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Study on Water Level Prediction Using Observational Data from a Multi-Parameter Phased Array Weather Radar

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A dual-polarization, phased array weather radar, also known as the multi-parameter phased array weather radar (MP-PAWR), was developed by the Japanese Cross-ministerial Strategic Innovation Promotion (SIP) Program. Since this weather radar has been made into an active phased array, three-dimensional observation of weather phenomena can be realized at high speed by means of electrical scanning in the elevation direction and mechanical scanning in the azimuth direction. This is expected to shed light on hydrological processes in river basins, such as those of urban rivers, and improve prediction accuracy. In this study, river water levels in urban areas were estimated from vertically integrated liquid (VIL) Nowcast water content results, a meteorological forecasting method based on the three-dimensional observation MP-PAWR data, using a synthesized rational formula. A runoff analysis for urban basins was carried out using the rainfall forecast results based on MP-PAWR observational data. Since it is known that this formula can be used to deliver a rapid response time for runoff phenomena in the basin, it is possible to fully exploit the features of the MP-PAWR. This study shows how MP-PAWR is used in a series of hydrological processes. In this paper, we report the results of a basic study on water level predictions based on MP-PAWR observational data and also present future prospects for the use of this technology.

Keywords: MP-PAWR, VIL Nowcast, water level prediction, sewerage management system

1. Introduction

In recent years, a wide variety of disasters such as fluvial flooding due to localized heavy rainfall, inundation of urban areas, and sediment-related disasters have been increasing. In 2008, a water-related accident occurred in the Toga River and Zoshigaya, Japan, due to localized heavy rainfall, which led to some deaths. The term localized heavy rainfall has now been publicly recognized and, starting from this year, countermeasures against localized heavy rainfall has been implemented.

The government has taken the initiative in promoting the installation of an X-band MP radar, which is more suitable for observing localized heavy rainfall than weather radars that have been mainly used until now, and an observation system using a radar network has been established, primarily in urban areas. The X-band MP radar has the advantage of being able to realize a greater number of quantitative estimates of rainfall by emitting two polarizations, horizontal and vertical, and using the polarization parameters. With the development of this X-band MP radar also led to research on localized heavy rainfall [1]; several studies were also conducted to examine the development and decay of cumulonimbus clouds [2] and to detect the early stages of localized heavy rainfall, that is a short, heavy sudden rainfall within a small area [3].

However, it is still difficult to catch the signs of localized heavy rainfall and accurately predict the timing and position of its occurrence. To protect human lives from the water-related accidents mentioned above, it is desirable to capture the phenomenon as early as possible, to one minute or one second, and establish a system of disseminating this information.

Under the Cross-ministerial Strategic Innovation Promotion Program (SIP), the Japanese Cabinet Office therefore initiated a five-year plan to promote more detailed meteorological observations on "Strengthening Resilient Functions of Disaster Prevention and Reduction" in 2014. One of the aims is the development of a multi-parameter phased array weather radar (hereinafter, referred to as MP-PAWR) (see **Fig. 1**) and the prediction of localized heavy rainfall using observational data. Toshiba is in charge of the development of the MP-PAWR and has conducted a feasibility study by applying observational data from the MP-PAWR data dissemination system. In addition, since the rainfall observation by the radar plays an important role in predicting river water levels, we have also validated predictions of river water levels based on MP-PAWR observational information.

The MP-PAWR observational data is expected to be utilized for "countermeasures against flooding" in the field of sewerage. Many civil engineering facilities, such as drainage pump stations, are maintained in urban areas, and the utilization of this information would improve

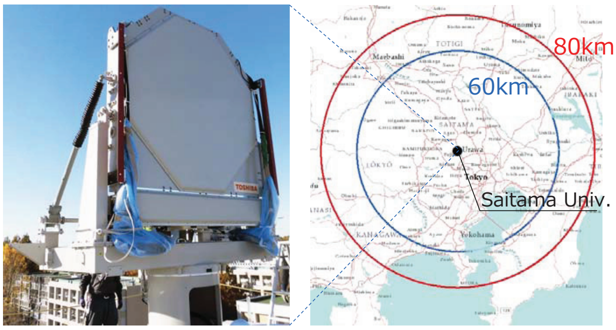

Fig. 1. MP-PAWR (left) and observation area centered on radar site (right).

