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APPLICABILITY OF A FLOOD FORECASTING METHOD UTILIZING GLOBAL SATELLITE INFORMATION TO AN INSUFFICIENTLY-GAUGED RIVER BASIN: A CASE OF A RIVER BASIN IN THE PHILIPPINES

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A basin-wide flood monitoring and warning systems is being implemented sequentially in river basins of the Philippines, which suffer from severe floods. The Cagayan River basin with draining area of 27,280km^2, that is the largest river basin in the Philippines, has five rainfall and water level gauges for the purpose of flood monitoring and warning. Despite the installed monitoring system, an operational flood forecasting model based on physical theories has not been performed for this basin. Then IFAS, a distributed hydrological model developed by ICHARM, was applied to the Cagayan River basin as a flood forecasting model. One of its notable functions is the capability of using both ground-gauge data and global satellite information, such as topography, land use, and rainfall in the model. This global satellite information is utilized as supplementary information to facilitate easier forecast of flood discharge in an insufficiently-gauged river basin. On the other hand, little has been addressed about accuracy validation of global satellite information as input data of the flood forecasting model. Therefore, GSMaP provided by the Japan Aerospace Exploration Agency (JAXA) was applied to the flood forecasting model as a rainfall input. The comparison shows ground rainfall excels at accuracy of quantity, whereas GSMaP excels at spatial distribution. As a result, the study found that simulation with calibrated GSMaP can reproduce river discharge with high accuracy, suggesting that satellite information combined with ground gauged data is applicable and effective for flood forecasting in the Philippines.

INTRODUCTION

The Cagayan River basin is suffering from frequent severe floods as well as other river basin in the Philippines. Although real-time flood monitoring system has been installed, floods remain as a serious menace due to torrential rainfall by typhoon and insufficient accumulation of reliable hydrological data. In order to improve current flood vulnerable situation, reliable and prompt forecasting is one of the most effective approaches.

Although a number of studies were previously conducted regarding the flood forecasting, little is clarified about applicability of flood forecasting in ungauged or poor-gauged river basin. Regarding rain forecasts, Toth *et al.* [1] made an attempt to use rainfall forecasts for effective flood forecasting. After a comparison in accuracy between short-term rainfall forecasting and time-series analysis techniques, they suggested that precipitation forecasting may allow an extension of the lead time. Jasper *et al.* [2] applied a coupling atmospheric and hydrological model to the Lago Maggiore basin for flood forecasting. Daniele *et al.* [3] tried to evaluate a threshold-based flash flood warning method, considering a wide range of climatic and physiographic conditions and focusing on ungauged basins. Using satellite rainfall data (3B42RT), Fotopoulos *et al.* [4] demonstrated the use of the Open Modeling Interface, which can facilitate the building of a component-based flood forecasting system. Despite above studies, reliability and advantage of global satellite-based information have not clarified from hydrological aspects.

This study aims to clarify the applicability and advantage of flood forecasting method utilizing satellite information such as topography data, land use and rainfall to insufficiently-gauged river basin. Authors applied IFAS, flood forecasting model developed by ICHARM. Both simulated results based on ground gauge and satellite-based are compared in terms of reproducibility of past flood events.

HYDROLOGICAL ASPECTS OF THE CAGAYAN RIVER BASIN

The Cagayan River basin, which is the largest basin in the Philippines with a drainage area of 27,280 km^2, shares topographical features of both mountain and plain. Figure 1 shows topographic features and hydrological gauge stations in the Cagayan River basin. The Cagayan is a vast expanse of plains and valleys, bordered by mountains, running south to north both on its east and west ramparts. Five rainfall and water level gauges are installed for real-time flood monitoring and warning. Most of typhoons that are possible causes of floods come through the Cagayan River basin from south-east to north-west statistically. Because main stream of the Cagayan River also flows from south to north, the scale of flood is subject to keep growth during flooding. Thus, downstream areas such as Tuguegarao and Tumauini are exposed to highly prone to flood disasters.

