A simulation study on modifying reservoir operation rules: tradeoffs between flood mitigation and water supply

CHERRY MAY R. MATEO[1], NAOTA HANASAKI[2], DAISUKE KOMORI[1], KEI YOSHIMURA[1], MASASHI KIGUCHI[1], ADISORN CHAMPATHONG[3], DAI YAMAZAKI[4], THADA SUKHAPUNNAPHAN[3] & TAIKAN OKI[1]

1 Institute of Industrial Science, the University of Tokyo, 4-6-1 Komaba, Meguro-ku, 153-8505 Tokyo, Japan
cherry.m@rainbow.iis.u-tokyo.ac.jp

2 National Institute for Environmental Studies, 16-2, Onogawa, Tsukuba, Ibaraki 305-8506, Japan

3 Office of Water Management & Hydrol., Royal Irrigation Department,811 Samsen Rd, Dusit, Bangkok 10300, Thailand

4 School of Geographical Sciences, University of Bristol, University Road, Clifton, Bristol BS8, UK

Abstract A simulation model was used to evaluate two proposed reservoir operation rules in Bhumibol and Sirikit reservoirs in the Chao Phraya River Basin. H08, an integrated hydrology and water resources model, was combined with CaMa-Flood, a river routing model considering inundation dynamics, to simulate the impacts of reservoir operation on the river basin. Simulated reservoir inflows were used as input to the reservoir operation module coupled with H08. The inclusion of CaMa-Flood in the system allows the assessment of impacts of reservoir operation on inundation within the entire river basin. It was found that hedging significantly reduces the occurrence of the reservoir emptying during dry seasons. A low linear storage constraint, set three months before the onset of the rainy season, significantly reduces the reservoir overflows. The simulation framework developed would be useful in designing optimal reservoir operation rules that are effective for mitigating both flood and drought damages.

Key words integrated hydrology and water resources model; H08; CaMa-Flood; balancing flood mitigation and water supply provision; Bhumibol and Sirikit Reservoir; Chao Phraya River Basin

INTRODUCTION

The worst flooding in the world in terms of economic losses occurred in the Chao Phraya River Basin in 2011 (EM-DAT, 2012). To prevent such disastrous events from occurring in the future, the Thai Government resolved to modify the operation of Bhumibol and Sirikit reservoirs, the two biggest reservoirs in the Chao Phraya River Basin.

Such modifications could induce tradeoffs between the contradicting demands of flood mitigation and drought mitigation. They could also induce significant impacts on streamflow and inundation in the entire river basin. As Chao Phraya River Basin is susceptible to floods as well as drought events, a tool for assessing the tradeoffs as well as the hydrological impacts on the river basin of modifications in reservoir operation is necessary.

Simulation modelling is one of the most common and reliable approaches to assess the detailed performance of reservoir operation policies (HEC-USACE, 1996). This paper discusses the development of a simulation modelling system which uses accurate simulated inflows as input, and could accurately simulate streamflow and inundation over the entire Chao Phraya River Basin.

STUDY AREA AND INPUT DATA

This study focuses on the Chao Phraya River Basin, the biggest and most important river basin in Thailand. Its catchment area is approx. 160 000 km^2, about 1/3 of the total area of Thailand. Simulation was done in the basin at a spatial resolution of 5′ × 5′ latitudinal and longitudinal grids and at a daily temporal scale. The computational domain was set at 97°E to 102°E longitude and 13°N to 20°N latitude in the H08 model and 97.5°E to 102°E longitude and 13°N to 20°N latitude in the CaMa-Flood model.

Eight meteorological inputs are needed to run the land surface module of H08. For simulations from 1981 to 2004, the following inputs with the corresponding units and sources were used: air pressure (in Pa, hourly), wind speed (in m/s, hourly) (both from Japanese Re-analysis (JRA), GAME-T2 Data Center, 2011), temperature (in K, 3 hourly), short-wave radiation (in W/m^2, daily), long wave radiation (in W/m^2, 3 hourly), specific humidity (in kg/kg, daily) (Hirabayashi *et al*., 2008), surface albedo (GSWP2 data interpolated for the Chao Phraya Basin), and precipitation forcing data set re-analysed from precipitation observation data within the river basin from the Royal Irrigation Department (RID) and Thai Meteorological Department (TMD), courtesy of Dr Kenji Tanaka. For simulations during 2010 and 2011, the re-analysed observed precipitation data have been combined with the seven other forecast meteorological datasets by Yoshimura *et al.* (2008).