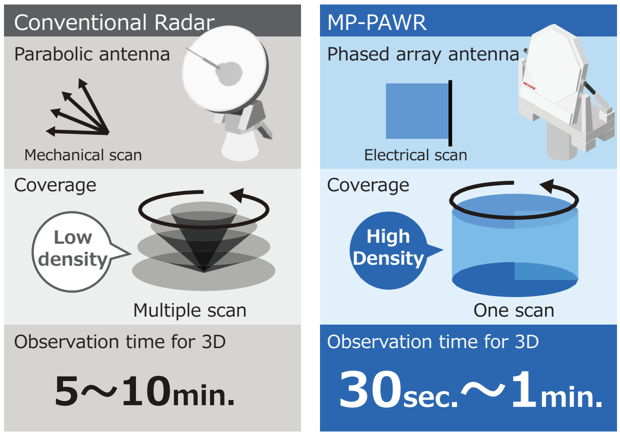

Fig. 2. Comparison of conventional radar and MP-PAWR.

facility operation, increase efficiency, provide real-time hazard map information that would contribute to a reduction of inundation risk, and facilitate other non-structural measures.

In this paper, we report the validation results of the feasibility study on water level prediction; we also describe the possibility of its use in the field of sewerage.

2. Features of MP-PAWR

In this section, we will describe the features of MP-PAWR, as well as the differences between MP-PAWR and the X-band MP radar, which is a conventional parabola radar. Conventional radars make observations by slightly changing the altitude angle of the observation radar and takes about 5–10 minutes to realize three-dimensional observations. Since the observations in the altitude angle are discrete due to the limited observation time, there are some spatial areas that cannot be observed. Like the conventional radar, the MP-PAWR is able to scan the antenna rotation direction (azimuth direction) using mechanical drive, but it can also simultaneously observe at high speed using electronic scanning. It is thus able to observe closely in three-dimensional space up to an altitude of about 15 km. The required time is about 30 seconds to one minute (**Fig. 2**). **Fig. 3** shows the three-dimensional observation results at a specific time at an observation radius of 60 km, an altitude of 15 km, and time interval of 30 seconds. Thus, MP-PAWR can observe three-dimensional precipitation distribution and wind information at high speed at time intervals of 30 seconds to one minute; a previous study [4] also points out that it is effective in clarifying physical mechanisms such as macrobursts.

In addition, the initial study results [5] suggest that it is able to estimate the amount of rainfall near the ground; this is comparable to the X-band MP radar.

Figure 4 gives the conceptual scheme showing the sharp rises in river water levels due to heavy rainfall from "Stage 1: occurrence of rainfall cloud," "Stage 2: rapid growth of rainfall cloud," and "Stage 3: precipitation," to "Stage 4: water level rise," and how the features of

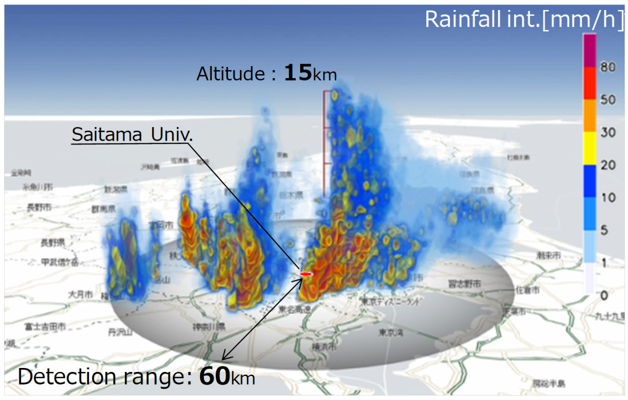

Fig. 3. Observed rainfall results using MP-PAWR (August 27, 2018).

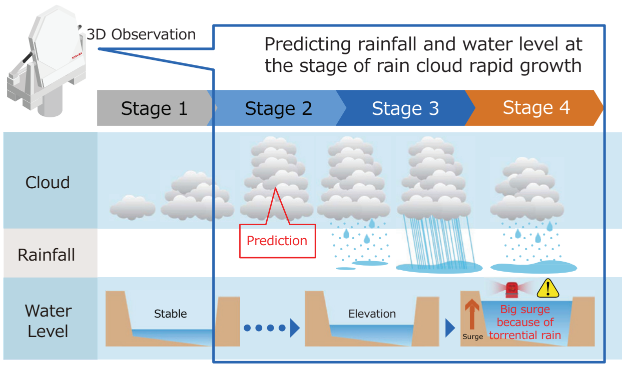

Fig. 4. Prediction of precipitation and water level using MP-PAWR.

