by Kawaike et al. [45], in which integrated model components of runoff from mountainous areas, river networks, urban inundation, and sewer networks, was applied to the low-lying areas of Neyu river in Osaka (Fig. 4). In their work, a sewer network was expressed as a simplified combination of main and branches, in which the designed flow velocity and discharges were given. Later on, Kawaike et al. [46] updated the sewer network model component by considering an open narrow slot at the top of pipes, enabling application of the continuity equation and the momentum equation of open channel flow, which is commonly referred to the Preissmann slot technique [47].

There is an ongoing effort in the enhanced application of the integrated urban flood models. Sekine [48] developed a numerical model of pluvial flooding targeting dense residential areas in downtown Tokyo by combining the river channel, sewer network, and road network models, in which one dimensional flow is considered on the ground surface. Later, the target areas were extended to most of the Tokyo metropolitan area, accounting for 390 km<sup>2</sup>, with an enabling evaluation of the submerging underpass phenomena [49]. Akiyama et al. [50] developed an integrated urban flood model by combining both pluvial and fluvial flood models with the sewer network model with the Preissmann slot technique, and the model was applied to evaluate the effect of flood countermeasures and potential economic damages due to flooding in Iizuka City, Kyushu [51]. Takeda et al. [52, 53] demonstrated another application of the integrated flood model by targeting the low-lying areas of Kasugai City, Nagoya. They analyzed the combined impact of fluvial flooding and storm surges [53] and fluvial and pluvial flooding [52] by considering the origin of the flooding source, that is, either a river or sea, by providing additional source terms in the continuity equation, which is methodology developed by Sayama and McDonnell [54].

A further advanced model is the seamlessly integrated model, which consists of the river, sewer network, and inundation models, targeting the coastal low-lying urbanized areas of the Tsurumi River basin [55]. In such areas, river discharge, tidal fluctuations, and city drainage altogether influence urban inundation, and therefore, it is necessary to consider their potential interference to understand the effect of compound water hazards. For instance, pump stations cannot pump out stormwater when the river water level is high, and in the meantime the river water level shall increase when it receives pumped water from cities. At the river mouth, as the tidal fluctuation regulates the water levels in the river, it will also affect the functionality of pump stations and possible inundation from rivers. In this regard, the seamless model has an advantage in having a direct connection with the river runoff model, Water and Energy Budget Based Distributed Hydrological Model (WEB-DHM), which encompasses the land surface model and thereby can estimate soil moisture and groundwater of the basin, enabling accurate estimates of upstream discharges resulting from an initial physical state of the basin [56]. Also the seamless model can be connected to the coastal hydraulic model so that the tidal changes estimated by the storm surge model can give the boundary condition in the river mouth [55]. With all these model components, the model can estimate the compound water hazards from the upstream to the river mouth.

### 3.3. Validation of Integrated Urban Flood Models

As such, several integrated urban flood models have been developed and applied domestically in Japan. Nevertheless, the problem persists in model validation, particularly in the sewer network, where observations are essentially missing. Kawaike et al. [57] argued the integration process between surface inundation and the sewer network model by verifying through the use of hydraulic laboratory experiments and highlighted the difficulty of simulating the surface- and sewer-network interactions, indicating need for model representation. Lee et al. [58] analyzed the records of water levels obtained from water loggers installed in the sewer network in the Tsurumi River basin, and showed that changes in water level in response to actual rainfall have characteristics specific to the length of sewer network and areas of drainage catchment, and demonstrated that calibration is necessary for the seamless model although the model was previously validated with observed water level in the river and flood control volume [55].

These imply that while there exist several integrated models, developed domestically or internationally, one should not become overly confident about the models even if the results show good agreement with the observed water levels in rivers or inundation depth on the ground surface unless the results are also validated against observations in the sewer network; moreover, one should be cautious about the interpretation of hydrodynamics in sewer networks. The problem will likely persist unless the problem in obtaining observations in the sewer network is solved.



**Fig. 5.** A Multi-Parameter Phased Array Weather Radar (MP-PAWR) by TOSHIBA (see [13]).

## 4. New Waves of Monitoring and Numerical Simulation

### 4.1. Next Generation of Radar Observation

Although X-band MP radars can be considered a breakthrough in measuring the spatiotemporally fine resolved observations of rainfall, further advanced radar is on the way. The next technology that can become the mainstream of radar observations is the Multi-Parameter Phased Array Weather Radar (MP-PAWR) [13, 59]. The MP-PAWR has a flat antenna panel, on which the antenna elements are aligned as an electronically scanned array (**Fig. 5**). By emitting radio signals from each antenna element with a slight shift in its beam foaming, the flat antenna can detect disturbances in reflected wave signals from the rainfall cloud by the Huygens–Fresnel principle, without changing the elevational and azimuthal direction of the antenna. By combining the antenna panel’s mechanical rotation for horizontal scan and electronic scan for vertical scan, the PAWR can rapidly detect a three-dimensional distribution of rain droplets that are falling in the atmosphere. As the radar also has the feature of dual polarization described in Section 2.2, “Radar Rainfall Observation,” there is no requirement of calibration with a ground observed rain gauge. Such detailed observations can be applied in early warning system aiming for disseminating warnings 10 to 20 min before torrential rainfall hits the ground.

It is said to be the first case globally where the phased array radar is dedicated to weather observation. The radar was developed in collaboration with Toshiba, Osaka University, and the National Institute of Information and Communication Technology (NICT), under the Cross-ministerial Strategic Innovation Promotion Program (SIP) in Japan. The MP-PAWR has already been implemented, and the antenna was installed in Saitama.

### 4.2. Opportunistic Observation of Rainfall

While remarkable advances in radar rainfall observation are ongoing, it is also worth mentioning about emerging methodologies in weather and hydrological observations.

