Hydrological modeling with reservoir operation in the Chao Phraya River Basin for flood mitigation

チャオプラヤ川の洪水被害軽減のための

貯水池操作を含む水文モデリング

CHERRY MAY ROSETE MATEO

マテオ　チェリー　メイ　ロセッテ

37-106941

Adviser: Professor Taikan OKI

Co-adviser: Professor Toshio KOIKE

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THE UNIVERSITY OF TOKYO

Summary

Flood disasters are the leading cause of deaths and economic losses among natural catastrophes. The extent of damages due to flood disasters is more pronounced in Asia [Berz, 2000]. In 2011, the worst flooding worldwide in terms of economic losses which happened from 1900 to 2012 occurred in Thailand [EM-DAT, 2012], particularly in the Chao Phraya (CP) River Basin. The geographic location and characteristics of the CP River Basin make it prone to flooding. The disaster is said to be mainly caused by occurrences of several intense rainfall [Komori, et al., 2012]. Although the flood disaster was mainly caused by extreme precipitation, other dimensions of the flood disaster such as reservoir operation should not be ignored. Around October 2011, for example, several local news [Bangkok Post, 2011] pointed out that too much water was being released from the big dams upstream while flooding is already occurring downstream. The main issue revolves around not reducing the dam storage to a low level because of fears of running out of water for the next dry season. It is important to note that Thailand is an agricultural country which makes it sensitive to droughts. The difficulty in flood risk management in this case arises from conflicting storage of water for agricultural purposes for the upcoming dry season.

This study aims to understand and resolve several issues in mitigating flood risks in the CP River Basin with the aid of hydrological models. It particularly focuses on three key factors which significantly affect flood mitigation in the CP River Basin: (1) rainfall-runoff relationships, (2) inundation, and (3) reservoir operation. The two biggest dams, Bhumibol and Sirikit, were chosen for the reservoir operation studies. Drought risk mitigation was taken into consideration due to its importance to the economy of Thailand. The results of this study are deemed to be

useful for implementation or further improvement of the Chao Phraya River Master Plan which is currently under revision.

The methodology and results of this study were presented in three parts. In the first part, the naturalized discharge was simulated using H08, an integrated global water resources model. H08 was calibrated at C2 Station, then simulations were conducted from 1981-2004. The results showed good correspondence with the naturalized observed discharge and yielded high Nash-Sutcliffe Efficiency coefficients in the daily, monthly, and annual scales. The results were then validated in four other stations. After which, simulations were conducted from 2010-2011. The simulation at 2010-2011 showed good results, attesting to the capability of the calibrated model to adequately predict river discharge given a good precipitation forecast.

The second part of the study deals with simulating both the naturalized discharge and inundation. The runoff output of H08 was used as input to CaMa-Flood, a global river routing model that incorporates floodplain inundation dynamics. Again, parameters of H08 and CaMa-Flood were calibrated to suit the local conditions in the CP River Basin. Simulations of naturalized discharge were again conducted from 1981-2004 and 2010-2011. The results of the coupled H08 and CaMa-Flood (H08-CaMa) models showed an improved simulation of naturalized river discharge as well as good simulation of the inundated area. The general shape of the simulated inundated areas showed good correspondence with satellite images taken during the 2011 flood event. However, the percent of flooded area was overestimated.

The third part deals with incorporating the effects of reservoir operation into the simulation of discharge and inundation in the CP Basin. The reservoir operation module of H08 was used to simulate the reservoir operation rules in the two big dams, Bhumibol and Sirikit. Two types of simplified reservoir operation schemes were explored: one using a 2-season, constant seasonal dam release and the other using a 5-season, varying seasonal dam release. The dam operations in the past were taken into account in creating these schemes. Using the 5-season, varying seasonal dam release type of operation, the storage levels that should be reached by the end of April and which could either mitigate flooding or drought were found. To simulate both discharge and inundation, the discharge at Bhumibol and Sirikit Dams were used as forcing input discharge to the coupled H08-CaMa model. The analysis showed that the model could simulate both the historical discharge and inundation with dam operation. Further analysis of several proposed dam operation schemes showed that lowering the dam storage to a certain level by the end of April and maintaining this low storage until the end of July would reduce the occurrence of dam overflows. Controlling the dam release as a function of storage during the dry season would prevent the occurrence of dam dry ups. This kind of operation was shown to reduce the dam discharge downstream as well as inundation during the wet season. This part of the study proved that reservoir operation could be modeled and its effects downstream could be simulated.

As a whole, this study proved that the current research framework is effective in simulating both the naturalized and dam-influenced discharge in the CP River Basin. The results of this study have numerous applications. First, it could be used to predict the discharge and inundation given a good precipitation forecast. Second, the long-term analysis of the discharge and inundation could help in revising the design of flood structures. Third, it could be used to analyze the effects of several planned reservoir operation to the downstream discharge and inundation. In summary, this research has developed a framework and a tool which could be used for decision and policy making towards flood mitigation in the Chao Phraya River Basin.

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- *Cherry May R. Mateo*

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Chapter 1

Introduction

1.1 General Background

Worldwide, flood disaster occurrences account for only a third of all the natural disasters from 1988-1997 but are responsible for more than half of the number of deaths and are the leading cause of economic losses [Berz, 2000], as shown in Figure 1.1. This is expected to increase through the years with the intensification of the water cycle due to climate change and with the higher exposure to flood risks due to increasing population and industrial activities. Due to the impacts and extent of damage caused by this natural phenomenon, a great deal of attention had been drawn towards it.

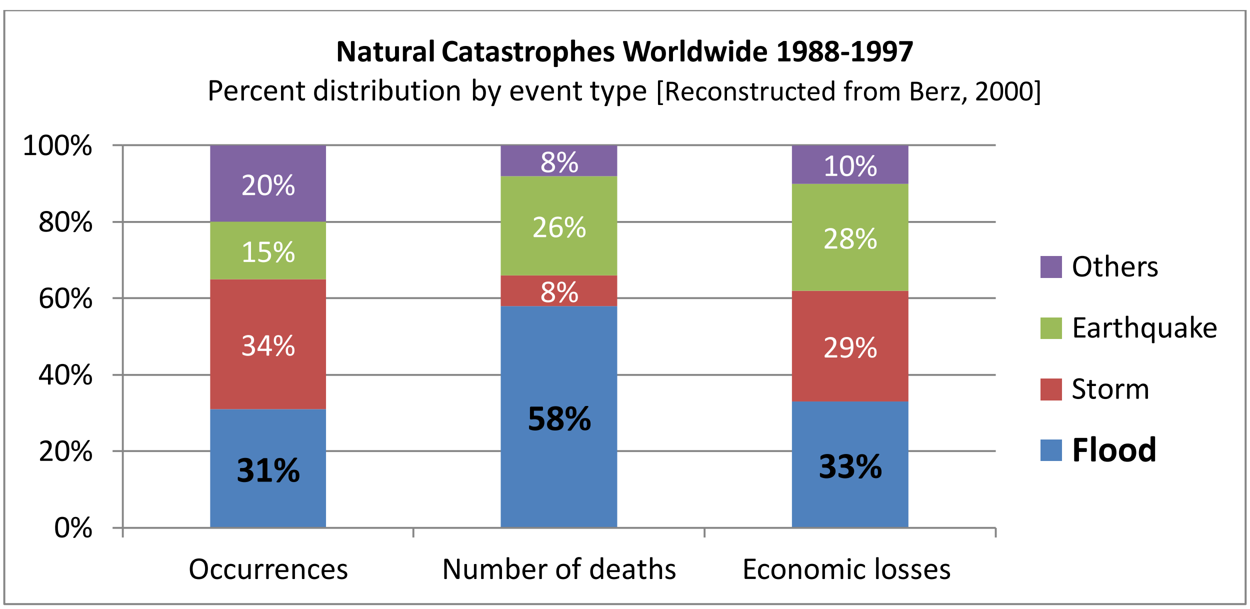


Figure 1.1 Statistics related to the natural catastrophes from 1988-1997 worldwide

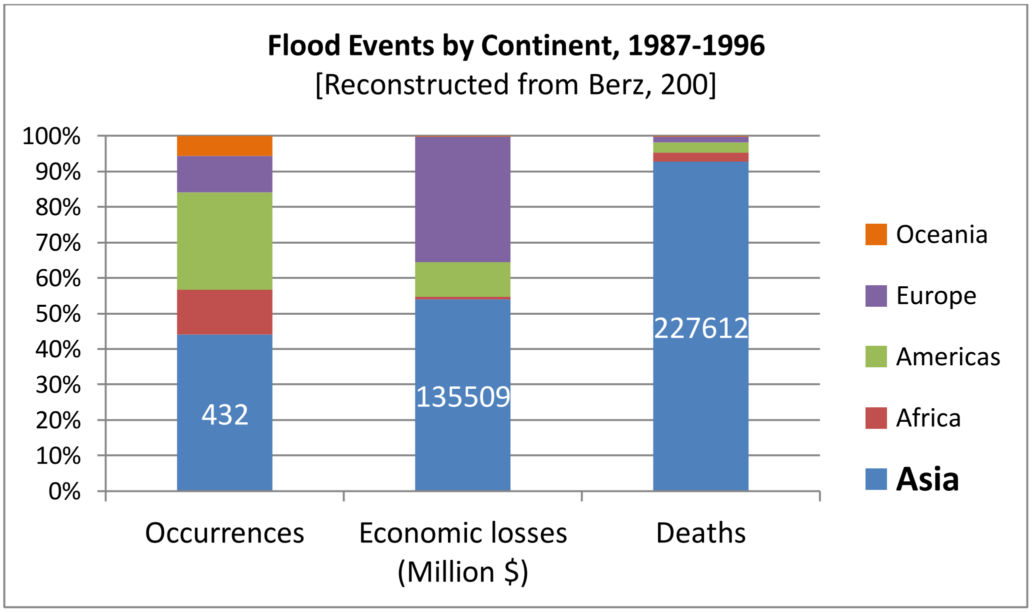


Figure 1.2 Impact of flooding in each continent group

The number of occurrences and effects of these flood events are more pronounced in the Asian region, as shown in Figure 1.2. Due to its climatology and geographical location, the Asian region is more susceptible to the occurrence of flooding. The impact of flooding in the Asian region is also more pronounced than in the Americas or Europe due to its higher population density and the limited capability of its relatively poor nations to increase their defenses against flooding. Analyzing global and regional population growth and industrial growth trends, the effects of flooding will seem to exacerbate as the development of defenses against flood may have difficulties catching up with the increase in population and industries exposed to flood risks.

Just recently, a massive flooding occurred in Thailand which is currently ranked as the worst flooding worldwide which occurred from 1900 to 2012 in terms of economic losses [EM-DAT, 2012]. This flooding which occurred from mid-May to December of 2011 has caused immense damages amounting to about 1.43 trillion Baht [World Bank, GFDRR, 2012]. These damages affected not only Thailand but the industries of other countries such as Japan as well.

The disaster is said to be mainly caused by occurrences of several intense rainfall. The recorded 1,439 mm rainfall during the rainy season in 2011 was found to be 143% of the average rainy season rainfall from 1982-2002. This amount of rainfall caused approximately 15 billion m^3 of flood volume even after approximately 10 billion m^3 of water was intercepted by two gigantic dams upstream [Komori, et al., 2012]. Clearly, the problem here arises from the uncertainties in meteorological factors which cause difficulties in estimating flood magnitude.

Although the flood disaster was mainly caused by extreme precipitation, other dimensions of flooding that should not be ignored in examining the extreme event would be the social and economical factors. Water ways are closely related to and are important to most peoples' livelihood and in some cases, to a region's economy. Thailand, for example, has a close kinship with one of its main river system, the Chao Phraya River. Several regions of the country rely on agriculture as their main source of livelihood which makes them more reliant on the water supply from the river system. This makes flood management more complicated in the Chao Phraya River Basin because it has to be concerned with the bigger issue of water resources management.

Around October 2011, for example, several local news [Bangkok Post, 2011] pointed out that too much water was being released from the big dams upstream while flooding is already occurring downstream. Other local news correspondents [Bangkok Pundit of Asian Correspondent, 2011] tried to investigate the "mismanagement" of dams. The main issue revolves around not reducing the dam storage to a low level because of fears of running out of water for the next dry season. The difficulty in flood risk management here arises with conflicting storage of water for agricultural purposes for the next dry season.

Even if virtually nothing could be done about the intensity of the rainfall which mainly caused the flooding, several things could be done to lessen its impacts. It is important to note that compared with the other natural catastrophes, flooding is relatively easier to monitor and predict

[Knight, D. and Shamseldin, A., 2006]. Its occurrence is also more gradual which could allow people to prepare at least several minutes before its onslaught given the necessary information such as forecasts and warnings. The areas which are prone to flooding are also easier to define as compared with the other natural disasters. Thus, risks due to flooding have a better potential for management and mitigation than the other natural disasters.

Management and mitigation of risks due to flooding could be better facilitated through the use of models. Models such as hydrological or hydrodynamics models help understand the relationship between rainfall, discharge, inundation, and propagation of floods. Thus, modeling allows forecasts to be made up to some degree of certainty. Several advanced models also allow the consideration of anthropogenic activities and interventions in the estimation of the extent of flooding. These models could also be used to assess the impacts of planned activities or interventions not only at the point of intervention but within the river basin as well. These models then prove to be good tools which could be used for decision-making and policy planning. It is important to understand though that the accuracy of these models is still affected by a lot of uncertainties and other limitations. An example would be the limited availability of input data which are needed to run these models or limited observational data with which the results of the simulations could be validated.

This research deals with the use of hydrological models for flood mitigation primarily in the Chao Phraya River Basin. Aside from the global importance of the 2011 flood event in terms of severity and magnitude of its economical impact, this study is also motivated by the decision of the Thailand Government to revisit and revise its River Management Plan with the help of the Japan International Cooperation Agency (JICA). Part of this research supports this initiative through the "Integrated study on hydroMeteorological Prediction and Adaptation to Climate change in Thailand (IMPAC-T)" project which is supported by the Science and Technology

Research Partnership for Sustainable Development (SATREPS) and JICA. The cooperation between JICA and the Thai Government allows better access to the observed precipitation and observed river discharge data in Chao Phraya River Baisn which aid in conducting better model simulation studies.

1.2 Characteristics of the Chao Phraya River Basin

The Chao Phraya River Basin is the largest and most important geographical unit in Thailand [Sripong, etal, 2000]. Located in the northern and central part of Thailand, it is home to about 23 million people (about 40% of the population) 8 million people of whom live at the capital city of Bangkok [1996 estimates, ONWRC report to the UN World Water Development Report]. About 70% of the population are farmers. Although the majority works for agriculture, manufacturing, not agriculture, accounts for the biggest percentage of the GDP in the basin at 33%. Agriculture accounts for 5% while wholesale and retail trade accounts for 17% of the GDP. The total GDP of the basin accounts for 66% of the country's GDP. These statistics attest to the importance of the Chao Phraya River Basin to the economy of Thailand. The basin, being the location of the Thailand's capital Bangkok, is also important to the South-East Asian region because it is the gateway to Indochina and South China.

The river basin has eight sub basins, Ping, Wang Yom, Nan, Pasak, and Sakae Krang in the Upper Chao Phraya basin, and Chao Phraya and Tha Chin in the Lower Chao Praya basin (see Figure 1.3). The entire basin covers an area of approximately 158,000 km^2, almost 35% of the total area of Thailand. It is approximately 700km long and has a relatively flat slope of 1.5m per 100km (~0.002% gradient), making it prone to flooding and inundation.

Average annual precipitation in the basin is about 1,300 mm/year, generating approximately 33,123 million m^3 of annual runoff. The climate is characterized by long, dry months from November to April, and then dominated by the Southwest monsoon from May to October when about 90% of the annual precipitation falls.

The geographic location and characteristics of the Chao Phraya River Basin make it prone to flooding. The high economic activities and concentration of its growing population within the basin increase the exposure of the region to flood risks. Equally important to note is the region's sensitivity and susceptibility to droughts. In the past, records of water shortages led to over pumping of the groundwater which led to subsequent land subsidence [ONWRC report to the UN World Water Development Report, 2003].

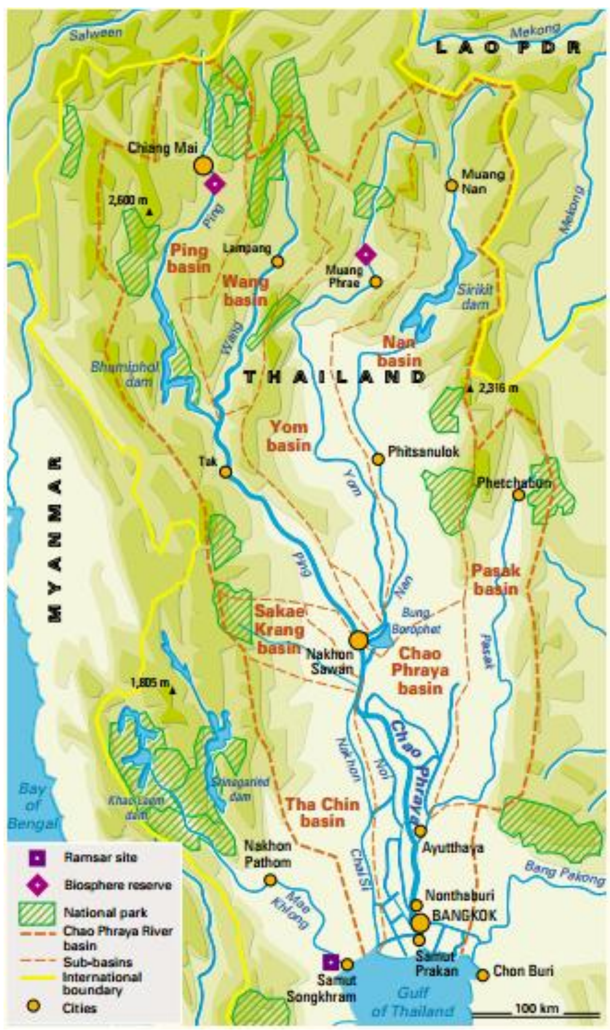


Figure 1.3 Map of the Chao Phraya River Basin shown within the red, dotted boundary lines. The boundaries of the sub basins are also shown in dotted lines. *Source: UN World Water Development Report as prepared by the Office of the National Water Resources Committee of Thailand.*

1.3 Managing the two biggest dams – Bhumibol and Sirikit

There are several dams built within Thailand to manage the seasonal availability of its water resources. The two most important and the biggest of these dams are the Bhumibol and Sirikit dams.

Bhumibol Dam, the biggest dam in Thailand, was constructed from 1958 – 1964 across the Ping River in Tak Province. It is a massive, multipurpose, concrete arch dam with a height of 154 m, crest length of 486 m, and a total retention capacity of 13,462 million m^3. Currently, the siltation volume in the dam is approximated to be 3,800 million m^3, bringing down the effective storage capacity to 9662 million m^3. It was primarily built for irrigation and electrical generation. Flood mitigation, inland navigation, and prevention of sea water intrusion in the lower Chao Phraya and Tha Chin River Basins are among the other important functions of the dam.

The second most important and biggest dam is the Sirikit Dam, an earth-fill dam built from 1963 – 1972 across the Nan River. It has a height of 113.6m, a crest length of 810 m, and a retention capacity of 9,510 million m^3. The effective storage capacity of dam was reduced to 6,660 million m^3 due to the siltation volume which is currently around 2,850 million m^3. Like Bhumibol Dam, it was primarily built for hydropower generation and irrigation. Flood mitigation is also one function of the dam though it is not the priority.

The importance given to irrigation and electrical generation in the management of these two dams are understandable because they have been built during the times when flood risk is not as imminent as drought risk. The water release and dam monitoring is managed by the Electricity Generating Authority of Thailand. The releases of water in the two dams are guided by upper and lower rule curves which have been based on historical dam inflows and outflows. It is unclear though how the management of the dams is handled during emergency situations such as when more water should be released to prepare for the upcoming flood or when more water has to be released to prevent overflowing of the dams. After the 2011 flood event, a committee was established to review the current water resources policies and to create a new master plan for future operations and courses of action, not only concerning the reservoir operation but other aspects of integrating water resources management.

Dam operation in Thailand is difficult because as had been mentioned in the previous section, the basin is susceptible to both drought and flood risks. The operation of a dam during a certain month could critically affect the operation of the dam several months after. Although rainfall prediction is now possible, it can only give accurate forecasts several days ahead and not months ahead. If the predicted scenario is that rainfall would be scarce and a dam did not release water so as to have enough storage space before heavy precipitation fall, the dam might not be able to hold enough water and easily overflow when heavy rainfall occurs. On the other hand, when a dam releases too much water but heavy rainfall did not occur during the rainy season, the dam storage may not be enough to supply water throughout the dry season. Both are potentially harmful to Thailand so a balance must be reached in operating the dams.

1.4 Rationale of this research: Flood mitigation in the Chao Phraya River Basin

In general, the goal of this research is to use hydrological models as tools to mitigate flooding in the Chao Phraya (CP) River Basin. However, as had been shown in the previous discussions, flood mitigation in the CP River Basin is a complicated problem which involves a lot of issues. This research then must provide a better understanding of and resolve some of these issues. As the problem is very complicated, this research has to narrow down its scope by focusing on several important factors.

In a recent meteorological study which aims to explain the extreme events of 2011, it was found that climate change does not play a role in the 2011 Thailand floods [Peterson, et al. 2012].

The study further suggests that non-meteorological factors such as the changing hydrography of the rivers, reservoir operation rules, and agricultural land conversion to industrial usage are much important in setting the scale of the disaster. In line with these findings, this study focuses on three key factors which significantly affect flood mitigation in the CP River Basin: (1) rainfall-runoff relationships, (2) inundation, and (3) reservoir operation. The two biggest dams, Bhumibol and Sirikit, were chosen for the reservoir operation studies. Although this study focuses on flood risk mitigation, drought risk mitigation was taken into consideration due to its importance to the economy of Thailand.

The interactions between these factors and how they affect flood risk mitigation are studied by answering these specific questions through the use of hydrological and hydrodynamics models:

1. Could natural variations in rainfall-runoff relationships be analyzed separately from the anthropogenic impacts on flooding?
2. How does rainfall affect the natural river discharge?
3. How does rainfall affect inundation?
4. Could the rainfall-runoff-inundation relationships be simulated well in the CP Basin?
5. Could reservoir operation be accurately represented in a model?
6. Could the effects of reservoir operation to the downstream areas be simulated well?
7. If (6) could be done, how would a certain change in reservoir operation affect the discharge and inundation downstream of the dams?
8. What would be the “best” operation scheme for the dams in CP Basin?

Ultimately, answering these questions could give a good answer to the main question of this research: *How could flood mitigation techniques in the Chao Phraya Basin be improved by considering the impacts of both natural and anthropogenic factors?*

This research is then organized to show how the following objectives were attained in the respective order:

1. Use a model to simulate the naturalized discharge which could elucidate rainfall-runoff patterns.
2. Use a model to simulate inundation which could help predict rainfall-runoff-inundation changes.
3. Create better reservoir operation schemes for Bhumibol and Sirikit Dams and verify their effects to the river discharge and inundation downstream through modeling.

The achievement of the objectives stated above would lead to the capability to forecast discharge and inundation, a more accurate basis of design of flood structures, and the improvement of the management of dam operations.

The next chapter gives a brief review of the previous studies done related to the CP River Basin. Chapters 3, 4, and 5 discuss the methodology and results in attaining the three objectives mentioned. The conclusions, contributions, and future directions are finally discussed in Chapter 6.

The results of this study are deemed to be useful for implementation or further improvement of the Chao Phraya River Master Plan which is currently under revision.

Chapter 2

Review of past hydrological modeling studies in the Chao Phraya River Basin

This chapter gives a brief review of several hydrological studies that have been done in the Chao Phraya River Basin to understand the previous efforts done, learn from them, or identify the gaps that the current research could fill in.

Probably due to the country's susceptibility to both drought and flood risks, a lot of studies have already been done in the Chao Phraya River Basin and in other river basins in Thailand. The tremendous amount of research about CP River Basin available online is quite remarkable and commendable. These studies have different goals and objectives which are usually influenced by the most current environmental event that had occurred in Thailand.

2.1 Modeling studies for simulating flood depth and discharge

In Yom river basin, the effect of planned retention area and various diversion channel sizes in reducing flood depth were simulated using HEC-RAS [Chuenchooklin, S, et al, 2007]. The study showed the reduction in flooded area in the Sukhothai province at several design discharges of a proposed diversion channel. In Nan river, an integration of wavelet analysis and artificial neural networks was used to predict water level for effective flood prevention [Amnatsan, S, et al, 2010]. The hybrid model called Wavelet Neural Network (WNN) predicted the water level at a gauging station in Nan River ranging from 1994-2010 at high Nash-Sutcliffe Efficiency coefficients.

Although these studies yielded good results, these studies were conducted on just one sub-catchment of a network of rivers. Flood mitigation would be more efficient and effective if done on an entire basin rather than on individual rivers or sub-catchment basins. The models used were also mathematical and not physically-based. Although the mathematical-based models could give accurate results, coupling or integrating them with physically-based models such as climate models or land surface models for considering more complex systems may be difficult.

2.2 Modeling studies involving reservoir operation

Numerous modeling studies about dam operation have been conducted in several reservoirs in Thailand, most of which have been conducted outside the CP River Basin. With the increased popularity of of fuzzy logic theory artificial neural networks, and evolutionary computations, reservoir operation studies in mid-2000 in Thailand were mostly based on simulation-optimization studies using such computational intelligence techniques. These include the optimization of multiple reservoir system done in Mae Klong system in Thailand, first using a combination of genetic algorithm and discrete differential dynamic programming, and the second using simulated annealing [both by Tospornsampan, J, et al., 2005], combined simulation-genetic algorithm optimization for generating the rule curves at the Nam Oon Irrigation Project [Tingsanchali, T., et al., 2007], and use of hybrid genetic algorithm and neurofuzzy computing in the Pasak Josalid Reservoir [Pinthong, P., et al, 2008], among others. Such combined models became popular to support the non-linear, complex, multi-function, and multi-stakeholder nature of dam operation and to deal with the many complicated variables such as storage, inflows, and discharge, among others [Rani, D and Moreira, M, 2010]. These models use simulation as the starting point. However, unlike pure simulation-based reservoir operation like the ones used in this study, reservoir release using simulation-optimization models are not calculated based on pre-determined operating rules. The operating rules are varied and optimized using computational intelligence techniques in simulation-optimization models. Simulation-based models, on the other hand, are usually based on preserving the water balance and on hydrological cycles. Several reviews of these approaches by several authors [ie Rani, D and Moreira, M, 2010] found that such methods are better for real-time operation and for managing water resources more efficiently.

Simulation-optimization techniques seem to be applicable in this study. However, using such technique would make physically-based analysis and verification of the results to be difficult. Understanding the hydrological cycle and water balance at this point is important to the author. Thus, simulation-based or hydrological-based reservoir model is still preferred by the author. Simulation-optimization techniques may be further explored in the future.

Two simulations-based studies done in the CP River Basin were found. The first is an earlier study similar to this research and is the foundation of the reservoir operation module used in H08. The reservoir operation module was used with TRIP, a global river routing model, to simulate discharge from an offline simulation of runoff generated by SiB by Sellers [Hanasaki, et al., 2003]. Reservoir operation was classified into two: the first was based on an operation where the main function of the dam is to reduce seasonal and inter-annual variations; the second was based on a unique operation determined by the agricultural and irrigation demands. The study simulated dam storage and dam release at the Bhumibol and Sirikit Dams, and computed the discharge at C2 Station well. Unlike the current research, though, the natural variation or the naturalized discharge was not simulated separately in this study. This study also did not consider inundation as it was mainly conducted for future water resources simulations.

The second study is about inundation due to backwater flow due to the operation of the Chao Phraya Dam [Visetumeteegorn, S., 2007]. This study uses HEC-RAS to carry out the simulation. The results of this study showed good correspondence with the observed. This study is very interesting in that it simulated inundation upstream of the Chao Phraya dam due to back flow whereas the current research simulated inundation downstream of the Sirikit and Bhumibol Dam.

2.3 Integrated modeling studies for flood mitigation

Probably the most detailed hydrological study with a research framework that includes simulation of both natural and anthropogenic impacts on flood management was done in the Chi River Basin [Kuntiyawichai, K, 2012]. It used the SWAT model to simulate runoff and the 1D/2D SOBEK to simulate overland flow. It studied different combinations of alternative flood mitigation options such as retention basins, bypass channel, reservoir operation, and river normalization. It then quantified the flood damage reduction from implementing the combination of these alternatives. This study not only showed changes in river discharge and inundation, it also showed the detailed calculation of the costs and benefits from the alternative flood mitigation options.

This study, however, was done on a short time scale from 2000-2002. Although changes in land use would have been observed as well as in flood management, the time period used may be too short to show the variations in land use and its corresponding effects on flood management. It was also noticed that the reservoir operation suggested does not explicitly take into account the possibility of drought occurrences.

2.4 Modeling studies including climate change scenarios

Although several reports state that Thailand is already preparing for climate change, few hydrological modeling studies have been found which focus on Thailand. One recent study was done in the CP River Basin which examined the impact of regional climate change to the hydrological cycle until 2099 using DHI MIKE 11 [Kure, et al, 2012]. Aiming to detect the changes to the hydrological cycle due to climate change, this study understandably did not include reservoir operations or other human impacts in its considerations. Although quite limited, the results of this study could be used as basis for extending the current research to account for climate change.

2.5 Strengths and points to consider in the current research

A review of the past studies revealed the strengths and points for improvement of the current research. It could be said that this research is the most comprehensive hydrological study done for flood mitigation in the CP River Basin. It is the only study that explicitly separates the analysis of the naturalized discharge from that of which has the effects of reservoir operation. Since it is completely physically-based, the methodology of the study could be easily replicated in any part of Thailand (or similar regions outside of Thailand). It also has, by far, the most detailed study of dam operations in the Bhumibol and Sirikit Dams.

A component that could be added to the current research is land use change as this would most probably have a significant effect on flood risks. Another significant component that could be added is climate change. This would enable policy planners and managers to set design standards for flood structures that are based on future design discharge rather than on past design discharge which may become obsolete through time due to the intensification of precipitation.