DESCRIPTION OF THE MODELLING SYSTEM

Two physically-based hydrological models have been combined in this study, the H08 integrated water resources model (Hanasaki *et al*., 2008) and Catchment-based Macro-scale Floodplain (CaMa-Flood) river routing model (Yamazaki *et al*., 2011). H08 is one of the available water resources models which can simulate both natural and anthropogenic processes. It has six modules which can be run separately or in a coupled manner – land surface processes, river processes, reservoir operation, anthropogenic water withdrawal, crop growth, and environmental flows (Hanasaki *et al*., 2008). CaMa-Flood is a newly developed river routing model which has the capability to simulate floodplain inundation dynamics through explicit parameterization of sub-grid scale floodplain topography (Yamazaki *et al*., 2011). Both are open source models, thus, enabling the user to manipulate the codes to suit their computational and research needs.

The combined modelling system can be used to simulate scenarios with and without reservoir operation conditions. The simplified process diagrams of the modelling system in these two cases are shown in Fig. 1. In simulations without reservoir operation (naturalized condition), the land processes module of H08 was used to simulate the runoff needed as input to the CaMa-Flood river routing model. The models were calibrated simultaneously to simulate streamflow and inundation that have good fits with that of the naturalized observed flow. The peak discharge, time of peaking, monthly and annual Nash-Sutcliffe Efficiency (NSE) coefficients, and percentage bias have been used as criteria for calibration. In simulations with reservoir operation, the rules for reservoir operation were encoded into the reservoir operation module of H08. The coupled land processes, reservoir operation, and river modules of H08 were then used to simulate the effect of reservoir operation on streamflow in the two reservoirs. The runoff in all grid cells and the streamflow at the respective grid cell locations of Bhumibol and Sirikit Reservoirs simulated by H08 were then used as input to the calibrated CaMa-Flood model. In CaMa-Flood, boundary conditions have been set in the grid cell locations of Bhumibol and Sirikit reservoirs to replace its simulated streamflow with the respective reservoir-influenced streamflow simulated by H08.

The combination of the two models improves the simulation of streamflow by using a more realistic river routing model. It enables the user to model reservoir operation in the reservoir operation module by specifying several characteristics of the dam such as location, capacity, purpose, etc., and by expressing the reservoir operation rules in terms of storage, inflow, and/or

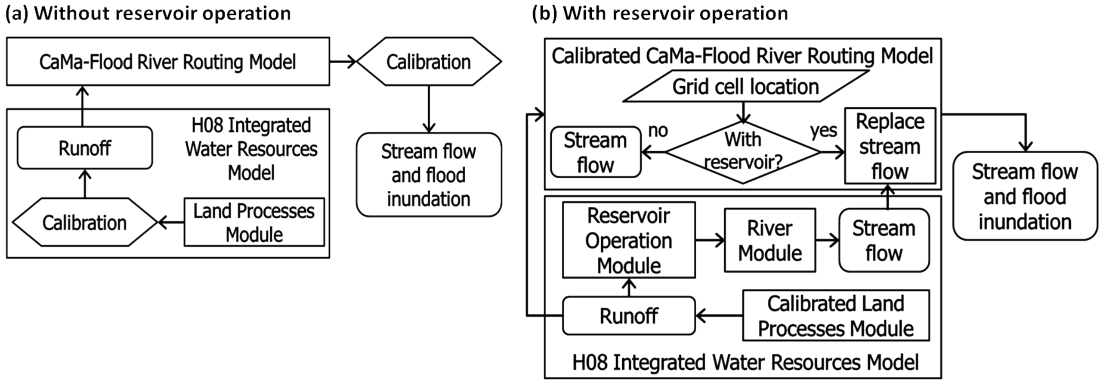

Fig. 1 Process diagram of the modelling system.

