A COMBINED MODEL FOR ASSESSING THE IMPACTS OF RESERVOIR OPERATION ON THE SPATIAL EXTENT OF FLOODING WITHIN A RIVER BASIN

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1. INTRODUCTION

This study presents a simulation framework using two models which were combined to simulate reservoir operation and assess its impacts on inundation within a river basin. Two models, H08, an integrated water resources model that could simulate human impacts [Hanasaki et al., 2008] and CaMa-Flood, a new global river routing model that uses physically-based representation of floodplain inundation dynamics [Yamazaki et al., 2011] were combined in this study. The use of H08 allows the simulation of reservoir operation coupled with land surface and river processes. The use of CaMa-Flood allows the simulation of flood depth and consequently, the extent of inundation within the river basin.

This study was applied in the Chao Phraya River Basin wherein the worst flood event in history, worldwide, in terms of economical damages occurred in 2011 [EM-DAT, 2012]. Even after approximately 10 billion m^3 of water was temporarily stored by two gigantic reservoirs upstream, the record-high 1,439 mm rainfall during the rainy season in 2011 (about 143% of the average rainy season rainfall from 1982-2002) caused inundation with an estimated flood water volume of 15 billion m^3, [Komori et al., 2012]. The impact of changing the reservoir operation rules in the two gigantic reservoirs, Bhumibol and Sirikit, to the inundation within the Chao Phraya River Basin is examined in this paper.

2. METHODOLOGY

The computational domain in H08 model was set at 13°N to 20°N latitude and 97°E to 102°E longitude (97.5°E to 102°E longitude in CaMa-Flood model). The catchment area of the basin is approximately 160,000 km^2. Simulation in the basin was calculated at a spatial resolution of 5’ × 5’ latitudinal and longitudinal grids and at a daily temporal scale.

The following meteorological inputs were used to run the land surface module of H08 from 1981 to 2004: air pressure (Pa), wind speed (ms^{-1}) [both from Japanese Reanalysis, GAME-T2 Data Center, 2011], temperature (K), short wave radiation (Wm^{-2}), long wave radiation (Wm^{-2}), specific humidity ($kg \cdot kg^{-1}$) [Hirabayashi et al., 2008], surface albedo [GSWP2 data interpolated for the Chao Phraya Basin], and precipitation forcing data set reanalyzed (courtesy of Kenji Tanakaet al.) from observed data within the river basin from the Royal Irrigation Department and Thai Meteorological Department. For simulations in 2010 and 2011, the reanalyzed observed precipitation dataset have been combined with seven other meteorological dataset by Yoshimura et al. (2008).

Simulation without reservoir operation (*naturalized* condition) was conducted by using the land processes module of H08 model to simulate runoff which was then used as input to the CaMa-Flood model. The CaMa-Flood then calculates the stream flow and inundation within the basin. The models were calibrated simultaneously to obtain a high Nash-Sutcliffe efficiency (NSE) coefficient between the simulated and observed monthly and annual *naturalized* discharge at C2 Station, a station located just downstream of the confluence of the four main tributaries of the Chao Phraya River Basin, and to obtain a good correspondence of the ratio of inundated area between the simulation results and satellite images.

In simulation with reservoir operation, the coupled modules, calibrated land surface processes, reservoir operation, and river processes, of H08 model were used to calculate the reservoir outflows at Bhumibol and Sirikit Reservoirs, the two biggest reservoirs in the Chao Phraya River Basin. The runoff values calculated by the calibrated land processes module were again used as input to CaMa-Flood to calculate the stream flow and inundation. However, to take into account reservoir operation, the reservoir outflows at Bhumibol and Sirikit Reservoirs calculated by H08 model were used as forcing data to replace the calculated stream flow at the grid cells in CaMa-Flood which correspond to the locations of the two reservoirs.

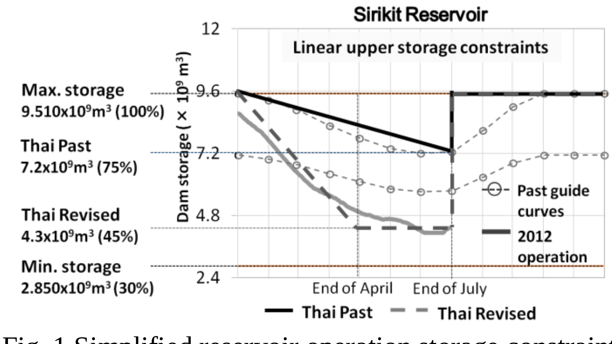

Fig. 1 Simplified reservoir operation storage constraints

Two kinds of reservoir operation rules were examined in this paper, one that represents the reservoir operation rules in the past (*Thai Past*), and one that represents the operation rules after revisions have been implemented in 2012 in response to the flood event in 2011 (*Thai Revised*). The actual reservoir operation rules in the two reservoirs were simplified by setting constant dry season and wet season reservoir releases which are equivalent to the long term observed mean from January to April and from May to December, respectively. Linear upper storage constraints as shown in Fig. 1 for Sirikit Reservoir were set to simplify the actual reservoir storage limits.