Chapter 3

Simulation of discharge using H08

This chapter shows that the first main objective of this research had been achieved – to simulate historical and future naturalized river discharge. It begins with a brief description of H08, the model primarily used in this chapter. It then discusses how H08 was used for this study, the input data needed, and the modules used. The methodology for simulating the historical naturalized discharge was then discussed in detail, particularly focusing on calibrating the model parameters. The simulation from 1981-2004 at C2 Station showed very god results with Nash-Sutcliffe Efficiencies (NSE) ranging from 76% to 85% and percent bias (PBIAS) as high as 1.02%. The calibrated parameter sets were then validated in four other stations in which two stations showed high NSE and PBIAS while the other two yielded unsatisfactory results. Lastly, this chapter shows the applicability and capability of the calibrated model to effectively simulate the 2010-2011 discharge. It ends with the conclusion that the calibrated model is an effective tool for river discharge forecasting and for decision making.

3.1 Introduction to H08

H08 is an integrated water resources model developed by Hanasaki, etal. It is one of the few models that were developed with an aim to reproduce the sub-annual variations in the water cycle [Hanasaki, etal, 2007a]. It is also among several models that integrate anthropogenic or human influences such as reservoir operation with the natural water cycle. Anthropogenic activities such as water withdrawal are usually driven by the seasonality of the abundance or lack of water. Thereby, a hydrological model that wishes to effectively simulate water resources with human influence should be able to do so in a sub-annual scale [Hanasaki, etal 2007a].

H08 integrates six main modules into a coupled module – the *land processes* and *river modules* which are necessary to simulate natural hydrological processes, the *reservoir operation module* which buffers the seasonality of water upstream, the *anthropogenic water withdrawal* model which is driven by the industrial, domestic, and agricultural demands downstream, the *crop growth module* which determines the water needs driven by agricultural demands, and the *environmental flow module* which determines the water flow that need to maintain good river environment downstream [Hanasaki, etal 2007a]. Each module could be run separately, if needed, while a coupled module exists to run all the processes in an integrated manner. Figure 3.1 shows a diagram of all the modules in H08, with names of the authors of the original models where each module was based on. The yellow, dashed line encircles the processes mainly concerned of anthropogenic or human-induced processes while the violet, solid line encircles the natural processes.

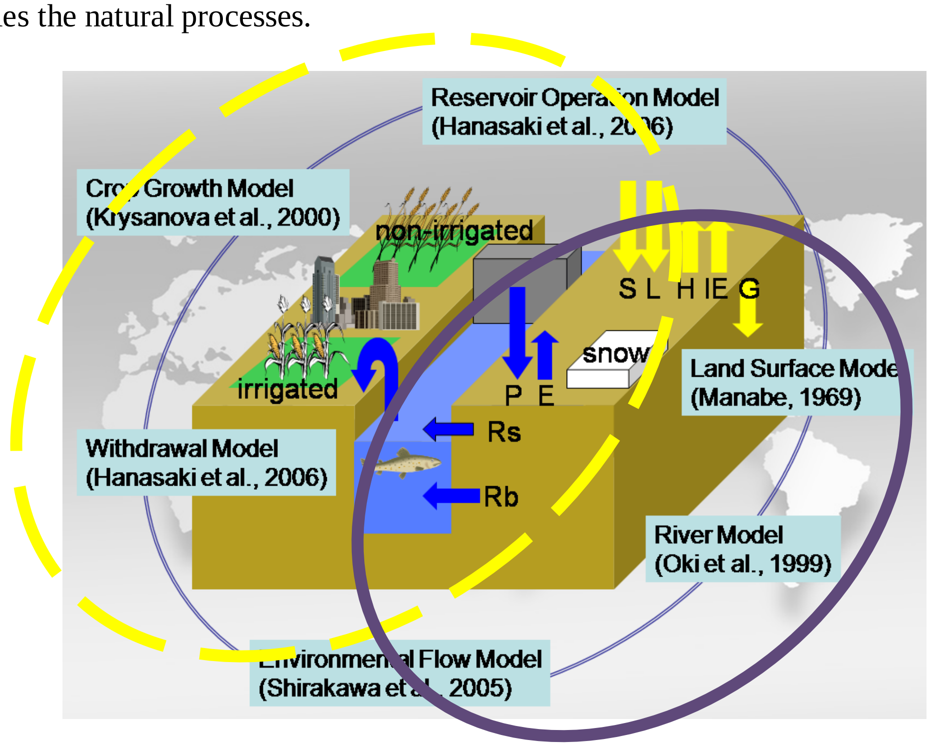


Figure 3.1 Modules consisting the H08 integrated water resources model.
Figure courtesy of Dr. Naota Hanasaki.

The land processes module of H08 was generally based on a leaky bucket model, a modified version of the original bucket type model by Manabe, etal 1969 and Robock, etal 1995. The leaky bucket model is a simple model that parameterizes subsurface runoff separation, simulates the diurnal cycle of surface temperature by calculating soil temperature using the force restore method by Bhumralkar, 1975 and by Deardoff, 1978, and simulates two independent land surface conditions within a single grid to separate irrigated cropland from other land types [Hanasaki, etal, 2007a].

Figure 3.2 below shows a simplified diagram of the calculation of the land processes in H08. For convenience and for easier reference, energy balance components were drawn at the right side in red arrows, the equation governing the interaction drawn inside a red box. Water balance components were drawn at the left side with blue arrows, with the governing equation written inside a blue box. On the right side, SWdown and SWup mean short wave downward and shortwave upward radiation, respectively, LWdown and LWup indicate long wave downward and longwave upward radiation, respectively, Tair is air temperature, Qair is specific humidity, Wind is wind speed, Qh is sensible heat flux, Qle is latent heat flux, Q g is ground heat flux, AvgSurfT is average surface temperature, and SoilTemp is soil temperature. On the water balance equation, Prcp means precipitation, SoilMoist means soil moisture, SWE is snow water equivalent, Evap is evaporation, and Qtot is total runoff. Arrows represent fluxes while those in circles and those that were underlined are state variables. In the simulation, usually, the first year is used to calculate in spinup mode until the state variables have stabilized or have reached a low difference compared with the previous spinup process.

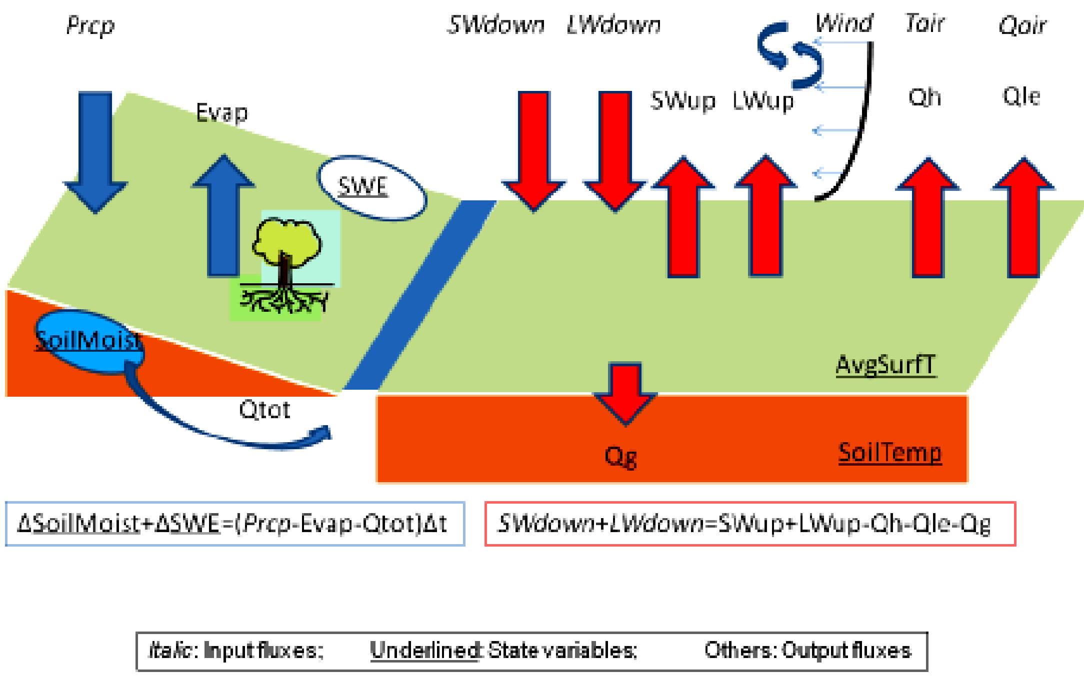


Figure 3.2 Schematic diagram of the land processes module of H08.
Figure courtesy of the H08 User's Manual by Hanasaki, et al.

The river module is based on the Total Runoff Integrating Pathways or TRIP model [Oki and Sud, 1998; Oki, et al 1999]. Runoff from the land processes module is used as input to calculate the stream flow. Some of the limitations of this module are that human-induced changes such as reservoir operation are not taken into account, evaporation from water surfaces are ignored, and lakes or swamps and similar inland water bodies are not considered.

To illustrate the calculation of the river module, Figure 3.3 below shows the fluxes in arrows and the state variables underlined. Qtot is the total runoff inflow from the land processes module coming from the upstream grid cell, RivInf is the river inflow from the upstream grid cells, RivOut is the river discharge or stream flow, and RivSto refers to river storage. Total runoff is taken to be equal to total runoff Qtot x total Area A, both from the upstream cell. The blue box contains the equation used to calculate the river water balance.

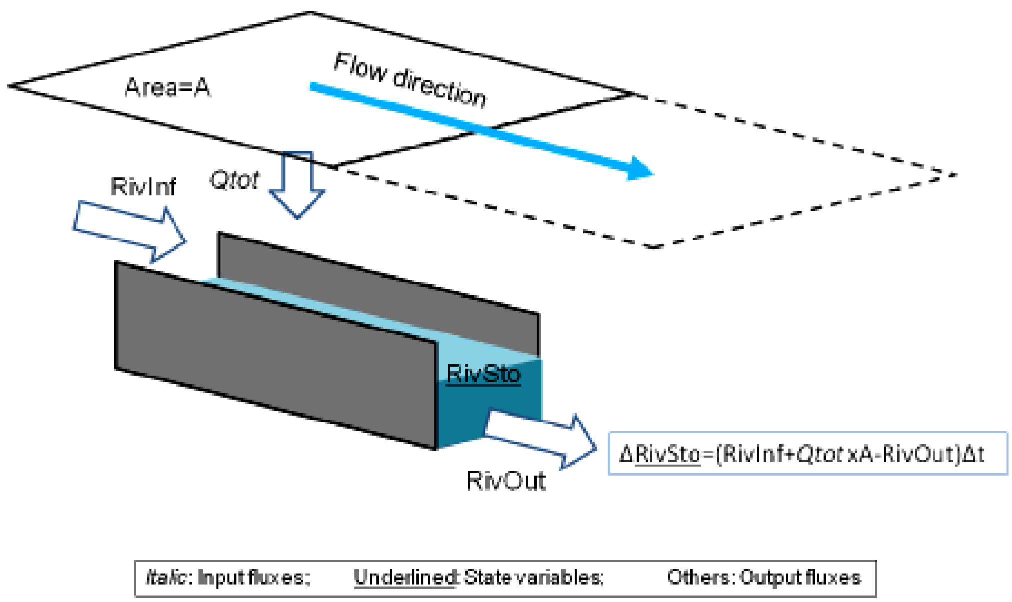


Figure 3.3 Schematic diagram of the river module of H08.
Figure courtesy of the H08 User's Manual by Hanasaki, et al.

Reservoir operation module considers large and medium scale reservoirs. Reservoir details that affect operation such as effective storage capacity, purpose in order of priority, surface area, and location are used as input. The reservoir operation module then sets the operating rules according to the purpose of the dam. For global calculations, reservoir operating rules are based on two types of reservoirs – one that is used for agricultural or irrigation supply purposes which will be operated based on the irrigation water demands downstream, and the second is to minimize interannual and subannual stream flow variation [Hanasaki, etal 2006]. For regional application, the code containing the reservoir operating rules could be edited and adjusted to incorporate the actual or simplified rules which could be a function of release, storage, or inflow in the reservoir.

The crop growth module is based on the Soil Water Integrated Model or SWIM by Krysanova et al, 1998 which integrates vegetation, nitrogen dynamics and erosion with hydrology at a watershed scale. Since H08 intends to use the model for estimating water for crop growth, only the parameters for crop vegetation was adopted from SWIM [Hanasaki, et al, 2007]. The H08 crop growth module works under the assumption that agricultural water demand in irrigated fields is equal to the water needed to maintain soil moisture at 75% of field capacity [Hanasaki, et al, 2007]. Water below this threshold prevents the optimal growth of the plant biomass due to water stress.

The environmental flow module was based on the algorithm by Shirakawa in 2004 and 2005. Environmental flow in this module was based on the minimum stream flow that has to be maintained in the channel (base requirement) plus an allocated amount that intends to take into account flush stream flow in the rainy season. The algorithm was based on several case studies and field work in heavily populated regions or in semi-arid to arid regions. At this stage, for several reasons, the algorithm does not require sufficient river flow for aquatic ecosystems. The algorithm also does not account for cultural and economic perspectives but simply accounts for natural hydrological conditions.

Information from AQUASTAT database was used to estimate the demand for the domestic and industrial water required to run the anthropogenic water withdrawal module. The anthropogenic water module withdraws water from the river channel for domestic, industrial, and agricultural purposes, in that order. This module plays an important role in coupling the water fluxes in the other modules.

3.2 Application of H08 to this research

H08 model was chosen for this research for three main reasons – (1) it has a good representation of anthropogenic activities integrated with the natural hydrological processes; (2) the code is open source, flexible, and could be easily modified according to the needs of the research; and (3) it is familiar with a group of Thai researchers and government officials who could potentially introduce and implement the findings of this research.

In this research, hydrological modeling using H08 was done in two main phases in order to attain distinct objectives – first, to simulate the natural river discharge or the river discharge without the effects of reservoir operation, and second, to simulate the effects of reservoir operation on the river discharge. It must be noted that natural river discharge is governed by physically-based land and natural river processes whereas reservoir operation is governed by policies and decisions made by humans. To attain consistency and to ensure adherence to the physical laws and basic principles of hydrology, it is important to ensure that natural river discharge is simulated well by the model first, before reservoir operation is considered or simulated. It is also important to simulate the natural discharge separately before simulating human activities-influenced discharge to be able to distinguish the impacts of anthropogenic activities from the effects of variations in natural processes. The first phase was carried out by using only the land and river modules of H08, while the second phase was carried out using the coupled land, river, and reservoir operation modules. This chapter focuses on the methodology and results of simulating the natural river discharge while Chapter 5 focuses on the methodology and results of simulating river discharge with reservoir operation.

In this chapter, parameters affecting the land processes of H08, originally set to match the global conditions, were calibrated at station C2 (Nakhon Sawan), one of the most critical stations in the Chao Phraya River Basin, to fit the local conditions at the Chao Phraya basin. The methodology for calibration will be discussed in detail in Chapter 3.4. Validation which is discussed in detail in Chapter 3.5, was then done to check the applicability of the calibrated parameters to all the grids in the river basin. After calibration and validation of simulated discharge from 1981-2004, the calibrated parameter set was then used to simulate the naturalized river discharge from 2010-2011. The same set of calibrated parameters was also used to run the coupled land, river, and reservoir operation modules. Simulation outputs are available in the daily, monthly, and annual scales.

3.2.1 General settings

Simulation was done at a spatial resolution of 5' x 5' on the river basin of Chao Phraya (CP). Since the CP river basin is between 97°E - 102°E longitude and 13°N - 20°N latitude, computation at 5 minute resolution produces 60 grid cells along the x-axis ((102-97)degrees*(60minutes/degree)/5minutes) and 84 grid cells along the y-axis, or 5040 grid cells. The format used for handling data was that of Hformat2D, a method wherein the data is divided into fixed elevation, time, experiment, and variable dimensions, and 2 flexible space dimensions (x,y) [see Chapter 5 of H08 User's Manual, by Hanasaki, etal, v20120101].

The modules and executable files shown in Table 3.1 were used in this research. Some simulations were run after editing the geographical setting, experiment name, and project name. Some programs and subroutines were edited though to reflect the changes made to the calculations. The executable files in italics shown in the table have been modified in this research.

Table 3.1 H08 modules and models used in this research*

Modules or models	Executable shell	Main program	Key subroutines	Key changes made
Land surface module	*lnd/bin/main006.sh* *lnd/bin/main007.sh*	*lnd/bin/main006* *lnd/bin/main007*	*lnd/bin/calc_leakyb006.o* *lnd/bin/calc_leakyb007.o*	Changed the r0cd (bulk transfer coefficients)
River module	riv/bin/main.sh	riv/bin/main	riv/bin/calc_outflow.o	
Reservoir operation module	None (used the shell from the coupled model instead)	*dam/bin/main_M12*	*dam/bin/calc_resope_M12*	Added new operation rules
Coupled model	*cpl/bin/main_M12.sh*	*cpl/bin/main_M12*	All of the above	

* Table adapted from H08 User's Manual by Hanasaki, N., 2012

3.2.2 Input map data

Four sets of maps are needed to execute the modules and models needed for this research. The first one which is called the base map sets the basic spatial information of Chao Phraya in H08. The second set is needed to execute the land surface module. This set includes the land sea mask and land area. The third set is needed to execute the rive module. It includes river flow direction, river sequence, the location of the next downstream cell, and the distance to the next downstream cell. The last set is needed to execute the reservoir operation module. It contains data about the location of the reservoirs in the basin, year of construction, priority of use, and other necessary information about the reservoirs to be used in the model.

The original files needed for preparing the maps for the land, river, and reservoir modules could be found and downloaded from the server of H08, https://fxp.nies.go.jp.

At least two versions of maps were used for this research – K10 which was prepared by Kotsuki, etal. 2010, and K10R which was a revised version of K10. The number of grid cells classified as land (land mask) differ between the two maps. When a map that has more land grid cells is used with a precipitation dataset that has lesser land grid cells, unnecessary drying and higher temperatures might be detected in the land grid cells which do not receive any precipitation. K10 map version has more grid cells classified as land than K10R. Due to the differences in the number of land grid cells in the precipitation dataset, K10 set of maps must be used with K10 rainfall data, while K10R set of maps must be used with T12 rainfall data. The difference between these two sets of data would be discussed in the next chapter.

3.2.3 Meteorological forcing data set

Three sets of meteorological forcing data were used in this study. The first one was compiled and prepared by [Kotsuki, etal, 2010], the second prepared by [Tanaka, etal, 2012], and the last prepared by [Yoshimura, etal, 2008]. Due to technical reasons, the first comprehensive meteorological dataset is hereafter called K10 [after Kotsuki et al., 2010], the second one T12 [after Tanaka et al., 2012], and the last set Y08 [after Yoshimura et al., 2008].

This study was initially conducted using the first set of dataset which consists of hourly precipitation forcing dataset from APHRODITE [Yatagai, et al. 2009] which ranges from 1981 to 2004 and combined with seven other meteorological inputs which range from 1980-2004 – pressure (in Pa, hourly), wind speed (in m/s, hourly) [both from JRA reanalysis], 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) [H08 outputs, 2008], and surface albedo [GSWP2 data interpolated for the Chao Phraya Basin].

It was found that the K10 precipitation underestimates the observed precipitation, as could be seen in Figure 3.4, courtesy of Mr. Masashi Kiguchi. Since the simulations are highly sensitive to precipitation, a new set of more accurate precipitation data prepared by Tanaka, etal (T12) was examined. T12 is a forcing data set available from 1981-2011 and is based from precipitation observation points around the CP basin (see Table 3.2 for comparison between K10 and T12). It does not include the other meteorological factors needed to run H08 so it has to be combined with other forcing data set such as K10 for simulations from 1981-2004 and Y08 for simulations from 2010-2011. To simplify the names for the simulation runs and avoid confusion, hereon, the combined T12 rainfall and seven other K10 meteorological variables simulation runs from 1981-2004 shall be referred to simply as *T12*, while simulation runs from 2010-2011 which combine T12 precipitation with Y08 meteorological variables, shall be referred to as *T12-Y08*.

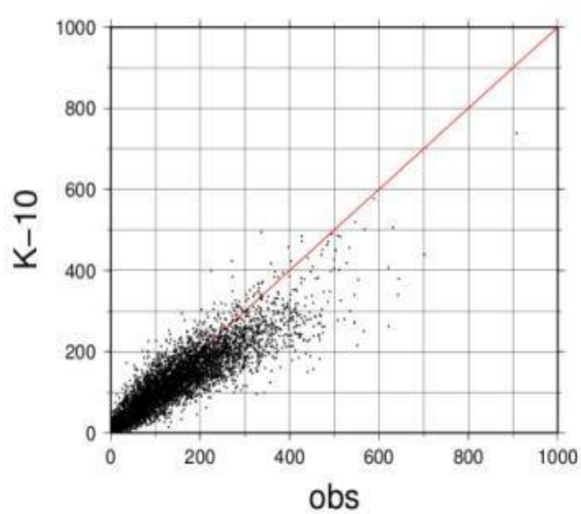


Figure 3.4 Comparison of K10 precipitation with observed precipitation shows that it is a bit underestimated. *Figure courtesy of Dr. Masashi Kiguchi.*

Table 3.2 Comparison between K10 precipitation and T12 precipitation

Comparison of Precipitation Data K10 and T12		
Name (prepared by)	K10 (Kotsuki, et.al. 2010)	T12 (Tanaka, et.al. 2012) – Observed
Source	Aphrodite	TMD/RID
Range of years	1981-2004	1981-2011
Time scale	Hourly	Daily
Resolution	5 min resolution	5 min resolution

Y08 is a set of forecasted meteorological values which are the results of a study done by Yoshimura, etal in 2008. Due to the limited range of the K10 dataset, Y08 dataset was combined with T12 precipitation to simulate the discharge in 2010-2011.

3.3 Naturalized discharge vs observed discharge

As had been mentioned in section 3.2, the objective of this chapter is to simulate the river discharge at the CP river basin at natural conditions. To check its efficiency and accuracy, as with any simulation studies, the simulated results must be compared with available data such as the observed data. This section introduces the observed discharge used for comparison and the correction done to make it comparable with the simulated discharge.

Human activities such as reservoir operation greatly affect river discharge. Comparing the river discharge simulated by H08 at default parameters and the observed discharge at C2 station [obtained from the Royal Irrigation Department (RID) of Thailand, 2012] in Figure3.5, it could be noticed that the observed river discharge hydrograph is higher during the dry season, the peak discharge is evidently lower, and the time of peaking occurred later. Aside from using non-calibrated parameters in this comparison, these discrepancies are due to the effect of reservoir operation upstream of the observation station. Reservoir operation increases discharge downstream during the dry season due to water released for irrigation. Meanwhile, it decreases peak discharge downstream and delays the peaking of the discharge during the rainy season due to the storage and delay of flood water release. The result of H08 land and river modules simulation which does not take into account the reservoir operation is therefore not comparable with the raw observed discharge at any point downstream of a dam.

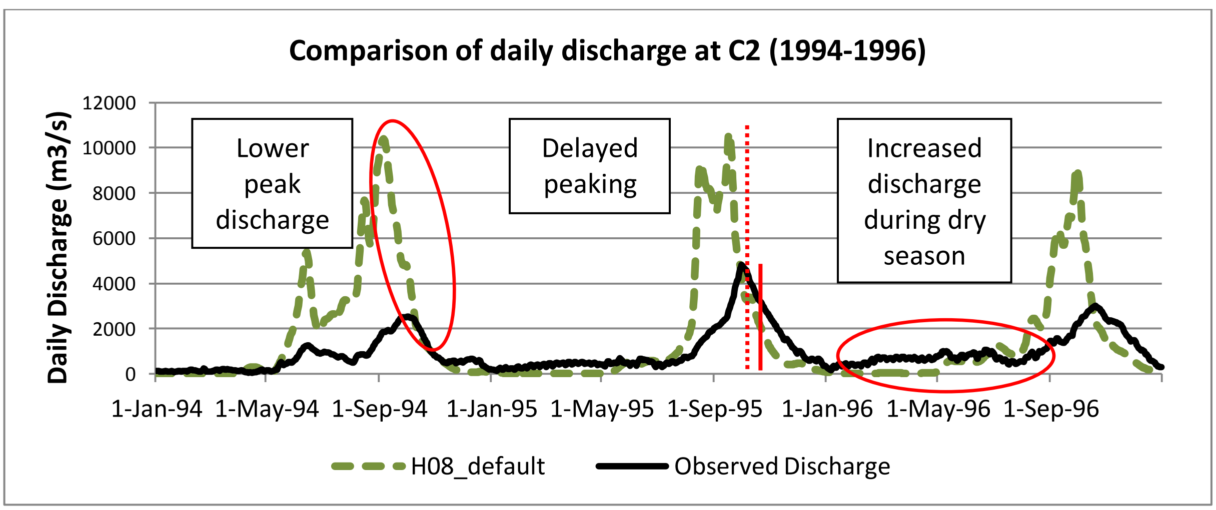


Figure 3.5 Comparison of simulated and observed daily hydrographs at C2 Station from 1994-1996. The green, dashed line represents the discharge simulated using default parameters of H08 while the black, solid line represents the raw observed discharge.

To make the H08 output and the observed discharge comparable, the effects of dams have to be removed from the observed discharge. In this research, this observed discharge without the effects of dam operation is called '*naturalized discharge*'. Naturalized discharge is obtained by simply adding the water intercepted by the dams upstream of the observation station. In this study, due to the limitation in time and data, for simplicity, it is assumed that only the two major and biggest dams in Chao Phraya Basin, the Bhumibol and Sirikit Dams, significantly affect the hydrographs of the observation stations downstream.

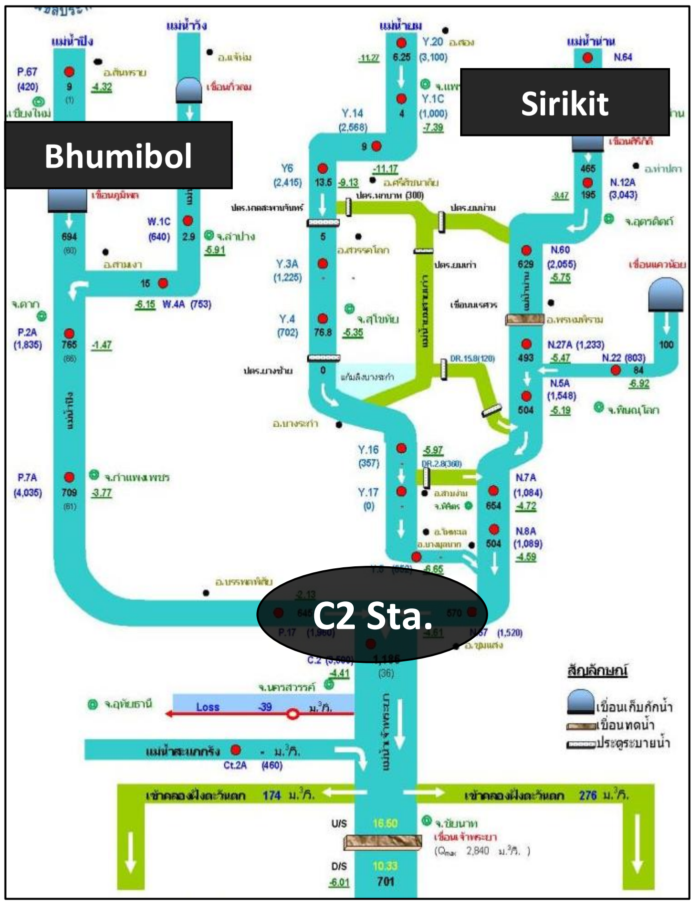


Figure 3.6 A diagram of the water ways and structures of the Northern Chao Phraya River Basin showing the relative location of C2 Station from Bhumibol and Sirikit dams. *Illustration courtesy of the Thai Royal Irrigation Department.*

As could be seen in Figure 3.6, C2 station is located downstream of Bhumibol and Sirikit Dams. Therefore, the observed discharge at C2 has to be naturalized using equation 3.1 shown below, where ND is naturalized discharge, OD is observed discharge, I is inflow to the dam, P is water pumped into the dam, R is water released, and S is water released through the spillway:

$$ND_{C2} = OD_{C2} + [I + P - R - S]_{Bhumibol} + [I + P - R - S]_{Sirikit} \qquad (3.1)$$

Figure 3.7 below shows the resulting daily hydrograph from 1994 to 1996 after the observed discharge has been naturalized (named "Nat_C2_Observed" in the graph). Hereafter, all simulations without consideration of dam operation shall be compared with the naturalized discharge. It could be seen that the naturalized discharge has a higher peak discharge, earlier occurrence of the peak, and lower discharge during the dry season as compared with the observed discharge. However, it could be noticed that the "H08_default" line or the hydrograph of the simulation using default H08 parameters is still quite far from the naturalized discharge. This just means that calibration of parameters is necessary. The method for calibration will be discussed in the next section.

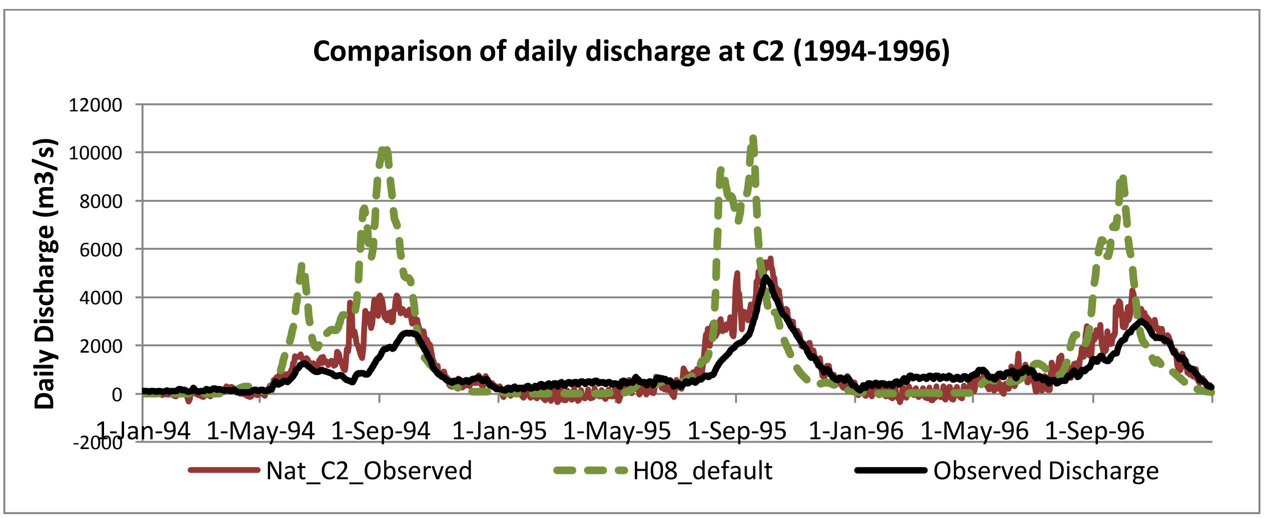


Figure 3.7 Comparison of simulated, observed, and naturalized daily hydrographs at C2 Station from 1994-1996.