release. This reservoir operation module can output the corresponding changes in reservoir storage and release, which are helpful for assessing the availability of water for supply. Finally, it enables the user to assess the impacts of reservoir operation on the river basin by checking outputs indicating the extent of inundation such as flood depth or inundated area. These model capabilities are valuable for making an accurate, reliable, and detailed assessment of the impacts of planned reservoirs as well as planned modifications to the operation of existing reservoirs in the river basin, especially in terms of flood mitigation and water supply provision.

RESERVOIR OPERATION RULES

The existing operation of Bhumibol and Sirikit reservoirs are dependent on two guide curves, a lower and an upper curve, which serve as storage limits. For simplicity of modelling the existing reservoir operation rule, the upper storage guide curve had been simplified by using a linear upper limit to the storage, as shown in Fig. 2(a). The minimum storage or dead storage capacity of the reservoir was set as the lower storage limit. The release function was simplified by using the mean of the observed dry season (January to April) and the mean of the observed rainy season (May to December) releases.

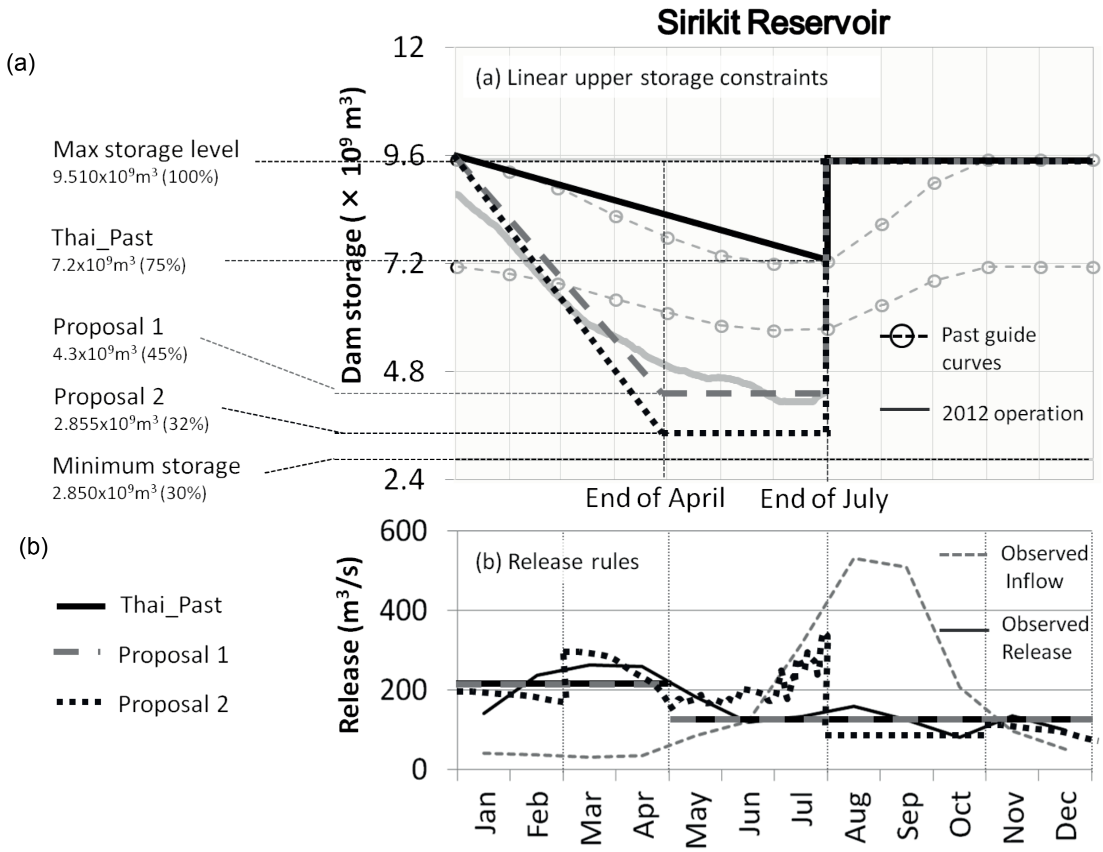

Fig. 2 (a) Dam operation at Sirikit Reservoir. The release rules (b) for Proposal 2 vary according to five seasons – Jan. to Feb., Mar. to Apr., May to Jul., Aug. to Oct., and Nov. to Dec.

