Long-term Water Balance Analysis Using Different Precipitation Products In Upper Chao Phraya River, Thailand

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Intermittent heavy rain from June 2011 led to massive flooding in the Chao Phraya River basin. An understanding of water-balance characteristics in the upper basin is required to revise the master plan for management of the entire basin. In this study, the authors have tried to figure out the water balance characteristics in upper Chao Phraya River in Thailand. The authors have conducted hydrological land surface analysis using SiBUC[1] with different precipitation products, which are GPCC, APHRODITE, GPCP, GSMaP MWR, and collected observed data (K12). The main findings were as follows: (1) More than 80 % of precipitation was lost through evapotranspiration in upper basin. Simulated evapotranspiration were almost the same, suggesting that evapotranspiration in this basin strongly depends not on precipitation but on other metrological forcing such as temperature and radiations. (2) While the simulated runoff using K12 corresponded well with a runoff record at the Nakhon Sawan station, simulate runoff using GPCC and APHRODITE have overestimation and underestimation to the runoff record. Because runoff ratio in the upper basin is low, small differences in precipitation data resulted in large differences in runoff. These findings demonstrate the importance of the quality of precipitation data for accurate simulations of the water balance in the upper basin.

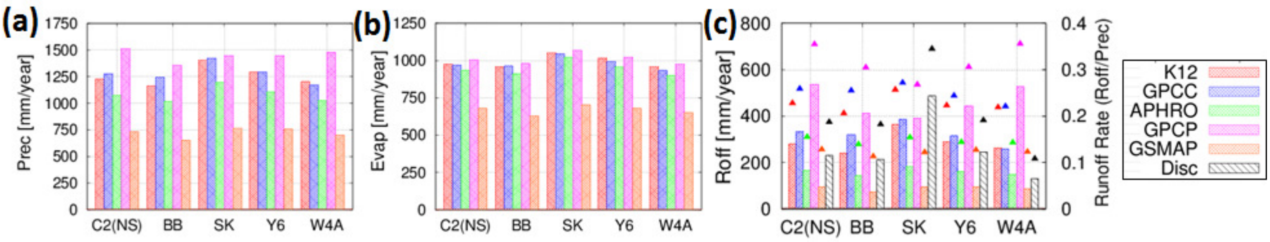

Figure 1. Mean annual (a) precipitation, (b) simulated evapotranspiration, (c) simulated runoff (bars) and runoff ratio (triangles) in the five catchments averaged from 1998 to 2006. Red, blue, green purple, orange, and black bars respectively represent collected precipitation (K12), GPCC, APHRODITE, GPCP, GSMaP_MWR, and observed discharge.

Keywords: Chao phraya river; Precipitation; Water resources management; Hydrological land surface model; Evapotranspiration

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References

[1] Tanaka, K (2004), Development of the New Land Surface Scheme SiBUC Commonly Applicable to Basin Water Management and Numerical Weather Prediction Model. *Doctoral Dissertation, Graduate School of Engineering, Kyoto University (Kyoto)*, pp.289.

Figure 1. (a) Diagram of the Chao Phraya River watershed, and (b) mean annual precipitation of the six products from 1998 to 2006. (b-1: APHRODITE, b-2: GPCC, b-3: H08, b-4: GPCP, b-5: GSMaP, and b-6: JRA25)

Many hydrological studies have been undertaken in the Chao Phraya River basin (e.g., Hanasaki et al.[3]). Additionally, estimates of the impacts of climate change have been made using the outputs from global climate models (e.g. Kure et al. [4]). However, few studies have reported the water-balance characteristics in the basin (e.g. Kotsuki and Tanaka [5,6]). The main objective of this study was to determine the water-balance characteristics in the upper Chao Phraya River basin through runoff simulations. Precipitation is one of the most important climate variables for runoff simulation since it is the predominant and ultimate source of water for the land surface water budget (Fekete and Vorosmarty [7]). Figure 1(b) shows the mean annual precipitation of the six precipitation products from 1998 to 2006 over Eastern Asia. Here, The Global Precipitation Climatology Centre (GPCC; Rudolf et al. [8]), APHRODITE (Yatagai et al. [9]), and the H08 product (Hirabayashi et al. [10]) are produced by observed precipitation on the land surface. The Global Precipitation Climatology Project (GPCP; Huffman et al. [11]) is the data derived from satellite and surface measurements. The Global Satellite Mapping of Precipitation (GSMaP; Ushio et al. [12]) is produced by satellite observation data. JRA25 is the reanalyzed precipitation data from a global climate model (Onogi et al. [13]). While the spatial distributions of precipitation coincide with each other, there are differences in the amount of precipitation. It is important to understand the accuracy of a product, the difference between precipitation products, and the impact that these differences in the amount of precipitation have on simulated runoff.