Interest in use of raw microwave signals from cellular communication networks as opportunistic sensors of rainfall [60] can be observed. The principle of observing rainfall signals from cellular networks is somewhat similar to the principle of radar rainfall observation, that is, the harder the rain falls, the more difficult it becomes for signals to propagate and attenuate. The relationship between rainfall intensity and signal attenuation can be utilized as an opportunistic measurement of rainfall from the existing cellular phone network infrastructure. The application could be powerful when one considers that the infrastructure required for rainfall observation is already built, and thereby expansion of the observation system can be done with relative ease even if it is for a continental scale.

A tipping bucket is not the only ground observation method of rainfall; several other types have been developed over the decades. The measurement can be performed manually or automatically, and the latter can be classified into impact technique based disdrometers, optical scattering based disdrometers, and optical imaging based disdrometers [61, 62].

Acoustic disdrometers and displacement disdrometers can be categorized as impact disdrometers as they are in common in use of kinetic energy. Acoustic disdrometers utilize the kinetic energy that is produced when a raindrop hits the surface, by applying the relationship between kinetic energy of a raindrop and acoustic energy when a raindrop hits the surface [63]. Displacement disdrometers estimate the size of a rain drop by magnetic induction that is created when the raindrop hits the surface of the device. The well-known Joss–Waldvogel Disdrometer [64] can be applied to this category. Optical scattering beams a horizontal light sheet, which is scattered in the presence of raindrops, and the reduction in light detected by the sensing unit is converted into raindrop information [62]. Optical imaging is based on the analysis of raindrops, e.g., size, velocity, and oblateness, from the captured images. The 2D-Video-Disdrometer [65] falls into this category.

Recently, Onomura et al. [66] extended the possibility of optical imaging disdrometers, which estimate the intensity of the rain on an acrylic plate through a comparison of successive images. The plate is cleared by wiper representing cars. Jiang et al. [67] used closed-circuit television (CCTV) systems, which are available urban areas as surveillance cameras, for developing optical imaging to measure rainfall. Similar to the indirect use of cellular phone networks, opportunistic use of imaging devices is considered to have advantage in the relative ease of their application in rainfall measurement, considering their widespread use.

### 4.3. Crowd Sourcing and Citizen Science

There has been a rise of citizen science in hydrometeorological monitoring. Personal weather stations installed by private weather enthusiasts for measuring air temperature, relative humidity, and pressure, may compensate a monitoring station that may not be dense enough to capture weather information by local authorities or the gov-

ernment agencies. For instance, Netatmo provides personal weather stations and hosts web services for individual users to share their monitoring data worldwide, and it is accessible from <https://weathermap.netatmo.com/>.

In Germany, Meier et al. [68] analyzed air temperature from ca 1500 of crowd sourced stations from Netatmo service against the reference data for a one-year period, and concluded that numerous individual sensors can provide robust air temperature in urban areas, and the data have the potential for further exploration, while quality assessment of data may be needed. In the Netherlands, de Vos et al. [69] examined the quality of rainfall measurement from personal weather stations in Amsterdam. They reported that while certain discrepancies exist between crowdsourced data and high-resolution electronic rain gauge data, where the difference originates due to data transfer to the online platform and is pronounced as light rain, the results are promising and deserve further exploration.

When discussing about crowdsourcing, one cannot avoid mentioning the potential strength of a mobile phone as an observation device. In Switzerland, crowdsourced monitoring of stream flows has been conducted under the citizen science project called the “CrowdWater.” In general, observation stations for estimating stream flow are less in number compared to meteorological stations, resulting in ungauged basins in the river basin. By providing a monitoring framework, citizens can report the water level in streams [70, 71] through a mobile app with virtual staff gauges, in which the water level in the stream is compared against the virtual gauge in a photo taken at the low flow period [72]. Such crowdsourced observations may provide valuable source of information as they can complement the existing observation stations and improve the performance of hydrological modelling through data assimilation [73, 74].

Citizen involvement in meteorological or hydrological observations can be effective in urban areas owing to dense population [68]. Along with growing awareness and interests for citizens in environmental issues, specifically in the context of global climate change, the number of crowdsourced observations may further expand, and individual observations can be a useful source of information also in stormwater management. Currently, participation in such crowd sourcing or citizen science applications are not common in Japan, but involvement of citizens has high potential in improving observations, such as water levels in small streams, which are typically ungauged and where hydrological information is unknown.

### 4.4. Internet of Things for Stormwater Management

In recent years, we have been observing major paradigm shift with the Internet of Things (IoT) that enables integration of diverse technologies and telecommunications [75]. Application of the IoT in the urban environment will lead to the concept of smart city through advanced telecommunication technologies that would pro-

vide added value for the local authority and residence [76, 77]. While the application of IoT in the field of stormwater management has been slow, it is proven to provide an economical solution for urban hydrological monitoring [78]. Furthermore, the use of IoT for correcting hydrological monitoring information itself has of great importance, but the application can be further advanced by adopting bidirectional information transfer, that is, sending information to an IoT device to control the ambient local hydrology [79]. Mullanpudi et al. [80] demonstrated that streamflow in an urban watershed can be systematically controlled to a certain extent by remotely controlling the inter-connected valves and sensors installed in streams, and achieving desirable hydrological responses and water quality in downstream.

For risk management in mega cities, where underground facilities have been developed, it is crucial to predict the onset of flooding as the subsurface space could be submerged when rainfall intensity exceeds the designed level [6]. Challenges in stormwater management in urban areas involve how one can predict the onset and the location of submerging areas on a real-time basis. In general, the size of a sub-catchment in urbanized areas is much smaller than that of river basin, and pluvial flooding can occur within a short time owing to the hydrological characteristics. Also, the affected areas can be localized as pluvial flooding can be triggered by sudden torrential rainfall from cumulonimbus clouds that have the scale of a few kilometers. While a priori estimate of the anticipated flooded areas by applying integrated urban flood models can help local authorities to plan risk management, detection of flooding in real-time is also important, for instance, for safe evacuation of people from vulnerable spaces in the underground [81]. Moreover, for that to happen, flood prediction by observation or modeling has great importance.