3.4 Calibration of parameters

Four parameters mainly affecting the land processes module were calibrated in this research – the bulk transfer coefficient (C_D), soil depth (SD), time constant for daily maximum subsurface runoff (τ), and shape parameter which sets the relationship between subsurface flow and soil moisture (γ). These parameters were originally set at global average values, $C_D = 0.003$, SD = 1.00m, $\tau = 100.00$, and $\gamma = 2.00$. As could be seen in the previous section, in Figure 3.7, this set of parameter values overestimate the peak discharge by almost double the observed and naturalized discharge values. To have a fairly good comparison and attain realistic values, calibration of parameters is greatly needed.

This section discusses the methodology for calibration which was done in two (2) stages, first using the K10 dataset, and second using the T12 dataset. As had been mentioned previously, calibration of the parameters was done at C2 Station mainly because it is at the confluence of the four main tributaries of the upper CP basin, one of the most critical stations at the basin due to its susceptibility to flooding.

3.4.1 Relationship between each parameter and the hydrograph

To effectively carry out parameter calibration, it is essential to examine and understand how changes in each parameter would affect the hydrograph and the water balance in the CP basin.

The bulk transfer coefficient (C_D), a unit less parameter, mainly affects the potential evaporation and the sensible heat flux. Consequently, it also affects the energy balance and the soil water balance since sensible heat flux is a component of the energy balance, while evaporation is a component of the soil water balance.

Potential evaporation (E_p in kgm^{-2}s^{-1}) in H08 was expressed as in equation 3.2, where ρ is the density of air (in kgm^{-3}), U is the wind speed (in ms^{-1}), $q_{sat}(T_s)$ is the saturated specific humidity at surface temperature, and q_a is the specific temperature (both in kg/kg) [Hanasaki, etal, 2007a]:

$$E_P(T_S) = \rho C_D U(q_{sat}(T_S) - q_a) \tag{3.2}$$

Potential evaporation affects the evaporation from a surface (E) through the following equation 3.3:

$$E = \beta E_p\,(T_S) \tag{3.3}$$

where β is expressed in equation 3.4 as a function of the soil water content W, and soil water content at field capacity W_f, which was fixed at 150 [both expressed in kgm^{-2}]:

$$\beta = \begin{cases} 1, & 0.75W_f \leq W \\ \frac{W}{W_c}, & W < 0.75W_f \end{cases} \tag{3.4}$$

Sensible heat flux (H) in equation 3.5, is expressed as a function of C_D, specific hear of air C^*_p (1005 J kg^{-1} K^{-1}) and air temperature T_a (in K):

$$H = C_p^* \rho C_D U(T_S - T_a) \tag{3.5}$$

Based on the above equations, it could be concluded that an increase in C_D results to an increase in potential evaporation, evaporation, and sensible heat flux. Examining equation 3.6, it further affects the soil water balance by decreasing the total runoff for a certain amount of rainfall. In the said equation, Q_{sm} is the snow melt rate (negligible or *0* in Thailand), Q_{sb} is the subsurface runoff, Q_s is the surface runoff (all in kg m^{-2} s^{-1}). It was found in this research that an increase of 0.001 in C_D results to a decrease of approximately 10% in the total runoff.

$$\frac{dW}{dt} = Rainf + Q_{sm} - E - Q_s - Q_{sb} \tag{3.6}$$

Soil depth *SD* (in m), affects the hydrograph by increasing the soil water content at field capacity W_f (see equation 3.7), an increase of which, causes a decrease in the surface runoff Q_s (equation 3.8). A higher SD also tends to delay the timing of the peak discharge as it tends to delay the saturation of the effective soil layer.

$$W_f = SD \cdot (\theta_{field\,capacity} - \theta_{wilting\,\mathrm{point}}) \tag{3.7}$$

$$Q_S = \begin{cases} W - W_f & W_f \leq W \\ 0 & W < W_f \end{cases} \tag{3.8}$$

Examination of the equation 3.9 for subsurface runoff (Q_{sb}) and the soil water balance (equation 3.6 shown previously) indicates that an increase in shape parameter γ increases the subsurface runoff, which then reduces the surface runoff at a constant precipitation and evaporation. From the same set of equations, it could be concluded that an increase in time constant for daily maximum subsurface runoff τ would result to a decrease in the subsurface runoff, thereby increasing the surface runoff at a constant precipitation and evaporation.

$$Q_{SB} = \frac{W_f}{\tau}\left(\frac{W}{W_f}\right)^{\gamma} \tag{3.9}$$

Simply examining the equations above has several limitations. First, it does not reveal how the changes in parameter could change the shape of the hydrograph at daily, monthly or annual time scales. Second, it does not indicate how the total runoff would change with an increase in *SD*, γ, or τ. The analysis of the equations needs to be supplemented with graphical examinations and soil water balance examinations of the output of simulations of H08. For example, Figure 3.8 shows how the daily hydrograph changes when τ is varied while keeping the three other parameters constant. The graph reveals that aside from increasing peak discharge, increasing τ reduces fluctuations, reduces discharge volume, and shortens the time of peaking. Analysis of the water balance (not explicitly shown here) further reveals that total runoff increases with a decrease in either *SD*, γ, or τ.

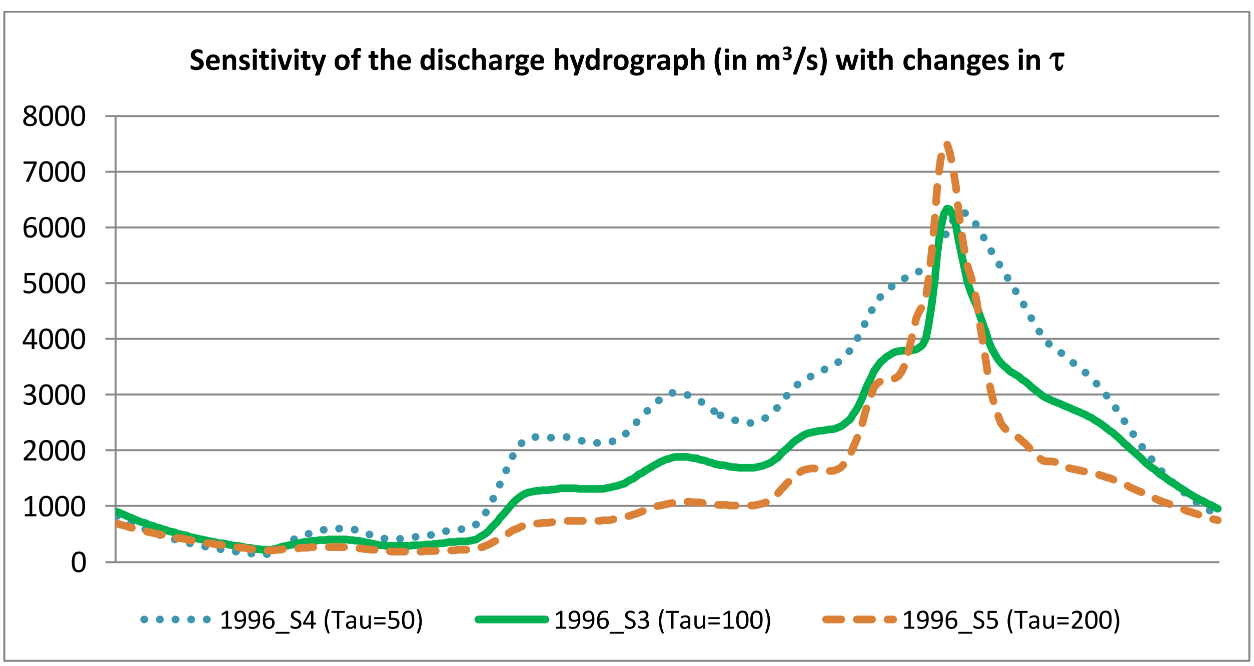


Figure 3.8 Graphical examination of the effect of the change in parameter Tau on the daily discharge. In this graph, 1996 stands for the year of comparison and S*N* is a name used to distinguish each simulation run.

3.4.2 Methodology for calibration: K10 Dataset

The methodology for calibrating H08 using the K10 dataset is a bit simple. It is a mix of mostly graphical inspection combined with computation of water balance equations. Most of the comparison with the naturalized discharge at C2 Station was done at a daily scale (in m^3/s) in the critical flood years 1996 and 2002. This was done to reduce simulation time which could take six to seven (6-7) hours if done for the entire 24 years (1981-2004). Daily scale comparison was chosen because changes in the shape of the hydrograph, discharge peak, and peak timing are difficult to detect in the monthly and annual time scales.

Approximately 30 combinations of parameters were checked. Parameters were varied one at a time at first, until a reasonable range of values for each parameter was determined. At first, large values of increment in parameters were used for each simulation run – C_D at increments of 0.001 ranging from 0.003 to 0.006, SD at increments of 1.0m ranging from 1.0m to 5.0m, τ at increments of 50.0 ranging from 50.0 to 250.0, and γ at increments of 0.50 ranging from 1.00 to 3.00. After determining the reasonable range of values for each parameter through screening, the parameters were then varied mostly two at a time, and at smaller increments.

At first, screening of various parameters set combinations was done by plotting the simulated daily discharge against the naturalized discharge from 1981-2004. The trend line of the H08 simulation run at default parameter set values was set as the upper bound and the y=x line was set as the lower bound. All simulation runs with trend lines that fall outside the bounds of these two lines were screened out from further analyses (see Figure 3.9 for example).

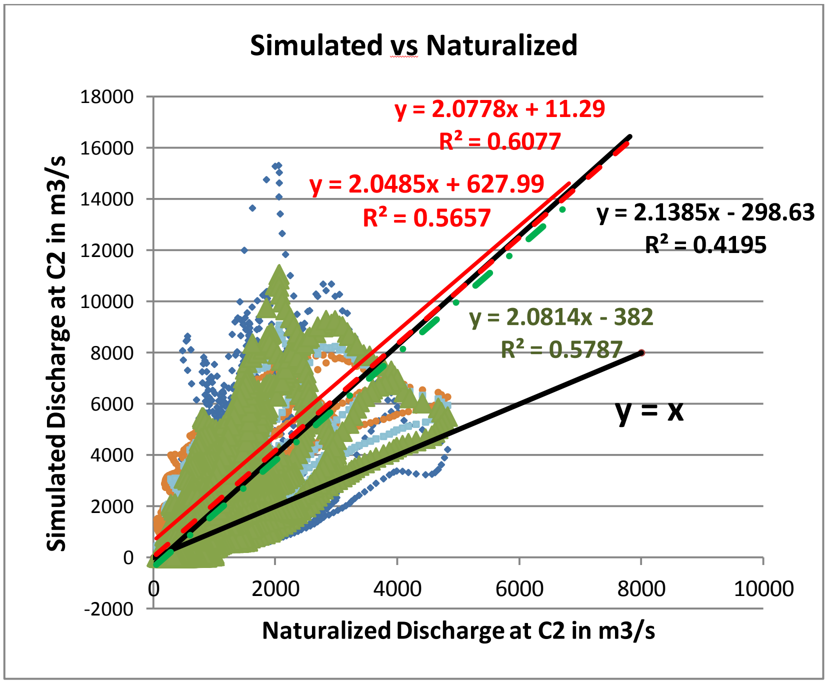


Figure 3.9 First screening of the simulation runs at various parameter combinations. This graph is an example of the first screening process. The simulation runs with red trend lines give discharge values that are farther from the naturalized discharge values than the simulation run using default H08 parameters. The simulation run with the green trend line, on the other hand, gives values nearer to the naturalized. Thus, in this example, only the simulation with the green trend line passes screening.

The daily discharge at 1996 and 2002 of the simulation runs that passed through the previous screening were then graphed and compared with the default H08 run and the naturalized discharge (see Figure 3.10 for example). Again, the default H08 run was use as the upper bound and the naturalized discharge as the lower bound. This time, particular attention was given to the general shape of the hydrograph, the discharge peak, and the time of peaking.

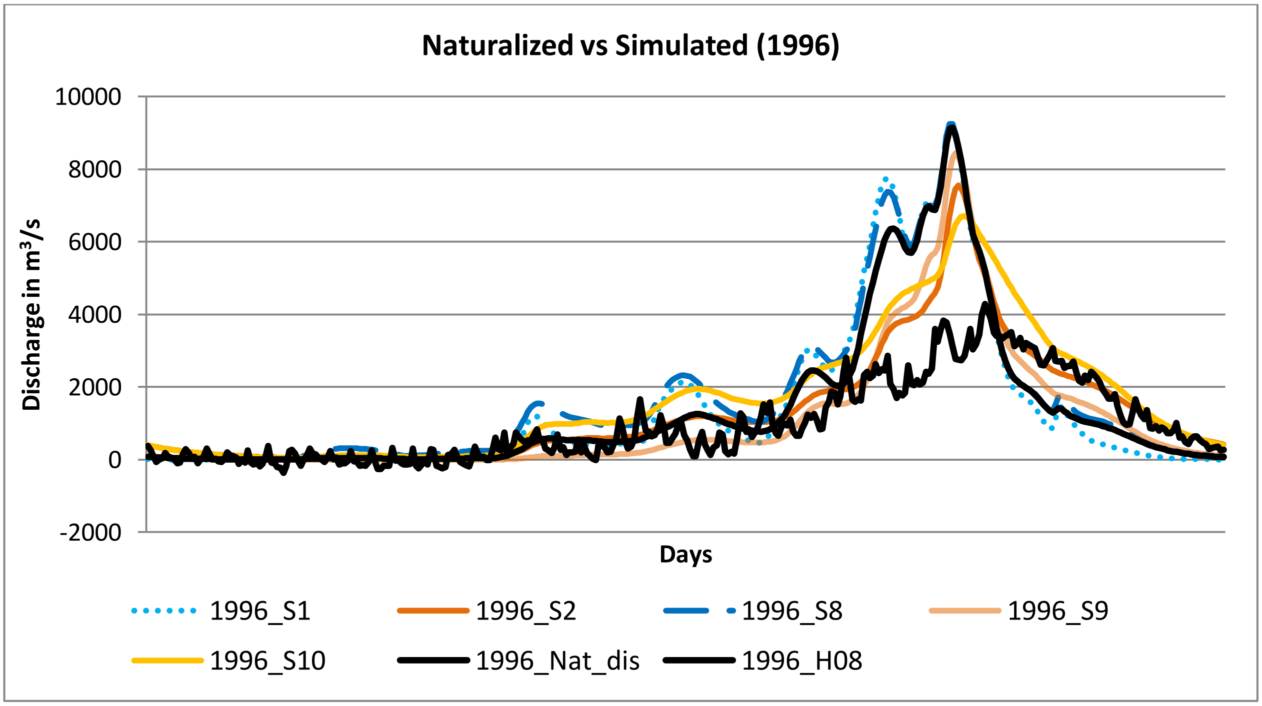


Figure 3.10 Second screening of the simulation runs at various parameter combinations. This graph is an example of the second screening process. The simulation with the blue, dashed lines are screened out while the simulation with yellow, solid lines are further examined and refined.

The refined simulation runs were compared with the naturalized observed both graphically and by comparing the water balance with the observed. Since it is difficult to obtain observed evaporation values, to compare water balance, the ratio of the annual discharge with the annual precipitation in 1996 and 2002 were compared with that of the observed mean annual discharge-precipitation ratio. Evaporation in Thailand is quite high, consequently making the discharge to be just around 20% of the precipitation on the average. This part of the methodology is a bit inaccurate because some studies reveal that the percentage of runoff and river discharge in Thailand varies greatly with increasing precipitation [Komori, etal, 2012].

The result of the calibration done in this section will be illustrated and discussed in section 3.5-3.7. Hereafter, the result of the calibration using the K10 dataset shall be referred to either as "K10-calibrated" or "K10-optimized".

3.4.3 Methodology for calibration: T12 Dataset

As had been mentioned in section 3.2.3, K10 precipitation was found to be underestimated and a new rainfall forcing dataset (named T12 in this research) based on rainfall observation stations around CP river basin was made. Since this precipitation dataset is higher than K10 dataset and runoff in CP river basin is highly sensitive to precipitation, simulation of discharge using the parameters calibrated using K10 resulted to overestimated river discharge. Thus, H08 parameters have to be calibrated again, this time with respect to T12 precipitation.

Several issues found in the calibration using K10 precipitation was tried to be addressed in this stage. First, average runoff rate in mm/day (or mm/month or mm/yr, whichever is applicable) was used instead of discharge in m^3/s as the unit for comparison. This is done to reduce biases which could result from the differences in simulated and observed catchment basin areas (Table 3.3). Second, *mean* annual water balance from 1981-2004 was compared with the naturalized observed *mean* water balance. Again, due to the difficulty in obtaining observed evaporation values, this was done by comparing the mean annual runoff with the mean annual runoff calculated from 1981-2004. This is done to reduce the bias from fluctuating annual discharge-precipitation ratios. Lastly, instead of comparing in just two critical years, comparison in the daily scale was done in three sets of critical three consecutive years 1984-1986, 1993-1995, and 2000-2002. These three sets of years were found to be the years with high mean annual discharge discrepancies in the previous stage. Particular attention was given to 1993-1995 set because 1993 is the worst drought year in the data set whereas 1995 is the worst flood year. This was done to ease the tendency to calibrate with bias towards flood years.

Table 3.3 Observed and simulated catchment basin areas upstream of C2 Station

	Catchment basin area (km^2) upstream of C2 Station	Source
Observed	109973	Royal Irrigation Department (RID)
K10	117955	K10 map
T12	119839	K10R map

This stage of calibration was also done more systematically than the previous. The previous stage of calibration was done mostly by changing all the parameters on the daily scale, and then verifying the result by checking the water balance on an annual scale. This methodology gave good results, but changing all the parameters at a time proved to be time consuming and a bit confusing. Thus, in this stage, calibration was tried to be done by calibrating and fixing at most two parameters at the annual scale, and then changing the other two parameters in the daily or monthly scale. C_D and SD were fixed first in the annual scale because these two parameters greatly affect evaporation and surface runoff, respectively. With the C_D and SD fixed, τ and γ were calibrated in the daily scale because these two parameters both affect the shape of the hydrograph significantly. However, since τ and γ also significantly affect annual runoff, the result of the calibration of τ and γ were verified by checking the annual water balance again. Generally, to maintain almost the same mean annual runoff while varying τ and γ, an increase of 10.0 in τ should be accompanied by a decrease of 0.10 in γ. These values are rough estimates and should be checked constantly.

Nash-Sutcliffe Efficiency coefficient, *NSE* (equation 3.10, where Q_o^t is observed value at time *t*, $\overline{Q_o}$ is the mean observed, and Q_m^t is modeled value at time *t*) [Nash and Sutcliffe, 1970], was used as basis for comparison on the annual and monthly scales. Parameters were changed until accurate values of NSE and annual runoff were obtained. The simulation of the daily runoff was evaluated using root mean square error (RMSE) and by comparing the date and magnitude of the peak runoff. As in the previous stage, the shape of the hydrograph was also considered.

$$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_o^t - Q_m^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q_o})^2} \qquad (3.10)$$

Table 3.4 in the next page shows the summary and comparison of the methodology used in calibrating H08 parameters in the first and second stage. The results of both calibrations would be discussed in the next section.

Table 3.4 Differences between the methodology used in the first stage and second stage of calibration

Variable	First Stage	Second Stage
Precipitation	K10	T12
Other meteorological data	K10	K10
Unit used	m^3/s	mm/yr (mm/mo or mm/day)
Sequence of calibration	Daily scale -> annual scale (monthly for verification) All parameters varied and calibrated at daily scale first, then calibrated at annual scale	Annual -> daily (monthly for verification) C_D and SD varied and fixed at annual scale; τ and γ varied at daily scale, then verified at annual and monthly scales
Method of comparison with naturalized	Daily: graphical Monthly: graphical Annual: water balance	Daily: RMSE and graphical Monthly: NSE and graphical Annual: NSE and water balance
Water balance	1996 average at C2 compared with naturalized mean annual water balance [RID]	Simulated mean annual water balance at C2 compared with naturalized mean annual water balance at C2

3.5 Simulated naturalized discharge from 1981-2004

The parameter set that showed the best results based on the calibration methods discussed in the previous section could be seen in Table 3.5. Although it is quite difficult to physically verify the accuracy of the parameters in the field or in real life, it could be observed that the values of both calibrated parameter sets are quite close to that of regions classified as tropical forests and of paddy fields, as reported in Hanasaki, etal, 2010. These values are reasonable because Thailand is a tropical country and C2 Station is close to areas that are used for agricultural purposes.

Table 3.5 Comparison between calibrated parameters, default values, and observed values in tropical forests and paddy fields

Parameter	Default Value	K10 - Calibrated	T12 - Calibrated	Tropical Forests*
Bulk transfer Coefficient (C_D)	0.003	0.006	0.007	0.006 for paddy fields; 0.007 for well-irrigated paddy fields
Soil depth (SD)	1.00 m	3.00 m	3.50 m	*No available reference data*
Tau (τ)	100 days	120 days	155 days	100 days
Gamma (γ)	2.00	2.30	2.30	2.00

*Hanasaki, etal, 2010

These calibrated parameters produced the hydrographs in Figures 3.11, 3.12(a), and 3.12(b) in daily (mm/day), monthly (mm/month), and annual time scales (mm/year), respectively. Note that all hydrographs hereafter will use (mm)/(unit of time) as the unit of runoff rate (discharge in m^3/s divided by their respective catchment areas in m^2) to avoid biases from differences in catchment areas and for consistency.

It could be seen that the hydrographs corresponded well with the naturalized discharge in all the time scales. As expected, T12 produced better results for the reason that the rainfall data used was more accurate than in K10. It could be noted though, that given this disadvantage, the K10-calibrated hydrographs still gave comparatively good results.

Showing the daily discharge hydrograph using the default parameters with that of using calibrated parameters in Figure 3.11 illustrates well the big effects and advantage of calibrating the parameters. The shape of the hydrograph, peak magnitude, and peak timing were captured well, as illustrated in Table 3.6. The percent difference in peak magnitude was reduced significantly from as high as 175% to as low as only 11%. It could also be noticed that the peak magnitude in the calibrated simulations in 1993 and 1995 are within 20% error. It could be noted, however, that the 1994 peak magnitude is still overestimated at as much as 31%, even after calibration. The peak timing became closer to the observed in most years, although some years still need to be improved so that the error could be just within 5 days from the observed. As have been mentioned in the previous section, 1993 was the worst drought year while 1995 was the worst flood year from 1981-2004, the range of years when calibration was done. Examining the hydrographs from 1993-1995 could give a better insight about the effectiveness of H08 in simulating runoffs not only during average years but during flood years and drought years, as well.

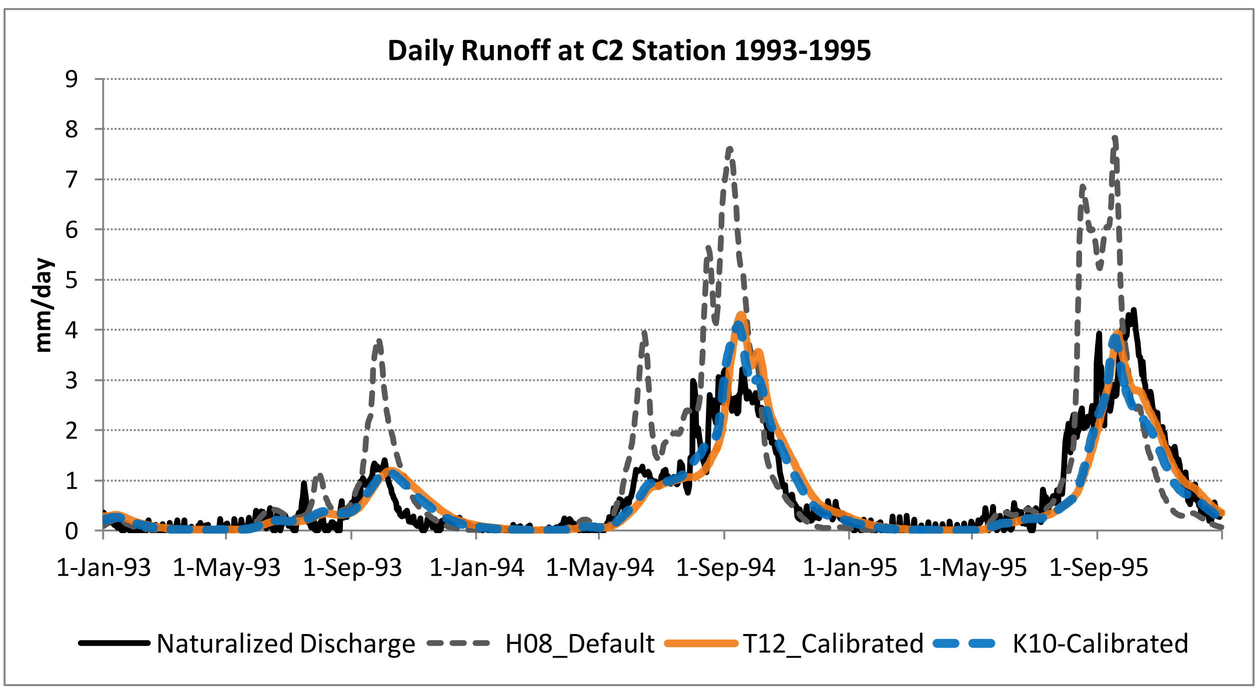


Figure 3.11 Daily discharge at C2 Station from 1993-1995 using default and calibrated parameter sets. A big difference could be seen between the default and calibrated simulation runs. After calibration, the shape of the hydrograph, peak magnitude, and peak timing could be simulated much better.

Table 3.6 Comparison of peak discharge magnitude and timing using default and calibrated parameter simulation runs. Values in parenthesis are % error in discharge and difference in days of the occurrence of the peak with respect to the naturalized discharge.

	Naturalized	Default	K10-Calibrated	T12-Calibrated
1993 Peak Runoff	1.41 mm	3.88 mm (175%)	1.16 mm (18%)	1.19 mm (16%)
1994 Peak Runoff	3.27 mm	7.61 mm (135%)	4.04 mm (24%)	4.30 mm (31%)
1995 Peak Runoff	4.40mm	7.83 mm (78%)	3.83 mm (13%)	3.93 mm (11%)
1993 Peak Date	Oct 3	Sep 27 (6 days)	Oct 6 (3 days)	Oct 10 (7 days)
1994 Peak Date	Sep 22	Sep 6 (16 days)	Sep 12 (10 days)	Sep 17 (5 days)
1995 Peak Date	Oct 6	Sep 18 (18 days)	Sep 17 (19 days)	Sep 20 (16 days)

To quantify the efficiency of the calibrated simulation results, the annual runoff values, NSE, and percent bias, *PBIAS* computed using equation 3.11 [Gupta, etal , 1999], for the monthly and annual hydrographs are calculated and shown in Table 3.7. It could be observed that the NSE coefficients are all greater than 75% while the PBIAS are all below 10%. According to model evaluation guideline [Moriasi, etal, 2007], such performance could be classified as "*very good*".

$$PBIAS = \frac{\sum_{t=1}^{T}(Q_m - Q_o)\times 100}{\sum_{t=1}^{T} Q_o} \quad (3.11)$$

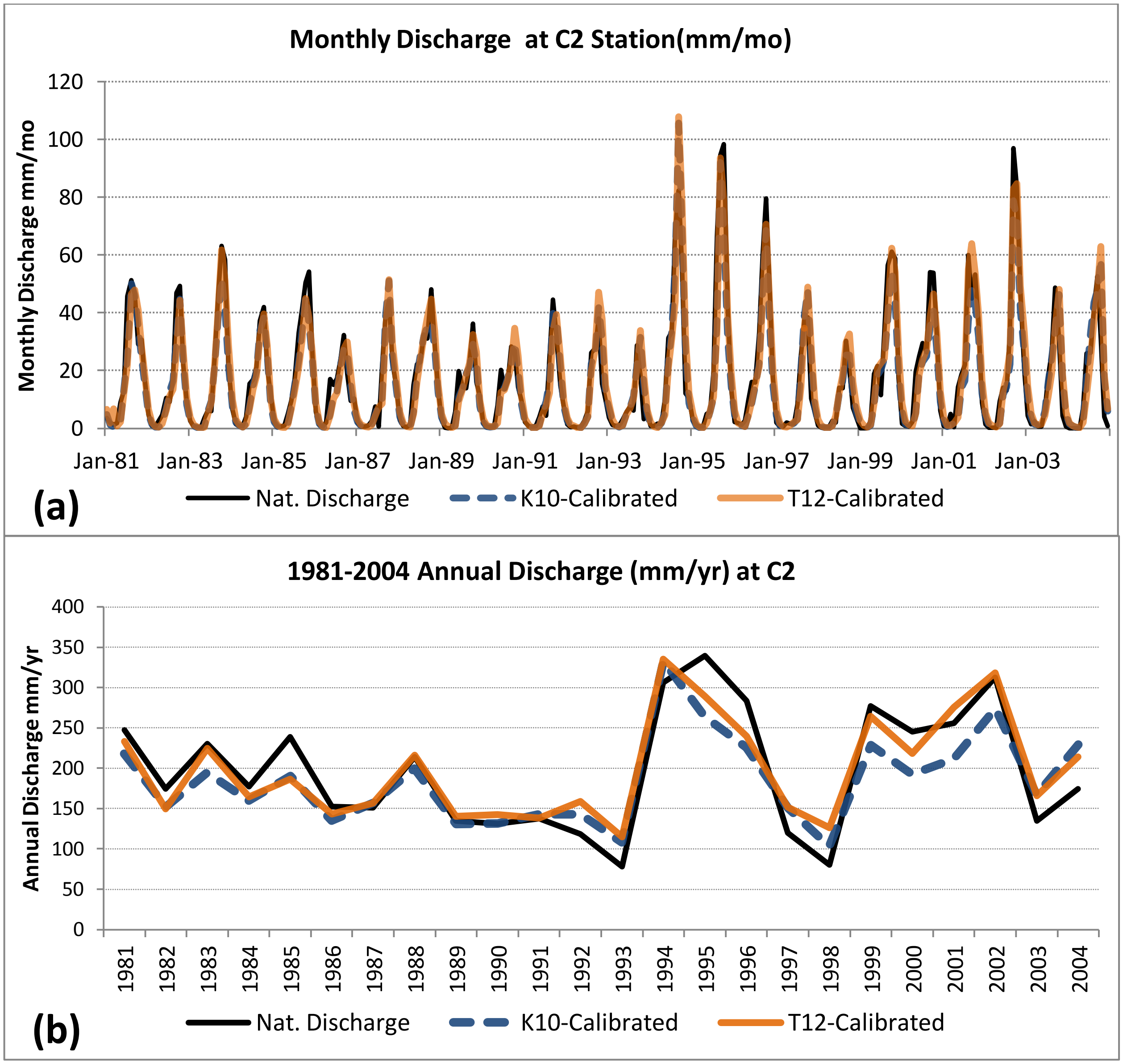


Figure 3.12 (a) and (b): Monthly and annual discharge, respectively, at C2 Station from 1981-2004 using calibrated parameters. The monthly and annual discharge corresponded well with the naturalized observed.