In Proposal 1, the upper storage limit curve of the Thai_Past was modified by following the trend of the new operation implemented by the Thai government in 2012. A low storage was targeted by the end of April in preparation for the upcoming rainy season. This low storage was maintained for 3 months by setting a linear storage limit from May to July. The release function was set to be the same as in Thai_Past.

Proposal 2 further modified Proposal 1 by lowering the linear storage from May to July. The annual release function was divided into five seasons which correspond to the perceived seasonal changes in water use and inflows in the two reservoirs. The release during the low inflow seasons (January to February, March to April, and November to December) were expressed as functions of the current storage ($k_n \times S$), following a concept similar to that of release hedging. Hedging constant k_n varies between the three dry seasons in order to prioritize the release of water during the cropping periods. The release from May to July was set to be the higher value between the inflow and the minimum water demand for electricity generation. The release from August to October was set as the minimum water needed for electricity generation.

RESULTS AND DISCUSSION

Observed discharge data from the RID and TMD, historical reservoir operation data from the Electricity Generating Authority of Thailand (EGAT), and observed satellite data from Moderate Resolution Imaging Spectroradiometer (MODIS) and Advanced Microwave Scanning Radiometer for EOS (AMSR-E) (courtesy of W. Takeuchi, K. Oki & H. Kim, 2012) have been used to validate the simulation results of the combined model. In simulations without reservoir operation, the output is compared with the "naturalized observed discharge" which was computed by removing the effect of Bhumibol and Sirikit reservoirs.

Daily discharge hydrographs in mm/day at three important stations are shown in Fig. 3: (a) Nakhon Sawan (also called C2 Station), and the two reservoirs (b) Bhumibol Dam, and (c) Sirikit

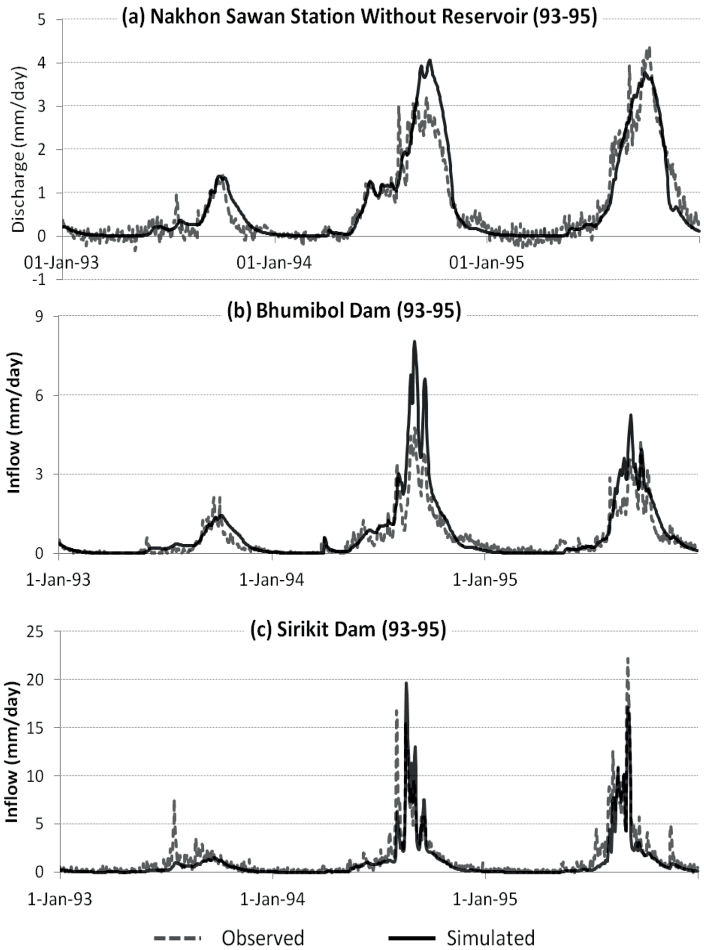

Fig. 3 Daily discharge without reservoir operation in mm/day from 1993 to 1995.