Algorithms were coded into the reservoir operation module of H08 model to adjust the reservoir releases such that the storage would be maintained to be within the upper storage constraint and the minimum storage level.

3. RESULTS AND CONCLUSION

The daily discharge hydrograph in with reservoir operation shown in Fig. 2 corresponds well with that of the observed. Since the worst drought year occurred in 1993 while the worst flood year occurred in 1995 within the basin, it could be said that the model could adequately represent the hydrological extremes within the Chao Phraya River Basin.

The monthly NSE coefficients in the without and with reservoir operation conditions are 90.4% and 65.7%, respectively. The high NSE coefficient in the without reservoir operation condition indicates that the hydrological processes are adequately simulated within the basin while the moderate NSE coefficient in the with reservoir operation condition indicates that the simplified algorithms used in the model adequately represent the more complicated, actual reservoir operation.

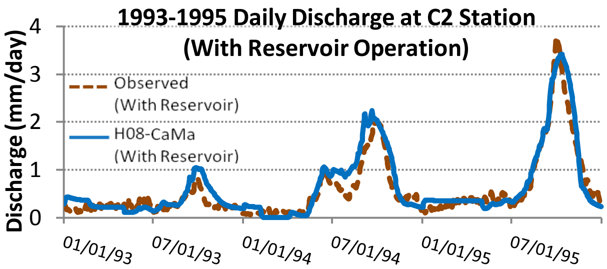

Fig. 2 Comparison of daily discharge at C2 Station; *Thai Past* operation rules were used for the H08-CaMa simulation

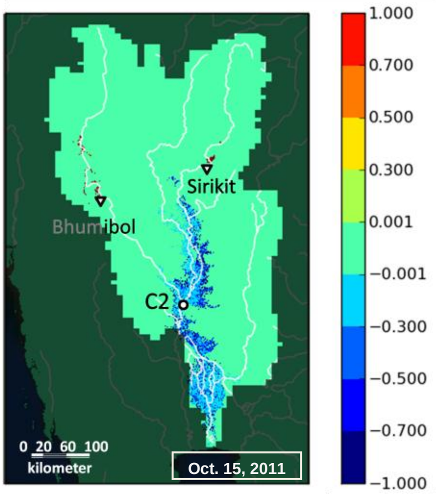

Fig. 3 Percent reduction in flood depth [(*Thai Revised* - *Thai Past*)/*Thai Past*] in 3arc-second resolution

The simulated ratio of inundated area within the river basin from September 25 to October 25 of 2011 (in 10-days interval, figures not shown in this paper) revealed a good correspondence with that of the observed satellite images from MODIS+AMSR-E (courtesy of Wataru Takeuchi and Kazuo Oki). This indicates that inundation dynamics could be simulated well by the model.

The impact of reservoir operation on inundation could be evaluated by several means such as in Fig. 3 wherein the differences in flood depth between *Thai Revised* and *Thai Past* is shown. By pre-releasing stored water from May and maintaining low storage until the end of July in the *Thai Revised* reservoir operation, it could be observed that flood depth could be reduced by more than 70% in some parts of the basin, particularly in the downstream of Sirikit Reservoir and the surrounding areas of C2 Station. The impact of reservoir operation on inundation could also be evaluated in terms of reduction in flooded area.

This paper had shown that the combined H08 and CaMa-Flood models could accurately simulate the discharge as well as inundation in the Chao Phraya River Basin in both naturalized and with reservoir operation conditions. The simulation framework introduced in this paper presents a robust approach in assessing the impacts of reservoir operation on flooding through the calculation and explicit representation of the spatial extent of inundation within a river basin.

In most studies done in the past, the impact of reservoir operation to flooding within the basin was commonly assessed by calculating the reduction in peak discharge in one or several gauging stations downstream of reservoirs. The inundation within the river basin is usually inferred based on statistical correlation between peak discharges and inundation. As inundation within a river basin is influenced not only by reservoir operation but also by other hydrological factors such as rainfall pattern within the basin, this methodology for assessment would only be accurate if the other hydrological factors do not vary significantly. However, several studies have already indicated that hydrological patterns in various parts of the world would most likely vary due to climate change.

On the other hand, this study used physically-based representations of hydrological processes and inundation. Thus, the simulation framework and models presented would still be applicable even under a changing climate. This study could then be a viable tool in assessing how reservoir operation should be adjusted in order to adapt to the varying future inflows and future hydrological changes within the river basin due to climate change.

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