We have conducted simulations using a hydrological model comprising a land-surface process and a river-routing process. This paper describes the methodology used to conduct the simulations and the results of the model application to the upper Chao Phraya River basin. Through the simulations using different precipitation products, this paper reveals the runoff characteristics of the basin.

Methodology

Hydrological Model

A long-term water-balance analysis was conducted using the distributed hydrological model. The land-surface process calculates the energy, radiation and water budgets on the land surface with seven meteorological forcings: temperature, specific humidity, short-wave radiation, long-wave radiation, atmospheric pressure, wind speed, and precipitation. In this study, the Simple Biosphere model including Urban Canopy (SiBUC; Tanaka, 2004 [14]) was used to calculate the land-surface process. Differences in land cover have a strong effect on energy, radiation, and water budgets. SiBUC uses the mosaic approach to reflect land-cover mixtures. Because all model parameters can be determined with land-surface products, the model does not require any parameter calibrations, normally. The river-routing process calculates the rivers discharge in the channel using the kinematic-wave method, which uses the surface and sub-surface runoff data from the land-surface process.

- Data Sets

The hydrological simulations were conducted using different six precipitation data sets (APHRODITE, GPCC, H08, GPCP, GPMaP, and JRA25). We also conducted the simulation using observed precipitation data. Precipitation data were provided by the Royal Irrigation Department (RID) and the Thai Meteorological Department (TMD) through two projects: IMPAC-T and GAME-T2 Data Center (GAME-T2). The number of precipitation stations per 1000 km2 of APHRODITE data and the observed precipitation in each catchment are as shown in Table1c and 1d. Monthly-averaged diurnal variation of a satellite mapping of precipitation (GSMaP-TMI; Ushio et al. [12]) from 1998 to 2006 was used for each precipitation data. Note that the intent of two simulations is not to discuss qualities of precipitation products, but to discuss the influence on runoff of the small differences in precipitation data. Short-wave radiation, long-wave radiation, specific radiation, and temperature data were recorded with the H08 product. Wind speed and atmospheric pressure were determined from JRA25 reanalyzed data. Original meteorological data was used to change the resolution for the model mesh size using an interpolating method.

Different land-cover fractions were determined from GLCC ver2.0 provided by USGS (US Geological Survey). Soil physical parameters were identified using Ecoclimap provided by Meteo-France. A flow-direction map of the river was produced using the steepest-slope method, which determines the flow direction of each mesh as the steepest slope among four neighboring meshes. SRTM 90-m digital elevation data, which was provided by the Consultative Group on International Agricultural Research (CGIAR), was used to determine the altitude used to determine flow directions. Calculated flow-accumulation areas for the reported catchment area at five river stations are shown in Table 1a.

Catchments in the Chao Phraya River

Simulated results were produced for five river stations: the Bhumibol Dam for the Ping River, Ban Wang Man (W.4A) for the Wang River, Ban Kaeng Luang (Y.6) for the Yom River, the Sirikit Dam for the Nan River, and Nakhon Sawan (C.2) for the entire upper basin. River runoff records from 1981 to 2004 were collected at three stations: C.2, Y.6, and W.4A. These runoff data were provided by RID and were obtained from the GAME-T2 Data Center. Inflow, release, pumped discharge, and evapotranspiration data for the Bhumibol Dam and the Sirikit Dam were provided by the Electricity Generating Authority of Thailand (EGAT).