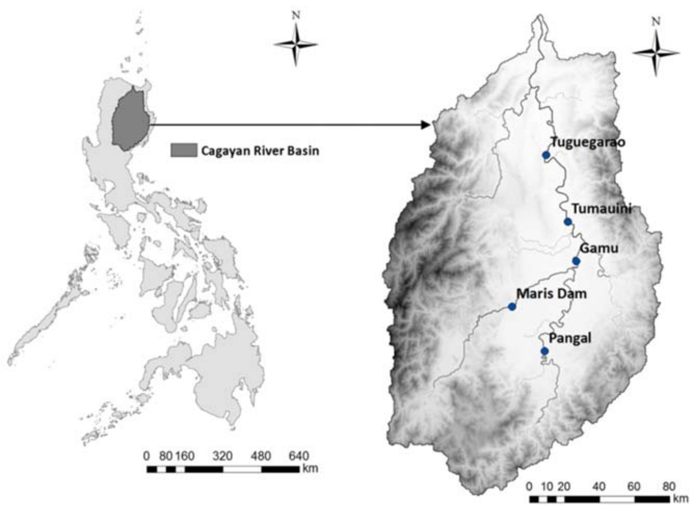

Figure 1. Topographic feature and hydrological stations in the Cagayan River basin, Philippines

Flood traveling time

Flood traveling time is one of the most important factors for both flood forecasting and flood early warning. Therefore, flood traveling times of recent floods are estimated as the time difference between rainfall which is calculated as the center of gravity of hyetograph and peak of runoff depth. Figure 2 shows flood traveling time of recent floods from 2003 to 2010 at Pangal, Gamu, Tumauini and Tuguegarao station. Flood traveling time at every station varies widely because of rainfall intensity, rainfall distribution, influence by dam, soil moisture conditions before and during flooding. Averages of flood traveling time are 12.5 hours at the Pangal, 22.1 hours at the Gamu, 28.7 hours at the Tumauini and 35.9 hours at the Tuguegarao as shown in Figure 2. Average flood propagation time among stations also estimated based on the differences of flood traveling time.

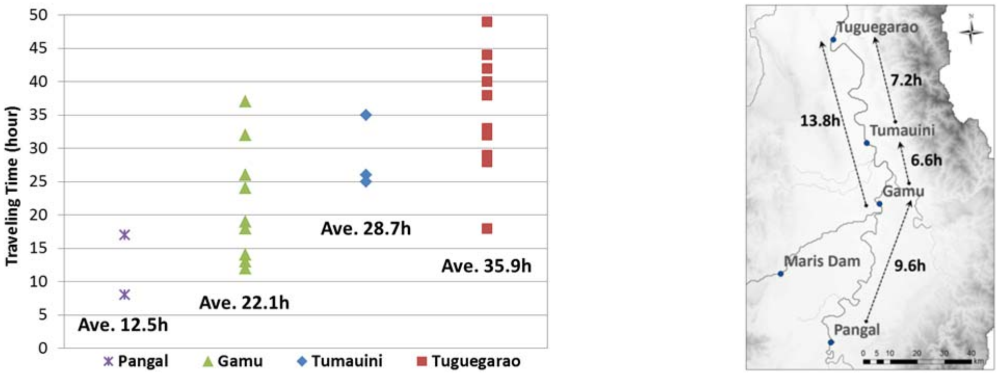

Figure 2. Flood traveling time at Pangal, Gamu, Tumauini and Tuguegarao station (Left)
Differences of average flood traveling time among stations (Right)

Existing flood forecasting

Water level correlation method has been applied as the existing flood forecasting method during flooding. Water correlation method is based on correlation of water level between upstream and downstream. This correlation is assumed based on past flood records as a linear relationship. Water level at downstream is estimated by following equation (1).

$$\mathrm{H}_{down} = a\,\mathrm{H}_{up} + b \qquad (1)$$

where, H_{down} is water level at downstream (m), H_{up} is water level at upstream (m), *a* and *b* are coefficients that should be determined according to past floods. Fixed flood propagation time from upstream to downstream must be determined, for example 15 hours in case between Gamu and Tuguegarao.