To summarize the results of the calibrated simulation runs from 1981-2004, it could be said that this research had succeeded in calibrating H08 at C2 Station. The calibrated model could now be used to reproduce the historical discharge at C2 Station, which could then be used for analyzing rainfall-runoff-discharge patterns in C2 Station. It could be noted, however, that analysis had been done just at C2 Station, so far. To be able to check the applicability of the calibrated parameter sets in other gauging stations within the CP basin, validation still has to be done.

Table 3.7 Comparison of mean and annual discharge with the observed. It could be seen that the simulated mean annual discharge is within 5% difference with respect to the naturalized.

	Naturalized	K10-Calibrated	T12-Calibrated
Mean annual precipitation	1138.61 mm	1005.24 mm	1138.61 mm
Mean annual runoff	196.39 mm	184.97 mm	198.60 mm
Annual runoff NSE		76.33%	85.33%
Annual PBIAS		-5.82%	0.038%
Monthly runoff NSE		84.34%	80.72%
Monthly PBIAS		-9.02%	1.12%

3.6 Validation of calibrated parameters

This section discusses the methodology and results of validation of the calibrated parameters at C2 Station. The current setting of H08 assumes that the parameters calibrated and set previously apply to all the grid cells within the CP basin. In the physical world, this means that the land cover and soil characteristics are assumed to be the same all over the CP river basin. This assumption is a simplification of the real world, and thus, has to be checked if it does not significantly affect simulations.

Ideally, validation should be done in as much number of hydrological stations as possible. However, most of the hydrological stations available for comparison were found to be unfit for mainly because the catchment area upstream of these stations considered by the model do not match or are not within 10% error with respect to that of the observed, even after adjusting the longitude and latitude to that of adjacent grid cells. This could have been addressed by a better river flow map to be used by the model. However, due to time limitation, this revised river flow map had not been completed by the author.

Thus, in this study, validation had been done in four stations upstream of the C2 Station. Though this number may seem to be quite small, it should be noted that the stations chosen for validation could be said to be representative of the four main tributaries and sub catchment basins of the CP river basin. These four stations – Bhumibol Reservoir in Ping River, Sirikit Reservoir in Nan River, W4.A Station in Wang River, and Y6 Station in Yom River – are all located at the downstream of the respective river basins. It could be assumed then, that their land surface and soil characteristics could be taken as representative of their respective river basins. Figure 3.13 shows the position of the four stations in the CP river basin, while Table 3.8 shows the positions and catchment areas of the four stations in the real world as well as in K10 and K10R maps (H08 'world').

Table 3.8 Location and catchment area of the stations used for validation. Values in parentheses are %error with respect to the observed.

	Bhumibol	Sirikit	W4.A	Y6
Observed longitude	99.02	100.55	99.10	99.79
Observed latitude	17.25	17.77	17.21	17.43
Observed catchment area	26400	13130	10493	12769
K10 catchment area (at observed lon and lat)	29294 (10.96%)	17099 (30.23%)	10069 (-4.04%)	326 (-97.44%)
K10 and K10R corrected longitude	99.04	100.63	99.13	99.79
K10 and K10R corrected latitude	17.29	17.88	17.13	17.54
K10 catchment area (at corrected lon and lat)	28967 (9.72%)	14169 (7.92%)	10233 (-2.48%)	12988 (1.72%)
K10R catchment area (at corrected lon and lat)	28478 (7.87%)	14657 (11.63%)	11126 (6.03%)	13802 (8.09%)

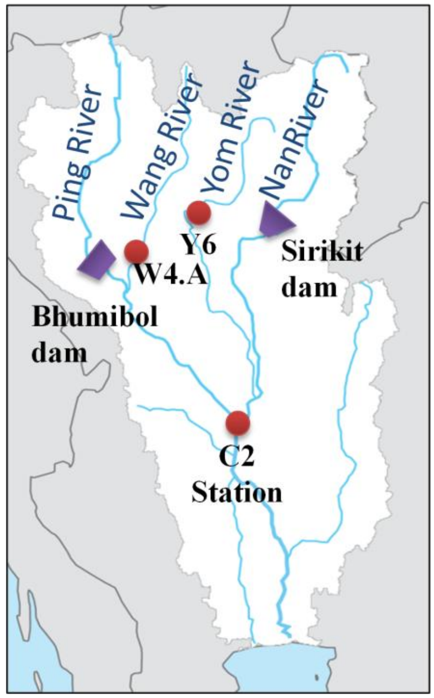


Figure 3.13 Positions of Y6, W4.A, Bhumibol, and Sirikit Stations

Figure 3.14 shows the monthly runoff while Figure 3.15 shows the annual runoff at the four stations used for validation. For the Bhumibol and Sirikit Reservoir, the inflow to the dam was used for comparison with the respective simulated river discharge. Table 3.9 shows the NSE and PBIAS at each station.

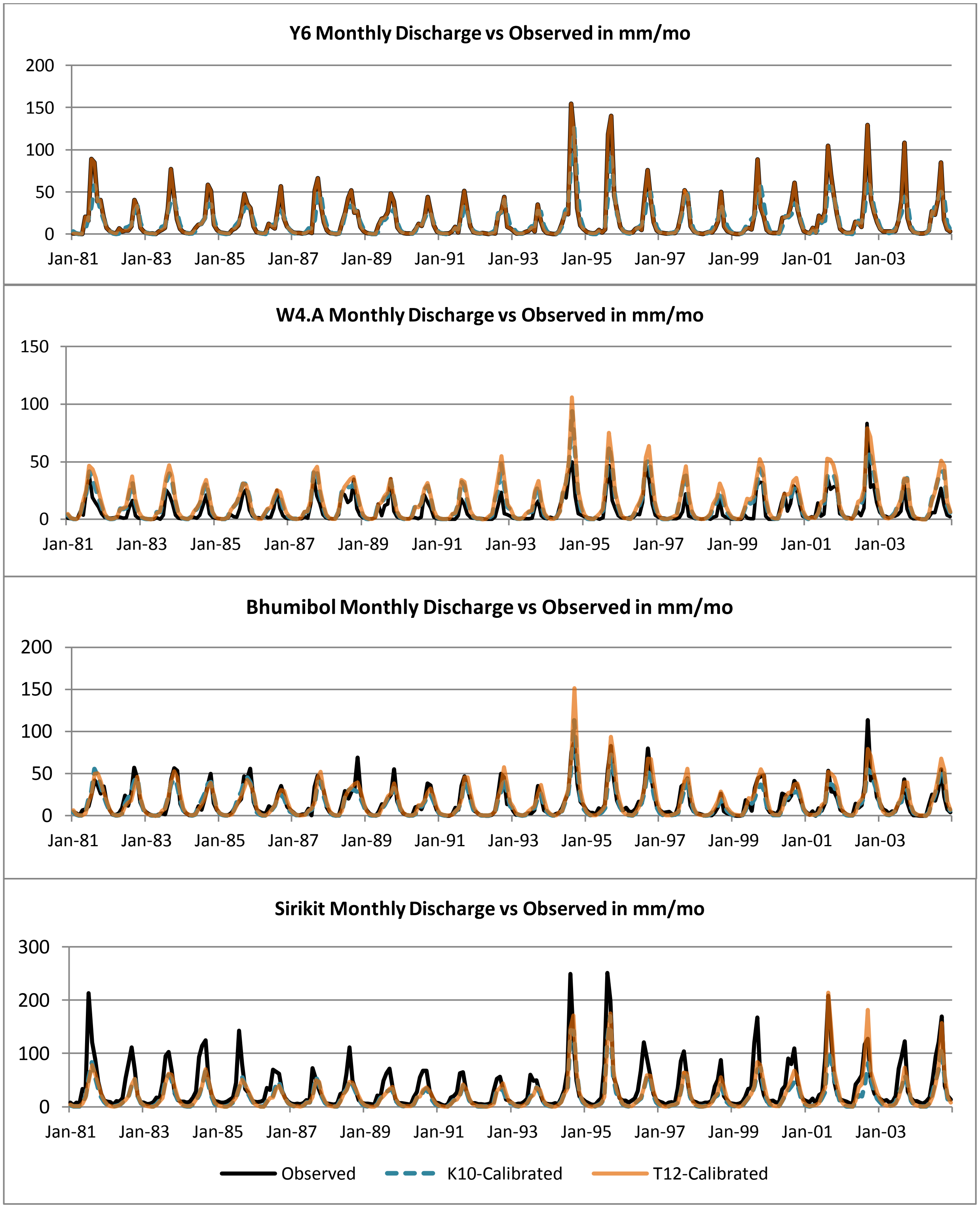


Figure 3.14: Observed and simulated monthly discharge at Y6, W4.A, Bhumibol, and Sirikit Stations from 1981-2004 using calibrated parameters.

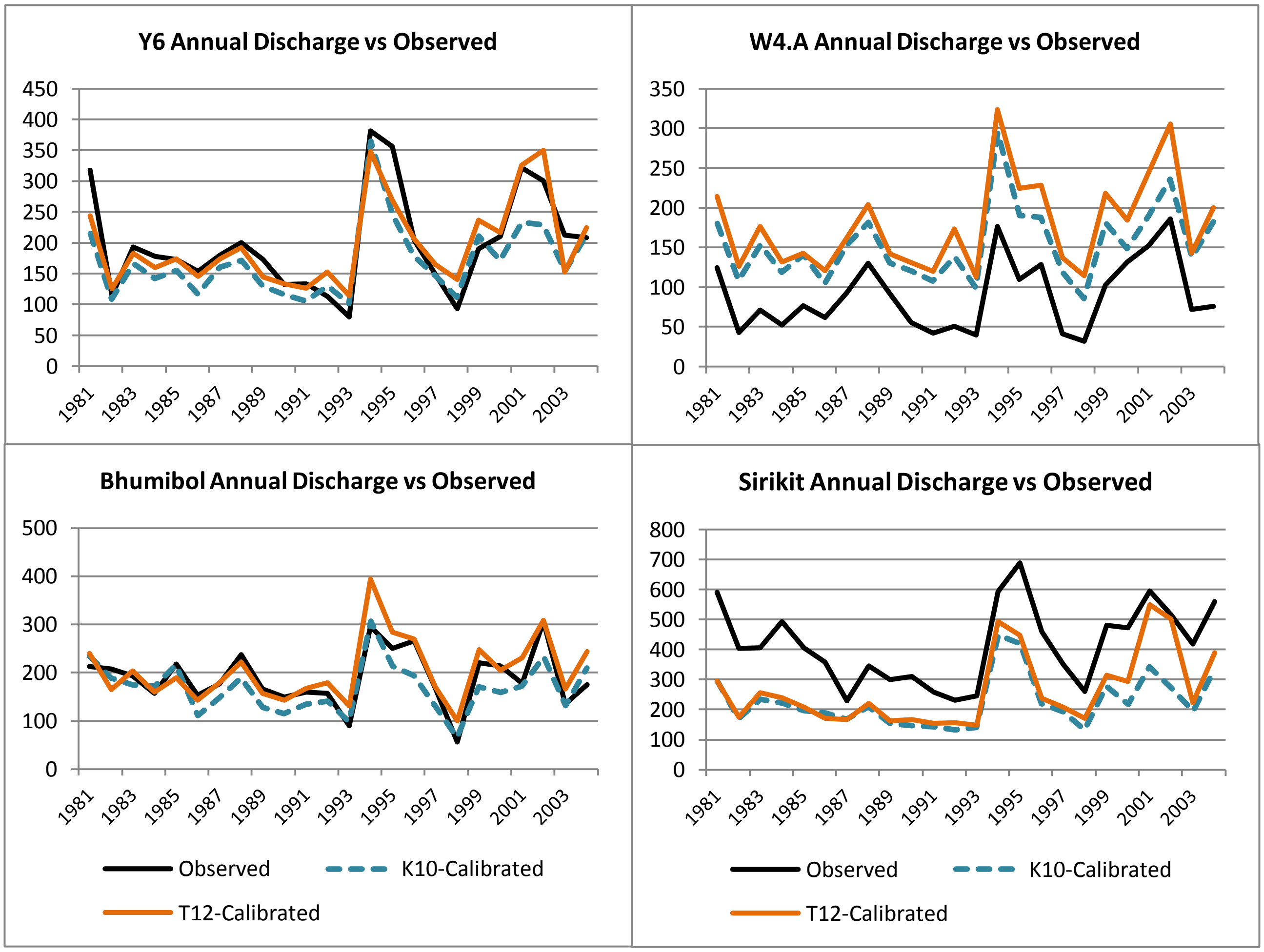


Figure 3.15 Observed and simulated annual discharge (in mm/year) at Y6, W4.A, Bhumibol, and Sirikit Stations from 1981-2004 using calibrated parameters.

Examination of the monthly and annual runoff hydrographs indicate that results are generally good for Bhumibol Reservoir and Y6 Station. This means that the same parameter set could possibly be used in the Ping and Yom River basins. However, it is quite evident from the hydrographs that in both calibrated simulation runs, W4.A is overestimated while Sirikit Reservoir is underestimated. These findings were further confirmed by evaluating the monthly NSE and PBIAS using the modelling evaluation guideline [Moriasi, etal 2007] where monthly stream flow or river discharge simulation with $0.75<NSE\leq1.00$ and $PBIAS<\pm10$ could be rated as "*very good*", $0.65<NSE\leq0.75$

and ±10≤PBIAS<±15 is rated “good”, 0.50<NSE≤0.65 and ±15≤PBIAS<±25 is rated “satisfactory”, and NSE≤0.50 and ±25≤PBIAS is rated “unsatisfactory”.

Table 3.9 Statistical evaluation of results of validation at Bhumibol. Sirikit, W4.A, and Y6 Stations. Values in red indicate unacceptable simulation results at that station.

	Bhumibol	Sirikit	W4.A	Y6
Observed mean annual precipitation (mm/yr)	1088.75	1233.84	1092.4	1114.44
Observed mean annual runoff (mm/yr)	189.14	415.78	89.22	198.46
K10 mean annual precipitation (mm/yr)	992.11	1087.13	934.47	993.72
K10 mean annual runoff (mm/yr)	168.05	226.99	153.71	169.85
T12 mean annual precipitation (mm/yr)	1088.75	1233.84	1092.4	1114.44
T12 mean annual runoff (mm/yr)	204.17	264.51	178.34	195.92
K10 Monthly NSE	80.45%	54.81%	32.06%	73.12%
K10 Monthly PBIAS	-11.15%	-45.41%	72.28%	-14.41%
K10 Annual NSE	61.53%	-137.80%	-141.42%	66.77%
K10 Annual PBIAS	-11.15%	-45.41%	72.28%	-14.41%
Evaluation of performance	Good	Unsatisfactory (Underestimated)	Unsatisfactory (Overestimated)	Good
T12 Monthly NSE	76.22%	59.11%	-13.18%	71.64%
T12 Monthly PBIAS	7.95%	-36.38%	99.88%	-1.28%
T12 Annual NSE	64.06%	-66.38%	-346.80%	80.53%
T12 Annual PBIAS	7.95%	-36.38%	99.88%	-1.28%
Evaluation of performance	Very good	Unsatisfactory (Underestimated)	Unsatisfactory (Overestimated)	Very good

There could be several reasons for the unsatisfactory results in W4.A station and Sirikit Reservoir. One could be due to the big differences in the land cover and/or soil characteristics in the two stations or basins from C2 Station, making the calibrated parameters unfit for simulating discharge in those two stations. Another reason could be the presence of human activities that were unaccounted for in the research. Lastly, it is possible that the observed discharge values have several systematic or unsystematic errors. An official of RID, for example, said that water is being pumped into the Sirikit

Reservoir for water supply, and that there are some difficulties in obtaining reliable data at W4.A station due to occurrence of backflows [initial, unofficial and unpublished findings]. However, as of this writing, there is still no conclusion about the real cause of the unsatisfactory results.

If the sole reason for the unsatisfactory results is the inapplicability of the calibrated parameters to all the stations within CP basin, then, ideally, this could be corrected by calibrating the parameters according to land cover and/or soil characteristics. However, due to time limitations, such procedure had not been done within this research. Addressing this issue is a research work that could be done in the near future.

To summarize this section, the validation of the calibrated parameter sets yielded both good and unsatisfactory results. This means that the current parameter set is expected to produce reliable results in areas near and possibly within the catchment basin of the Bhumibol Reservoir, and Y6 or Yom River, but not in Sirikit Reservoir or W4.A Station.

3.7 Simulated naturalized discharge from 2010-2011

After checking if the calibrated model could reproduce the discharge in the four stations, it is also important to verify if it could give reliable simulations of the "future" naturalized discharge. In this study, it is imperative to verify the capability of the calibrated H08 model to simulate the 2010-2011 river discharge.

Figure 3.16 shows the monthly discharge in mm/mo at C2 Station from 2010-2011. Table 3.10 shows the statistics related to this hydrograph. It should be noted in the 2010-2011 simulation, only one set of data, T12-Y08 (T12 precipitation and Y08 other meteorological factors) was used. In the following graphs, "K10-Calibrated" represents the result of the simulation run using the parameter set calibrated using K10 precipitation rather than the result of simulation using K10 as precipitation input.

K10-Calibrated simulation was included in the graphs and table to illustrate the difference of results between using K10-calibrated parameters and T12-calibrated parameters when using the same input dataset. It is evident from examining the hydrographs that K10-calibrated parameters tend to overestimate the runoff and delay the peak timing. Peak discharge is actually overestimated by almost 50 mm/mo, a value that is quite high and could be misleading if used for forecasting or decision making.

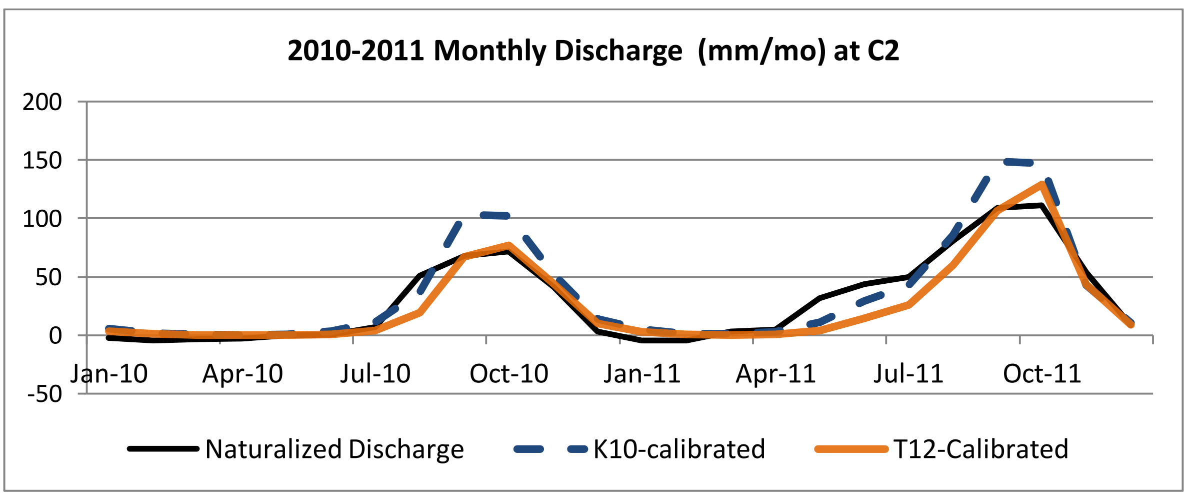


Figure 3.16 Observed and simulated monthly discharge at C2 Station from 2010 - 2011

Checking the NSE and PBIAS at Table 3.10 below, it could be observed that although the NSE coefficient of both simulations could be categorized under "very good" in model performance rating [Moriasi, etal. 2007], because of the high PBIAS values, K10-Calibrated is evaluated as "satisfactory" performance because it is overestimated while T12-Calibrated is evaluated as "good" performance because it is underestimated.

Table 3.10 Statistical evaluation of simulation results from 2010-2011

	Naturalized	K10-Calibrated	T12-Calibrated
Mean annual precipitation	1530.65 mm	1530.65 mm	1530.65 mm
Mean annual discharge	357.99 mm	437.24 mm	311.60
2010 peak	71.73 mm	104.97 mm	77.05 mm
2011 peak	111.43 mm	148.57 mm	129.35 mm
2010 peak month	October	September	October
2011 peak month	October	September	October
Monthly discharge NSE		77.61%	86.43%
Monthly PBIAS		22.20%	-12.91%

Upon examining the hydrographs and statistically evaluating the calibrated model, it could be concluded that the calibrated models have successfully simulated the 2010-2011 discharge. Take note that except for precipitation, the meteorological factors that were used in these simulations were values forecasted for 2010-2011 back in 2008. This proves that given a good meteorological forecast, the calibrated model could actually generate good simulation results of river discharge at C2 Station. Thereby, river managers could be adequately informed and guided on what to do and how to manage their rivers and water resources at least months before peak discharge would occur. The calibrated model could then serve as a good tool for forecasting and decision making.

Chapter 4

Simulation of discharge and estimation of inundated areas using coupled H08 land surface module and CaMa-Flood river routing model

Originally intended for estimating global water resources, H08 uses a river routing model that does not incorporate flood inundation dynamics. The flood discharge may be simulated very well but this information could not be directly translated to measures of flood extent such as flood depth, flood height and inundated areas. Such measurements of flood extent are indispensible in attaining the primary goal of this research which is to use hydrological modeling to aid in decision making for flood mitigation.

This chapter discusses how the outputs from H08, particularly runoff, are coupled with CaMa-Flood, a physically based global river routing model that incorporates floodplain inundation dynamics [Yamazaki, etal 2011]. It briefly describes the newly developed Catchment-Based Macro-scale Floodplain (CaMa-Flood) model, highlighting its advantages over most river routing models. It then proceeds to briefly discuss how the new model was coupled with H08. Like H08, CaMa-Flood is originally set at global average values. A section in this chapter discusses the parameters that were tuned to give accurate simulations in the CP river basin. The result of the coupled H08-CaMa models were then discussed and shown to have not only improved the simulation of naturalized river discharge, but also managed to simulate the inundated area well. The general shape of the simulated inundated areas showed good correspondence with satellite images taken during the 2011 flood event.

4.1 Introduction to CaMa-Flood

Floodplain inundation dynamics are governed by the movement and storage of surface waters at small-scale topography which are difficult to represent in the spatial resolution used by most global river routing models [Yamazaki, etal, 2011]. Catchment-based Macro-scale Floodplain (CaMa-Flood) model is a new river routing model that was developed to describe floodplain inundation dynamics through explicit parameterization of the subgrid-scale topography of a floodplain. This model has improved previous simplifications by describing the relationship between river stage, water volume, and flooded area using subgrid-scale topography.

CaMa-Flood routes runoff generated by a land surface model along a river network map. Fine resolution digital elevation maps (DEM) and flow direction maps were used to derive river networks and subgrid topographic parameters. Aside from river discharge and river storage, it calculates water depth, floodplain water storage, and inundated area for each grid point.

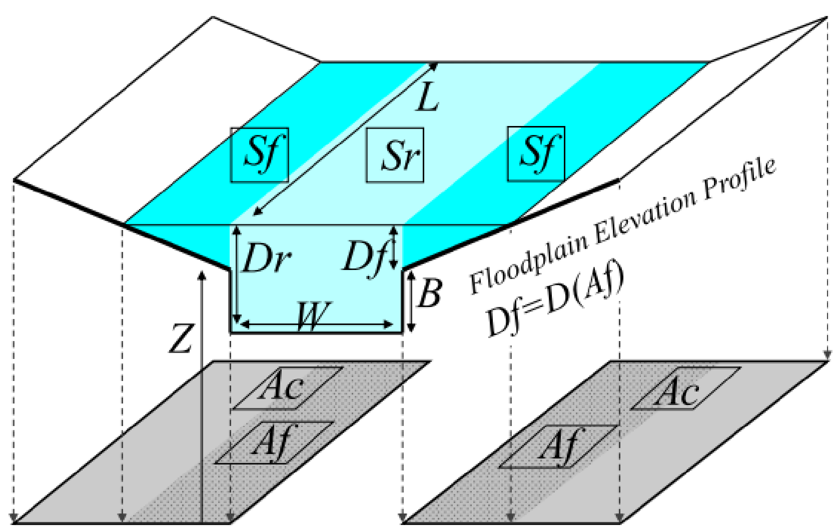


Figure 4.1 Illustration of river channel reservoir and floodplain reservoir assumed in each grid cell in CaMa-Flood. *Illustration adapted from [Yamazaki, et al, 2011]*

Instead of assuming a rectangular river channel at each grid, CaMa-Flood assumes that each grid point has a river channel reservoir and a floodplain reservoir as shown in Figure 4.1. In this figure, L is channel length, W is channel width, B is bank height, Dr is the water depth, Df is the flood water depth which is a function of the flooded area Af, Ac is the unit catchment area, Z is surface altitude. Total water storage S is the sum of river channel storage Sr and floodplain storage Sf. These parameters could be tuned to closely represent river topography in real life.

Aside from utilizing a more explicit representation of subgrid-scale topography, CaMa-Flood also improved the calculation of horizontal water transport. It uses a diffusive wave equation, a simplification of the full on-dimensional St. Venant momentum equation, to calculate horizontal water transport and river depth. Backwater effect in flat river basins is also taken into account through the use of the diffusive wave equation.

4.2 Application of CaMa-Flood to this research

The simulation of the naturalized discharge in the Chao Phraya Basin using H08 is already very good, as had been discussed in the previous chapter. It was also shown that it could be used as an effective tool for flood prediction and forecasting. However, one limitation of the model is that it cannot be used to illustrate the extent of inundation, as the river routing model it is currently using does not explicitly consider floodplain inundation dynamics. As had been discussed in the introduction, CP Basin is highly prone to inundation due to its rivers with low discharge capacity and with gentle slopes. Illustrating the extent of flooding would then be of great impact, if included in this study.

This research addresses this issue by coupling H08 with CaMa-Flood (H08-CaMa). This chapter discusses how H08-CaMa was used to simulate the naturalized discharge and inundation without reservoir operation at CP Basin. Chapter 5 discusses how H08 was coupled with CaMa-Flood to simulate discharge and inundation considering reservoir operation.

Total runoff (Qtot) calculated by H08 was used as input to CaMa-Flood. H08 outputs runoff at a spatial resolution of 5'x5' (approximately 8km) ranging from 97°-102° longitude and 13°-20° latitude (60 grid cells in the x-direction and e84 grid cells in the y-direction), in binary form of big endian sequence. These outputs are available in daily scale with a unit of $kg \cdot m^{-2} \cdot s^{-1}$. On the other hand, CaMa-Flood reads and writes binaries in little endian sequence. Its readily-prepared river network maps of the CP Basin, one with a resolution of 2.5'x2.5' and another with a resolution of 5'x5', both cover 97.5°-102° longitude and 13°-20° latitude, shorter than the H08 outputs by 0.5° in the x-direction. It requires daily runoff input at a unit of mm/day. H08 runoff output must then be converted first for its grid cells to fit in the dimension of the CaMa-Flood river map and for its byte order to be recognizable. A code originally written by Dr. Yamazaki was edited to convert inputs.

After conversion of input data, the parameters of CaMa-Flood have to be tuned in order to increase its accuracy. Parameter tuning will be discussed in detail in the next section. Two means of evaluation were used. First is by comparing discharge at different time scales with the naturalized discharge at C2 Station and with T12-Calibrated simulation results from 1981-2004 and from 2010-2011. Second is by comparing simulated percent of inundated area with 5 minute resolution inundation maps from satellite observations from MODIS. The simulated and observed inundation maps were compared on October 15 and 25 of 2011, dates when the dams were almost at capacity, making the outflow from the dam almost equal to the inflow. Therefore, during these dates, discharge downstream could be assumed to be almost similar to naturalized conditions.

4.3 Calibration of CaMa-Flood parameters and H08 parameters

Initially, simulations using the coupled H08-CaMa were intended to be carried out using the runoff output from T12-Calibrated simulation runs. However, a big discrepancy was observed in the annual discharge of the H08-CaMa simulations and the naturalized observed. To address this, the H08-CaMa needs to be recalibrated. The reason for recalibrating will be discussed in the next subsection, along with the methodology for calibration. The methodology for tuning the CaMa-Flood parameters will be discussed in subsection 4.3.2

4.3.1 Calibration of H08 parameters for coupling with CaMa-Flood

Initially, it was assumed that because water balance should be maintained, the calibrated H08 runoff outputs could be used as input to CaMa-Flood without significantly changing the previously calculated mean annual discharge at any point within the basin. Under this assumption, H08-CaMa simulations were initially carried out using T12-Calibrated H08 runoff. The daily discharge calculated using this set up seemed to fit very well with the naturalized discharge at C2. However, when the annual water balance was checked, the mean annual runoff rate (mm/yr=mean annual discharge/catchment area) which was expected to be approximately 198mm/yr, the value calculated using T12-Calibrated H08 simulation, was significantly reduced to just 175mm/yr. The discrepancy was too high to be ignored.

What could have caused this big discrepancy? Four possible reasons mainly due to the differences between the CaMa-Flood and the river model currently being used by H08 (simply referred to as H08 in the next paragraphs) were identified.

