A quasi-real-time hydrological simulation of the Chao Phraya River using meteorological data from the Thai Meteorological Department Automatic Weather Stations

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Abstract:

A quasi-real-time hydrological simulation system was developed for the Chao Phraya River in Thailand. The system was largely based on ground meteorological observations from the Thai Meteorological Department (TMD) Automatic Weather Stations (AWSs), which are updated daily and available online. As radiation data were not measured by the TMD AWSs, they were obtained from the global meteorological data of the Japan Meteorological Agency Climate Data Assimilation System. A macro-scale water resources model termed H08 was used for hydrological simulations. The model’s hydrological parameters were set from a series of sensitivity simulations for 2012. The model effectively reproduced the monthly hydrograph at the Nakhon Sawan and other major river gauging stations. The performance at the Sirikit Dam was poor, which could be attributed to erroneous input rainfall data due to the low density of AWSs. The simulation was continued up to September 30, 2013, or the date for which the latest data were available. The overall performance was fair and implied potential applicability of the system for quasi-real-time flood tracking and basic forecasting.

KEYWORDS hydrological model; real-time simulation; Southeast Asia

INTRODUCTION

The Chao Phraya River in Thailand experienced a record-breaking flood in 2011. The flood was primarily caused by lingering rainfall events that resulted in rainfall levels that were 143% of the average for the rainy season from May to October (Komori et al., 2012). The flood was characterized by a vast inundated area that peaked at 14,241 km² on November 9, 2011 (Koontananakulvong et al., 2011). More than 800 people died in the flood and the 2011 fourth quarter GDP dropped by 9.0% compared to a 3.7% rise in the third quarter due to a marked fall in output from the non-agricultural sector as a result of the flood disaster (Office of the National Economic and Social Development Board, 2011). The propagation and recession of the flood were difficult to predict, which hampered disaster mitigation.

Several studies have succeeded in reproducing the flood event in numerical simulations. Kotsuki and Tanaka’s (2013) land surface model successfully reproduced the historical river discharge of this basin. Sayama et al. (2013) reproduced the area inundated by the flood with their Rainfall-Runoff-Inundation Model. Mateo et al. (2013) conducted a numerical river discharge simulation for the period of 2010 to 2011 using a macro-scale hydrological model called H08 (Hanasaki et al., 2008a, b) and a floodplain inundation dynamics model called CaMa-Flood (Yamazaki et al., 2011). They succeeded in reproducing not only the variation of river discharge but also the extent of the inundated area during the event. As H08 also includes a reservoir operation sub-model, they suggested some alternative reservoir operation options for effective flood control.

To make use of simulation techniques for flood disaster mitigation, a real-time or forecast simulation system is required. This type of simulation is well established in the field of meteorology (i.e., weather prediction), but is still in its infancy in hydrology. There are two major challenges in the development of such a system. The first is the accuracy of input data, particularly for precipitation; hydrological simulations are sensitive to precipitation data, but reliable and up-to-date ground observations are difficult to obtain, particularly in Southeast Asian countries. The second challenge is the complexity of the basins; most of the populated Asian basins are regulated by reservoirs and weirs, and their flows are affected by water abstraction by humans. Incorporation of these human activities into macro-scale hydrological models is still uncommon, with the exception being the model used by Mateo et al. (2013).

In this study, a quasi-real-time hydrological simulation system was developed for the Chao Phraya River, Thailand. This system was largely based on meteorological data from the Thai Meteorological Department Automatic Weather Stations (TMD AWSs; http://www.aws-observation.tmd.go.th), which have been publicly available since 2012. We used the H08 macro-scale hydrological model that can
simulate not only the natural hydrological cycle but also major human activities, including reservoir operation and water use. However, all of the sub-models regarding human activity were intentionally disabled in this study to focus on the performance of the natural hydrological simulation or the basis of the system. Models that consider human aspects will be developed and discussed in future reports. The simulation was performed for the period from January 1, 2012, to September 30, 2013. This research was performed to determine accuracy of the system (or the expected error in simulations) and the key sources of error (and how they can be resolved).