Dam. Nakhon Sawan Station was the gauging station used for calibrating the model because it is critically located downstream of the two dams, just after the confluence of the four major tributaries of the Chao Phraya River Basin. As 1993 was the worst drought year while 1995 was the worst flood year from 1981 to 2004, the daily discharge hydrographs in Fig. 3 are shown from 1993 to 1995 to illustrate the efficiency of the model in simulating even the extreme events.

High monthly NSE-coefficients for simulations without reservoir operation from 1981 to 2004 in Bhumibol Dam, Sirikit Dam, and Nakhon Sawan of 76.62%, 74.17%, and 90.43%, respectively (hydrographs not shown here), along with the evidently good fit of the daily hydrographs indicate good accuracy of the combined model in simulating the streamflow within the river basin even during extreme events.

Good fit of the daily discharges simulated using the actual reservoir operation releases as forcing input from 2010 to 2011 in Nakhon Sawan, shown in Fig. 4, indicates that using reliable meteorological forecast values as input, the model can also simulate future streamflows.

Validation of the simulation of inundation is shown in Fig. 5(a),(b). It can be seen that the shape of the inundated area was simulated adequately by the combined model. However, it tends to overestimate the inundation ratio in several areas.

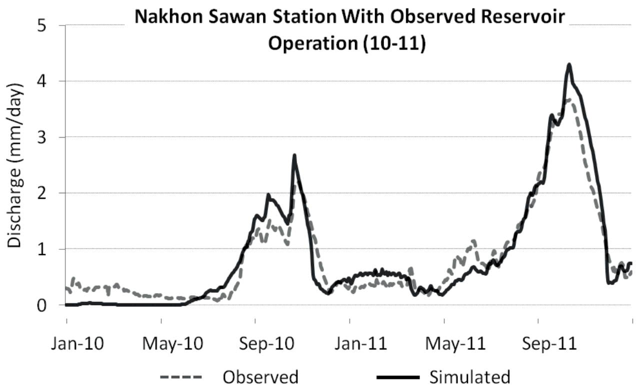

Fig. 4 Daily discharge with reservoir operation in mm/day from 2010 to 2011.