Kobayashi [82] has developed an energy and cost-effective sensor for detecting water level. The sensor identifies its status of submergence and transmits its status as either an “on” or “off” signal through wireless transmission of information using Low Power Wide Area (LPWA), which is a telecommunication standard. While the device focuses on detecting its submergence status and does not measure the water level directory, it can be installed on ground surface or gutters with relative ease and can be highly effective in identifying the onset of a flood hazard.

Targeting the subsurface area, Meidensha Corporation has developed the “smart manhole cover” together with the Tokyo Metropolitan Sewerage Service Corporation and Hinode, Ltd. (Fig. 6). The smart manhole cover has a built-in telecommunication and battery unit attached to its backside, which allows transmission of monitoring information observed from water level sensors installed in a sewer network. The device has an advantage as it is relatively simple in implementation, and it can be easily installed to the sewerage infrastructure by replacing the existing manhole covers, thus allowing less difficulties in its wide application. The water level information obtained

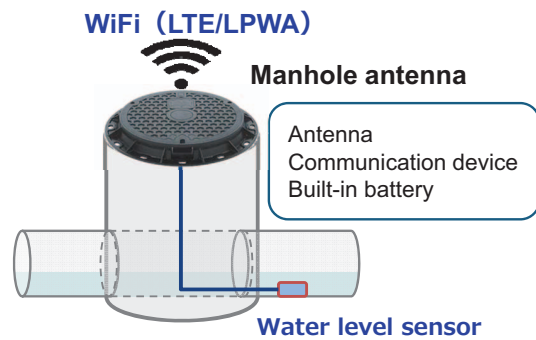


Fig. 6. A schematic image of a manhole IoT by Meidensha Corporation.

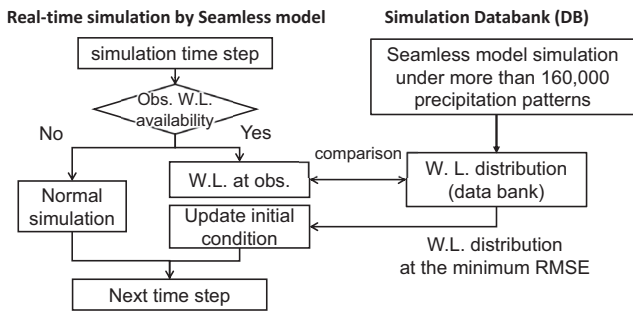
from a smart manhole cover on real-time basis can be used to detect signs of pluvial flooding at an early stage, which has of vital importance for safe evacuation of main underground.

Such observed information is highly beneficial in predicting water levels in sewer networks. In the current issue, Nakashima et al. [10] constructed and compared models of the empirical statistical method and Convolutional Neural Network model, which is a type of an Artificial Neural Network, both of which employ an observed relationship between rainfall and water level in sewers and demonstrated that both models can predict water level in sewer networks reasonably well [10]. Similar to the methodology based on machine learning techniques [83], the advantage here is that both models are computationally effective, which is an important aspect in the real-time prediction of pluvial flooding, compared to the physics-based integrated urban flood models.

#### 4.5. Fusion of IoT with Integrated Urban Flood Modeling

Using observed water levels in sewer networks through the smart manhole cover, a further advanced methodology is under development. Regardless of the simulation models applied, be it empirically based, statistically based, or physics-based, one must acknowledge that simulated results are not equivalent to reality, and errors and uncertainty may arise from the model parameters, model assumptions, or even in errors in the observation itself.

Wu et al. [84] developed a novel methodology of combining the integrated urban flood model of the seamless model with the observed water level in the sewer network through data assimilation. The uniqueness of their approach is that numerous sets of pluvial simulation are conducted for making the databank of water levels of sewer networks, and model bias is minimized in the real-time simulation by comparing the water level in the simulation with the observation through the smart manhole cover and updating the simulated hydraulic condition in sewer networks with the one having the least error from the databank (Fig. 7). By doing so, the seamless model can update its physical state so that it becomes closer to reality, and having it as the initial condition, the model can have better



**Fig. 7.** Flow chart of flood simulation with databank-based data assimilation method.

chance in prediction of pluvial flooding.

Shibuo et al. [85] applied the databank-based data assimilation approach for estimating improved accuracy in water levels in pumping stations, showing that stormwater pipes in the vicinity of a pumping station would require further information of pumping operations. When such information becomes available, the approach may contribute to effective countermeasure in stormwater management by identifying at which hour the pumping operations ought to be started [8]. As an example of assisting flood countermeasures in real time, **Fig. 8** shows the advanced application, in which various types of information of observation and simulated results, such as CCTV cameras, radar rainfall, simulated river water level, and sewer network and flooding states, are combined.

## 5. Summary

This study reviewed research developments in stormwater management in Japan, specifically focusing on rainfall observation, urban flood modeling, and emerging technologies. As for rainfall observation, there has been long history in Japan for observations over its territory, which has led to high resolution spatio-temporal variabilities in rainfall by ground observed radars. Two decades have passed since the emergence of an integrated urban flood modeling approach, which has replaced the classical conceptually simple methodology, e.g., the rational formula. Although several integrated models have been domestically developed, commercial software are still popular and widely applied for the practical design of infrastructure, which was earlier designed with a simplified rainfall-runoff scheme, as mentioned above. One must be aware of such differences in the methodology applied for designing stormwater systems. Together with such differences, the difficulty in observing the underground environment poses challenges in estimating the hydraulic status in a sewer network. Application of IoT based observations, such as the smart manhole cover, may minimize such uncertainties.