**METHODS**

**Study area**

The study area was the Chao Phraya River excluding the tributaries of the Pasak and the Sakae Krang Rivers (Figure 1). The river has four major tributaries: the Ping, the Wang, the Yom, and the Nan Rivers. The rivers join at upper Nakhon Sawan. There are two major dams in the basin: the Bhumibol Dam in the Ping River, which has a storage capacity of $13,462 \times 10^6$ m$^3$, and the Sirikit Dam in the Nan River with a storage capacity of $9,510 \times 10^6$ m$^3$.

For the purposes of this study, the basin was subdivided into 1836 $5' \times 5'$ grid cells. The river boundary and flow direction maps were digitized from printed maps. We validated our simulation results at four major river gauging stations: the Bhumibol Dam (BB, catchment area: $26400$ km$^2$), Si Satchanalai (Y6, $12769$ km$^2$), the Sirikit Dam (SK, $13130$ km$^2$), and Nakhon Sawan (C2, $109973$ km$^2$). As the recorded river flow at Nakhon Sawan is heavily influenced by the operations of the Bhumibol and the Sirikit Dams, we estimated naturalized flow as shown below.

$$Q_{\text{nat}} = Q_{\text{rec}} - Q_{\text{Bhumibol}} + I_{\text{Bhumibol}} - O_{\text{Sirikit}} + I_{\text{Sirikit}}$$

where $Q$ is river discharge, and $O$ and $I$ are the observed outflow and inflow from reservoirs, respectively. The subscripts nat, rec, Bhumibol, and Sirikit denote estimated naturalized flow, recorded flow, the Bhumibol Dam, and the Sirikit Dam, respectively.

**Hydrological model**

A macro-scale hydrological model termed H08 was used in this study (Hanasaki et al., 2008a, b). The model consists of land surface hydrology, river routing, reservoir operation, crop growth, water withdrawal, and environmental flow sub-models. In this study, we only used the first two sub-models for natural flow, and the remaining four sub-models for human activities were disabled. The fully functional model will be discussed in a future report.

The land surface hydrology sub-model calculates the energy and water balance on the land surface (see Hanasaki et al., 2008a for technical details). The sub-model has four adjustable hydrological parameters of soil depth ($SD$) [m], bulk transfer coefficient ($C\gamma$) [-] and two shape parameters for subsurface flow generation ($\gamma$ [-] and $r$ [day]). $C_D$ directly controls the evapotranspiration ($E$) as follows:

$$E = \beta \rho C_D U(q_{S\text{AT}}(T_S) - q_o)$$

where $\beta$ is the evapotranspiration efficiency, $\rho$ is the density of air [kg m$^{-3}$], $U$ is the wind speed [m s$^{-1}$], $q_{S\text{AT}}(T_S)$ is the saturated specific humidity [kg kg$^{-1}$] at a surface temperature $T_S$ [K], and $q_o$ is the specific humidity [kg kg$^{-1}$]. $SD$, $\gamma$, and $r$ control the baseflow. The total runoff ($Q_{tot}$) is expressed as:

$$Q_{tot} = Q_s + Q_{sb}$$

where $Q_s$ is the surface runoff generated when the soil water content ($W$) [kg m$^{-2}$] exceeds the capacity of soil water ($W_f = 0.15 \times SD$) [kg m$^{-2}$], and $Q_{sb}$ is the subsurface runoff [kg m$^{-2}$ s$^{-1}$], which is expressed as:

$$Q_{sb} = \frac{W_f}{r \times 86400 \left(\frac{W_f}{W_s}\right)^\gamma}$$

All of the above are physical parameters that reflect the conditions of the land surface. However, it is difficult to obtain representative values for each of the grid cells due to the heterogeneity of topography, land use, vegetation, soil, and manmade structures. Therefore, we selected a parameter set for better performance as shown below.