Result and Discussion

Figure 2 shows difference between results using APHRODITE and other precipitation products in mean annual precipitation, simulated evapotranspiration, and simulated runoff from 1998 to 2006 over Eastern Asia. Cold and warm colors mean results using APHRODITE are lower and higher than results using other products. Large differences in precipitation are shown in Figure 2a in Myanmar, Malay Peninsula, and Sumatera Islands. Although precipitation has large difference as shown in Figure 2a, simulated evapotranspiration has small difference as shown in Figure 2b. Most of difference in precipitation translates to difference in runoff shown in Figure 2c. As Fekete et al. [7] pointed out, any error in the precipitation translates to approximately the same absolute error in runoff in wet region, where the precipitation always exceeds the potential evaporation.

Two hydrological simulations were conducted for a 24-year period using data from APHRODITE and the observed precipitation in the Chao Phraya River basin. Figure 3 shows comparisons of monthly runoff from 1995 to 2004 at the C.2 station. Black, blue, and red lines represent the observed natural runoff, simulated runoff using APHRODITE data, and simulated runoff using observed precipitation, respectively. Because our model did not include dam effects, the observed runoff at the C.2 station were naturalized to remove the effects of the upper Bhumibol Dam and Sirikit Dam as follows:

$$ND_{C2} = OD_{C2} + \left[Inf + Pump - Ouf\right]_{BB,SK} \quad (1)$$

where ND is the naturalized runoff (m^3s^{-1}), OD is the observed runoff (m^3s^{-1}), Inf is the inflow runoff at dams (m^3s^{-1}), Pump is the water pumped into dams (m^3s^{-1}), and Ouf is the discharge released from dams (m^3s^{-1}). The released discharge includes water released from spillways and irrigation gates. Subscripted *BB* and *SK* mean the Bhumibol Dam and the Sirikit Dam, respectively.