Figure 3 shows correlation of water level between Gamu and Tuguegarao station. Water level at Tuguegarao is 14 hours later than Gamu station in order to consider flood propagation time. Black solid line means relationship of existing forecast. Although water level correlation through flood period is poor, rough correlation lying on upper gray zonal line is found with confining only peak of each flood. However, there is a significant difference on water level at Gamu station between older period from 2003 to 2006 and recent period of 2010. Peak values of recent floods lying on lower gray zonal line are clearly lower than old records. A possible reason of the difference is change of river bed. Figure 4 shows change of cross-section at

Gamu station. The significant change of river bed that is found from the figure is a critical issue, because it causes less-accurate flood forecasting.

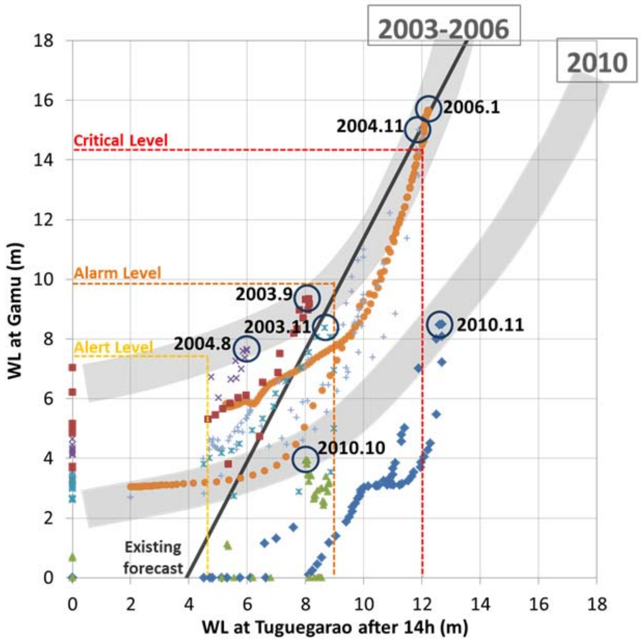

Figure 3. Water level correlation between Gamu and Tuguegarao

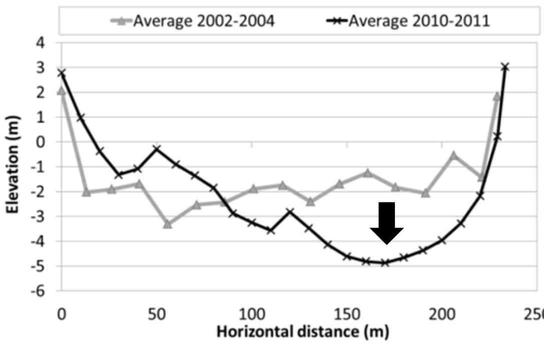

Figure 4. Change of Cross-section at Gamu station

FLOOD FORECASTING WITH IFAS

Basic structure of IFAS

For more effective and efficient flood forecasting in the insufficiently-gauged river basin, ICHARM has developed Integrated Flood Analysis System called "IFAS" [5]. IFAS employs the Public Works Research Institute Distributed Hydrological Model (PDHM) as its runoff simulation model. The conceptual structure of PDHM is shown in Figure 5. Surface flow, rapid subsurface flow, infiltration, slow subsurface flow and base flow are calculated by the following equations from (2) to (6). In the process of river routing, the Kinematic Wave Model is employed. Also, IFAS can import some kinds of satellite-based rainfall data such as GSMaP and 3B42RT for insufficient ground observation area. IFAS has been applied some other insufficiently-gauged river basin [6].