**Meteorological data**

H08 requires seven meteorological variables: air temperature (Tair), relative humidity (RH), surface air pressure (PSurf), wind speed (Wind), precipitation (Prep), longwave downward radiation (LWdown), and shortwave downward radiation (SWdown). These variables must be recorded at least at daily intervals.

The TMD has installed 91 AWSs across the country and observed meteorological data are available on their website (http://www.aws-observation.tmd.go.th). The data have been made available from January 1, 2012, to one day before present, and include Tair, RH, PSurf, Wind, and Prep. We downloaded records for 40 AWSs within and around the basin (Figure 1). We interpolated the daily AWS records
QUASI REAL TIME HYDROLOGICAL SIMULATION

Table I. Parameters tested in this study

|        | SD  | CD  | γ   | r   |
|--------|-----|-----|-----|-----|
| A (Parameters perturbed toward lower values) | 2.0 | 0.004 | 1.3 | 60  |
| B (Parameters used in Mateo et al., 2013)   | 3.0 | 0.006 | 2.3 | 120 |
| C (Parameters perturbed toward higher values) | 4.0 | 0.008 | 3.3 | 240 |

and converted them into daily 5' × 5' grids. During the interpolation of Tair, an elevation correction was applied using elevation data provided by the Shuttle Radar Topography Mission (2013). Note that the density of AWS coverage is particularly low in the east of the basin, as shown in Figure 1.

As LWdown and SWdown are not included in the TMD AWSs, they were obtained elsewhere. Recently, reliable and current global meteorological gridded data have become publicly available, e.g., the Japan Meteorological Agency (JMA) Climate Data Assimilation System (JCDAS, Onogi et al., 2007). This is a regularly updated reanalysis product covering the period from 1979 to two days before present. The spatial resolution is approximately 1.125° × 1.125°. We downloaded the global LWdown and SWdown data, and interpolated them into the same spatial resolution as TMD.

Simulation and analyses

We conducted two simulations: a parameter sensitivity simulation and a regular simulation. First, we conducted a series of parameter sensitivity simulations for 2012 to understand the behavior of four hydrological parameters and select appropriate parameter combinations for this study. We first set the parameters that were used by Mateo et al. (2013; shown as B in Table I) and then ran the model. Then, we tested lower (A) and higher (C) values for each parameter and repeated model runs for 81 (= 34) combinations of parameters. Here, we defined an objective function (O) as follows:

\[ O_s = \min(NRMSE_s) \]  \hspace{1cm} (5)

where NRMSE is the normalized root mean square error of daily discharge, and \( s \) denotes the river gauging station. We selected one parameter combination that minimized \( O_s \) at four stations.

Second, we conducted the regular simulation for the period of January 1, 2012, to September 30, 2013, with the selected combinations of parameters. The simulation period was rather short but was the longest that was possible because TMD AWS data were only available from January 2012.

RESULTS AND DISCUSSION

Meteorological data

Figure 2 shows the annual mean meteorological data in 2012. The key characteristics are as follows. As an elevation correction was applied, the air temperature shows an elevation pattern (i.e., temperature is lower in mountainous regions). Relative humidity shows no clear spatial pattern, and the wind speed was generally low. Shortwave and longwave downward radiation display smooth spatial changes, because we interpolated the coarse global meteorological data from JCDAS. The variable pattern of rainfall was attributed to the considerable variety in rainfall amounts reported at each AWS and the low density of AWS coverage. The rainfall in the west of the basin was clearly higher than in other areas. The westerly wind from the Andaman Sea generates plentiful rainfall in this area.