Flooding is expected to increase in accordance with the climate change [86]. Reportedly, the number of occurrences of heavy rainfall that exceeds 50 mm/h has in-

creased by 1.4 times in the recent decade compared to the earliest decade in the observation records of AMeDAS in Japan. Indeed, the highest total rainfall in July related to the Baiu front was recorded in 2020. Such evidence suggests that there will be challenges to come in urban flood management in future.

Typically, the designed rainfall standard for stormwater management is approximately 50 mm, and sometimes 60 mm for flood prone areas. However, implementation is still ongoing and local municipalities are yet to complete the designed standard. Notably, the magnitude of designed rainfall was derived based on a statistical analysis of the observed rainfall record, and it cannot be guaranteed that it will remain the same in the future. Numerous structural measures have been implemented in the field of river management, sewerage management, and watershed management by corresponding authorities, e.g., retarding basins by the river manager, underground stormwater storage pipes by city, all of which could increase designed capacities in flood management.

Nonetheless, independent application of structural measures may not be sufficient to cope with the increasing magnitude of flood hazards, and a multi-disciplinary approach with dynamic collaborations among river managers and local municipalities is encouraged to maximize countermeasures against flooding. Furthermore, an interdisciplinary approach of structural and non-structural measures, e.g., updating city planning for reflecting flood prone areas to promote residential reallocation, and preparation of evacuation plans reflecting multiple plausible inundation scenarios, may alleviate urban flood damages by the same magnitude of flood hazards.

Among non-structural measures, the role of an early warning system is becoming increasingly important as compared to structural measures, for which implementation is subject to available budget for either the central government or local municipality. Consequently, the application of numerical models has become ever more important. The common weakness of an integrated urban flood modeling related to limited availability of observations in sewer networks can be relaxed with IoT based observations, such as the smart manhole cover. Fusion of IoT based observations with an integrated urban flood modeling is an emerging technology in stormwater management. To apply such advanced methodologies, integrated collaboration among academia, local authorities, and private companies is recommended to realize resilient society against urban flood issues.

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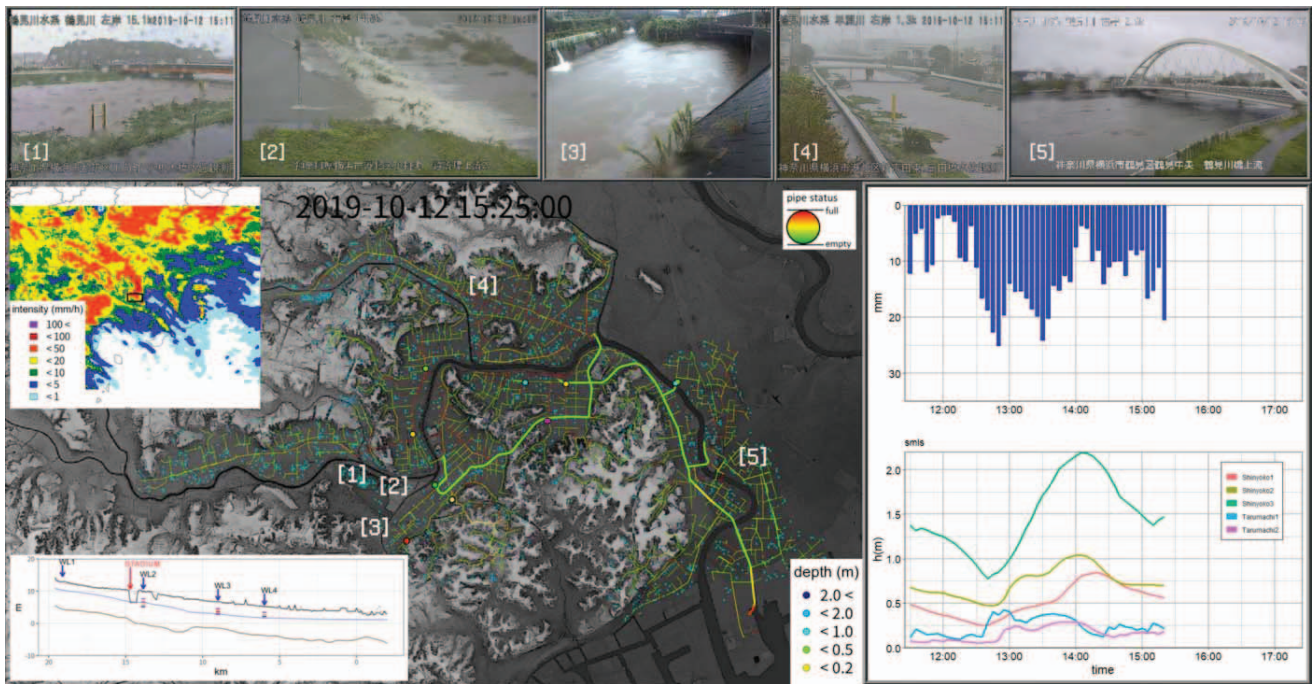


Fig. 8. An integrated image of real-time simulation by the seamless model with various observation.