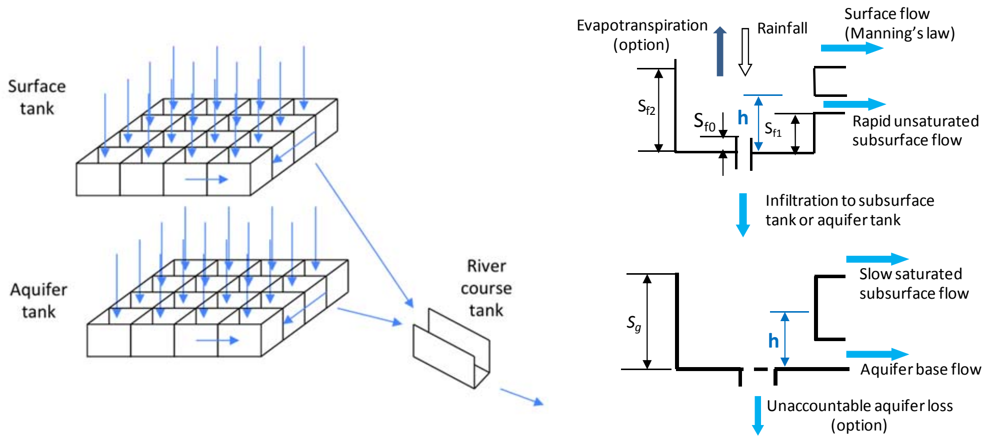

Figure 5. Conceptual structure of IFAS

$$Q_{sf} = L\frac{1}{N}\left(h - S_{f2}\right)^{\frac{5}{3}}\sqrt{i} \quad (2)$$

$$Q_{ri} = \alpha_n \cdot A \cdot f_0 \frac{\left(h - S_{f1}\right)}{\left(S_{f2} - S_{f1}\right)} \quad (3)$$

$$Q_0 = A \cdot f_0 \frac{\left(h - S_{f0}\right)}{\left(S_{f2} - S_{f0}\right)} \quad (4)$$

$$Q_{g1} = A_u^{\ 2} \cdot \left(h - S_g\right)^2 \cdot A \quad (5)$$

$$Q_{g2} = A_g \cdot h \cdot A \quad (6)$$

where Q_{sf}: surface flow (m^3/s), L: mesh length (m), N: manning's roughness coefficient ($m^{-1/3}/s$), h: water height for the tank (m), S_{f2}: height from which surface flow occurs (m), i: slope with the adjacent cell, Q_{ri}: rapid unsaturated subsurface flow (m^3/s), A: mesh area (m^2), S_{f1}: height from which rapid unsaturated subsurface flow occurs (m) Q_0: infiltration to aquifer tank (m^3/s), S_{f0}: height where ground infiltration occur (m), Q_{g1}: slow saturated subsurface flow (m^3/s), S_g: height from which slow saturated subsurface flow occurs (m), Q_{g2}: base flow (m^3/s), α_n ,f_0, A_u, A_g: coefficients.

Reproduction of past floods by IFAS

River discharge of 2006 and 2005 flood at the Gamu station has been simulated by the IFAS as shown in Figure 6. For each flood event, two types of rainfall: ground gauge and GSMaP are applied as a rainfall input. Hydrologic parameters were calibrated based on the flood occurred in 2006 because it is the largest flood in recent years. Although simulated discharge with ground gauge rainfall has high reproducibility, simulated discharge with GSMaP is significantly underestimated.

Discussion about lead time

Existing flood forecasting is based on flood propagation time from upstream reference station to downstream target station. Water level at Tuguegarao can be forecasted from water level at Gamu before 14 hours. According to flood traveling time and propagation time in Figure 2, approximately 22 hours that is flood traveling time at Gamu can be added as lead time at Tuguegarao, because IFAS forecasts from rainfall input. Additionally, IFAS enabled the forecast of water level at Gamu. However, IFAS forecasting requires one hour or less by normal-performance computer. Furthermore, if satellite-based rainfall is applied as a rainfall

input of forecasting, there is time lag of delivery which is four hours in case of GSMaP. These time losses by simulation and data delivery must be deducted from 22 hours.

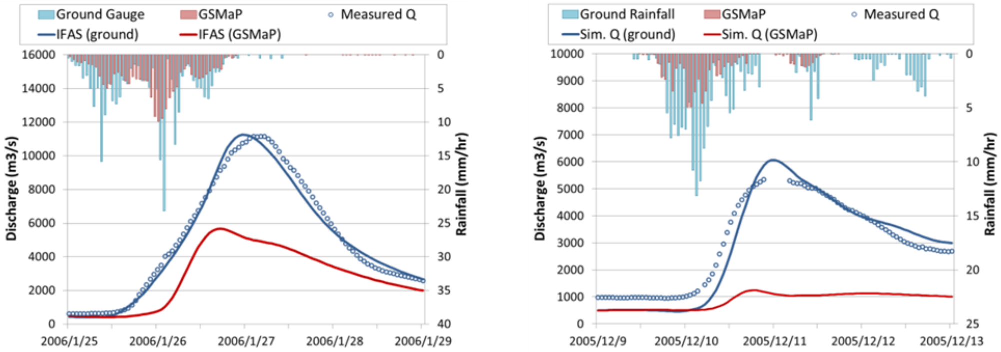

Figure 6. Simulated results of IFAS at Gamu station (Left: 2006 flood, Right: 2005 flood)