the MP-PAWR can be utilized at each stage. Compared to the parabola radar, the MP-PAWR is able to observe the amount of rainfall in the sky at high speed before the precipitation reaches the ground, that is, at Stage 2; it is thus possible to detect precipitation before it reaches the ground with spatially dense and high temporal resolution. By calculating the amount of rainfall in the sky based on the MP-PAWR observational information detected at this stage, information can be disseminated in principle earlier than before by calculating the predicted rainfall using it as an input, and then predicting the water level. This method can be compared to an earthquake early warning system. An earthquake early warning system detects earthquakes that have "already occurred" at the epicenter and disseminates information a few seconds before to the areas where the quake is expected to arrive. The idea is the same for the prediction of localized heavy rainfall by detecting "already occurring" heavy rainfall in the sky, it is possible to convey information 10 to 20 minutes before the rain reaches the ground.

3. Prediction of River Water Levels Using MP-PAWR When Heavy Rain Occurs

3.1. Implementation Content

In urban areas such as the Toga River and Zoshigaya, where water-related accidents are frequent due to the extremely short time required for the rainfall to flow out into rivers and sewage, it is desirable to gain as much lead time as possible and secure time for information dissemination and evacuation guidance. Taking advantage of MP-PAWR's features of high-speed and high-density rainfall observation, we validated the effect of water level prediction in Stage 2.

First, the vertical integrated liquid (VIL) water content was calculated from MP-PAWR observation data according to Eq. (1),

$$\mathrm{VIL} = \begin{cases} 3.93 \times 10^{-3} \displaystyle\int_0^{h_t} Z^{0.55} \cdot \mathrm{dh}, & K_{DP} < 0.3^\circ \ \mathrm{km}^{-1} \text{ or } \\ & 10\log_{10} Z < 35 \text{ dBZ}, \\ 0.991 \times \displaystyle\int_0^{h_t} K_{DP}^{0.713} \cdot \mathrm{dh}, & \text{otherwise}, \end{cases} \quad \ldots\ldots (1)$$

where Z represents the reflection intensity (dBZ) observed by MP-PAWR, K_{DP} represents the rate of change in phase difference between polarizations (°/km), and h_t represents the echo peak altitude (m). Each parameter in the equation is based on values in [6].

Using the VIL derived from Eq. (1) and using the rainfall intensity estimation method applied in XRAIN, etc., by the Ministry of Land, Infrastructure, Transport and Tourism, observed rainfall [7] and predicted rainfall were estimated by using the VIL Nowcast prediction methodology [8]. The predicted rainfall was calculated at 10-minute intervals up to 40 minutes in advance. The spatial resolution was a 100 m square grid.

The water level forecast was validated for the Shibuya River basin. The basin area is about 10 km^2, and the urbanization rate in the basin is about 80%. A rational formula was used to calculate the water level. Watanabe et al. [9] provided an analytical solution using the rational formula (see Eq. (2)); the hydrograph was obtained by applying the rational formula to each small basin and linearly superimposing these according to the time of concentration according to the following formula:

$$q_n(t) = r_n^{ave} v \Big[\{(t-t_n)H[t-t_n] - (t-(t_n+t_r))H[t - (t_n+t_r)]\} - \Big\{ \Big(t - t_n - \frac{x}{v}\Big) H\Big[t - t_n - \frac{x}{v}\Big] - \Big(t - (t_n+t_r) - \frac{x}{v}\Big) H\Big[t - (t_n+t_r) - \frac{x}{v}\Big] \Big\} \Big], \quad \ldots\ldots (2)$$

where q_n is flow rate per unit width (m^2/s), t_n is start time of rainfall (s), t_r is rainfall duration (s), v is cross-sectional average flow velocity (m/s), r is rainfall intensity (m/s), and x is slope length (m). $H(t)$ is the Heaviside step function and is given by the following equation:

$$H(x-a) = \begin{cases} 1 & (x > a), \\ 0 & (x < a). \end{cases} \quad \ldots\ldots (3)$$

3.2. Validation Results

Figure 5 shows the time-series data on precipitation and water level in the validation case. At 19:50, no rainfall was observed near the ground; however, the predicted water levels for the same time have begun to rise. This indicates that it is possible to predict subsequent rainfall before it began to rain, and this is because the amount of rainfall in the sky could be observed using MP-PAWR.

In addition, the predicted water levels 30 to 40 minutes ahead, at 20:00, indicated that it would exceed the flood danger water level (4.0 m); it was thus possible to predict that the flood risk water level would be exceeded about 30 to 40 minutes before the time when the maximum water level of 4.3 m was recorded. Furthermore, the predicted water levels 30 to 40 minutes ahead, at 20:10, was able to capture the downward trend in the water levels. We believe that this was because the predicted rainfall for the same time was able to reproduce the decreasing tendency.