First, the calculation of river discharge differs between the two models. H08 assumes constant flow velocity of 0.5m/s across the basin and water flows along virtual river elements which are depicted as straight lines that do not have any cross-sectional component. CaMa-Flood calculates velocity as a function of Manning's coefficient, water depth, and water surface slope. Water flows along a channel with a cross-section shown in Figure 4.1. Because H08 does not consider floodplain storage and does not consider cross-sectional components, during flood seasons, large volumes of water would be directly discharged to the downstream cell. On the other hand, for the same volume of water, water would spread towards the floodplain in CaMa-Flood during flood season, thereby decreasing the water depth. This would have decreased the flow velocity and the cross-sectional area (assumed to be equal to the water depth multiplied by the river width in CAMA-Flood), thereby decreasing the discharge Q=Av to a certain extent.

Second, the discrepancy could be due to the treatment of flood water. Related to the previous argument, because H08 lacks cross-sectional components, it does not spatially recognize flooding. On the other hand, flood water is temporarily stored in the floodplain storage of CaMa-Flood. For the same volume of total runoff at a certain time increment, discharge calculated by CaMa-Flood will be lower than H08 due to the temporary flood storage. This was verified by drastically changing the parameters of CaMa-Flood to increase the H08-CaMA discharge. Doing so increases the capacity of the river channel reservoir and thereby decreases the flood water. This resulted to almost zero inundation during the months when there was severe inundation.

Third, H08 assumes that water always flow towards the downstream grid cell at the same velocity, regardless of the conditions downstream. On the other hand, velocity in CaMa-Flood is affected by the velocity downstream, the dynamics of which is dictated by the differences in surface elevation in the grid cell and the downstream cell considered in the calculation of effective water depth. Effective water depth, H adjusts when the surface water elevation is higher at the downstream grid cell or when backflow occurs. This means that in CaMa-Flood, water may flow backwards or it may decrease the velocity of some grid cells upstream when the water level downstream is too high. Again, this could affect the calculated river discharge.

Lastly, the river network maps for CP Basin used by the models are different. This is evident in the different catchment area calculated by the two models at the same point and in the different shape of the network of rivers. For example, the catchment basin of C2 in the K10R map is 119,839.3 km^2, whereas it is just 110,202km^2 in the map used by CaMa-Flood. Some water routed towards C2 in the H08 river simulation using K10R map may have been routed elsewhere outside the catchment basin of C2 by the different river network in the CaMa-Flood simulation.

These arguments are based on the analysis between the H08 and CaMa-Flood, as described in the full paper and documentation of the two models. However, due to time limitations, the correctness of these arguments have not been checked by investigating the calculated grid by grid discharge, velocity, and storage simulated by each model. Nevertheless, because the assumptions of CaMa-Flood are more realistic and its river flow map more accurate, it is assumed that the H08-CaMa (runoff calculated by H08, river routing calculated by CaMa-Flood) will give more realistic representation than H08 alone, if proper adjustments would be made.

Based on the second argument above, it is assumed that the current T12-Calibrated parameters would result to zero inundation in H08-CaMa. Therefore, H08-CaMa has to be recalibrated.

Adjusting both the H08 and CaMa-Flood parameters for every simulation run would be tedious and complicated. An initial good guess of parameter sets for each model was set first. For H08, T12-Calibrated parameter set was used as the initial good guess because the H08-CaMa simulation at this parameter set reproduces the shape of the hydrograph well. There is just a need to adjust the total runoff volume. For CaMa-Flood, parameter *W* was tuned first according to the methodology in the next section, using the initial H08-CaMa simulation. Parameter *B* was then tuned to give a realistic shape of the flooded area. The parameters of CaMa-Flood were then temporarily fixed, and then H08 parameters were calibrated, this time evaluating the discharge from the coupled H08-CaMa.

Since the T12-Calibrated parameters result to underestimation in H08-CaMa, the four parameters have to be adjusted to increase the runoff. The methodology and evaluation parameters used for calibrating the coupled H08-CaMa are similar to that in section 3.4.3 in the previous chapter. The soil depth was lowered in increments of 0.5m first to get a NSE coefficient higher than 80% in both the annual and monthly runoff rate values and to get a value of annual runoff rate close to 196mm/yr. C_D was not readjusted because the current value of 0.007 seems to be realistic. τ and γ were then adjusted to bring the value of the annual runoff rate close to that of the observed and to get the best possible daily, monthly, and annual hydrographs.

After calibration, the best parameter set for H08-CaMa was found to be: C_D = 0.007, SD = 2.50m, τ = 140 days, and γ = 2.40. Notice that the values of these parameters are quite close to that of K10 and T12 parameter sets.

4.3.2 Tuning of CaMa-Flood parameters

Three parameters of CaMa-Flood that were empirically determined, originally, have been tuned in this research – the river channel width, bank height, and Manning's roughness coefficient. The channel width and bank height were expressed as a function of historical monthly discharge written in equations 4.1 and 4.2, respectively, where R_{up} is the 30-day runoff from upstream of the cell.

$$W = \max\left[1.00 \times R_{up}^{0.7}, 10.0\right] \tag{4.1}$$

$$B = \max\,[0.35 \times R_{up}^{0.5}, 1.00] \tag{4.2}$$

B and W primarily affect the river storage which affects the effective water depth. Increasing Manning's coefficient decreases the flow velocity. Consequently, all of these parameters significantly affect river discharge and flooded area. Generally, an increase in bank height increases the peak discharge, results to earlier peaking, increases perturbations in the hydrograph, and lowers the flooded area. Increasing the channel width has the same effects as increasing the bank height. On the other hand, increasing the Manning's coefficient will have the opposite effects of increasing channel width or bank height. For a more detailed discussion on the sensitivity of the river discharge and inundation to the parameters, please refer to the original paper [Yamazaki, et al 2011].

The bank height and channel width were altered and calibrated by multiplying factors a, b, c, d, e, and f to the original equations in 4.1 and 4.2 as shown in equation 4.3.

$$W = \max\left[a * 1.00 \times R_{up}^{0.7*b}, 10.0 * c\right] \quad (4.3)$$

$$B = \max\left[d * 0.35 \times R_{up}^{0.5*e}, 1.00 * f\right]$$

Parameter W was tuned first because there is a set of data available for verifying the correctness of the calculated river width values. Observed river width data at 25 gauging stations in the CP Basin, kindly provided by Mr. Adisorn Champathong and his colleagues from RID, were used for comparison with the simulated. Since it is difficult to attain a good correspondence in river width in all the stations available, the parameter set that gives a 20% or less error in river width in more than 50% of the gauging stations and at the same time minimizes the RMSE across the data set was chosen.

Tuning parameter B is more difficult because it is difficult to judge the effective bank height from the river profiles available. Thus, B was tuned by changing d and e while keeping the factors of W constant, and then running a simulation for years 2010 and 2011. Only d and e were changed because initial calibration trials showed that changing both c and f does not significantly affect the discharge and inundation. Thus, to minimize the number of factors being changed, both were set at a very low value of 0.1 first.

It was also found that changing *W* and *B* does not significantly affect the annual water balance. Thus, in tuning parameter *B*, comparison with discharge and inundation was done on daily and monthly scales. The "best" values for *B* were determined by graphically evaluating the shape of the hydrographs, particularly the slopes in monthly hydrographs, the peak discharge, peak timing, perturbations in the hydrograph, and the shape of the inundated area. As in chapter 3, the hydrographs were compared with the naturalized discharge. The inundated area was compared with various satellite images and the MODIS data. Equation 4.4 shows the tuned W and B equations.

$$W = \max\left[\mathbf{16.6} \times R_{up}^{\mathbf{0.35}}, \mathbf{3}\right] \tag{4.3}$$

$$B = \max\left[\mathbf{0.70} \times R_{up}^{\mathbf{0.23}}, \mathbf{0.20}\right]$$

The Manning's coefficient was the last parameter to be calibrated. It was lowered to give enough perturbations in the hydrograph and to shift the peak discharge timing nearer to that of the naturalized. The final Manning's coefficient value used for this research is 0.024, lower by 20 percent than the default value of 0.03.

4.4 Simulated naturalized river discharge and inundation

The figures below show the results of the coupled H08-CaMa simulation run from 1981-2004 and from 2010-2011. Results of the T12-Calibrated simulation from original H08 model were also included in the graphs to show the difference between the results of the two models. In all figures, it could be seen that the pure H08, T12-Calibrated simulation is quite at par with the coupled H08-CaMa simulation.

Daily hydrographs from 1993-1995 show that the H08-CaMa simulation reproduces the fluctuations and the hydrograph shape much better than T12-Calibrated. Table 4.1 shows that H08-CaMa also simulates the peak timing and peak discharge from 1993-1995 better than T12-Calibrated, except for the peak magnitude in 1995. The peak timing difference between simulated and naturalized was greatly reduced which is now just 7 days at the most. The H08-CaMa is better in almost all aspects, yet it still overestimates in 1994 and underestimates in 1995.

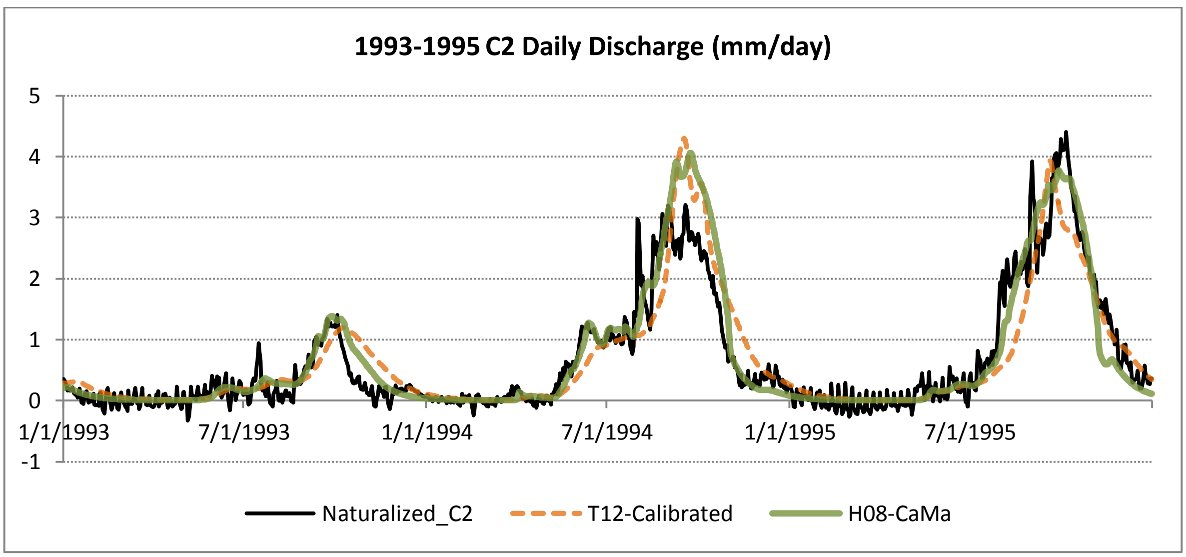


Figure 4.2 Graph of daily discharge at C2 showing that H08-CaMa simulation fits well with the naturalized discharge. Peak timing and peak discharge were also generally improved.

Table 4.1 Comparison of peak magnitude and peak timing of T12-Calibrated and H08-CaMa simulations with the naturalized discharge from 1993-1995

	Naturalized	T12-Calibrated	H08-CaMa
1993 Peak Runoff	1.41 mm	1.19 mm (16%)	1.38 mm (2.13%)
1994 Peak Runoff	3.27 mm	4.30 mm (31%)	4.06 mm (19.46%)
1995 Peak Runoff	4.40mm	3.93 mm (11%)	3.78 mm (14%)
1993 Peak Date	Oct 3	Oct 10 (7 days)	Sep 29 (4 days)
1994 Peak Date	Sep 22	Sep 17 (5 days)	Sep 23 (1 day)
1995 Peak Date	Oct 6	Sep 20 (16 days)	Sep 29 (7 days)

The monthly discharge shown in Figure 4.3 also shows good correspondence with the naturalized discharge. The difference between T12-Calibrated and H08-CaMa is difficult to see from the hydrographs. Figure 4.4 illustrates the difference in the goodness of fit with the naturalized between the two simulations. This graph shows that H08-CaMa has a much better fit with an R^2 value of 91.23% and with its trend line almost identical with the y=x line. Table 4.2 further illustrates the evaluation statistics related to both monthly and annual discharge simulations.

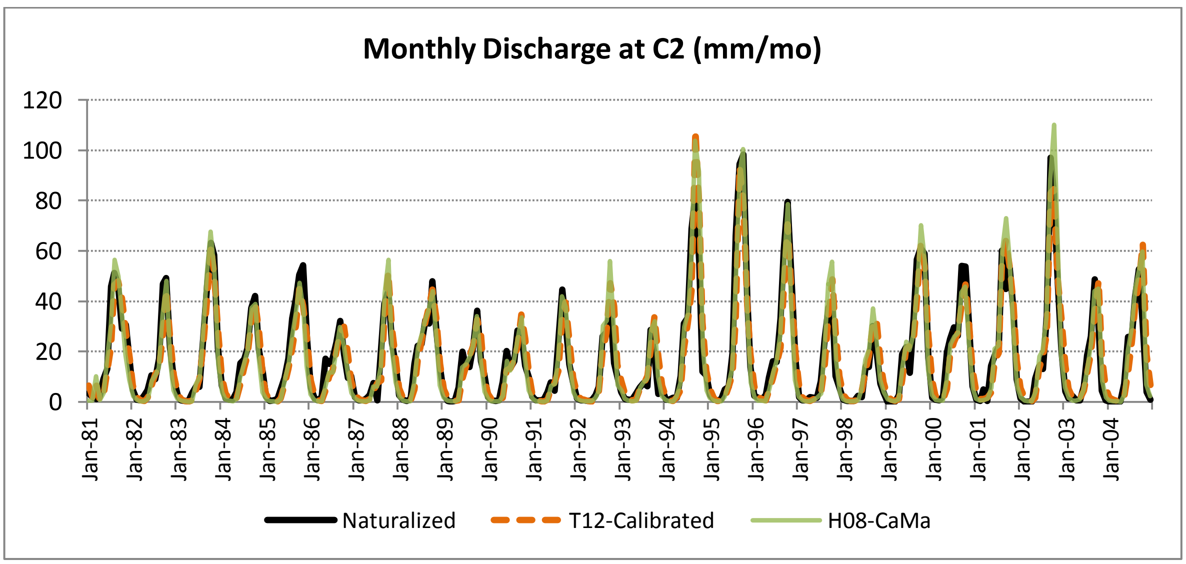


Figure 4.3 Comparison of monthly discharge from 1981-2004 simulated using H08-CaMa with the naturalized discharge and T12-Calibrated.

The annual hydrograph shown in Figure 4.5 does not show much improvement as compared with T12-Calibrated. Years 1994 and 2002 were overestimated by more than almost 50mm by H08-CaMa. Table 4.3 shows that the NSE of T12-Calibrated in the annual simulation is slightly higher than that of H08-CaMa. However, annual runoff rate of H08-CaMa is quite closer to the observed and is also less biased (less than 1%), as could be seen in the Table 4.2.

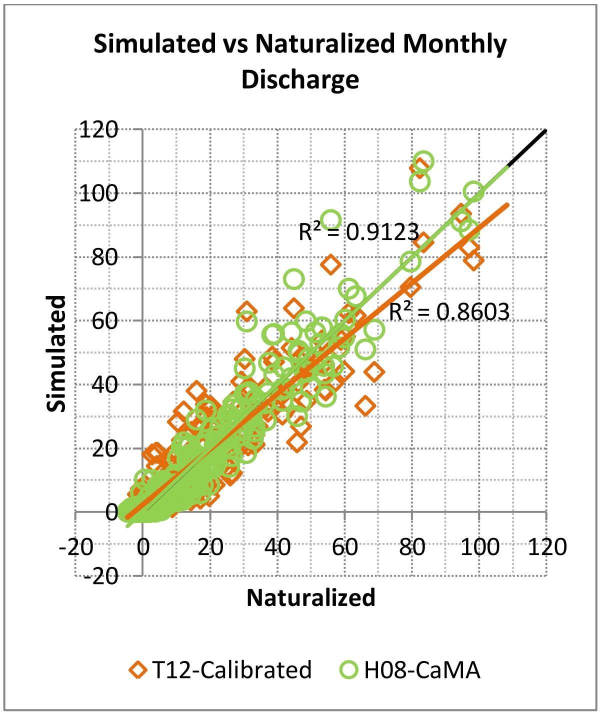


Figure 4.4 Illustration of the goodness of fit of T12-Calibrated and H08-CaMa simulation of monthly discharge. Its trend line lies almost exactly on the y=x line.

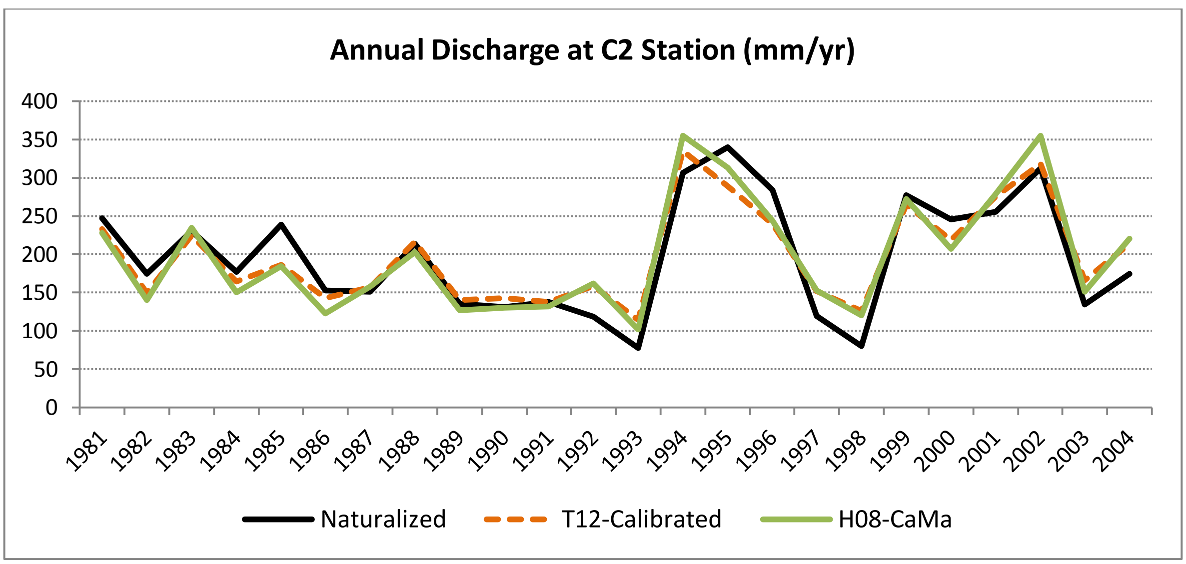


Figure 4.5 Comparison of annual discharge simulated using H08-CaMa with the naturalized discharge and T12-Calibrated.

Table 4.2 Evaluation statistics related to the monthly and annual hydrographs from 1981-2004 of T12-Calibrated and H08-CaMa simulation

	Naturalized	T12-Calibrated	H08-CaMa
Mean annual runoff rate	196.39 mm	198.60 mm	197.96 mm
Annual runoff NSE		85.33%	82.97%
Annual PBIAS		1.12%	0.59%
Monthly runoff NSE		80.72%	90.43%
Monthly PBIAS		1.12%	0.59%

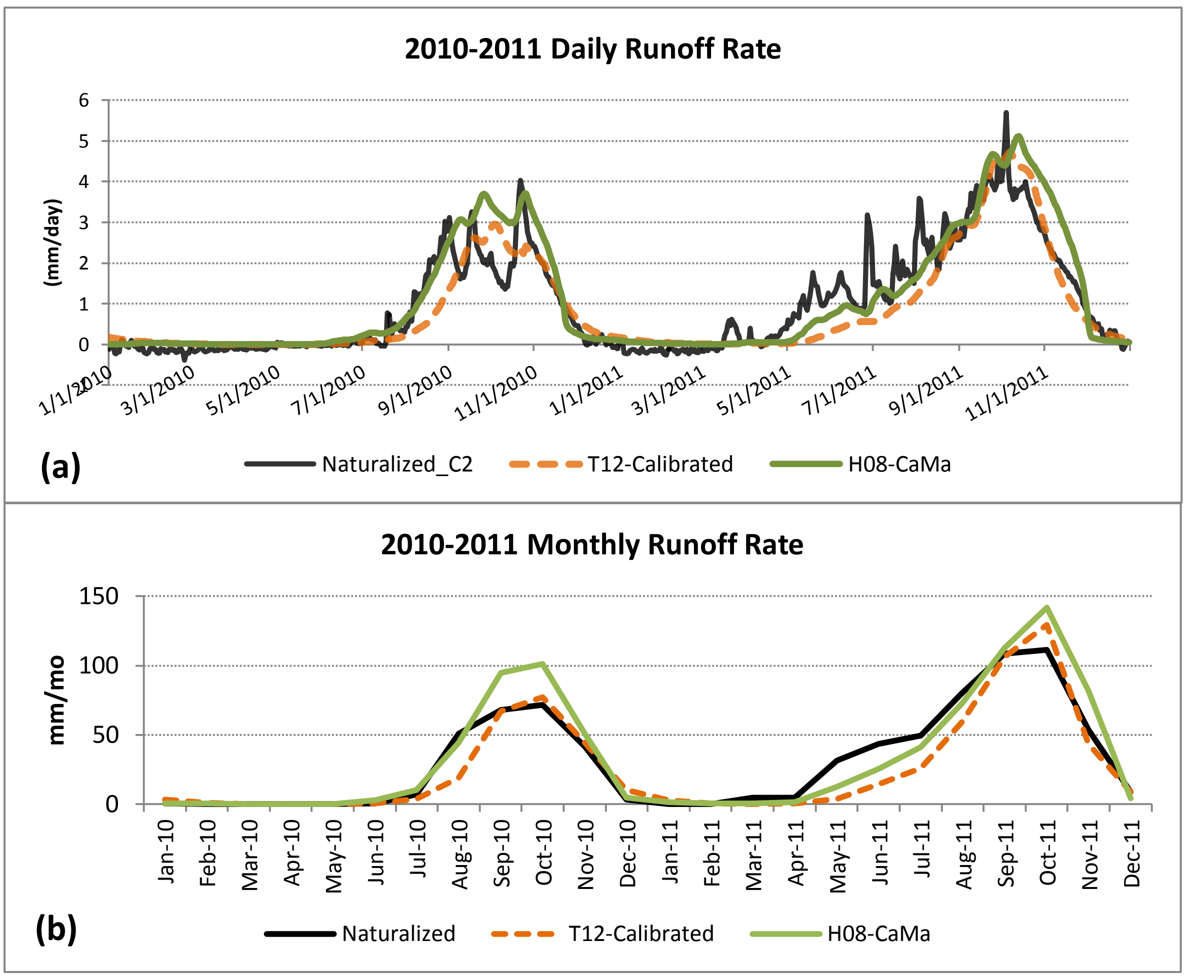


Figure 4.6 (a) and (b) Comparison of monthly discharge from 2010-2011 simulated using H08-CaMa with the naturalized discharge and T12-Calibrated.

Figures 4.6 (a) and (b) show the simulation result for 2010-2011. CaMa-H08 seems to simulate the naturalized discharge better than T12-Calibrated in the daily scale. The table (Table 4.3) of evaluation statistics confirms this as the peak of H08-CaMa is nearer to the naturalized in both years and the peak timing difference is within 10 days. However, the monthly hydrograph shows that H08-CaMa overestimates the 2010 and 2011 monthly peaks by 41.25% and 27%, respectively. However, Table 4.3 shows that overall, H08-CaMa is positively biased by just 12.93%. With a daily and monthly NSE values greater than 80%, H08-CaMa could still be evaluated to have good performance [Moriasi, et al 2007] in simulating the naturalized discharge.

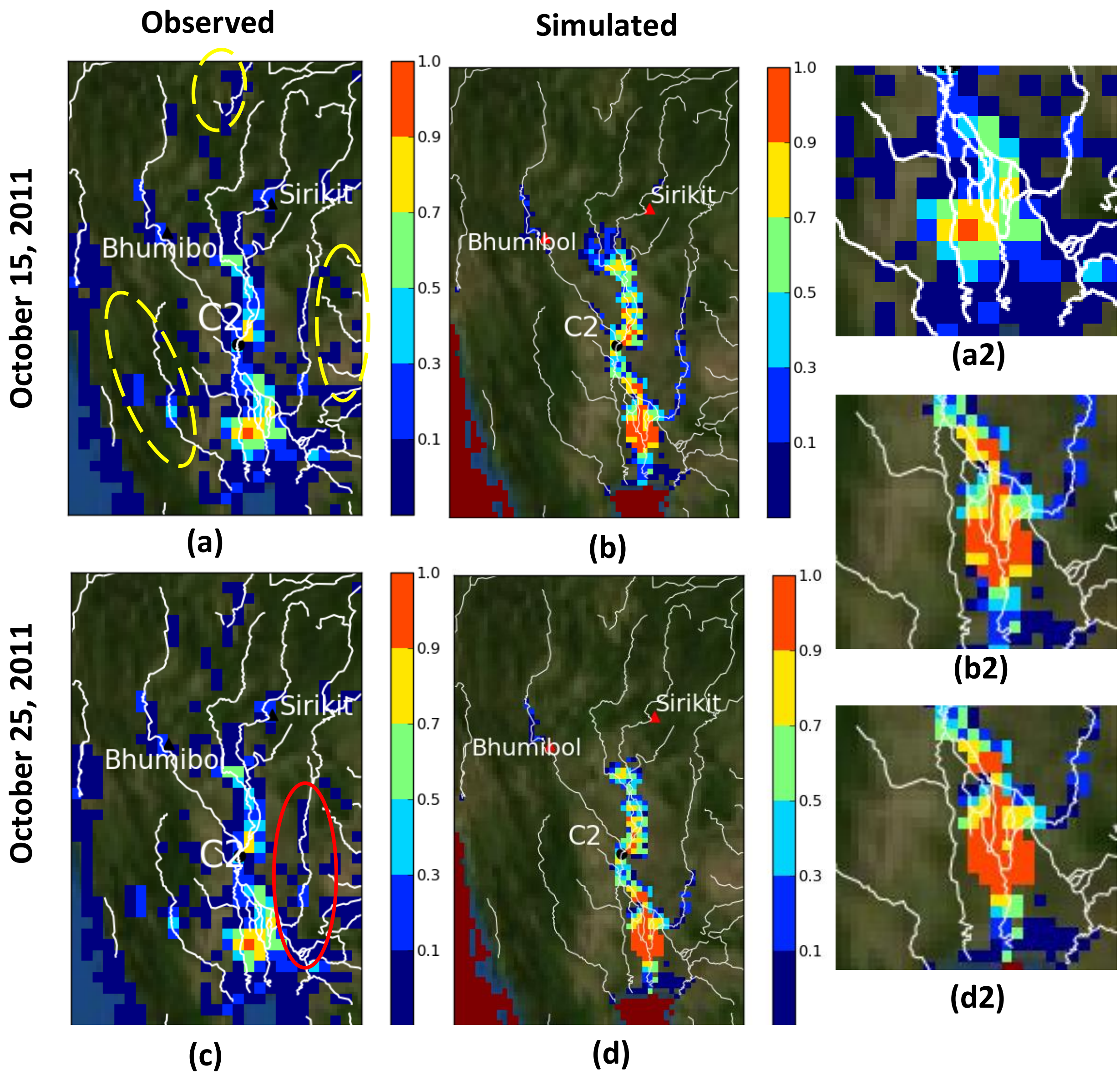
Table 4.3 Evaluation statistics related to the daily and monthly hydrographs from 2010-2011 of T12-Calibrated and H08-CaMa simulation

	Naturalized	T12-Calibrated	H08-CaMa
2010 Daily Peak Runoff	4.02 mm	2.96 mm (-26%)	3.72 mm (-7.46%)
2011 Peak Runoff (Daily)	5.69 mm	4.59 mm (-19.33%)	5.12 mm (-10.02%)
2010 Peak Runoff (Monthly)	71.73 mm	77.05 mm (7.42%)	101.32 mm (41.25%)
2011 Peak Runoff (Monthly)	111.52 mm	129.35 mm (15.99%)	141.63 mm (27%)
2010 Peak Date	Oct 22	Oct 4 (18 days)	Oct 25 (3 days)
2011 Peak Date	Oct 4	Sep 29 (5 days)	Oct 13 (9 days)
NSE-Daily		80.11%	80.30%
NSE-Monthly		86.43%	86.02%
PBIAS		-12.91%	12.93%

The result of the simulation of inundation on is illustrated in Figures 4.7 (b) and 4.7 (d), percent of flooded area on October 15 and October 25, 2011, respectively. These maps were created by dividing the simulated flooded area calculated by H08-CaMa by the area of the corresponding grid cell. These maps were compared with Figures 4.7 (a) and 4.7 (c), the observed percent of flooded area from MODIS satellite observations. Some inundated areas in the northern part and the south-western part shown in the observed maps encircled with yellow dashed lines are actually outside the bounds and were masked out in H08 as they are not within the CP Basin. Ignoring these inundated areas, it could be observed that the simulation results could predict the general shape of the inundated area along the CP Basin well. However, it could be observed that currently, H08-CaMa overestimates the extent of flooded area in most parts.

The accuracy of the temporal change in inundated area is still difficult to verify as of this moment because the observed data is available on 10-day intervals only and as could be seen in the figures below, the difference in inundated area in the two pictures are not so evident due to its quite coarse resolution.

To conclude this chapter, it could be said that the objective of illustrating the extent of flooding with a model that could simulate naturalized discharge well, has been achieved by using the coupled H08-CaMa model. This coupled model could actually be used for understanding rainfall-inundation patterns in the past and in the future. It could also be further applied to land use planning and as basis of flood mitigation plans.



Figures 4.7 Observed and simulated percent of area flooded on October 15 and 25, 2011. (a) and (c) are observed by MODIS while (b) and (d) are simulated by H08-CaMa. (a2), (b2) and (d2) are zoomed in versions of a, b, and d for easier reference. The differences between (a) and (c) are hard to see so one part where a decrease in inundated area was observed was encircled in red.

Chapter 5

Simulation of discharge with dam operation at Bhumibol and Sirikit dams

During the onslaught of the massive flooding in Thailand, stories about dam mismanagement have spread around the internet and local news. The two biggest dams released water at the beginning of October due to its critical high water level. People are claiming that flooding could have been mitigated if the dams were managed properly. Is this true? Could the proper dam management significantly reduce the impacts of flooding? In a country where keeping the dam storage low to prevent flood is as important as keeping the dam storage high to prevent losses due to drought, how should "good dam management" be defined?