APPLIING CALIBRATED SATELLITE-BASED RAINFALL

Generally, ground gauge rainfall excels at accuracy of quantity at gauging point, whereas satellite-based rainfall excels at basin-wide spatial distribution. In order to get the advantage of both products, satellite-based rainfall was calibrated by ground gauge and applied to flood forecasting. GSMaP with 10km grid was calibrated by five gauging stations in the Cagayan River basin.

Calibration method of satellite-based rainfall by ground gauge rainfall

For calibration of satellite-based rainfall, correction factors CF_g that is ratio between ground gauge and satellite is determined at the grid where ground gauge is extant. Next, correction factor at every grid was calculated by following equation (7). Upper and lower limit of CF was set as 5.0 and 0.2 for every grid.

$$CF = \frac{\sum \frac{CF_g}{r_g}}{\sum \frac{1}{r_g}} \qquad (7)$$

where CF: correction factor, CF_g: correction factor at grid of gauging station, r_g: distance between target grid and gauging grid (m).

Calibrated satellite-based rainfall

Comparison of average rainfall at Gamu station among ground gauge, GSMaP and calibrated GSMaP is shown in Figure 7. Although raw GSMaP is underestimated in both floods, rough intensity of calibrated GSMaP is corresponding to ground gauge. Figure 8 shows the spatial distribution of total rainfall through flood event. It is found from the figure that calibrated GSMaP can describe spatial distribution of rainfall in the basin. Moreover it is also found that extent of heavy rainfall is smaller than represented area of ground gauge. Considering spatial distribution of rainfall is significantly important for flood forecasting in case that flood forecasting model is hydrological distributed model.

Application of calibrated rainfall to flood forecasting model

Figure 9 shows the simulated discharge including the case of calibrated GSMaP. Simulation result with calibrated GSMaP provided improved agreement compare to GSMaP without calibration. The result with calibrated GSMaP obtained similar precision as ground gauge in case of 2006 flood; however it is less reproducibility than ground gauge particularly latter of

hydrograph. This gap derives fromis caused by low accuracy of rainfall data rather than issue of hydrological model. However it is estimable to reproduce rising part of hydrograph, because the most important part for flood forecast is beginning and peak of hydrograph. On the whole, it can be mentioned that calibrated GSMaP is applicable to flood forecasting in terms of reproducibility of flood discharge. It can exert more effect on increasing applicability of GSMaP to flood forecasting in case of further poor-gauged river basin.

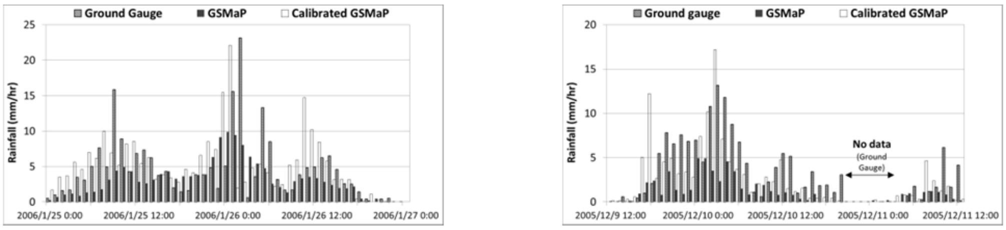

Figure 7. Comparison of average rainfall at Gamu station among ground gauge, GSMaP and calibrated GSMaP (Left: 2006 flood, Right: 2005 flood)