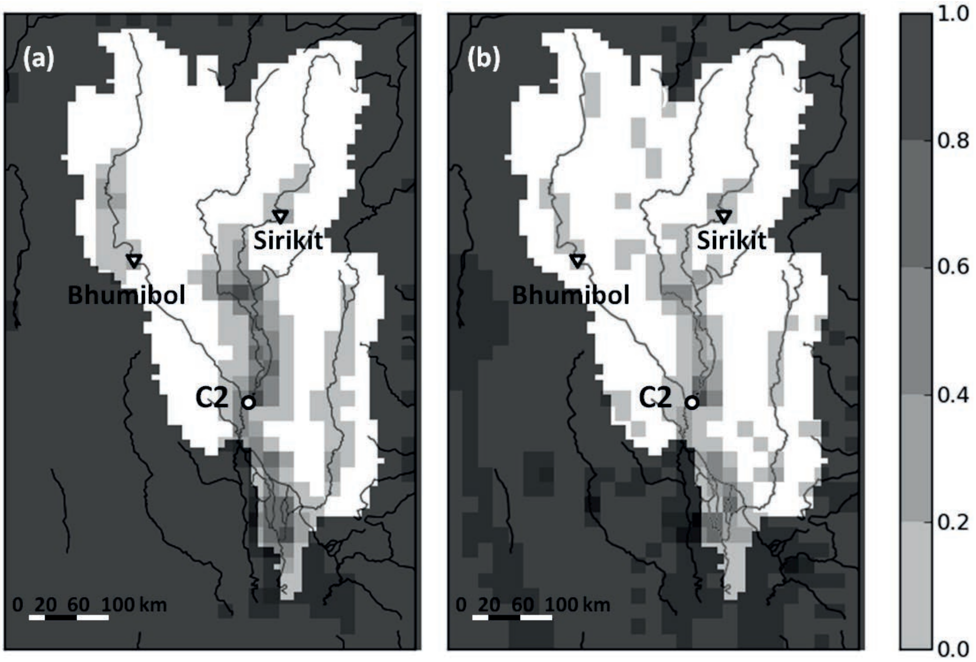

Fig. 5 Inundation ratio (inundated area/total area) on 25 Sep. 2011 for (a) simulated using the observed reservoir outflows as forcing data, and (b) observed satellite data (MODIS+AMSR-E); dark grey shaded region indicates the area outside of the Chao Phraya River Basin, as depicted in the model.

An example of an assessment of the impact of modifications in reservoir operation rules on the inundation within the basin is shown in Fig. 6(a),(b). The effect of reservoir operation on flood depth could be evaluated at a very fine scale (maximum resolution of 3 arc-sec × 3 arc-sec, or approximately 90 m × 90 m grid scale) using the combined model. However, for the purpose of better visibility, Fig. 6(a),(b) are shown at a 5 min × 5 min resolution. It can be observed that the percentage reduction in flood depth using Proposal 2 is much higher than that of Proposal 1, as evidenced by the darker grey pixels in Fig. 6(b) than in Fig. 6(a), particularly in the areas downstream of Sirikit Reservoir and around C2 Station. This is primarily because of the lower storage set during May to July targeted by Proposal 2. Thus, it is more effective than Proposal 1 in reducing the streamflow and, consequently, inundation downstream of the two dams.

The reliability of the two dams in terms of providing enough water for supply during the dry season and preventing spills of water during the rainy season is shown in Table 1. The percentage of years below target storage is obtained after determining the equivalent effective storage by the end of October needed to meet the average water supply target from the two reservoirs (approx. $6200 \times 10^9\,m^3$ in total) set by the Thai Government. The numbers of failures (reservoir emptying) overflows were obtained by counting the number of months wherein the minimum and maximum storage capacities were reached, respectively.