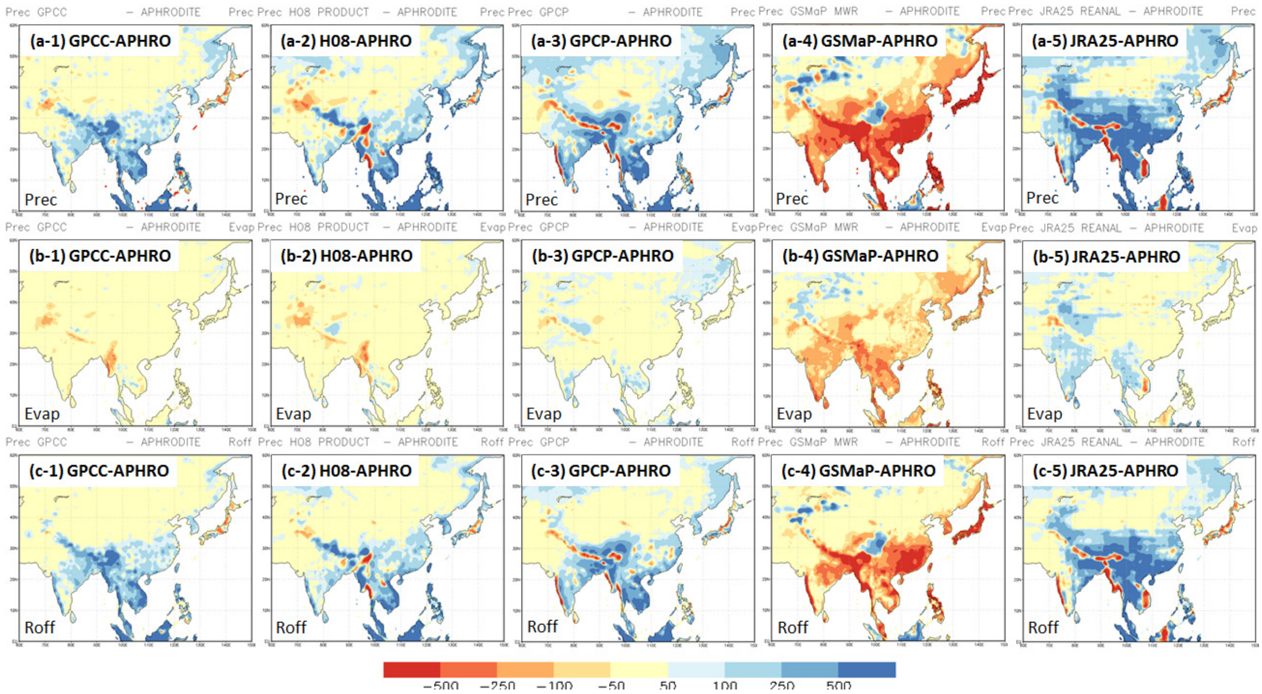

Figure 2. Difference in mean annual precipitation (a-1, a-2, a-3, a-4, a-5), simulated evapotranspiration (b-1, b-2, b-3, b-4, b-5), and simulated runoff (c-1, c-2, c-3, c-4, c-5) from 1998 to 2006. Units of the figure are mm･yr^{-1}.The results using GPCC minus that of APHRODITE are shown in a-1, b1, and c-1. The results using H08 minus that of APHRODITE are shown in a-2, b-2, and c-2. The results using GPCP minus that of APHRODITE are shown in a-3, b-3, and c-3. The results using GSMaP minus that of APHRODITE are shown in a-4, b-4, and c-4. The results using JRA25 minus that of APHRODITE are shown in a-5, b-5, and c-5. Cold color means precipitation, evapotranspiration, and runoff using APHRODITE are lower than those of using other precipitation products.

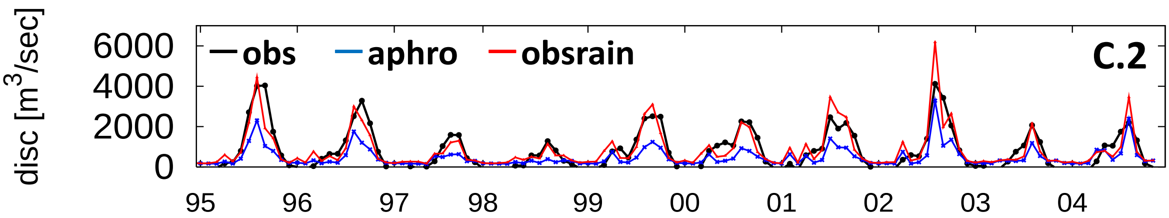

Figure 3. Comparison of monthly runoff from 1995 to 2004 at the Nakhon Sawan [m^{3}s^{-1}]. Black, blue, and red lines represent observation, simulation using APHRODITE, and simulation using observed precipitation, respectively.

Figure 3 shows that the simulated runoff using the observed precipitation corresponded well to the naturalized runoff compared with the simulated runoff using APHRODITE data. The Nash–Sutcliffe model efficiency coefficient, using 24-years of monthly runoffs, was 0.70 for results using the observed precipitation and 0.47 for results using APHRODITE data. These results were obtained without any parameter calibrations, as previously mentioned.

Table 1 presents the water-balance characteristics of the five upper catchments. Table 1b shows the observed average runoff during the 24-year study period. Table 1c and 1d shows simulated results over the same period using APHRODITE data and the observed precipitation, respectively. Stat, Prec, Roff, and Rate refer to the number of precipitation stations per 1000 km^2, precipitation, runoff and runoff rate, respectively. Table 1c and 1d shows that more than 80% of the precipitation was lost through evapotranspiration in the basin. Therefore the runoff ratios in both simulations were low. Simulated runoff ratios using APHRODITE data were 0.10–0.11, whereas those calculated using the observed precipitation were 0.15–0.18. In the five catchment areas, the average observed annual precipitation exceeded the values from APHRODITE data by about 10%. It is considered that small difference in used precipitation stations of each product causes the differences in annual precipitation. Because runoff ratios in the upper basins were low, a 10% difference in the precipitation data resulted in 50–100% differences in runoff ratios. It is clear that the quality of the precipitation data is very important for the simulation of water balance in the upper Chao Phraya River basin.