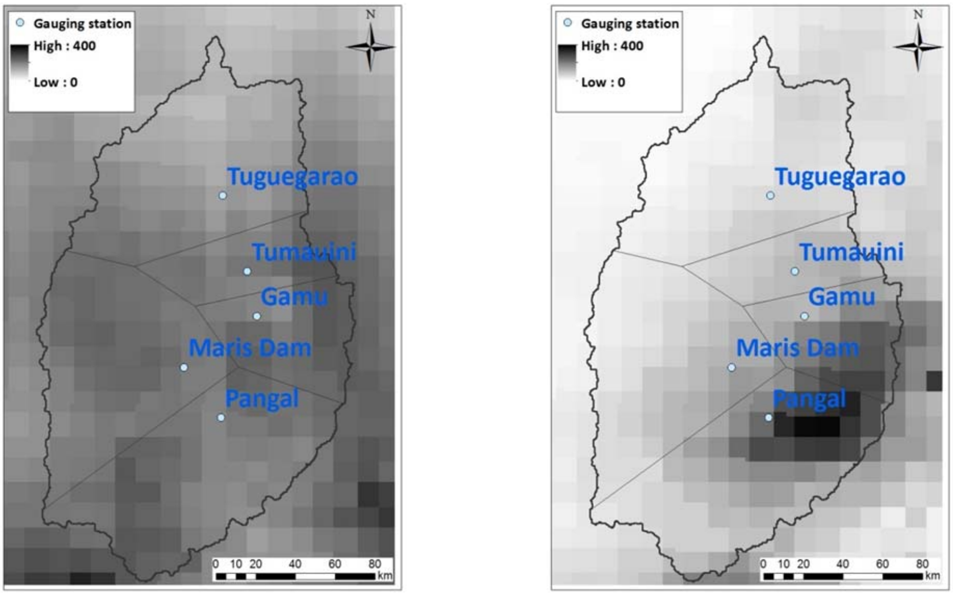

Figure 8. Spatial distribution of calibrated GSMaP (Left: 2006 flood, Right: 2005 flood)

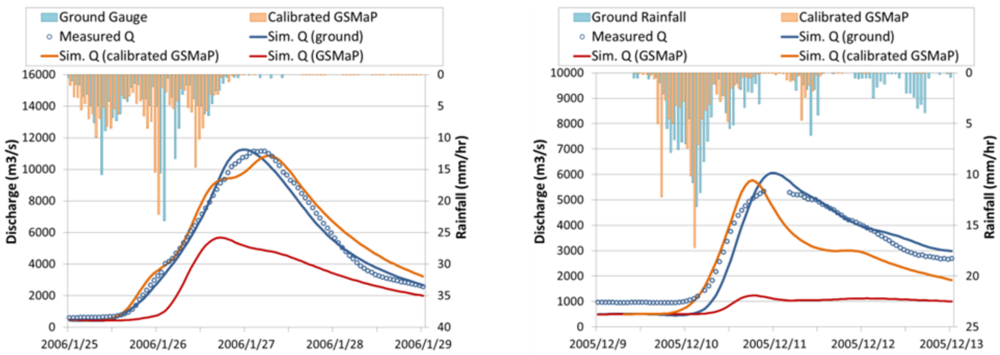

Figure 9. Simulated discharge at Gamu station using calibrated GSMaP (Left: 2006 flood, Right: 2005 flood)

CONCLUSIONS

Applicability of flood forecasting method with utilizing satellite-based information was clarified in this study. GSMaP calibrated by ground gauge was also validated as rainfall input for flood forecasting model. The achieved results are listed below.

1. Rough correlation of water level between Gamu and Tuguegarao is found with confining only peak of each flood. However, there is a significant difference on water level at Gamu station between older period from 2003 to 2006 and recent period of 2010. A possible reason of the difference is change of river cross-section.
2. Regarding lead-time, IFAS can prolong about 22 hours that is flood traveling time at Gamu as lead time at Tuguegarao and make possible to forecast the discharge at Gamu. However, the time losses due to IFAS simulation and data delivery must be deducted from 22 hours, because IFAS forecasting requires one hour or less by normal-performance computer and there is time lag of delivery which is four hours in case of GSMaP if satellite-based rainfall is applied.
3. According to spatial distribution of calibrated GSMaP, represented area of ground gauge is wider than heavy rainfall area. This result means ground rainfall at present cannot describe exact rainfall distribution in the whole basin.
4. Flood forecasting with calibrated GSMaP performed higher reproducibility than GSMaP without calibration particularly beginning and peak of hydrograph. It can be mentioned that calibrated GSMaP is applicable to flood forecasting in terms of reproducibility of flood discharge with the same precision as ground rainfall, because rising part and peak are the most important factors for flood forecasting.

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