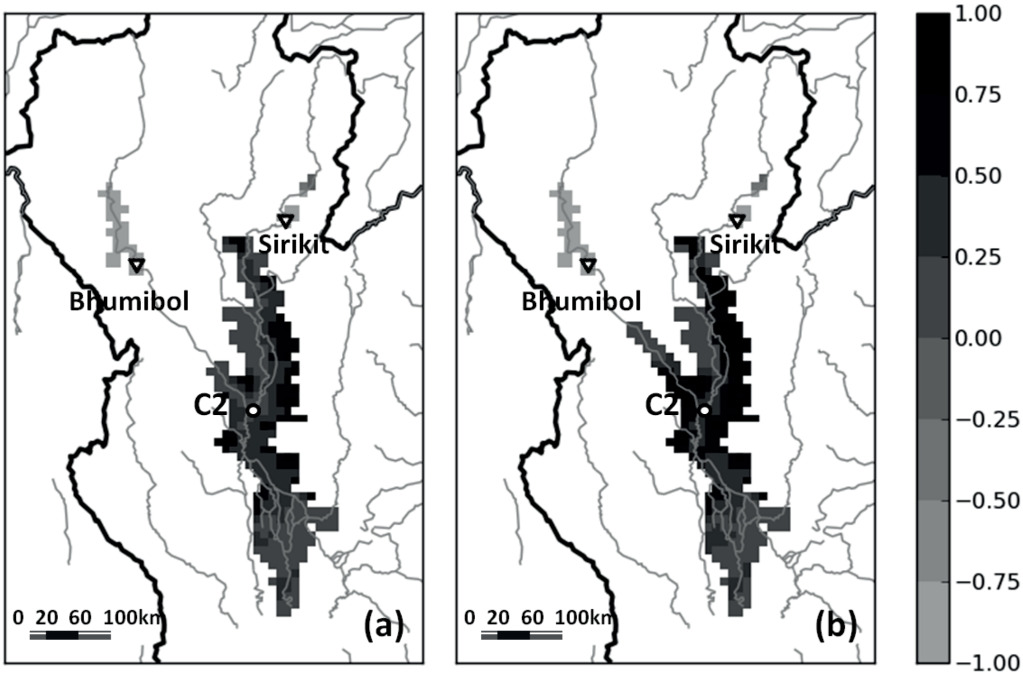

Fig. 6 Percentage difference of flood depth on 15 Oct. 2011 in 5 min × 5 min resolution: (a) (Thai_Past – Proposal 1)/Thai_Past, and (b) (Thai_Past – Proposal 2)/Thai_Past; darker grey pixels indicate higher reduction in flood depth; thick, black outline indicates the country boundary of Thailand.

Table 1 Summary of reliability statistics in the two reservoirs.

Sirikit Reservoir ($9.51 \times 10^9\,m^3$ total ($6.66 \times 10^9\,m^3$ effective) storage capacity				Bhumibol Reservoir ($13.46 \times 10^9\,m^3$ total ($9.66 \times 10^9\,m^3$ effective) storage capacity)			
Operation	Overflow (months*)	Below target storage (years*)	Reservoir Empty (months*)	Operation	Overflow (months*)	Below target storage (years*)	Reservoir Empty (months*)
Thai_Past	13	8	36	Thai_Past	12	7	13
Proposal 1	5	10	42	Proposal 1	0	10	20
Proposal 2	0	17	0	Proposal 2	0	13	0

*Simulation period spans a total of 24 years or 288 months.

Both proposals have significantly reduced the number of overflows by setting a low storage from May to July; although, as expected due to the lower target storage set, Proposal 2 performed much better by completely reducing the number of overflows to zero. However, this good performance in terms of flood mitigation led to tradeoffs in reliability in terms of water supply. It could be observed that the number of years below target storage have significantly increased in the two proposed modifications, especially in Proposal 2. However, it could be observed that as compared with the old operation, the number of dry ups has increased in Proposal 1, whereas it is completely reduced to zero in Proposal 2. Hedging the release in Proposal 2 led to more frequent but less severe and sudden shortages in both dams, with the water prioritized to be released during the cropping seasons.

CONCLUSIONS

A combined model useful for simulating and assessing the impacts of reservoir operation in an entire river basin was introduced in this paper. The incorporation of a river routing model with inundation dynamics added value to the system by allowing the assessment of the impacts of reservoir operation to the extent of inundated area within the river basin. This feature allows a better and more detailed assessment than the usual measure of flood reduction by means of flood peak reduction.

The combined model was then used to model and assess the impacts of two proposed reservoir operation rules in the Chao Phraya River Basin, particularly focusing on the tradeoffs between flood mitigation and water supply. Although the two proposed modifications to the old reservoir operation have advantages and disadvantages to them, they could be used to guide researchers and the Thai Government in finding the optimized reservoir operation for the two reservoirs; the combined model could be used to model and assess several other reservoir rule modifications. The simulation framework introduced could be useful and could be replicated in other river basins, especially where modifications in reservoir operation rules are required for alleviating flood and drought damages.

Acknowledgements The authors are thankful to all the people who have provided the necessary data and valuable comments to conduct and to improve this study. They are also thankful to the following agencies for providing support to this research by several means: Integrated study on HydroMeteorological Prediction and Adaptation to Climate change in Thailand (IMPAC-T) Project through the Science and Technology Research Partnership for Sustainable Development (SATREPS), Japan Science and Technology Agency and Japan International Cooperation Agency (JST-JICA) and the Japan Society for the Promotion of Science KAKENHI, Grant-in-Aid for Scientific Research (S) (23226012). Finally, the authors would like to thank Shunji Kotsuki who kindly provided the dataset used for calibration during the initial stages of this study.