This chapter helps to answer these questions by incorporating the effects of reservoir operation into the simulation of discharge in the CP Basin. The study focused on the two biggest dams in the CP Basin which affect the discharge downstream significantly – Bhumibol and Sirikit Dams. It begins with a brief discussion of the current and past reservoir operation technique used in the two dams. The historical reservoir operation techniques were used as guides for simplifying the reservoir operation. Two types of simplification were proposed and explored in this study, one fixes release according to season, while the other releases water as a function of storage. The effects of these proposed operation rules to the river discharge and inundation were then examined.

5.1 Reservoir operation in the past

Reservoir operation of the Bhumibol and Sirikit dams in the CP Basin are governed by an upper and lower rule curve as shown in Figure 5.1. These rule curves have been set for each dam based on inflows, storage, and dam operations in the past. The frequency of updating or revising these operation guide curves is unknown.

The basic and *simple* operating rule is, "do not go outside the boundaries of the two lines". However, as could be seen in Figure 5.1, this rule had been broken many times in the past, some of which were due to natural causes such as the drought year of 2010, while some were due to decisions made by the reservoir operation managers.

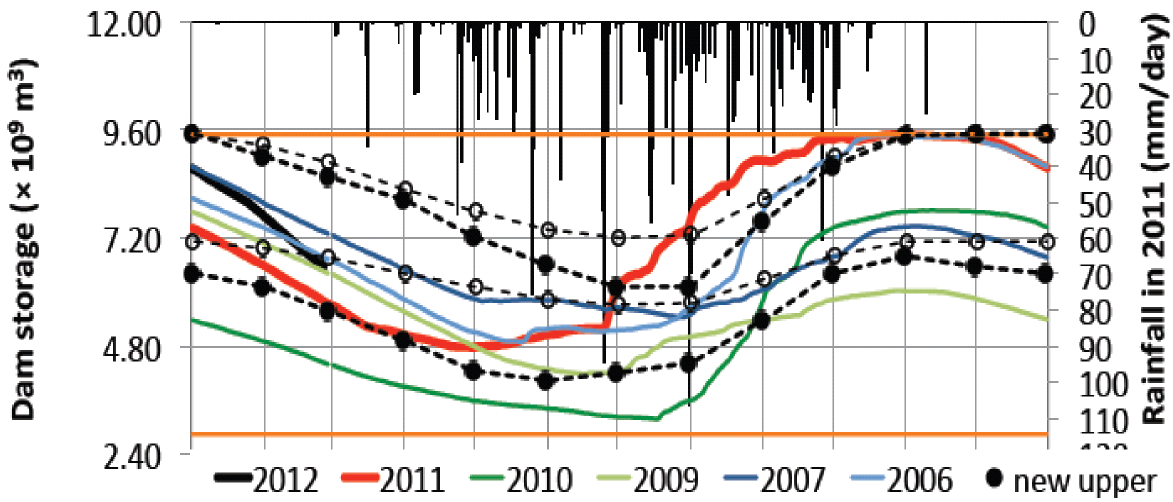


Figure 5.1 Illustration of the actual reservoir operation at the Sirikit Dam which is guided by upper and lower curves. The lines with unfilled, circular markers were used as guides before the 2011 flood while the lines with filled markers are the revised rule curves. *Illustration courtesy of the Thai Royal Irrigation Department.*

What could have driven the reservoir managers to operate outside the upper and lower guide curves? This question could be answered in many ways, but on the hydrological perspective, it is because of the difficulty to predict the upcoming inflows and the effect of these to the storage level not only on the current month but also on the proceeding months. There is a danger of keeping the storage too high that the dam will be easily filled and overflow when an unanticipated heavy precipitation falls. On the other hand, there is a danger of keeping the storage too low that there will be a lack of water for the coming drought season. Both are potentially disastrous to Thailand because the country which is one of the major exporters of rice crops is sensitive to drought. However, due to its topography, it is also flood-prone. These factors are important to understand in conducting studies related to the dam operation in the CP Basin.

5.2 General methodology for simulating discharge with reservoir operation

The methodology for simulating discharge with dam operation was formulated based on the following objectives:

1) Reproduce the historical discharge with the dam operation. Along with the results of the previous chapters, this would enable researchers and planners to study the effects of dam operation on the river discharge separately from other factors.
2) Suggest new operation rules for flood mitigation. This is essential for attaining the main objective of this research.
3) Reduce bias of suggested operation against drought. Thailand is an agricultural country and one of the main purposes of the dam is to supply agricultural water.

To be able to reproduce the historical discharge with dam operation, the historical reservoir operation must be incorporated into the model. This means that a simple algorithm that could represent the reservoir operation in the past should be developed. Thus, as a first step, the hydrological and other factors affecting dam operation such as inflow to the dam, rate of release, and storage capacity, were studied and understood. Patterns of operation related to these factors were identified. It was found that two main types of simplified operating rules could be implemented in the model. These simplified operating rules will be discussed more in detail in the next sections of this chapter. These operation patterns were then coded into the H08 reservoir operation module. River discharge was then simulated from 1981-2004 and 2010-2011, and then compared with the observed (non-naturalized) discharge at C2 station. Simulation of river discharge was done in 3 stages, first using K10-Calibrated parameters, then using T12-Calibrated parameters, both of which were run using the coupled model of H08, and lastly using the calibrated coupled H08-CaMa model.

Next, critical parameters or variables in the simplified operating rules that could significantly affect the river discharge downstream should be identified. These critical parameters were varied and several simulation runs were conducted to see their effect on mitigating flood. The effects of varying these parameters to the dam storage and dam release were also checked, particularly paying attention to dam overflows and dam dry ups. The effect on inundation was also checked from the results of the coupled H08-CaMa model.

Lastly, in the second type of operation, critical parameters for preventing the occurrence of drought were identified. Lower bounds and upper bounds for those critical parameters were identified so as to mitigate the effects of both flood and drought.

For consistency and to avoid confusion between so many runs, only the results of the H08-CaMa will be presented in the following sections. The author assures though that the methodology and the code is readily implementable for use with any of the three calibrated parameters sets and their corresponding input forcing data. Both K10-Calibrated (when used with K10 input forcing) and T12-Calibrated (when used with T12+K10 or T12+Y08) yielded good results when used for simulating the observed discharge.

5.3 Simplification of operation 1: Fixed seasonal release

This simplified operation was mainly conceptualized by Dr. Hanasaki and was just modified and implemented by the author. It is based on the principle that the dam operation could be simplified, first, by setting a constant wet season release and a constant dry season release that would maintain water balance within the dam. Second, to have enough storage for the flood season, this wet season and dry season release should be restricted by an upper guide curve.

5.3.1 Setting the parameters for modeling

Based on the historical inflows to and the observed release from the dam, dry season was identified to be from January to April and the rest of the year was categorized under wet season. The average dry season and wet season release from 1981-2004 were then calculated for both Sirikit and Bhumibol dams. The average dry season release was found to be 231m^3/s and 223m^3/s for Bhumibol and Sirikit, respectively. Average wet season release was calculated to be equal to 108m^3/s and 132m^3/s, respectively.

As have been shown in chapter 3.6, discharge at Bhumibol and Sirikit Dams have biases, particularly in Sirikit Dam, where discharge was greatly underestimated. These biases have to be taken into account in the simulation by adjusting the wet and dry season accordingly. Not adjusting the wet and dry release would lead to too much water being stored or too much water being released which could eventually either dry up the dam or fill it to its capacity. In reality, annual release is not equivalent to the annual inflow due to higher evaporation losses in a dam. Sometimes, this difference in annual release and annual inflow could be simply due to water stored to prevent drought. In reality, outflow/inflow ratio in both Bhumibol and Sirikit dams were found to be 0.94. Since evaporation in dams is not being considered by H08, this outflow/inflow ratio value could also be factored in adjusting the wet and dry season release. However, it was found that most of this 0.06 difference were not due to evaporation losses. It was also found that the amount of water released would still increase or decrease and may not remain constant all the time due to the presence of upper curves and storage capacity limit. Thus, the author decided to just ignore and not factor in the 0.94 outflow/inflow ration in the calculation of release. Table 5.1 shows the adjusted dry and wet release for K10-Calibrated, T12-Calibrated, and H08-CaMa simulations.

Table 5.1 Values of observed and simulated wet and dry season release

	Bhumibol Dam (m^3/s)	Sirikit Dam (m^3/s)
Dry observed release	231	223
Wet observed release	108	132
Observed inflow	159	173
K10-Calibrated inflow	186	187
K10-Calibrated dry season release	270	241
K10-Calibrated wet season release	126	143
Mean annual release	174.3	175.5
T12-Calibrated inflow	184	123
T12-Calibrated dry season release	267	158
T12-Calibrated wet season release	125	94
Mean annual release	172.33	115.33
H08-CaMa-Calibrated inflow	191	130
H08-CaMa-Calibrated dry season release	277	167
H08-CaMa-Calibrated wet season release	129	99
Annual release	178.33	121.67

An upper limit was then coded into the reservoir module which is based on the actual operation upper guide curve (upper line marked with unfilled circles). The lowest point of the actual operation upper guide curve was set as the "target storage" before the heavy precipitation falls. For convenience, the corresponding month when the "target storage" occurs is called the "target date". From January to the target date, a line (green line) was drawn from the storage capacity limit to the "target storage" as shown in Figure 5.2. If ever the computed storage exceeds this upper limit, the reservoir operation code increases the release by an amount that is just enough to bring down the storage to allowed limits. From the target date to the end of December, the dam storage capacity (100% storage) was set as the limit. Again, if computed dam storage exceeds this line, dam release is increased to keep storage within the limit. This situation depicts overflowing of the dam in real life. Since this line (green line) follows the actual old upper guide curve and the fixed dry season and wet season release were set at the historical averages, this dam operation could be expected to give results that are quite close and similar to the historical discharge downstream of the dams and thus will be called Old hereafter (Old operation).

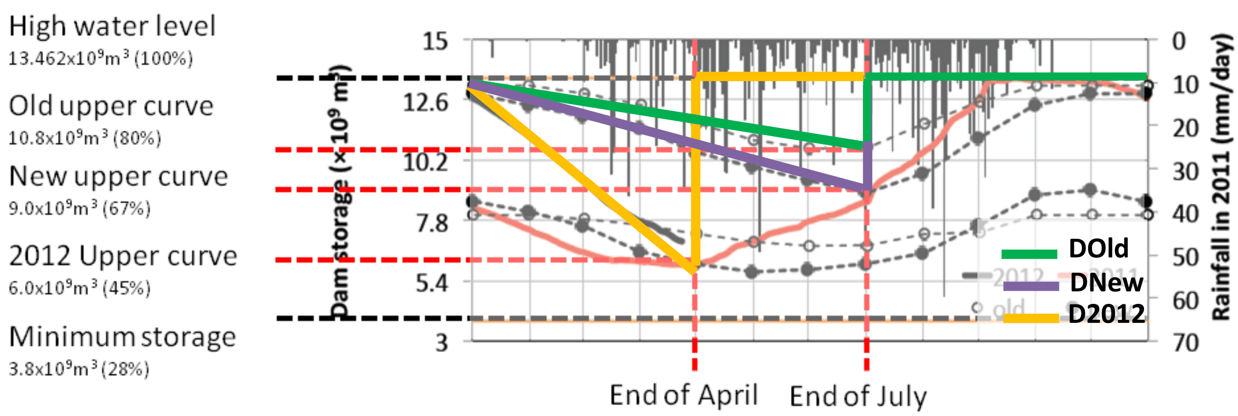


Figure 5.2 Illustration of simplified reservoir operation upper guide curves. The green line simplifies the actual upper guide curve. The violet and yellow lines represent the upper limit curves of alternative dam operating schemes.

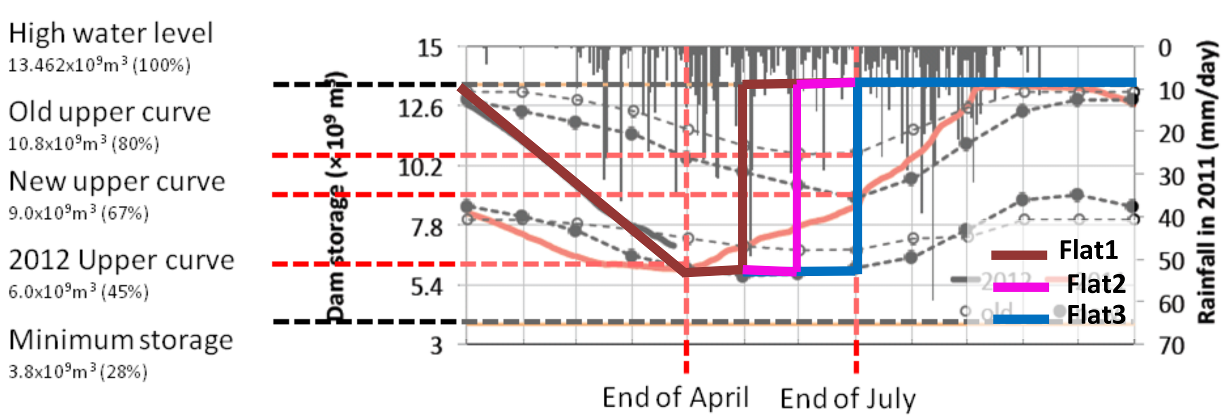


Figure 5.3 Alternative dam operation schemes which allow more room for heavy rainfall storage.

It could be noticed that Old could be defined by four important parameters – (1) rate of dry season release; (2) of wet season release; (3) target storage point; (4) target storage date. Several alternative dam operation schemes could be examined by changing these parameters. The dry season and wet season release could also be varied but due consideration must be given to keeping the water balance closed and meeting the demands for outflow during the wet and dry season. In this study, parameters (3) and (4) were varied first to study the effects of changing the target time and storage level, parameters which might significantly affect the occurrences of flood and drought. The “target point” (approximately 70% of the total dam storage or 50% of the effective storage) and “target date” (end of July) of the violet line (named New) in Figure 5.2 was set at the lowest point of the new upper curve which was proposed after the 2011 big flood. The “target point” and “target date” of the yellow line (named 2012) was set at the targets set by RID for the year 2012. The target point for this line is approximately 45% of the total storage or 25% of the effective storage of the two dams, and the target date is the end of April. The upper guide curves in Figure 5.3 are modified 2012 curves. These modified curves aim to examine the effect of keeping a low storage level for 1-3 months. Keeping storage at a low level for several months prepares more storage room for heavy rainfall which is expected to occur from August to October.

5.4.2 Examination of the effects on dam storage and dam release

This section examines the effect of the schemes described above in relation to the dam storage and dam release. Particular attention was given to the number of occurrences of dam over flows and dam dry ups. A month when the dam storage reaches or exceeds capacity is counted as an overflow, while a month when dam storage reaches zero is counted as a dry up.

The graphs in Figure 5.4 show the simulated monthly dam storage and dam release of Bhumibol and Sirikit Dams. The dam storage shown in the following figures are effective dam storage which is just the total storage less the siltation volume, approximately 3800 million m^3 and 2850 million m^3 in Bhumibol and Sirikit Dam, respectively. The graphs of Flat1 and Flat2 were not omitted because they do not show significant changes relative to the 2012 and Flat3 curves.

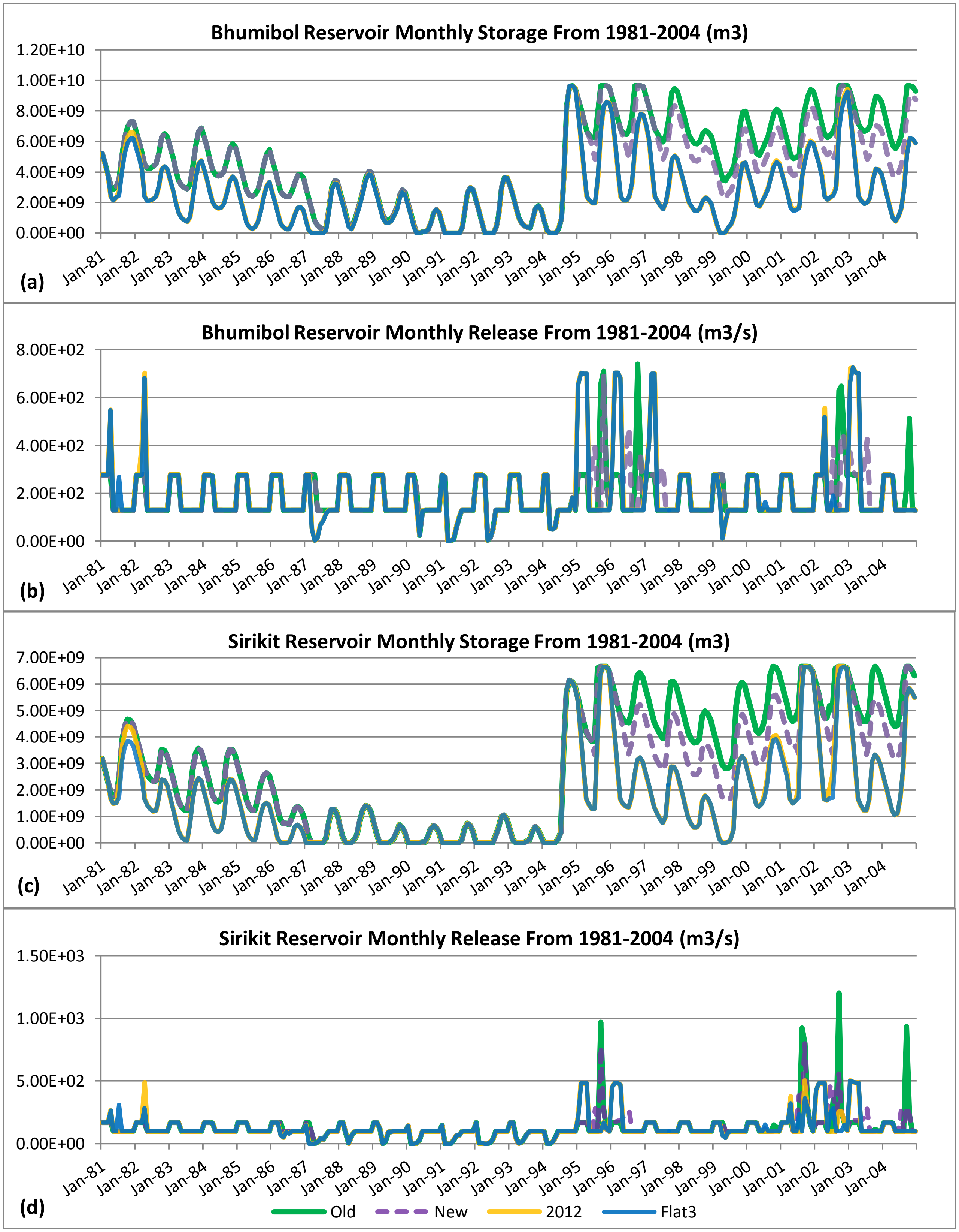


Figure 5.4 Simulated dam storage (a) and (c) and dam release (b) and (d) for Bhumibol and Sirikit dams, respectively. [Constant 2-season dam release]

Table 5.2 Dam overflow and dry up counts for each reservoir operation

	Old	New	2012	Flat3
Bhumibol Dam Overflow	12	6	0	0
Sirikit Dam Overflow	13	11	7	5
Bhumibol Dam Dry Up	13	13	20	20
Sirikit Dam Dry Up	36	36	42	42

Table 5.2 shows that dam overflows have significantly reduced by lowering the target storage and setting the target date earlier. It also shows that maintaining a low storage for several months, in this case 3 months, could further reduce the occurrence of dam overflows. Figures 5.5 showing the monthly dam release from 2000-2004 further illustratess that 2012 and Flat3 are very effective in reducing the volume of dam release during the peak rainy season (August to October). However, implementing 2012 or Flat3 operation has some drawbacks. Table 5.2 shows that implementing 2012 or Flat3 operation would also increase the risks of drought occurrences, as shown by the dramatic increase in the number of dam dry ups. These operations mitigate the risk of flooding but increase the risk from drought.

Generally, it could be concluded that identifying and setting the "target point," the low storage level that has to be reached before the intense precipitation falls, and the date when this target has to b reached are very critical for water management in the CP Basin. If the target level is set a little high or the target date quite late, the dam might be easily filled thereby increasing the risk of flooding. If the target level is set too low or the target date too early, there is a high potential of drying up the dams. Since flood mitigation and drought mitigation are both important in the CP Basin, a reservoir operation that could potentially achieve both is ideal. This section showed that "good" target points range from 45% to 70% of total dam storage while target dates range from end of April to end of July.

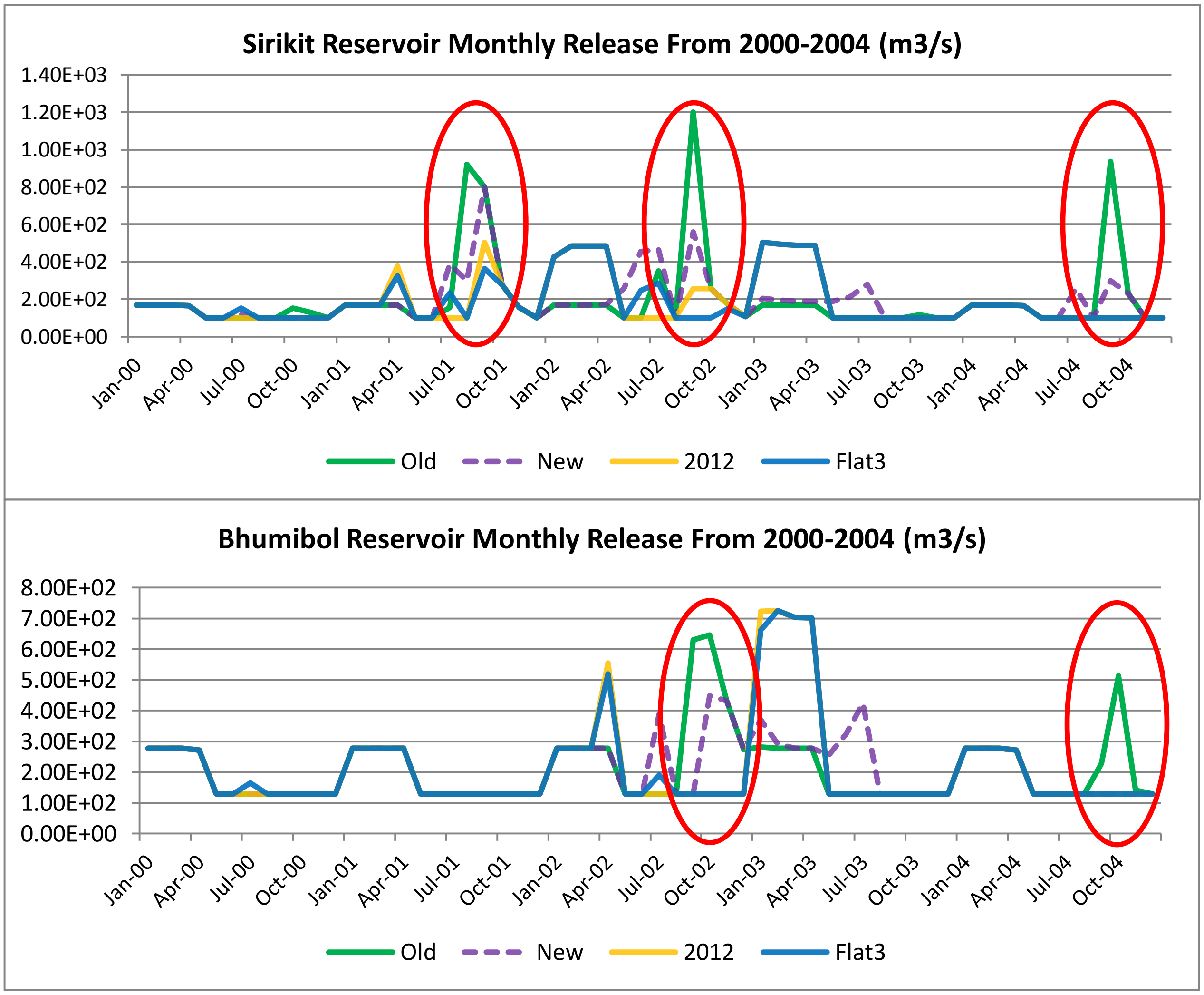


Figure 5.5 Monthly release from 2000-2004 at (a) Sirikit Dam and (b) Bhumibol Dam. Graphs show that 2012 and Flat3 are effective for lowering the dam release during rainy season.

5.4 Simplification of operation 2: Release as a function of storage

This section aims to develop reservoir operation schemes that minimize the risks of both flooding and drought. The objective of this section is to answer the following questions:

(1) What is the minimum storage needed to prevent overflows during rainy season?

(2) What is the minimum level of storage that could store rainwater that could supply the water demand of the proceeding year?

In this section, a slightly more sophisticated approach was used by setting the dry season release as a function of storage rather than at a fixed value. The number of seasons was also increased to five, the details of which will be discussed in section 5.4.1.

5.4.1 Setting the parameters for modeling

The historical reservoir operation was revisited, this time examining not only the inflow but the outflow and storage as well. The objective of this step is to identify several seasonal patterns.

Figure 5.6 shows the inflow and outflow at Bhumibol Dam from 1991-1994. An annual pattern was seen which could be divided into 5 groups as shown. The same pattern could be observed in examining Sirikit Dam at any year. Table 5.3 shows the inflow and outflow patterns observed in these 5 groups or "seasons".

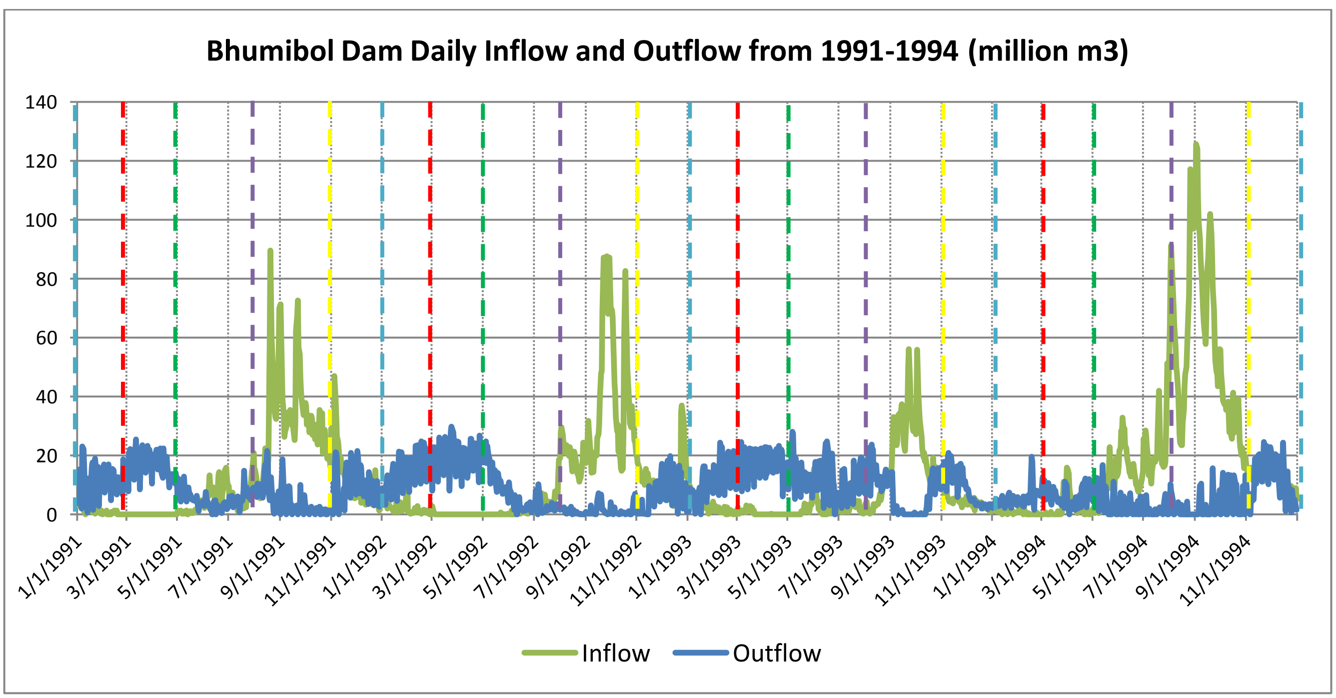


Figure 5.6 Daily inflow and outflow at Bhumibol Dam from 1991-1994 showing an annual 5-season pattern delineated by the 5 dashed lines.

Table 5.3 Dam inflow and outflow patterns based on a 5-season division

	Months	Inflow	Outflow
Season 1 (blue to red lines)	January – February	Decreasing (to almost zero)	Increasing
Season 2 (red to green lines)	March – April	Slightly increasing	Slightly decreasing
Season 3 (green to violet lines)	May – July	Increasing	Almost equal to inflow
Season 4 (violet to yellow lines)	August – October	Very high	Kept low (sometimes equal to zero)
Season 5 (yellow to blue lines)	November – December	Decreasing	Higher than inflow

This pattern was investigated further by getting the total inflow, outflow, and average cumulative storage at the end of each season for every year. The average from 1981-2011 is shown in Table 5.4 below. Based on these patterns, a scheme was proposed as indicated in the last column. The percentage of storage (%a, %b, and %c) were determined based on the historical values of these percentages (average daily %percent values).

Table 5.4 Historical and proposed 5-season operation scheme

Season (Months)	Inflow, Outflow, Storage	Bhumibol Dam	Sirikit Dam	Scheme (daily release)
Season 1 (Jan – Feb)	Inflow ($x10^6$ m^3)	164.51	216.01	Release as (**% a**) of the previous day's cum. storage
	Outflow ($x10^6$ m^3)	1100.60	1084.94	
	Cum. Storage ($x10^6$ m^3)	5053.33	3865.71	
Season 2 (March – April)	Inflow ($x10^6$ m^3)	91.71	189.32	Release as (**% b**) of the previous day's cum. storage
	Outflow ($x10^6$ m^3)	1447.29	1378.70	
	Cum. Storage ($x10^6$ m^3)	3678.02	2694.49	
Season 3 (May – July)	Inflow ($x10^6$ m^3)	975.44	1484.00	Release = max[inflow, 88m^3/s]; Storage kept at target level
	Outflow ($x10^6$ m^3)	1079.37	1150.58	
	Cum. Storage ($x10^6$ m^3)	**2756.86**	**1904.63**	
Season 4 (Aug – Oct)	Inflow ($x10^6$ m^3)	3550.82	3512.06	Release = **88 m^3/s** (Bhum) and **133m^3/s** (Siri) (approx. = to total outflow by the end of Oct.)
	Outflow ($x10^6$ m^3)	696.57	1056.71	
	Cum. Storage ($x10^6$ m^3)	4004.59	3784.79	
Season 5 (Nov – Dec)	Inflow ($x10^6$ m^3)	847.78	413.92	Release as (**% c**) of the previous day's cum. Storage
	Outflow ($x10^6$ m^3)	700.81	700.88	
	Cum. Storage ($x10^6$ m^3)	5756.37	4601.03	

Indicated in red are the parameters which could be changed to prioritize flood mitigating operation or drought mitigating operation. The key parameter is the storage at May-July which should be set at the target storage limit and should be reached by the end of April. This parameter and technique is almost the same as in Flat3 scheme in the previous section. The main difference is that the values of release from November-December and during the dry season are also adjusted accordingly through parameters %a, %b, and %c.