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References:

- [1] S. Ohtomo, R. Kimura, Y. Kawata, and K. Tamura, "The Determinants of Residents' Evacuation Behavior in the Torrential Rain in Western Japan in 2018: Examination of Survey Data of Victims in Okayama Prefecture," *J. Disaster Res.*, Vol.15, No.7, pp. 1011-1024, 2020.
- [2] T. Sayama, M. Yamada, Y. Sugawara, and D. Yamazaki, "Ensemble flash flood predictions using a high-resolution nationwide distributed rainfall-runoff model: case study of the heavy rain event of July 2018 and Typhoon Hagibis in 2019," *Progress in Earth and Planetary Science*, Vol.7, No.1, Article No.75, 2020.
- [3] M. Takeda, D. Sato, K. Kawaike, and M. Toyota, "Inundation Analysis of the Dike Breach of the Chikuma River Taking Drainage Process and House Damage into Consideration," *J. Disaster Res.*, Vol.16, No.3, pp. 343-350, 2021.
- [4] Ministry of Land, Infrastructure, Transport and Tourism, "Recent rainfall and pluvial flood damages, and situation of sewer management 2018," <https://www.mlit.go.jp/mizukokudo/sewage/content/001320996.pdf> (in Japanese) [accessed September 1, 2020]
- [5] K. Fukumori, Y. Kurita, and H. Furumai, "Validation of Inundation Damage Reduction by a Pump Gate with the New Type of Horizontal Axial Submersible Pump," *J. Disaster Res.*, Vol.16, No.3, pp. 381-386, 2021.
- [6] M. Hayakawa, T. Nakajima, and R. Hakoda, "Examination of Flood Countermeasures Utilizing a Yokohama City Main Rainwater Pipeline and Public-Private Anti-Flood Measures," *J. Disaster Res.*, Vol.16, No.3, pp. 437-441, 2021.
- [7] R. Matsuoka and S. Oki, "Demonstration of Stormwater Management Technology by Short-Term Rainfall Prediction and Real-Time Runoff Analysis System Using Small X-Band Radar," *J. Disaster Res.*, Vol.16, No.3, pp. 403-409, 2021.
- [8] H. Mitamura and M. Fujie, "Evolutionary Transition of Stormwater Pump System in Tokyo," *J. Disaster Res.*, Vol.16, No.3, pp. 421-428, 2021.
- [9] H. Muroi, K. Mine, and Y. Eguchi, "Scenario Analysis of Sluice Gate Operations for Evaluating Inland Flood Damage," *J. Disaster Res.*, Vol.16, No.3, pp. 429-436, 2021.
- [10] M. Nakashima, S. Sameshima, Y. Kimura, and M. Yoshimoto, "Evaluation of Real-Time Water Level Prediction Technology Using Statistical Models for Reducing Urban Flood Risk," *J. Disaster Res.*, Vol.16, No.3, pp. 387-394, 2021.
- [11] K. Park, Y. Shibuo, J. Katayama, S. Baba, and H. Furumai, "Applicability of High-Resolution Geospatial Data Obtained by UAV Photogrammetry to Develop Drainage System Models for Pluvial Flood Analysis," *J. Disaster Res.*, Vol.16, No.3, pp. 371-380, 2021.
- [12] Y. Sakae, M. Endo, and Y. Nakayama, "Development and Evaluation of ICT Operation Support System for Urban Flood Control Facilities," *J. Disaster Res.*, Vol.16, No.3, pp. 395-402, 2021.
- [13] K. Yoshimi, M. Wada, and Y. Hiraoka, "Study on Water Level Prediction Using Observational Data from a Multi-Parameter Phased Array Weather Radar," *J. Disaster Res.*, Vol.16, No.3, pp. 410-414, 2021.
- [14] A. Kawamura, "Status Quo and Perspectives of Flood Runoff Analysis for Urban Watersheds," *J. of Japan Society of Hydrology and Water Resources*, Vol.31, No.6, pp. 451-466, 2018.
- [15] K. E. Trenberth, A. Dai, R. M. Rasmussen, and D. B. Parsons, "The changing character of precipitation," *Bulletin of the American Meteorological Society*, Vol.84, No.9, pp. 1205-1217, 2003.
- [16] D. Kamiya, H. Sakakibara, S. Morioka et al., "The Relationship between Disaster Prevention Weather Information and Evacuation Information and Evacuation Problems in Welfare Facilities," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.75, No.1, pp. 370-377, 2019 (in Japanese).
- [17] Y. Shibuo, S. Lee, H. Sanuki et al., "Evaluating Characteristics of XRAIN and Numerical Rainfall Predictions for Urban Inundation Simulation," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.74, No.4, pp. L1381-L1386, 2018 (in Japanese).
- [18] M. Ikeda, Y. Watanabe, and M. Ushiyama, "Regional meteorological observation from the Meteorological Agency," *J. of Japan Society of Hydrology and Water Resources*, Vol.13, No.4, pp. 313-319, 2000 (in Japanese).
- [19] Japan Meteorological Agency, "Automated Meteorological Data Acquisition System 2020," <https://www.jma.go.jp/jma/en/Activities/amedas/amedas.html> [accessed September 1, 2020]
- [20] Ministry of Land, Infrastructure, Transport and Tourism, "Water Information System 2020," <http://www1.river.go.jp/> (in Japanese) [accessed September 1, 2020]
- [21] X. Xue, Y. Hong, A. S. Limaye et al., "Statistical and Hydrological Evaluation of TRMM-Based Multi-Satellite Precipitation Analysis Over the Wangchu Basin of Bhutan: Are the Latest Satellite Precipitation Products 3B42V7 Ready for Use in Ungauged Basins?," *J. of Hydrology*, Vol.499, pp. 91-99, 2013.