Results of parameter sensitivity simulation

Figure 3 shows the sensitivity of hydrological parameters. We focused on the sensitivity of the four hydrological parameters to the monthly discharge at Si Satchanalai. All were fixed at B in Table I (i.e., \( SD = 3.0 \), \( C_D = 0.006 \), \( γ = 2.3 \), and \( r = 120 \)). Then, each was changed from A to C. The results indicate that SD controls the sharpness of the hydrological response. If SD is lower (i.e., shallower soil depth), the simulated peak of discharge becomes larger and decays faster. \( C_D \) controls the total discharge. If \( C_D \) is lower (i.e., lower drag coefficient), the simulated evaporation decreases and results in a higher discharge without changing the shape of the hydrograph. \( γ \) controls the discharge of the intermediate period between wet and dry conditions (see Equation 4). The discharge in the wettest and driest months (September and April) showed small differences among parameters, while these differences were larger in the other months, particularly in June. In the wettest and driest months, the term \( W/W_f \) approaches 1 and 0, and subsurface runoff \( (Q_{sb}) \) becomes insensitive to \( γ \). In contrast, in the intermediate months, the term \( W/W_f \) often remains between 0 and 1, and this makes subsurface runoff quite sensitive to \( γ \). Finally, we calculated the objective function shown in Equation 5. The combinations of the four parameters that minimized the objective function in the four basins are shown in Table II. The selected parameters differ widely among basins. Kotsuki and Tanaka (2013) reported that the rainfall-runoff ratio is considerably different among basins, which is supported by our results. However, taking into account the short period for calibration (i.e., only 2012) and the low density of AWS coverage, the parameters should be further examined and updated.

Results of the regular simulation

Figure 4 shows the monthly and daily hydrographs at the four river gauging stations in 2012 with the selected parameters. Table III shows the bias of annual river discharge and monthly and daily NRMSE for the same simulation. The monthly hydrographs at Nakhon Sawan, Si Satchanalai, and Blumibol Dam were reproduced well. The bias ranged from −12% to +13% and the NRMSE was 32%–34%. The simulated daily hydrograph captured the long-term variation in observations fairly well, but its temporal variation was too smooth and failed to reproduce the observed daily-scale fluctuations. This resulted in a high daily NRMSE. This is likely to be due to the model structure of H08. As shown
in Equations 3-4, runoff is generated by surface runoff ($Q_s$) and subsurface runoff ($Q_{sb}$). Due to the formulation of the subsurface runoff (Equation 4), the largest value is $W_f / \tau \times 86400$, and it decays sharply with decreases in $W/W_f$. In many cases this is too small to explain the peaks in the hydrographs in the upper basins. $Q_s$ is generated only when the soil is completely saturated ($W=W_f$). This condition can occur only in the late rainy season. In reality, heavy rainfall rapidly generates abundant surface runoff due to excess infiltration and other processes. The lack of these detailed hydrological processes is considered to be one of major reasons for the limitation in daily performance.

The monthly NRMSE at the Sirikit Dam was substantially higher than in other basins (67% for monthly and 95% for daily data). This was primarily due to the poor reproducibility of observed discharge peaks in August and September (Figure 4). Note that all of the available AWSs are located a considerable distance from this basin (Figure 1). This implies that some important rainfall events may have been missed in the current input data. As the catchment area of Sirikit Dam is an important source of river discharge, additional AWSs are needed for better hydrological simulations. In addition, the daily NRMSE at Si Satchanalai is higher than in the other basins. As shown in Figure 4, the observed daily hydrograph at this station has more peaks than others. Due to the lack of a fast hydrological response, the performance could be particularly low in this basin.

Figure 5 shows the hydrographs at four river gauging stations in 2013. The simulation was conducted up to September 30, i.e., the middle of the high-flow season. Although the simulation captured the magnitude and the pattern of river discharge in all four basins fairly well, the performance was limited. In general when using hydrological models, it is more difficult to reproduce the discharge in the dry season than the wet season. Note that the naturalized discharge at Nakhon Sawan became negative from January to May. This was attributed to water withdrawal between Nakhon Sawan and the two reservoirs being neglected. The vast irrigated cropland in this area relies on river water abstraction in the dry season, and such processes should be incorporated to improve the performance of the model.