The values of the target storage from May to July for drought condition (minimum value, lower bound) for each dam were found from studying the inflow and outflow values from 1981-2011 based on the 5-season scheme. It was found by getting the maximum historical deficit (most negative value), *D*, using equation 5.1 where I is inflow, O is outflow which includes evaporation, S_n is season *n* in the same year, and $S_{n'}$ is the season *n* in the previous year. This assumption was made so that in any year, the water stored at level *D* in season 3 plus all the water stored from season 4 to 5 in that same year will be sufficient to supply the demand for the dry season of the next year. This assumes an annual cycle wherein enough storage is left such that whatever amount of rainwater stored during the rainy season will be enough to supply the demand during the dry season. Note that this procedure was done on a long-term basis using observed values to reduce the biases from merely taking averages. It also takes into account consecutive years of low precipitation within the dataset.

$$D = I_{S_{4'}} - O_{S_{4'}} + I_{S_{5'}} - O_{S_{5'}} + I_{S_1} - O_{S_1} + I_{S_2} - O_{S_2} \quad (5.1)$$

For modeling purposes, this amount of *D* was adjusted by using a constant amount of $O_{S_{4'}}$ which is equivalent to the total volume from the constant release set from August to October (in this case, 700 x 10^6 m^3 for Bhumibol, and 1055 x 10^6 m^3 for Sirikit. These values were used instead of the actual $O_{S_{4'}}$ values for simplification.

On the other hand, the values of the target storage for flood mitigation (maximum value, upper bound) for each dam were found by simply finding the highest volume of total inflow to the dam during season 4. The target storage was found by deducting this volume of inflow from the effective capacity of the respective dams (total capacity – volume of siltation). The outflow during this season was not taken into account because it usually includes the water which overflowed from the dam during heavy precipitation.

These limits are shown on Table 5.5. The adjusted limits used for modeling are also shown. Adjustments are necessary to take into account the differences made in the proposed scheme as well as the differences in actual and simulated dam inflows. Based on these limits, the specific values of %a, %b, and %c for each season were obtained as shown in Table 5.6, calculated for three cases, based on the old operation, operation for flood mitigation, and operation for drought mitigation. Note that *storage* in Table 5.6 refers to the effective storage at that time or the storage deducted by the siltation volume.

Table 5.5 Actual and adjusted target storage limits for drought and flood mitigation

	Bhumibol Dam	Sirikit Dam
Total storage capacity	13462 million m^3	9510 million m^3
Effective storage capacity	9660 million m^3	6660 million m^3
Target level for flood mitigation - actual	1322 million m^3	1.30 million m^3
Target level for drought mitigation - actual	2924 million m^3	1875 million m^3
Target level for flood mitigation – model	370 million m^3	5 million m^3
Target level for drought mitigation - model	2820 million m^3	1735 million m^3

Ideally, the storage limit for flood mitigation should be greater than that of for drought mitigation. In such a case, the water manager could choose any value within the limits and both extreme events could be prevented. However, in the case of Bhumibol and Sirikit Dams, it could be seen from Table 5.5 that the limit for drought mitigation is higher than that of flood mitigation. Thus, if drought mitigation is chosen, there is a possibility that the dam capacity would be exceeded during the wet season and at some point, the dam would overflow.

Table 5.6 Table of operation schemes showing the release in m^3 at each season and the target storage by the end of April

Bhumibol Dam	Old operation (f(sto)_old)	Flood operation (f(sto)_flood)	Drought operation (f(sto)_drought)
Season 1 (Jan-Feb)	$0.34\%\times \frac{sto(m^3)}{86400s}$	$0.58\% \times \frac{sto(m^3)}{86400s}$	$0.33\% \times \frac{sto(m^3)}{86400s}$
Season 2 (Mar-Apr)	$0.51\% \times \frac{sto(m^3)}{86400s}$	$1.03\% \times \frac{sto(m^3)}{86400s}$	$0.50\% \times \frac{sto(m^3)}{86400s}$
Season 3 (May-July)	Max [inflow, 88m^3/s (105m^3/s modeled)]	Max [inflow, 88m^3/s (105m^3/s modeled)]	Max [inflow, 88m^3/s (105m^3/s modeled)]
Target level at season 3 (max. limit)	2755million m^3	370 million m^3	2820 million m^3
Season 4 (Aug-Oct)	88m^3/s (105m^3/s adj. for model)	88m^3/s (105m^3/s adj. for model)	88m^3/s (105m^3/s adj. for model)
Season 5 (Nov-Dec)	$0.21\% \times \frac{sto(m^3)}{86400s}$	$0.37\% \times \frac{sto(m^3)}{86400s}$	$0.21\% \times \frac{sto(m^3)}{86400s}$
Sirikit Dam	**Old operation (f(sto)_old)**	**Flood operation (f(sto)_flood)**	**Drought operation (f(sto)_drought)**
Season 1 (Jan-Feb)	$0.39\% \times \frac{sto(m^3)}{86400s}$	$0.72\% \times \frac{sto(m^3)}{86400s}$	$0.41\% \times \frac{sto(m^3)}{86400s}$
Season 2 (Mar-Apr)	$0.61\% \times \frac{sto(m^3)}{86400s}$	$1.36\% \times \frac{sto(m^3)}{86400s}$	$0.64\% \times \frac{sto(m^3)}{86400s}$
Season 3 (May-July)	Max [inflow, 132m^3/s (100m^3modeled)]	Max [inflow, 132m^3/s (100m^3modeled)]	Max [inflow, 132m^3/s (100m^3modeled)]
Target level at season 3 (max. limit)	1905million m^3	5 million m^3	2820 million m^3
Season 4 (Aug-Oct)	132m^3/s (100m^3/s adj. for model)	132m^3/s (100m^3/s adj. for model)	132m^3/s (100m^3/s adj. for model)
Season 5 (Nov-Dec)	$0.22\% \times \frac{sto(m^3)}{86400s}$	$0.39\% \times \frac{sto(m^3)}{86400s}$	$0.23\% \times \frac{sto(m^3)}{86400s}$

Figure 5.7 shows a diagram of the proposed scheme. The red upper line is a simplified upper curve which is just an adaptation from the previous section. This upper curve was set to

ensure that the target level set at the end of April would be actually reached. The blue line shows the projected storage curve based on the varying release shown at the lower half of the diagram.

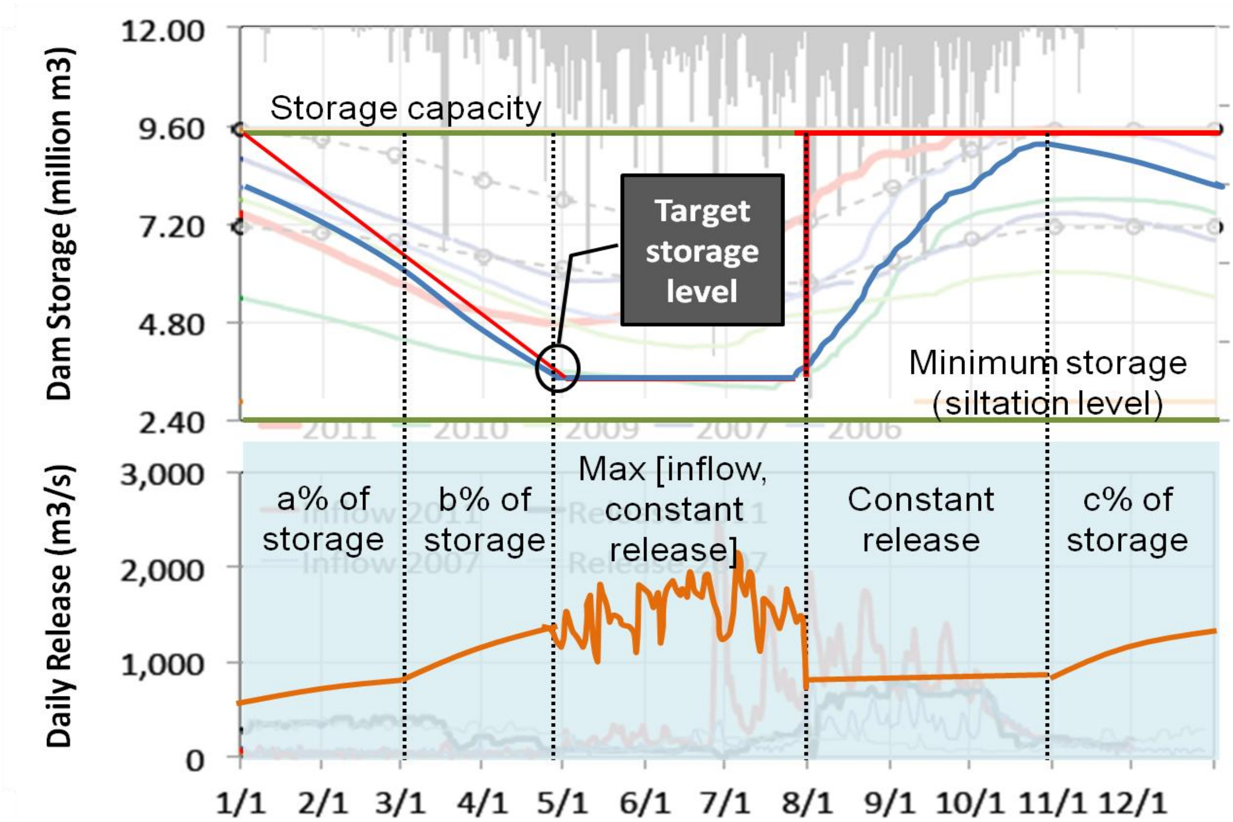


Figure 5.7 Diagram of the proposed scheme with varying release based on 5-season operation. The values of a, b, c, constant release, and target storage level are indicated in Table 5.6.

5.4.2 Examination of the effects on dam storage and dam release

The simulated dam storage and dam release are shown in Figures 5.8. For comparison, the results of "Old" and "Flat3" from the previous simulations based on a constant 2-season release are also shown in some of the figures. Table 5.7 shows the table of overflow and dry up statistics for each scheme.

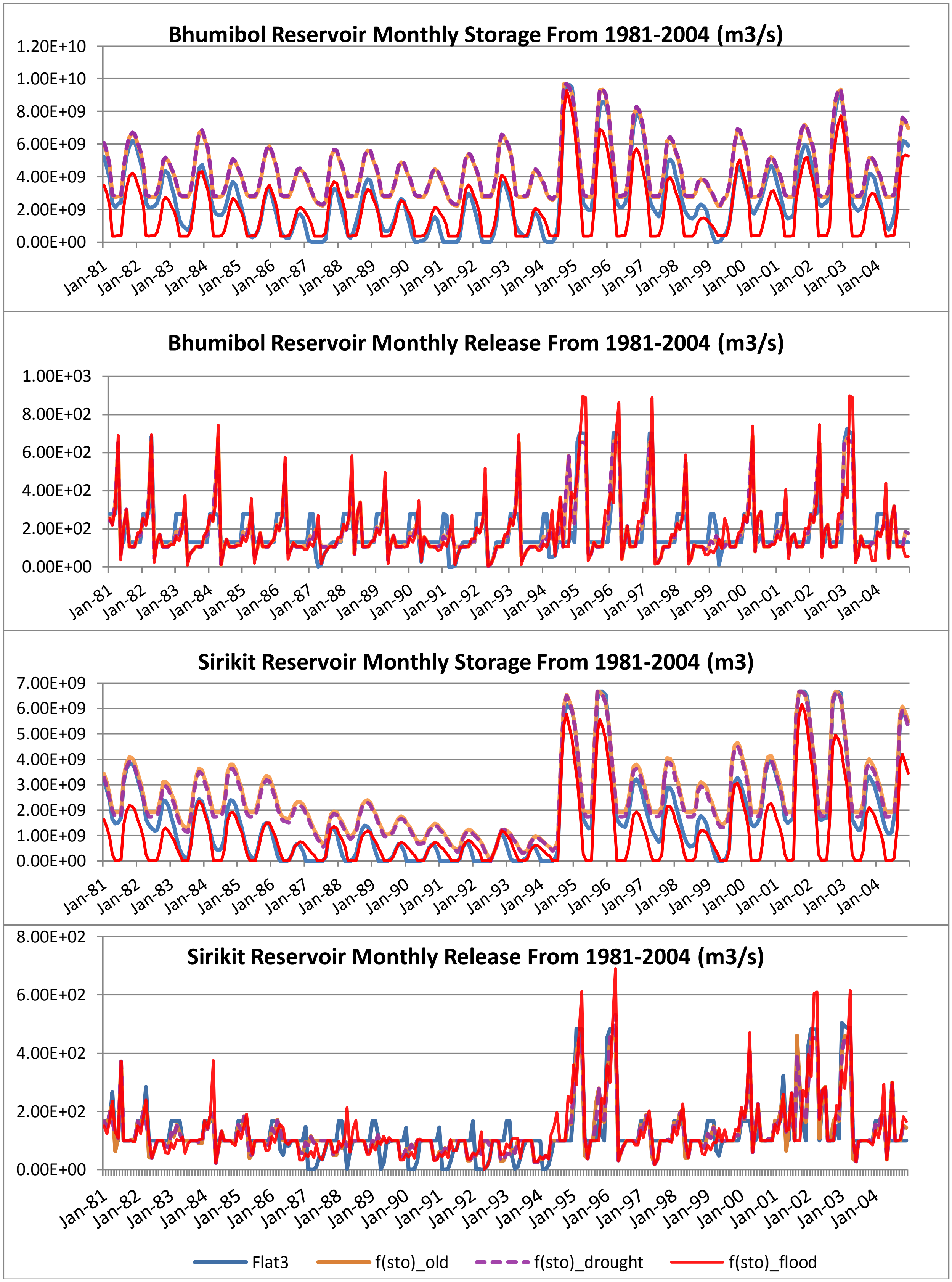


Figure 5.8 Simulated dam storage (a) and (c) and dam release (b) and (d) for Bhumibol and Sirikit dams, respectively. [Varying 5-season dam release]

Table 5.7 Dam over flow and dry up counts for each reservoir operation [5-season]

	f(sto)_old	f(sto)_ drought	f(sto)_flood	Flat3	Old
Bhumibol Dam Overflow	2	2	0	0	12
Sirikit Dam Overflow	5	5	0	5	13
Bhumibol Dam Dry Up	0	0	0	20	13
Sirikit Dam Dry Up	0	0	0	42	36

Although it seems from the graphs that the f(sto)_flood scheme seems to cause a lot of dry ups, checking the numerical output reveals that none of the dams actually reached 0.0 storage. Rather, the levels were too low to be seen from the graphs. Although it was expected at first that choosing the flood mitigation operation would cause several dry ups, simulation results show that water resources have been managed quite well using f(sto)_flood scheme. No droughts occurred primarily because the release of water had been adjusted to the availability of water or the current storage through the parameters %a, %b, and %c. This could be taken both as a drawback and an advantage. It has drawbacks in that there is a possibility that the demand for water may not have been adequately met by the adjusted water outflow. On the other hand, this could be taken as an advantage because although lesser water may have been reduced during certain planting season months, the complete drying up of both dams were prevented by simply following the new scheme.

Note too that the release and storage time series graphs of the f(sto)_old scheme is quite similar to that of the f(sto)_drought scheme. This makes perfect sense because in the historical years of operation of the dams, storing water for irrigation or supplying water at the dam were given higher priority than flood mitigation.

Figures 5.9 (a) and (b) show a closer look at the dam release from 1993-1996 at Bhumibol and from 2000-2004 at Sirikit dam, respectively. It could be seen that the f(sto)_flood option regulated the water release well. Dam release was kept at a minimum from August to October. Water release during the dry months was regulated such that more water was released from March-April than in January-February, similar to the pattern observed in actual dam operation (see Figure 5.6 for example).

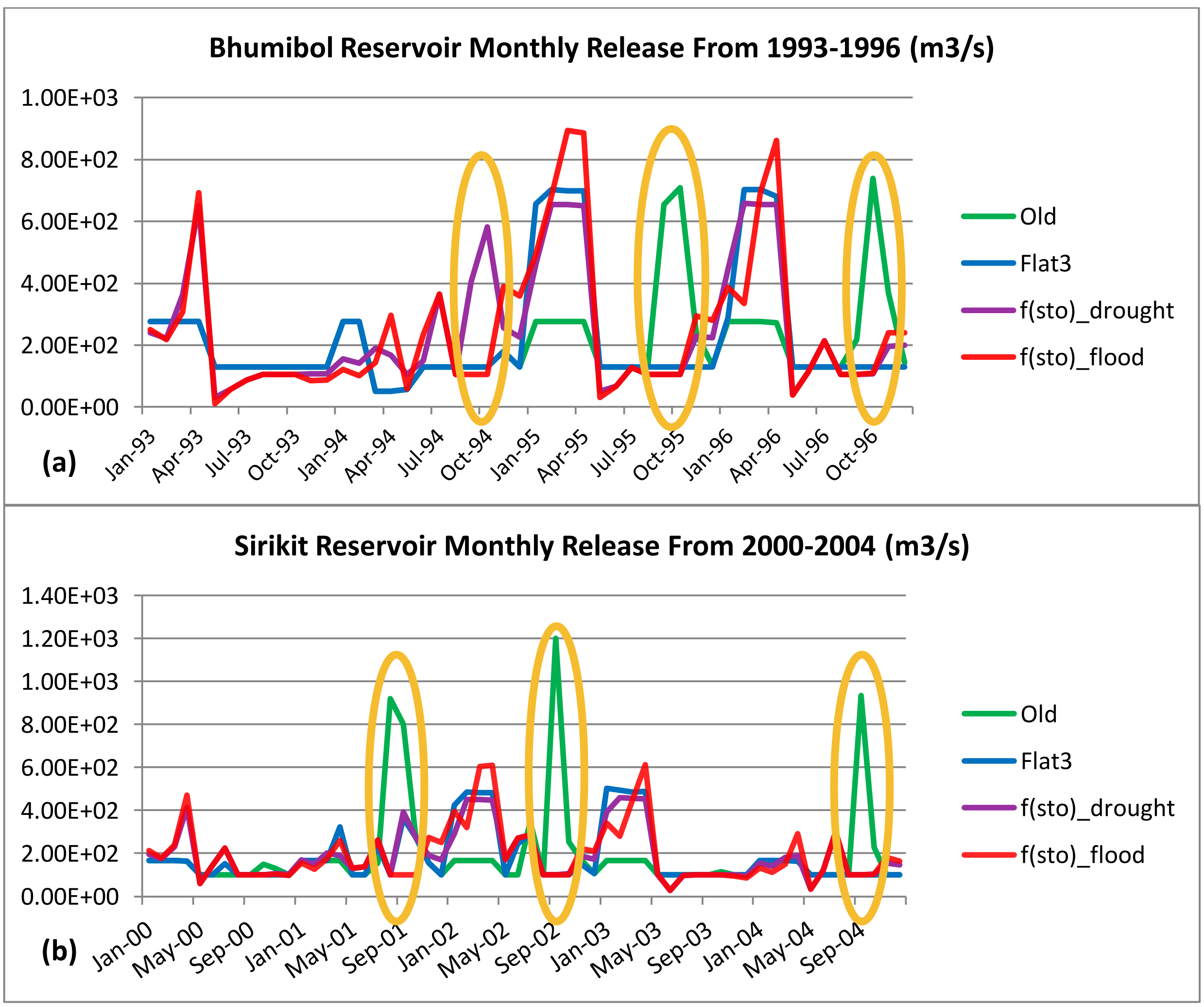


Figure 5.9 Monthly release at (a) Bhumibol Dam from 1993-1996 and (b) Sirikit Dam from 2000-2004. The graphs show that water was managed well by the f(sto)_flood option.

5.5 Incorporating dam discharge into CaMa-Flood

The effect of the reservoir operation schemes to the downstream stations such as C2 could all be examined using H08. However, as have been discussed in Chapter 4, the coupled H08-CaMa has a few advantages over the pure H08 simulation results. H08-CaMa could simulate better and more accurate hydrographs using more realistic parameters. It also has the capability to visualize the inundated area. These improved simulations of discharge and visualization of inundated areas could benefit and support the analysis of the effects of reservoir operation on reducing percentages of inundated areas through H08-CaMa. However, CaMa-Flood, being a river routing model, does not have a capability to compute reservoir operation. This section discusses a simple methodology for incorporating the dam discharge into H08-CaMa.

Dam discharge was treated like a forcing data. All calculation of dam discharge was conducted using H08. The result of the H08 simulation was then converted, just like the conversion of dimension, endian, and units done using the input runoff.

Then, the exact positions of the grid cells of the two dams were located in the river sequence of CaMa-Flood. The code of CaMa-Flood which calculates river discharge was then edited such that the river discharges at the grid cells of Bhumibol and Sirikti dams were replaced by the respective dam discharge calculated by H08. Then, the main shell script of CaMa-Flood was edited to call on the converted discharge data file as input to the river discharge calculation of CaMa-Flood.

Lastly, a "switch" was added to CaMa-Flood so that the user could choose to turn off the dam discharge calculation option.

It could be argued that this methodology is too simplistic and might cause an imbalance in the water processes in CaMa-Flood. However, it could be recalled that CaMa-Flood computes river discharge using diffusive wave equation. Through this equation, the effect of the sudden increase in discharge will not really cause an imbalance to the system because water level at the nearby cells would be recalculated by the system.

The next section discusses how the success of the combination of CaMa-H08 with dam discharge was verified.

5.6 Simulated discharge and inundation with dam operation

This section discusses the results of simulation with dam operation using the coupled H08-CaMa. Since almost all discharge comparisons in this chapter deal with simulations with reservoir operation, hereafter, the term "discharge" refers to that which includes reservoir operation (non-naturalized). Although simulations were also conducted using plain H08, this chapter focuses on presenting the results of the coupled H08-CaMa. All H08-CaMa simulations used the parameters indicated in Chapter 4.

First, the simulated discharge using the actual dam release (here referred to as Dam_Obs_) as forcing discharge was compared with the observed discharge at C2. This was done to confirm that the forcing of dam discharge into H08-CaMa is successful. Then, the simulations using the discharge from simplified dam operation simulations patterned after the old or historical operation (the "Old" and "f(sto)_old "operation from the previous sections) were compared with that of the observed discharge at C2. This was done to confirm that the effect of these operations to the downstream discharge could actually be predicted. Hence, the changes in simulated discharge using the proposed reservoir operation schemes could also be simulated.

Figure 5.10 shows the daily discharge from 1993-1995. For comparison, the result from plain H08 usingT12-Calibrated parameters is shown just in this figure. The naturalized discharge and the result of the H08-CaMa naturalized simulations are also shown for reference. It could be observed that the H08-CaMa simulations gave better results than the plain H08 simulation using

T12-Calibrated. The NSE coefficients are 85.48%, 88.42%, and 91.48%, while PBIAS values are 2.13%, 12.78%, and 6.01% for T12-Calibrated, Old, and Dam_Obs_, respectively. Expectedly, Dam_Obs_ give the best result because the actual dam release was used.

Figure 5.11 shows the monthly discharge from 1981-2004 at C2 station. It could be seen that both the simplified reservoir operation simulations (2-season, constant release and 5-season, function of storage release) gave quite good fit with the observed discharge. The NSE coefficients are 65.65%, 67.36%, and 81.91% while the PBIAS are 2.99%, 2.57%, and -0.38% for the “Old”, “f(sto)_old”, and Dam_Obs_, respectively. The quite low NSE coefficients of “Old” and “f(sto)_old” are expected because the reservoir operations used were simplifications and estimations of the historical. Although the NSE coefficients are quite low as compared with the that of the naturalized discharge simulations, the NSE values of “Old” and “f(sto)_old” are still considered as good model performance. Thus, it could be confirmed that the effect of reservoir operations to the discharge downstream could be simulated.

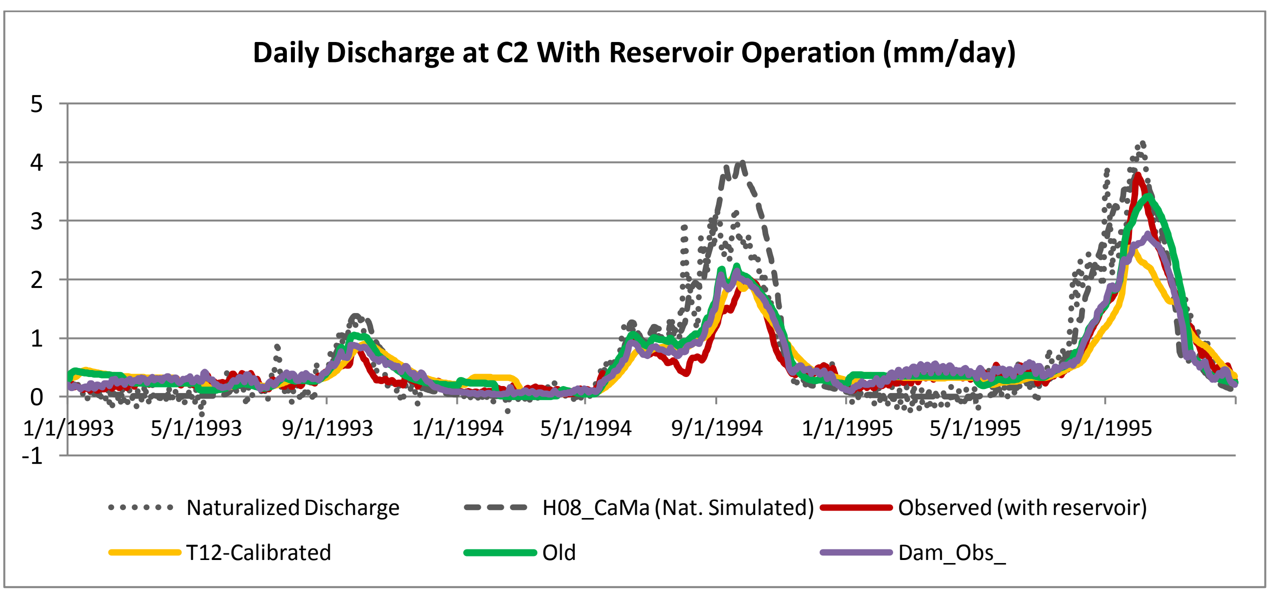


Figure 5.10 Daily discharges from 1993-1995 at C2 Station considering dam operation

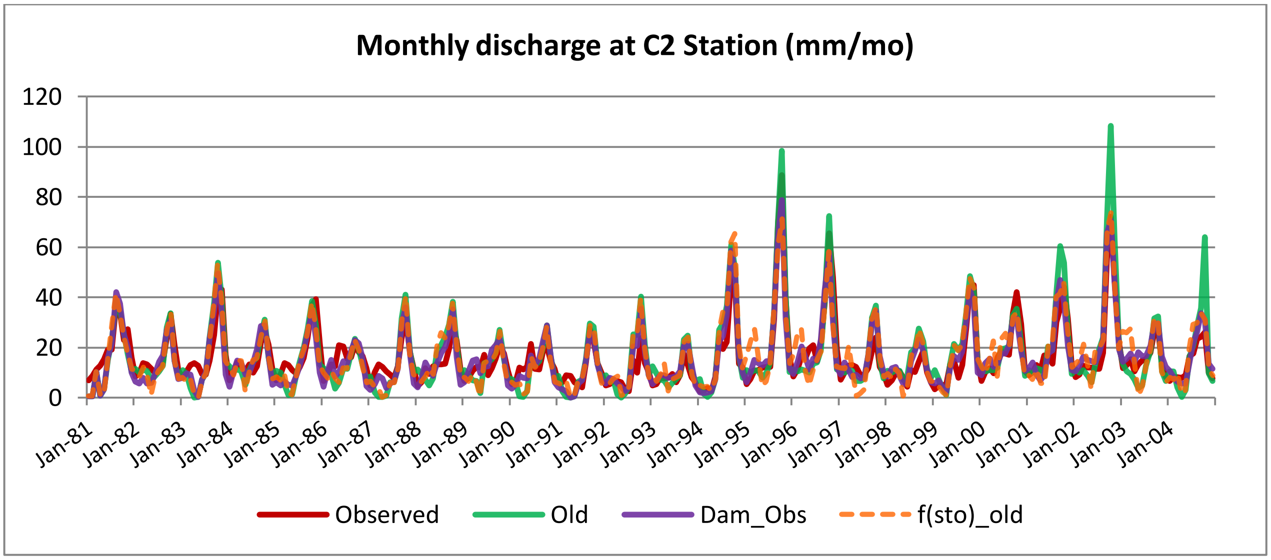


Figure 5.11 Monthly discharges from 1981-2004 at C2 Station considering dam operation.