- [22] T. Dinku, C. Funk, P. Peterson et al., "Validation of the CHIRPS satellite rainfall estimates over eastern Africa," *Quarterly J. of the Royal Meteorological Society*, Vol.144, No.51, pp. 292-312, 2018.
- [23] I. Fujita and Y. Kunita, "Flash flood simulation of the Toga River caused by localized torrential rain in urbanized area," *Proc. of the Int. Conf. on Fluvial Hydraulics (River Flow 2010)*, pp. 1605-1613, 2010.
- [24] E. Nakakita, H. Sato, R. Nishiwaki, H. Yamabe, and K. Yamaguchi, "Early Detection of Baby-Rain-Cell Aloft in a Severe Storm and Risk Projection for Urban Flash Flood," *Advances in Meteorology*, Vol.2017, pp. 1-15, 2017.
- [25] E. Nakakita, K. Yamaguchi, Y. Sumida et al., "Classification of Hydrometeors Using a C-band Polarimetric Radar and Validation by In-Situ Campaign Observation Synchronized with Video-Sonde," *Disaster Prevention Research Institute Annuals*, Vol.51, pp. 519-533, 2007 (in Japanese).
- [26] K. Fukami, M. Kawasaki, S. Tsuchia, and H. Fujimaki, "History of 'Radar Raingauges' as the Precipitation Radar System of MLIT and its Future Direction," *Civil Engineering J.*, Vol.58, No.7, pp. 20-25, 2016 (in Japanese).
- [27] Bureau of Sewerage Tokyo Metropolitan Government, "Tokyo Amesh 2021," <https://tokyo-ame.jwa.or.jp/en/index.html> [accessed September 1, 2020]
- [28] C. Kummerow, W. Barnes, T. Kozu, J. Shiue, and J. Simpson, "The Tropical Rainfall Measuring Mission (TRMM) Sensor Package," *J. of Atmospheric and Oceanic Technology*, Vol.15, No.3, pp. 809-817, 1998.
- [29] T. Kubota, S. Shige, H. Hashizume et al., "Global precipitation map using satellite-borne microwave radiometers by the GSMaP project: Production and validation," *IEEE Trans. on Geoscience and Remote Sensing*, Vol.45, No.7, pp. 2259-2275, 2007.
- [30] Q. H. Sun, C. Y. Miao, Q. Y. Duan, H. Ashouri, S. Sorooshian, and K.-L. Hsu, "A Review of Global Precipitation Data Sets: Data Sources, Estimation, and Intercomparisons," *Reviews of Geophysics*, Vol.56, No.1, pp. 79-107, 2018.
- [31] N. Mastrantonas, B. Bhattacharya, Y. Shibuo, M. Rasmy, G. Espinoza-Dávalos, and D. Solomatine, "Evaluating the Benefits of Merging Near-Real-Time Satellite Precipitation Products: A Case Study in the Kinu Basin Region, Japan," *J. of Hydrometeorology*, Vol.20, No.6, pp. 1213-1233, 2019.
- [32] R. A. Acierito, A. Kawasaki, W. W. Zin, A. T. Oo, K. Ra, and D. Komori, "Development of a Hydrological Telemetry System in Bago River," *J. Disaster Res.*, Vol.13, No.1, pp. 116-124, 2018.
- [33] D. E. Alsdorf, E. Rodríguez, and D. P. Lettenmaier, "Measuring surface water from space," *Reviews of Geophysics*, Vol.45, No.2, pp. 1-24, 2007.
- [34] Y. Kwak, S. H. Yun, and Y. Iwami, "A New Approach for Rapid Urban Flood Mapping Using ALOS-2/PALSAR-2 in 2015 Kinu River Flood, Japan," *2017 IEEE Int. Geoscience and Remote Sensing Symp. (IGARSS)*, pp. 1880-1883, 2017.
- [35] J. C. Y. Guo, "Rational hydrograph method for small urban watersheds," *J. of Hydrologic Engineering*, Vol.6, No.4, pp. 352-356, 2001.
- [36] L. Tolland, J. G. Cathcart, and S. O. D. Russell, "Estimating the Q100 in British Columbia: A practical problem in forest hydrology," *J. of the American Water Resources Association*, Vol.34, No.4, pp. 787-794, 1998.
- [37] Y. Tanioka, S. Fukuoka, M. Taniguchi, and Y. Koyama, "Characteristics of Floods in Small Urban Rivers," *Proc. of JSCE*, Vol.586, pp. 1-11, 1998 (in Japanese).
- [38] S. Tanaka, T. Sakakibara, S. Fujita, I. Tanaka, and K. Furukita, "Comparative Survey of Storm Runoff and Pollutant Load Models," *Japan Institute of Wastewater Engineering and Technology*, 1994.
- [39] Japan Institute of Wastewater Engineering and Technology, "Runoff Analysis Model Application Manual: Operation Guidance of Runoff Analysis Model in Rainfall Management," 2003.
- [40] P. M. Bach, W. Rauch, P. S. Mikkelsen, D. T. McCarthy, and A. Deletic, "A critical review of integrated urban water modelling – Urban drainage and beyond," *Environmental Modelling & Software*, Vol.54, pp. 88-107, 2014.
- [41] Y. Yamagishi, T. Nonaka, and T. Nakamura, "Development of New Integrated Lowland Inundation Model," *Public Works Research Center*, 2006.
- [42] M. Sunaguchi and M. Tsuchiya, "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," *Doboku Gakkai Ronbunshuu B*, Vol.64, No.4, pp. 240-250, 2008 (in Japanese).
- [43] H. Yoneda, M. Satoh, I. Kawamura, M. Yamaguchi, K. Matsumoto, and T. Yamada, "The Risk Assessment of The Flood Damage By Inner and River Water Simultaneous Flood Analysis with Uncertainty of Rainfall and Runoff Analysis," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.74, No.5, pp. L1387-L1392, 2018.