Table 1. Water-balance chracteristics of the upper catchments. Table (a) shows reported catchement areas and areas in the model [km^2]. Table (b) shows the observed average runoff during the 24-year study period. Table (c) and (d) shows simulated results using APHRODITE data and the observed precipitation. Stat, Prec, Roff and Rate refer to the number of precipitation station per 1000 km^2, precipitation [$mm \cdot yr^{-1}$], runoff [$mm \cdot yr^{-1}$] and runoff rate[-].

Station	(a) Catchment		(b) Obs.	(c) Sim. (APHRODITE)				(d) Sim. (observed prec.)			
	Report	Model	Roff	Stat	Prec	Roff	Rate	Stat	Prec	Roff	Rate
C.2	110,569	110,070	195	1.18	1005	109	0.11	1.37	1144	192	0.17
Bhumibol Dam	26,400	27,951	190	1.17	989	105	0.11	1.69	1101	169	0.15
Sirikit Dam	13,130	14,439	415	0.69	1086	109	0.10	0.84	1246	212	0.17
Y.6	12,658	13,786	200	1.17	992	106	0.11	1.07	1164	200	0.17
W.4A	10,507	10,677	89	1.58	935	97	0.10	1.69	1101	182	0.17

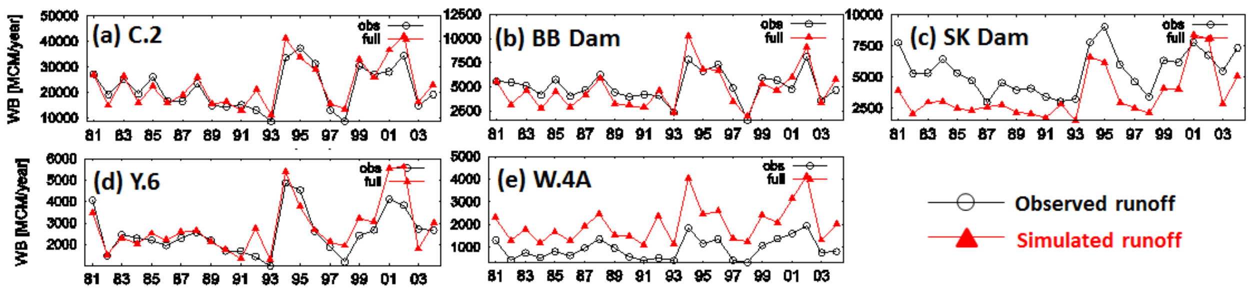

Figure 4. Comparison of annual runoff during the 24- years study period at (a) the C.2, (b) the Bhumobol Dam, (c) the Sirikit Dam, (d) the Y.6, and (e) the W.4A [MCM·yr-1]. Black and red lines represent observed runoff and simulated runoff using observed precipitation, respectively.

Figure 4 shows a comparison of annual runoff during the 24-year study period at (a) C.2, (b) the Bhumobol Dam, (c) the Sirikit Dam, (d) Y.6, and (e) W.4A. Black and red lines represent observed runoff and simulated runoff using the observed precipitation, respectively. It can be seen that simulated runoff using the observed precipitation corresponds well to the observed runoff at C.2, the Bhumibol Dam, and Y.6. However, the simulated runoff was overestimated at W.4A and was underestimated at the Sirikit Dam. Because the simulated runoff rates in the five catchments were almost the same, the cause of the underestimation at the Sirikit Dam and the overestimation at W.4A was not due to the operation of the hydrological model. The overestimation at W.4A was considered to be caused by inundations in the lower Wang River. Field interviews revealed that the W.4A station is located on a flood plain, which is inundated more than once a year. The authors presume that the accuracy of precipitation data is responsible for the underestimation in the Nan River basin. As mentioned previously, runoff in the upper Chao Phraya River basin is heavily dependent on the amount of precipitation. Precipitation observation stations have now been installed through the IMPAC-T project in the Khuwaenoi basin, which is lower part of Nan River basin. Although the Khuwaenoi basin is not included the Sirikit Dam catchment, the installations are expected to lead to a better understanding of the Nan River basin.