REFERENCES

EM-DAT: The OFDA/CRED International Disaster Database, www.emdat.be, Université catholique de Louvain, Brussels, Belgium. Version 12.07 (retrieved August 2012).

GAME-T2 Data Center (2011) http://hydro.iis.u-tokyo.ac.jp/GAME-T/GAIN-T/index.html GaME-T2 Data Center.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y. & Tanaka, K. (2008) An integrated model for the assessment of global water resources – Part 1: Model description and input meteorological forcing. *Hydrol. Earth Syst. Sci*. 12, 1007–1025, doi:10.5194/hess-12-1007-2008.

Hanasaki, N., Kanae, S., Oki, T., Masuda, K., Motoya, K., Shirakawa, N., Shen, Y. & Tanaka, K. (2008) An integrated model for the assessment of global water resources – Part 2: Applications and assessments. *Hydrol. Earth Syst. Sci*. 12, 1027–1037, doi:10.5194/hess-12-1027-2008.

Hanasaki, N., Kanae, S. & Oki, T. (2006) A reservoir operation scheme for global river routing models. *J. Hydrol.* 327(1–2), 22–41.

Hanasaki, N., Kanae, S., Oki, T. & Musiake, K. (2003) Simulating the discharge of the Chao Phraya River taking into account reservoir operation. In: *Water Resources Systems – Hydrological Risk, Management and Development* (ed. by G. Bloeschl *et al.*), 215–223. IAHS Publ. 281, IAHS Press, Wallingford, UK.

Hanasaki, N. & Yamamoto, T (2010) *H08 Manual User's Edition*. National Institute for Envi. Studies, Tsukuba, Japan, 75 pp.

Hirabayashi, Y., Kanae, S., Motoya, K., Masuda, K. & Döll, P. (2008) A 59-year (1948–2006) global near-surface meteorological data set for land surface models. Part I: Development of daily forcing and assessment of precipitation intensity. *Hydrol. Res. Letters* (2), 36–40.

Komori, D., Nakamura, S., Kiguchi, M., Nishijima, A., Yamazaki, D., Suzuki, S., Kawasaki, A., Oki, K. & Oki, T (2012) Characteristics of the 2011 Chao Phraya River flood in Central Thailand. *Hydrol. Res. Letters* 6, 41–46.

Mateo, C. (2012) Hydrological Modeling with Reservoir Operation in the Chao Phraya River Basin for Flood Mitigation. MS Thesis, The University of Tokyo, Tokyo, Japan.

Mateo, C., Hanasaki, N., Komori, D., Tanaka, K., Yoshimura, K., Kiguchi, M., Champathong, A., Sukhapunnaphan, T., Yamazaki, D., & Oki, T. (2013) Modeling of reservoir operation for balancing flood mitigation and water supply in the Chao Phraya River Basin, Thailand (in preparation).

Oki, T. & Sud, Y. C. (1998) Design of Total Runoff Integrating Pathways (TRIP) A global river channel network. *Earth Interactions*, 2 Jan. 1998.

US Army Corps of Engineers (1996) Developing Seasonal and Long-term Reservoir System Operation Plans using HEC-PRM. Hydrologic Engineering Center, US Army Corps of Engineers Report RD-40, Davis CA 95616–4687.

Yamazaki, D., Kanae, S. Kim, H. & Oki, T. (2011) A physically based description of floodplain inundation dynamics in a global river routing model. *Water Resour. Res*. 47, W04501, doi: 10.1029/2010WR009726.

Yamazaki, D., Oki, T. & Kanae, S. (2009) Deriving a global river network map and its sub-grid topographic characteristics from a fine-resolution flow direction map. *Hydrol. Earth Syst. Sci*. 13, 2241–2251.

Yoshimura, K., Sakimura, T, Oki, T, Kanae, T & Seto, S. (2008) Toward flood risk prediction: a statistical approach using a 29-year river discharge simulation over Japan. *Hydrol. Res. Letters* 2, 22–26.