- [44] N. Koyama and T. Yamada, "A Proposed Simultaneous Calculation Method for Flood by River Water, Inland Flood, and Storm Surge at Tidal Rivers of Metropolitan Cities: A Case Study of Katabira River in Japan," *Water*, Vol.12, No.6, p. 1769, 2020.
- [45] K. Kawaike, K. Inoue, K. Toda, H. Sakai, and R. Sagara, "Inundation Flow Analysis Due to Heavy Rainfall in Low-Lying River Basin and its Application to Neya River Basin," *Proc. of Hydraulic Engineering*, Vol.46, pp. 367-372, 2002.
- [46] K. Kawaike, K. Inoue, K. Toda, and M. Noguchi, "Refinement of Inundation Flow Model Applied to Neya River Basin," *Proc. of Hydraulic Engineering*, Vol.47, pp. 919-924, 2003.
- [47] J. A. Cunge and M. Wegner, "Numerical integration of Barré de Saint-Venant's flow equations by means of an implicit scheme of finite differences," *La Houille Blanche*, No.1, pp. 33-39, 1964 (in French).
- [48] M. Sekine, "Numerical Analysis of Inundation in the Region of Downtown Tokyo with Residence Area," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.67, No.2, pp. 70-85, 2011.
- [49] M. Sekine and K. Kodama, "Evaluation of Inundation Risk During Heavy Rain in Tokyo 23 Wards and Pre-Flooding of Underpass," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.74, No.4, pp. L1543-L1548, 2018 (in Japanese).
- [50] J. Akiyama, M. Shige-Eda, and T. Tanabe, "Numerical Simulation of Inundation Flow with Sewer Network in the Onga River Basin," *Annual J. of Hydraulic Engineering*, Vol.53, pp. 829-834, 2009 (in Japanese).
- [51] J. Akiyama, M. Shige-Eda, and H. Kusano, "Economic Loss Estimation in Iizuka City Using Numerical Simulator for Rainfall-Runoff/Flood Inundation Process in Urban Area Wit River and Sewer Network," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.68, No.4, pp. L1063-L1068, 2012 (in Japanese).
- [52] M. Takeda, M. Murase, R. Mouri, and N. Matsuo, "Numerical Analysis on Water Behaviour in Urban Area by Inundation Due to River Flood and Heavy Rain Considering the Origin," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.74, No.5, pp. L1465-L1470, 2018 (in Japanese).
- [53] M. Takeda, M. Murase, Y. Nakajima, K. Komatsu, and N. Matsuo, "Numerical Analysis on Water Behaviour in Urban Area Due to Overlapping of Storm Surge and Flood Considering the Origin of the Inundation," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.74, No.4, pp. L1429-L1434, 2018 (in Japanese).
- [54] T. Sayama and J. J. McDonnell, "A new time-space accounting scheme to predict stream water residence time and hydrograph source components at the watershed scale," *Water Resources Research*, Vol.45, No.7, W07401, 2009.
- [55] H. Sanuki, Y. Shibuo, S. Lee et al., "Inundation Forecast Simulation in Urbanized Coastal Low-Lying Areas Considering Multiple Flood Causing Factors," *J. of Japan Society of Civil Engineers, Ser. B2 (Coastal Engineering)*, Vol.72, No.2, pp. L517-L522, 2016 (in Japanese).
- [56] L. Wang, T. Koike, D. Yang, and K. Yang, "Improving the hydrology of the Simple Biosphere Model 2 and its evaluation within the framework of a distributed hydrological model," *Hydrological Sciences J.*, Vol.54, No.6, pp. 989-1006, 2009.
- [57] K. Kawaike, A. Shimizu, Y. Baba, H. Nakagawa, and M. Takeda, "Verification of numerical model for urban inundation due to torrential rainfall using physical experimental flume with a sewer pipe," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.67, No.4, pp. L985-L990, 2011 (in Japanese).
- [58] S. Lee, Y. Shibuo, and H. Furumai, "Change of Water Level and Electric Conductivity Using Monitoring Data at Combined Sewer Pipes in Tsurumi River Basin," *J. of Japan Society of Civil Engineers, Ser. G (Environmental Research)*, Vol.75, No.2, pp. 55-64, 2019 (in Japanese).
- [59] T. Adachi, K. Kusunoki, S. Yoshida, K. I. Arai, and T. Ushio, "High-Speed Volumetric Observation of a Wet Microburst Using X-band Phased Array Weather Radar in Japan," *Monthly Weather Review*, Vol.144, No.10, pp. 3749-3765, 2016.
- [60] R. Uijlenhoet, A. Overeem, and H. Leijnse, "Opportunistic remote sensing of rainfall using microwave links from cellular communication networks," *Wiley Interdisciplinary Reviews: Water*, Vol.5, No.4, e1289, 2018.
- [61] G. Kathiravelu, T. Lucke, and P. Nichols, "Rain Drop Measurement Techniques: A Review," *Water*, Vol.8, No.1, p. 29, 2016.
- [62] M. Löffler-Mang and J. Joss, "An optical disdrometer for measuring size and velocity of hydrometeors," *J. of Atmospheric and Oceanic Technology*, Vol.17, No.2, pp. 130-139, 2000.
- [63] P. Winder and K. S. Paulson, "The measurement of rain kinetic energy and rain intensity using an acoustic disdrometer," *Measurement Science and Technology*, Vol.23, No.1, 015801, 2012.