**CONCLUSIONS**

A quasi-real-time hydrological simulation system was developed for the Chao Phraya River in Thailand. This system uses the TMD AWS and JCDAS meteorological data and enables simulations to be made up to two days before present. The model parameters were set from a series of sensitivity simulations for 2012. The model effectively
reproduced the monthly hydrographs at the Nakhon Sawan and other river gauging stations. The limited performance at Sirikit Dam can be attributed to erroneous input rainfall data due to the low density of AWS coverage. The simulation was continued up to September 30, 2013, or the date for which the latest data were available. The performance was fair, implying its potential applicability for real-time flood tracking and basic forecasting.

The simulation described in this study provides two major advantages. First, the system utilizes recently available meteorological data, which are automatically and systematically updated. As such data disclosure is expected to

Table II. Parameters that minimized the objective function

|          | SD  | CD  | y   | r  |
|----------|-----|-----|-----|----|
| Bhumibol Dam (BB) | 4.0 | 0.008 | 3.3  | 240 |
| Si Satchanalai (Y6) | 2.0 | 0.004 | 1.3  | 240 |
| Sirikit Dam (SK) | 4.0 | 0.006 | 1.3  | 120 |
| Nakhon Sawan (C2) | 3.0 | 0.006 | 2.3  | 240 |

Table III. Bias and normalized root mean square error (NRMSE)

|          | bias | NRMSE (monthly) | NRMSE (daily) |
|----------|------|-----------------|----------------|
| Bhumibol Dam (BB) | −12% | 32%            | 65%            |
| Si Satchanalai (Y6) | +13% | 34%            | 123%           |
| Sirikit Dam (SK) | −2%  | 67%            | 95%            |
| Nakhon Sawan (C2) | +3%  | 32%            | 65%            |

Figure 3. River discharge at Si Satchanalai [m³ s⁻¹]. The four sub-panels show the sensitivity of the hydrological parameters $SD$, $C_D$, $\gamma$, and $\tau$, respectively, when fixing the other parameters at $SD = 3.0$, $C_D = 0.006$, $\gamma = 2.3$, and $\tau = 120$ (B in Table I). Black lines indicate the observations.

Figure 4. (a) Monthly and (b) daily river discharge at four stations in 2012 [m³ s⁻¹]. Black lines show the observations. The horizontal axis shows the month and day of the year.
increase in Southeast Asian countries, thus some of the findings of this study could be applicable to other regions. Second, the system is based on the global hydrological model H08. This enables more sophisticated modeling, including the influence of major human activities, such as reservoir operation and irrigation water withdrawal, because it already includes such sub-models.

Three major tasks remain. First, input meteorological data should be further investigated, particularly for precipitation data. This includes the methods used for interpolation and data quality checking. Kotsuki and Tanaka (2013) demonstrated that the selection of precipitation data considerably influences the performance of hydrological simulations in this basin. Second, the hydrological parameters and models should be further examined. Extension of the calibration and validation period is particularly important. The addition of hydrological processes for the fast rainfall-runoff response is also urgently needed. The H08 model currently lacks these processes, because it was originally designed to simulate long-term continental-scale river flows. This study showed that H08 captured the aggregated hydrological response fairly well on a monthly time scale for four basins with catchment areas larger than 10000 km$^2$, whereas it failed to reproduce the daily details. The introduction of new models is also promising. For example, Mateo et al. (2013) demonstrated that by replacing the H08 river model with the CaMa Flood model, the hydrological simulation was substantially improved. Third, the sub-models for human activities should be enabled. For example, the incorporation of the water withdrawal sub-model would improve performance at Nakhon Sawan, where the abstraction of irrigation water is not negligible in the dry season.

ACKNOWLEDGMENTS

The study was funded by JST/JICA SATREPS and JSPS Kakenhi 23760468. The authors are grateful to the Thai Meteorological Department, the Royal Irrigation Department, Thailand, and the Japan Meteorological Agency for providing us with meteorological and hydrological data.

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