4. Utilization of MP-PAWR Observation Data in the Field of Sewerage

MP-PAWR observational data is also expected to be used for countermeasures against flooding in the field of sewerage. In urban areas, many civil engineering facilities such as drainage pipes, stormwater storage facilities, and drainage pump stations have been developed as countermeasures against flooding. Of these, the drainage pump station is an important facility in urban areas for quickly draining stormwater into rivers; however, it often takes several minutes for the generator to actually drain the drainage pump; therefore, depending on the rainfall situation, the timing of pumping may be delayed due to the delay in the operation timing of the drainage pump, which may lead to inundation in the area. It is therefore often difficult for operators to decide when to start the operation of the drainage pump station.

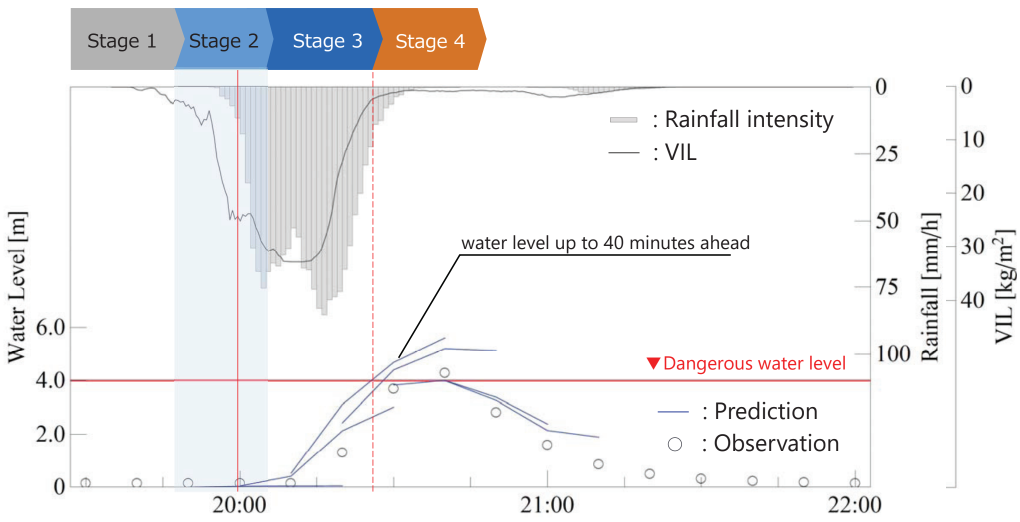

Fig. 5. An example of predicted water level results.

The fact that MP-PAWR provides information 10 to 20 minutes before the local heavy rain reaches the ground makes it possible for the operator to prepare to operate the drainage pump in advance. In addition, like the river water level predictions described in Section 3, it is possible to improve the prediction accuracy of stormwater inflow to the drainage pump station, and water levels in inflow culverts and drainage pump wells by using the MP-PAWR observational data. This makes it possible to accurately time the operation of the drainage pump. Furthermore, it also leads to efficient automatic operation (automatic control) of the drainage pump.

A real-time hazard map that predicts the inundation area and inundation levels in real time by utilizing artificial intelligence (AI) based on MP-PAWR observation information is also being considered. This would contribute to the efficient operation of civil engineering facilities and promote self-help among the general public by disseminating information.

By utilizing the advanced observation and forecast information provided by MP-PAWR, and by improving the efficiency of drainage pump facility operation through non-structural measures, it would be possible to provide more effective information.

5. Conclusions

We conducted a study on the prediction of water levels using MP-PAWR in an urbanized river basin; our findings indicate that the rise of river water levels can be predicted in advance. We also described the possibility of utilizing MP-PAWR observational data in the field of sewerage.

As mentioned in Section 2, information about rainfall using MP-PAWR is similar to an early warning earthquake system. Currently, earthquake early warnings are used not only to disseminate information on detected seismic waves that have already occurred, but also to control social infrastructures, such as the automatic deceleration of Shinkansen trains, and prevent elevator confinement. Nowadays, there are concerns about damage to humans and infrastructures associated with local heavy rainfall, and we hope that the solution based on MP-PAWR observational data will help in the effective and efficient operation of social infrastructure, such as river gates and drainage pumps, which are expected to become IoT-based in the future, and in information dissemination

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