- [64] J. Joss and A. Waldvogel, "A Spectrograph for Raindrops with Automatic Interpretation," *Pure and Applied Geophysics*, Vol.68, No.3, 240-246, 1967.
- [65] M. Schönhuber, G. Lammer, and W. L. Randeu, "One decade of imaging precipitation measurement by 2D-video-distrometer," *Advances in Geosciences*, Vol.10, pp. 85-90, 2007.
- [66] S. Onomura, K. Suzuki, and M. Nakayoshi, "Development of Image Disdrometer," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.75, No.2, pp. L1159-L1164, 2019 (in Japanese).
- [67] S. Jiang, V. Babovic, Y. Zheng, and J. Xiong, "Advancing Opportunistic Sensing in Hydrology: A Novel Approach to Measuring Rainfall With Ordinary Surveillance Cameras," *Water Resources Research*, Vol.55, No.4, pp. 3004-3027, 2019.
- [68] F. Meier, D. Fenner, T. Grassmann, M. Otto, and D. Scherer, "Crowdsourcing air temperature from citizen weather stations for urban climate research," *Urban Climate*, Vol.19, pp. 170-191, 2017.
- [69] L. de Vos, H. Leijnse, A. Overeem, and R. Uijlenhoet, "The potential of urban rainfall monitoring with crowdsourced automatic weather stations in Amsterdam," *Hydrology and Earth System Sciences*, Vol.21, No.2, pp. 765-777, 2017.
- [70] B. Strobl, S. Etter, I. van Meerveld, and J. Seibert, "Accuracy of crowdsourced streamflow and stream level class estimates," *Hydrological Sciences J.*, Vol.65, No.5, pp. 823-841, 2020.
- [71] S. Etter, B. Strobl, I. van Meerveld, and J. Seibert, "Quality and timing of crowd-based water level class observations," *Hydrological Processes*, Vol.34, No.22, 2020.
- [72] J. Seibert, B. Strobl, S. Etter, P. Hummer, and H. J. van Meerveld, "Virtual Staff Gauges for Crowd-Based Stream Level Observations," *Frontiers in Earth Science*, Vol.7, Article No.70, 2019.
- [73] M. Mazzoleni, M. Verlaan, L. Alfonso et al., "Can assimilation of crowdsourced data in hydrological modelling improve flood prediction?," *Hydrology and Earth System Sciences*, Vol.21, No.2, pp. 839-861, 2017.
- [74] P. M. Avellaneda, D. L. Ficklin, C. S. Lowry, J. H. Knouft, and D. M. Hall, "Improving Hydrological Models With the Assimilation of Crowdsourced Data," *Water Resources Research*, Vol.56, No.5, e2019WR026325, 2020.
- [75] L. Atzori, A. Iera, and G. Morabito, "The Internet of Things: A survey," *Computer Networks*, Vol.54, No.15, pp. 2787-2805, 2010.
- [76] H. Schaffers, N. Komninos, M. Pallot, B. Trousse, M. Nilsson, and A. Oliveira, "Smart Cities and the Future Internet: Towards Cooperation Frameworks for Open Innovation," *Lecture Notes in Computer Science: The Future Internet: Future Internet Assembly 2011: Achievements and Technological Promises Proc.*, pp. 431-446, 2011.
- [77] A. Zanella, N. Bui, A. Castellani, L. Vangelista, and M. Zorzi, "Internet of Things for Smart Cities," *IEEE Int. of Things J.*, Vol.1, No.1, pp. 22-32, 2014.
- [78] B. Kerkez, C. Gruden, M. Lewis et al., "Smarter Stormwater Systems," *Environmental Science & Technology*, Vol.50, No.14, pp. 7267-7273, 2016.
- [79] B. P. Wong and B. Kerkez, "Real-Time Control of Urban Headwater Catchments Through Linear Feedback: Performance, Analysis, and Site Selection," *Water Resources Research*, Vol.54, No.10, pp. 7309-7330, 2018.
- [80] A. Mullanpudi, M. Bartos, B. Wong, and B. Kerkez, "Shaping Streamflow Using a Real-Time Stormwater Control Network," *Sensors*, Vol.18, No.7, 11, 2018.
- [81] Y. Nakasaka and T. Ishigaki, "Vulnerability to Mega Underground Inundation and Evacuation Assuming Devastating Urban Flood," *J. Disaster Res.*, Vol.16, No.3, pp. 321-328, 2021.
- [82] W. Kobayashi, "Reliability Assessment in Wireless Apparatus Using LoRa and Sigfox in Catch Basin," *J. Disaster Res.*, Vol.16, No.3, pp. 363-370, 2021.
- [83] H. Minakawa, I. Azechi, M. Kimura, N. Okumura, N. Kimura, and D. Baba, "Utilization of simulated data for development of a deep learning flood prediction model as support of drainage pump operation," *Annual J. of Hydraulic Engineering*, Vol.76, No.2, pp. L349-L354, 2020 (in Japanese).
- [84] L. Wu, Y. Tajima, D. Yamazaki, Y. Shibuo, H. Sanuki, and H. Furumai, "Development of Real-Time Assimilation Model for Prediction of Inundation on Urbanized Coastal Lowland," *Proc. of the 10th Int. Conf. on Asian and Pacific Coasts (APAC 2019)*, pp. 1343-1349, 2019.
- [85] Y. Shibuo, L. Wu, Y. Tajima, D. Yamazaki, H. Sanuki, and H. Furumai, "Application of Databank-Based Data Assimilation to Urban Inundation Model for Improved Accuracy and Sensitivity Analysis of Pumping Operation," *J. of Japan Society of Civil Engineers, Ser. B1 (Hydraulic Engineering)*, Vol.75, No.2, pp. L199-L204, 2019.
- [86] P. H. Whitfield, "Floods in future climates: a review," *J. of Flood Risk Management*, Vol.5, No.4, pp. 336-365, 2012.



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- Y. Shibuo, J. Jarsjö, and G. Destouni, "Hydrological responses to climate change and irrigation in the Aral Sea drainage basin," *Geophys. Res. Lett.*, Vol.34, No.21, L21406, doi:10.1029/2007GL031465, 2007.
- Y. Shibuo, J. Jarsjö, and G. Destouni, "Bathymetry-topography effects on saltwater-fresh groundwater interactions around the shrinking Aral Sea," *Water Resour. Res.*, Vol.42, No.11, W11410, doi:10.1029/2005WR004207, 2006.

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