Summary

In this study, the authors have conducted hydrological simulations using different six precipitation data. The long-term water balance analysis has been performed using APHRODITE and the observed precipitation from 1981 to 2004 in the upper Chao Phraya River basin. The main findings are as follows:

- Although precipitation has large difference between products, simulated evapotranspiration using products has small difference. Most of difference in precipitation translates to difference in runoff. Any error in the precipitation translates to approximately the same absolute error in runoff over the Eastern Asia.\

- Simulated runoff using the observed precipitation corresponded well with a naturalized runoff at the C.2 station compared with the runoff simulated using APHRODITE data. More than 80% of precipitation was lost through evapotranspiration in the upper basin. Because runoff ratios in the upper basins were low, a 10% differences in precipitation data resulted in a 50–100% difference in the runoff ratio.

- Although small differences were found between the APHRODITE data and the observed precipitation during the rainy season, there were almost no differences between computed evapotranspiration using APHRODITE and observed precipitation data. This suggests that the evapotranspiration in the rainy season depends not on precipitation but on other meteorological parameters such as temperature and radiation.

These findings demonstrate uncertainties in precipitation have large impact on runoff simulation in the upper Chao Phraya River basin.

Acknowledgments

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References

[1] The World Bank. (2012), Thai Flood 2011: Rapid Assessment for resilient recovery and reconstruction planning. https://www.gfdrr.org/thaifloods2012. Last access April 10, 2013.

[2] Komori D. and Coauthors. (2012), Characteristics of the 2011 Chao Phraya River flood in Central Thailand. *Hydrological Research Letters*, 6, 41-46.

[3] Hanasaki N, Kanae S, Oki T, Musiake K. (2003), Simulating the discharge of the Chao Phraya River taking into account reservoir operation. *IAHS Publication*, 281, 215-223.

[4] Kure S, and Tebakari T. (2012), Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand. *Hydrological Research Letters*, 6, 53-58.

[5] Kotsuki S. and Tanaka K. (2013a), Impacts of Mid-Rainy Season Rainfall on Runoff into the Chao Phraya River, Thailand. *Journal of Disaster Research*, 8-3, 397-405.

[6] Kotsuki S. and Tanaka K. (2013b), Uncertainties of precipitation products and their impacts on runoff estimates through hydrological land surface simulation in Southeast Asian region. *Hydrological Research Letters*. (revision)

[7] Fekete B. M. and Vorosmarty C. J. (2004), Uncertainties in precipitation and their impacts on runoff estimates. *Journal of Climate*, 17, 294-304.

[8] Rudolf B, Andreas B, Udo S, Anja MC, Markus Z. (2010), GPCC status Report December 2010. http://gpcc.dwd.de. Last access Mar 20, 2013.

[9] Yatagai A, Kamiguchi K, Arakawa O, Hamada A, Yasutomi N, Kitoh A. (2012), APHRODITE: Constructing a Long-term Daily Gridded Precipitation Dataset for Asia based on a Dense Network of Rain Gauges, *Bulletin of American Meteorological Society*, 93, 1401-1415.

[10] Hirabayashi Y, Kanae S, Motoya K, Masuda K, Doll P. (2008), A 59-year (1948-2006) global near-surface meteorological data set for land surface models. *Hydrological Research Letters*, 2, 36-40.

[11] Huffman G. J, Bolvin D T. (2013), Version 1.2 GPCP One-Degree Daily Precipitation Data Set Documentation. http://precip.gsfc.nasa.gov. Last access Mar 20, 2013

[12] Ushio T and Coauthors. (2009), A Kalman filter approach to the Global Satellite Mapping of Precipitation (GSMaP) from combined passive microwave and infrared radiometric data. *Journal of the Meteorological Society of Japan*, 87A, 137-151.

[13] Onogi K. and Coauthors. (2007), The JRA-25 reanalysis. *Journal of the Meteorological Society of Japan*, 85, 369-432.

[14] Tanaka K. (2004), Development of the New Land Surface Scheme SiBUC Commonly Applicable to Basin Water Management and Numerical Weather Prediction Model. Doctoral Dissertation, Graduate School of Engineering, Kyoto University: Kyoto; 289