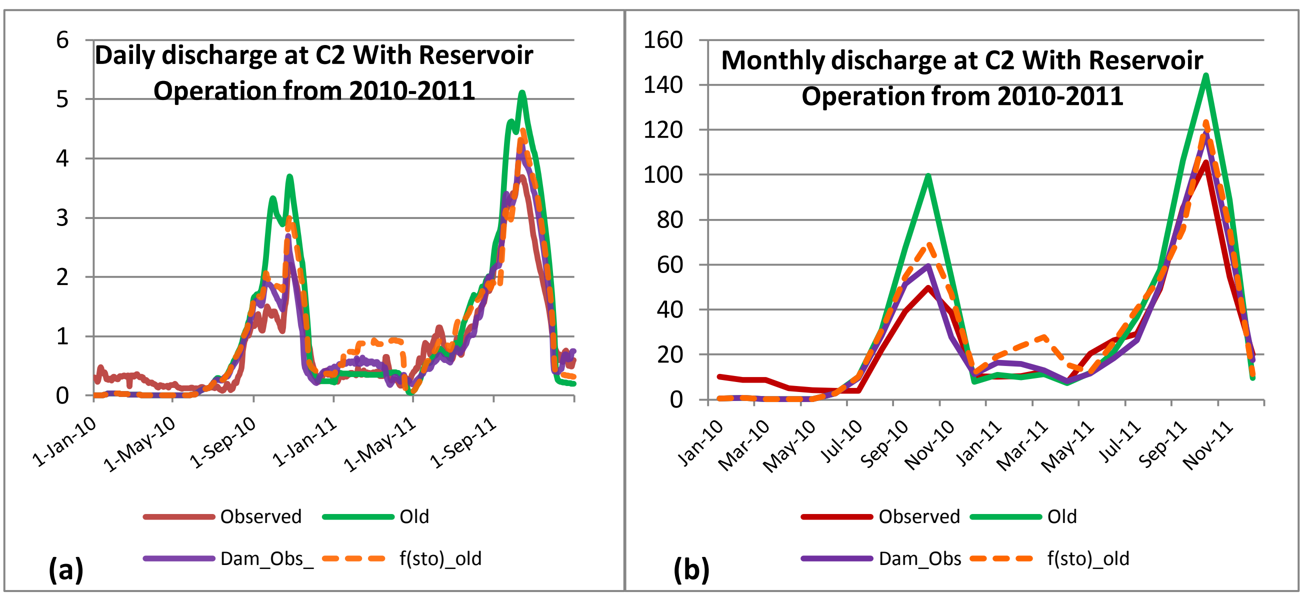


Figure 5.12 Daily (a) and monthly (b) discharges from 2010-2011 at C2 Station considering dam operation

Figures 5.12 (a) and (b) show the simulated discharge at C2 from 2010 -2011. The "Old" reservoir operation overestimates the discharge while the f(sto)_old seems to simulate the 2010-2011 discharge quite well. These graphs prove that the H08-CaMa with dam operation has a potential to predict discharges with effects of dam operation in the future. However, it still has some biases which have been carried over from the quite overestimated simulation of naturalized discharge. The low discharge of all the simulated results in the first few months of 2010 must be ignored as the model is still in the initialization or spin up mode in these periods.

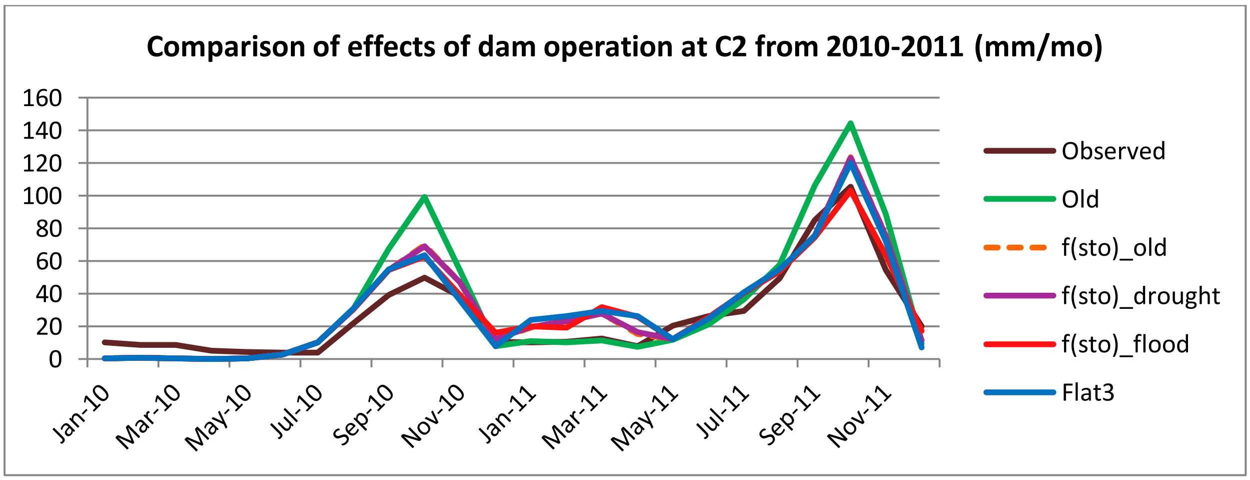


Figure 5.13 Monthly discharges from 2010-2011 at C2 Station at different reservoir operation schemes

Figure 5.13 shows the comparison of the effects of the various dam operation schemes to the monthly discharge at C2. It should be noted that the simulations were positively biased. Even so, the effects of the dam operation could be quantified by comparing their peaks with either the Old or f(sto)_old operations. It could be observed that f(sto)_flood has the greatest effect on reducing the monthly peak, lower by about 20 mm as compared with f(sto)_drought and Flat3.

Figures 5.14 show the observed (radar images) and simulated inundation by the H08-CaMa model. It could be seen that the shape of the simulated inundated area generally matches that of the observed. However, Dam_Obs_ and the Old operation inundated area are overestimated, partly due to the overestimated inundation from the naturalized simulations discussed in the previous chapter. As had been mentioned in the previous chapter, this overestimation could still be corrected by using better parameter sets.

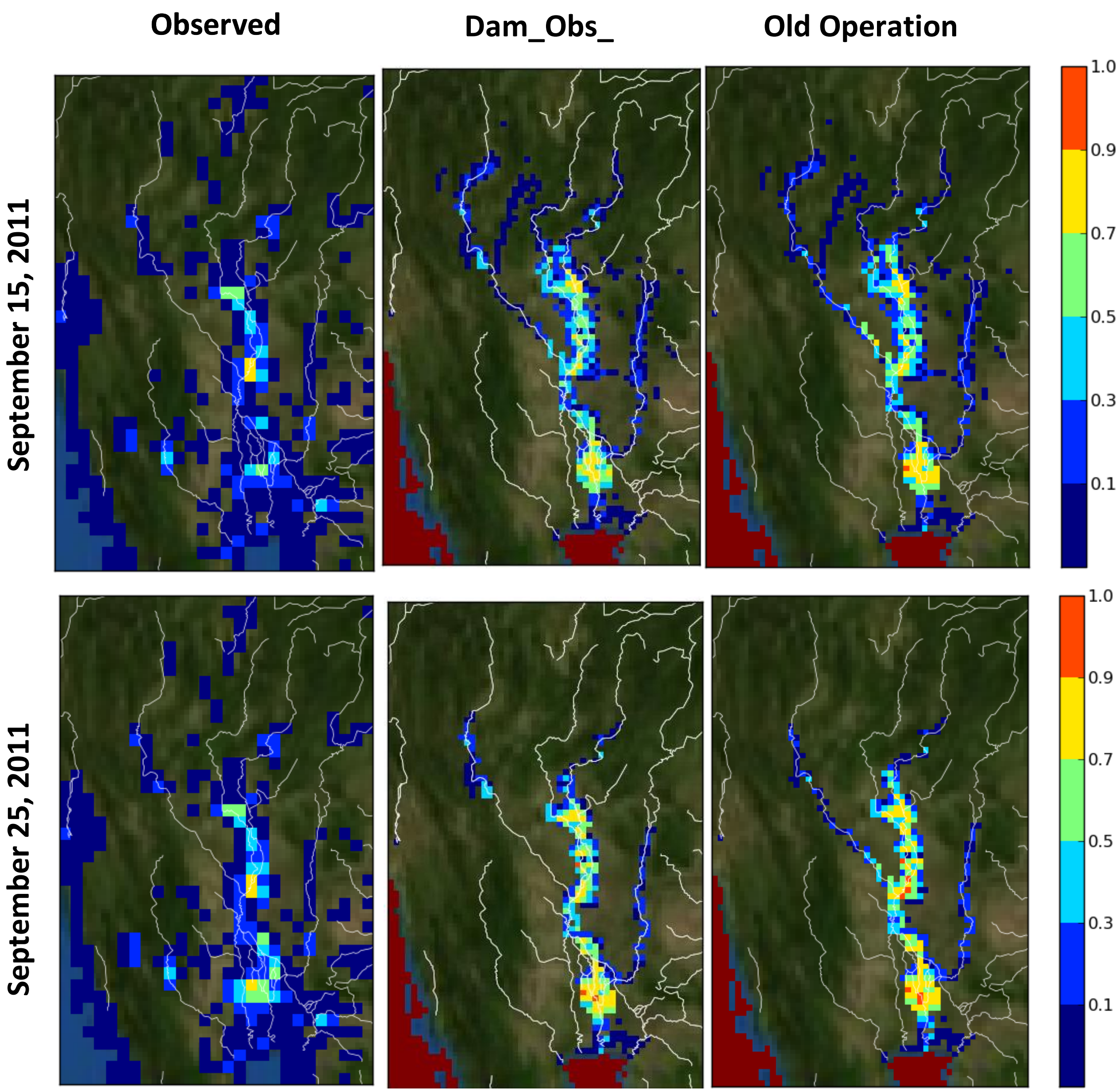


Figure 5.14 Simulated and observed inundated area with dam operation (expressed as percent of grid area)

To compare the effects of the proposed dam operations to inundation, the differences between their flooded area and the "Old" operation were graphed in September 25 and October

15, 2011 in Figures 5.15. It could be seen that in both days examined, the reduction of percent inundation was greater when f(sto)_flood option was used. The dark red spots in the map are areas which have increased percent inundation that exceeded the limit set as boundaries for the color bars. These areas are upstream of the reservoirs Bhumibol and Sirikit which means that these red spots simply indicate highly increased discharge.

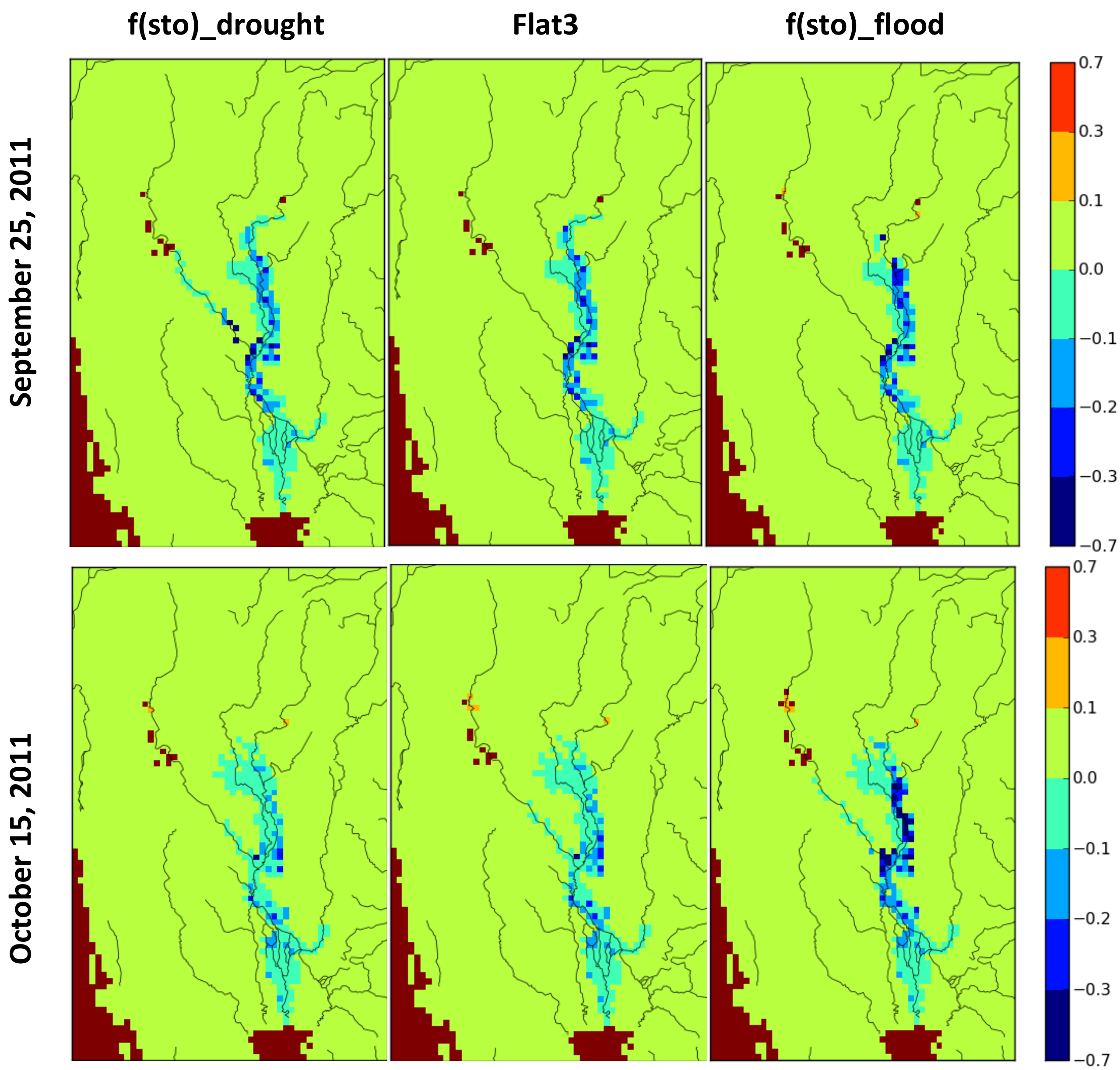


Figure 5.15 Difference between the percent flooded area between the respective dam operation schemes and the "Old" dam operation scheme.

Chapter 6

Conclusions, contributions, and future directions

Hydrological modeling was used in this study with the main goal of mitigating flood risks in the Chao Phraya River Basin. Generally, this study presented a research framework which could be a basis of future studies dealing with river basin modeling for mitigating flood risks. Particularly, this research elucidated how the main goal was achieved by (1) simulating naturalized discharge, (2) simulating both the naturalized discharge and inundation, and (3) simulating the effects of historical and proposed reservoir operation schemes to the discharge and inundation. This chapter presents the conclusions and contributions that could be drawn from this research as well as future directions based on these three main parts in detail.

1. Simulation of the naturalized discharge

1.1. Naturalization of observed discharge is necessary in comparing and validating results from hydrological models that do not consider reservoir operations. Raw observed discharge is greatly affected by anthropogenic interventions upstream. To set the observed and the simulated discharges at a comparable basis, it is necessary to naturalize the observed discharge first.

1.2. Methodology for calibration was discussed in detail. This research showed that four parameters, (i) time constant for daily maximum subsurface runoff, tau, (ii) shape parameter which sets the relationship between subsurface flow and soil moisture, gamma, (iii) bulk transfer coefficient, and (iv) soil depth, greatly affect the simulation results. The effects of these parameters on the annual, monthly, and daily discharge have also been discussed. This detailed discussion could serve as a guide to researchers who wish to use H08 in the future. The methodology could also be adjusted and may be applied to similar models. Thus, a detailed account of the calibration allows the replication of this study in other river basins.

1.3. Manual calibration of the parameters led to a better understanding of their relationships with the discharge. This leads to a better understanding of the sensitivities of the model which is useful not only to the user but to the model developer as well. However, manual calibration proved to be very inefficient, subjective, and time consuming. One of the future directions of this research is to develop an algorithm for and then implement automatic calibration.

1.4. The calibrated parameters changed with a change in precipitation dataset. The calibrated parameter sets, then, are not universally applicable to any precipitation dataset. Meant to be representative of real life conditions, there must be a one-to-one correspondence between the parameters and a specific location. However, currently, these parameters are just abstract representations of the real, physical conditions because their correctness and accuracy are very difficult to verify. The best means of evaluating their correctness is by comparison with published, estimated values and comparison of the simulated results with the observed. The evaluation of the closeness to the published, estimated values is quite subjective. The simulated results greatly change with a change from precipitation reanalysis to actual precipitation dataset. As expected, the accurate precipitation dataset yielded better results. Thus, it is important to inspect and verify the accuracy of the input data first before calibration.

1.5. Validation of the applicability of the calibrated parameter showed both good and unsatisfactory results. There is a limitation in the number of validation points due to inaccuracy in the river flow map and availability of data. It was unofficially reported that some stations are affected by errors in gauging while some stations are greatly affected by fluctuations due to anthropogenic activities. Causes for such errors in real life must be identified and understood. As for modeling, a more accurate river network map is needed. A manually corrected river network map was made available recently but its accuracy is yet to be verified. This is one future direction in this part.

1.6. The unsatisfactory results, however, could also be attributed to the fact that the land cover and soil conditions at C2 Station may not be the same as in the other locations within the basin. Currently, H08 assumes a uniform land cover and soil conditions within the basin to simplify the real world. However, H08 was made flexible enough to change this assumption by changing the parameters calibrated in this study at each grid cell. Thus, the parameters should be changed and calibrated based on the land cover and soil conditions within the Chao Phraya Basin. This is one of the planned developments in the next few months. Initial steps have already been taken towards this direction.

1.7. Naturalized discharge was simulated at very good accuracies in the annual, monthly, and daily scales. This proves that the calibration method was done successfully. The simulation results serve as baseline data which has many applications. First, it could be used to analyze the historical naturalized rainfall-runoff patterns, other hydrological factors and interactions, and seasonal and longer time scale variations in the Chao Phraya

Basin. Second, it could be used to differentiate and quantify the effects of natural variations from that of anthropogenic effects or climate change effects. This leads to the third application which is the use of these results as baseline study and as basis for hydrological modeling with anthropogenic interventions such as reservoir operation. Lastly, it could be used to reevaluate the current and future design standards and policies for flood risk mitigation in the Chao Phraya River Basin.

1.8. Actual precipitation was used with forecasted meteorological values as input to simulate the naturalized discharge in 2010-2011. It is understandable that the results are not as accurate as the 1981-2004 discharge because forecasted meteorological forcing input was used. However, the simulation results are still good enough, showing high NSEs albeit overestimating the monthly peaks. This proves that given a good meteorological forecast, the calibrated model could actually predict and forecast the naturalized discharge. It also proves applicability to extreme events. Thus, it could serve as a tool for preparing mitigation measures against upcoming flood events and as a basis for making critical decisions such as when to start and give orders for evacuation.

1.9. An improvement in this direction would be to calculate the naturalized discharge for the next 100 years, with and without climate change. This could then be used for assessing the impacts of climate change in the Chao Phraya Basin. It could also be used to plan for the future according to different climate scenarios, update the design standards for flood mitigating structures, and create other flood prevention strategies.

2. Simulation of both naturalized discharge and inundation

2.1 Recalibration of H08 parameters was done to yield better, more realistic results using CaMa-Flood. It was found that using the runoff from the H08 simulation utilizing optimized parameter set would yield a mean annual volumetric flow that is much smaller (175 mm/yr) than the observed (196 mm/yr) and that of calculated (198 mm/yr) by the plain H08 model. Inundation was also found to be underestimated. Several reasons which are mainly due to the differences in the river routing schemes used in H08 and CaMa-Flood were given to explain this discrepancy. Thus, this study showed that the river routing scheme significantly affects the simulated discharge and inundation. It also showed that the use of a more realistic and detailed river routing schemes would lead to a better and more realistic estimation of the H08 parameters.

2.2 The parameters of CaMa-Flood were tuned for application in the Chao Phraya River Basin. Just as in the calibration of parameters in H08, the methodology and results of this step could serve as a guide and reference for other researchers.

2.3 The naturalized discharge was calculated and was shown to produce better results than plain H08. The 2010-2011 naturalized discharge was also calculated. In both cases, the fluctuations, discharge peak, and discharge volume were all simulated better due to the use of a more advanced river routing scheme.

2.4 The shape of the inundated area was simulated well for 2010-1011 but overestimation was seen especially in the flat areas of Bangkok. This shows the potential of this research to be used as a tool for creating flood risk maps and for land use planning. Given a good meteorological forecast, it could also be used as a tool for flood inundation forecasting. In short, the results of this part of the study further supports and improves the applications stated in (1e) and (1f) through the addition of simulated inundation.

2.5 Investigation of the overestimated areas should be carried out. The discrepancies between the modeled and the observed inundation could be due to the factors within the model, the factors in processing the radar images, or the factors in real life such as the presence of small canals and other human intervention which were not taken into account in the model For the factors within the model, further tuning of the CaMa-Flood parameters could be done to improve flood inundation simulations.

3. **Simulation of the effects of historical and proposed reservoir operation schemes to the discharge and inundation**

3.1 The dam discharges calculated by H08 were used as input in the H08-CaMa model. The success of this improvement was confirmed by comparing the discharge of the H08-CaMa with dam discharge with the raw observed (non-naturalized) discharge at C2 Station. Thus, the effects of reservoir operation to the simulated discharge as well as the inundated area could be examined.

3.2 The historical reservoir operation was simplified and used to identify reservoir operation parameters that are critical for flood risk mitigation. These parameters are (1) the target storage level that has to be reached before the start of the intense rainy season, (2) the date when this target storage level should be reached, and (3) the seasonal release. Two types of reservoir operation schemes were developed, one based on a 2-season, constant seasonal release, and the other one based on a 5-season, varying functions of release. Both were based on the historical reservoir operation from 1980-2011. The 2-season, constant seasonal release proved to be a good tool for flood mitigation by setting a low storage at the end of April and maintaining this low storage until the end of July. This has reduced the total number of simulated dam outflows from 1981-2004. However, it also increased the number of dry ups. The 5-season, varying functions of release proved to be a better type of reservoir operation scheme. It prevents overflowing of dams as well as droughts by managing the release of water as a function of the current storage.

Considering drought operation and flood operation, the boundaries for target storage level that have to be reached by the end of April were also found in the 5-season scheme. These boundaries set for drought-mitigation operations and flood-mitigation operations were then used to adjust the other parameters for modeling. Finding these boundaries help ease the difficulty in assessing how low the water level should be kept to ease flooding and how high it should be kept to prevent water shortage. This could then serve as a tool which enables decision makers and flood managers to wisely and objectively choose which kind of operation should be taken. These newly developed reservoir operation schemes could also be used as basis for revising the old operation schemes in the Chao Phraya Basin.

3.3 The downstream discharge and inundated area were simulated considering dam operations. This part of the research elucidates the effect of reservoir operation on the discharge downstream of the two dams, particularly at C2 Station. It further shows the effect of changing the reservoir operation to the downstream discharge and to the inundation in the basin. This would allow reservoir managers to check the possible effects of the planned reservoir operation to the downstream areas. Thus, this developed schemes and model serve as a good decision-making tool. It serves as a good platform for a more integrated approach at managing water resources and flood risks throughout the entire Chao Phraya basin.

References

1. Amnatsan, S, Jayawardena, A (2010). Water level prediction in Nan River, Thailand using wavelet neural network. Master's Thesis at International Centre for Water Hazard and Risk Management (UNESCO-ICHARM) course 2009-2010. Retrieved from www.icharm.pwri.go.jp/training/master/pubilication/pdf/2010/somchit.pdf
2. Bangkok Post. *More flood mayhem on the way*. Online news article. www.bangkokpost.com/news/local/259907/more-flood-mayhem-on-the-way. 10 June 2011.
3. Bangkok Pundit. *Thailand: Why was so much water kept in the dams?* Online news article. www.asiancorrespondent.com/67239/why-was-so-much-water-kept-in-the-dams. 14 October 2011.
4. Berz, G., (2000). Flood disasters lessons from the past – worries for the future. Proceedings of the Institution of Civil Engineers, Water, Maritime and Energy Division, London, Vol. 142, Issue 1, 01 March 2000, Paper No. 12212, 3-8.
5. Chen, Pengyu, Flood impact assessment using hydrodynamic modeling in Bangkok, Thailand. Master thesis submitted to the International Institutre for Geo-information Science and Earth Observation, Enschede, Netherlands. 2007. Retrieved from www.gem-msc.org/Academic Output/Pengyu_Chen.pdf.
6. Chuenchooklin, S., Mekprugsawong, P., Chidchob, P (2007). The river analysis simulation model for the planning of retention area and diversion channel for flood reduction in the lower Yom's River, Thailand. Proceedings of the 4th INWEPF Steering Meeting and Symposium. Paper 2-01.

7. Daisuke Komori, Shinichirou Nakamura, Masashi Kiguchi, Asako Nishijima, Dai Yamazaki, Satoshi Suzuki, Akiyuki Kawasaki, Kazuo Oki and Taikan Oki: "Characteristics of the 2011 Chao Phraya River flood in Central Thailand", Hydrological Research Letters, Vol. 6, pp.41-46, (2012).
8. DHI. *Thailand floods 2011, The need for holistic flood risk management*. Online article. www.globalcateye.com/media/861/Thailand_Floods_2011.pdf. Retrieved on July 2012.
9. EM-DAT: The OFDA/CRED International Disaster Database, www.emdat.be - Université catholique de Louvain - Brussels – Belgium. Version 12.07. Aug 2012.
10. Emori, S., *Description of Minimal Advanced Treatments of Surface Interaction and Runoff (MATSIRO) Land Surface Parameterization*, Frontier Research System for Global Change, 2001.
11. GaME-T2 Data Center. 2011. http://hydro.iis.u-tokyo.ac.jp/GAME-T/GAIN-T/index.htmlGaME-T2 Data Center.
12. Hanasaki, N., S. Kanae, T. Oki, K. Masuda, K. Motoya, and K. Tanaka (2007a), An integrated model for assessment of global water resources. Part 1: Input meteorological forcing and natural hydrological cycle modules, Hydrol. Earth Syst. Sci. Discuss., 4, 3535-3582.
13. Hanasaki, N., S. Kanae, T. Oki, and N. Shirakawa (2007b), An integrated model for assessment of global water resources. Part 2: Anthropogenic activities modules and assessments, Hydrol. Earth Syst. Sci. Discuss., 4, 3583-3626.
14. Hanasaki, N., S. Kanae, T. Oki (2006). A reservoir operation scheme for global river routing models. Journal of Hydrology, vol. 327, Issues 1-2, 22-41.
15. Hanasaki, N., S. Kanae, T. Oki and K. Musiake, Simulating the discharge of the Chao Phraya River taking into account reservoir operation, Water Resources Systems -

Hydrological Risk, Management and Development(Proceedings of a symposium held during the Seventh IAHS Scientific Assembly at Sapporo, Japan), Guenter Bloeschl, Stewart Franks, Michio Kumagai, Katumi Musiake & Dan Rosbjerg Eds., IAHS Publ. no.281, 215-223, July 2003.

16. Hanasaki, N., T. Inuzuka, S. Kanae, T. Oki (2010). An estimation of global virtual water flow and sources of water withdrawal for major crops and livestock products using a global hydrological model. *Journal of Hydrology*, **384**, 232-244.
17. Hanasaki N,. Yamamoto T,. 2010. H08 User's Manual, H08 Documentation. (obtained through the H08 website)
18. Kei Yoshimura, Takahito Sakimura, Taikan Oki, Shinjiro Kanae, Shinta Seto (2008). Toward flood risk prediction: a statistical approach using a 29-year river discharge simulation over Japan. Hydrological Research Letters, vol. 2, pp. 22-26, 2008.
19. Knight, Donald W., Shamseldin, Asaad Y. *River Basin Modelling for Flood Risk Mitigation.* Taylor & Francis Group plc, London, UK. 2006.
20. Kuntiyawichai, Kittiwet (2012). Interactions between land use and flood management in the Chi River Basin. CRC Press/Balkema, AK Leiden, the Netherlands. 2012.
21. Kure, S., Tebakari, T. (2012). Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand. Hydrological Research Letters, 6, 53-58, 2012. DOI: 10.3178/HRL.6.53
22. Kotsuki, S., et al. (2010), The water budget analysis with land surface model in Chao Phraya River basin, 23rd annual conference, JSHWR, 44-45.
23. Office of Natural Water Resources Committee (ONWRC) of Thailand Working Group. *Chao Phraya River Basin, Thailand*. UN Water Virtual Learning Centre.

www.wvlc.uwaterloo.ca. World Water Development Report – 2003. Part V, Chapter 16, pages 387-400.

24. Oki, T., Y. Agata, S. Kanae, T. Saruhashi, D. Yang, and K. Musiake (2001), Global Assessment of Current Water Resources using Total Runoff Integrating Pathways, Hydrol. Sci. J., 46, 983-996, Dec. 2001.
25. Oki, T. and S. Kanae, Aug. 2006: Global Hydrological Cycles and World Water Resources, *Science*, Vol. **313**. no. 5790, pp. 1068-1072. DOI: 10.1126/science.1128845.
26. Oki, T. , T. Nishimura, and P. Dirmeyer, Assessment of annual runoff from land surface models using Total Runoff Integrating Pathways (TRIP), *J. Meteor. Soc. Japan*, **77**, 235-255, Mar. 1999.
27. Oki, T. and Y. C. Sud, Design of Total Runoff Integrating Pathways (TRIP) A global river channel network, *Earth Interactions*, 2, Jan. 1998
28. Peterson, T., Stott, P., Herring, S. (2012. Explaining extreme events of 2011 from a climate perspective. Bulletin of American Meteorological Society, pp. 1041-1067. 2012. DOI:10.1175/BAMS-D-12-00021.1
29. Pokhrel, Yadu N. *Study of the Global Terrestrial Water Cycle Using a Land Surface Model with Representations of Human Impacts*. Doctor of Engineering Thesis, Oki Laboratory, Department of Civil Engineering, The University of Tokyo, Japan. September 2011.
30. Pokhrel, Yadu, Naota Hanasaki, Sujan Koirala, Jaeil Cho, Pat J.-F. Yeh, Hyungjun Kim, Shinjiro Kanae, Taikan Oki, 2012: Incorporating Anthropogenic Water Regulation Modules into a Land Surface Model. J. Hydrometeor, 13, 255-269. doi: http://dx.doi.org/10.1175/JHM-D-11-013.1

31. Prajamwong, S and Suppataratarn, P. Integrated flood mitigation management in the lower Chao Phraya River Basin. Proceedings of the Expert Group Meeting on Innovative Strategies Towards Flood Resilient Cities in Asia-Pacific. Bangkok, Thailand. 21-23 July 2009. Retrieved from www.unescap.org/idd/events/2009_EGM-DRR/Thailand-TMD-Sampan-Innovative-Strategies-for-Effective-Urban-Flood-Management.pdf

32. Rani, D., Moreira, M. (2010), Simulation-optimization modeling: A survey and potential application in reservoir systems operation, Water Resources Management, 24:1107-1138, 2010. DOI 10.1007/s11269-009-9488-0.

33. Royal Irrigation Department. Important storage dams of Thailand. Retrieved from www.rid.go.th/eng/kw-w2-7i_eg.htm on June 2012.

34. Sripong, H., Khao-uppatum, W., Thanopanuwat, S., *Flood management in Chao Phraya River Basin.* Proceedings of the International Conference, The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl. Kasetsart University, Bangkok. December 2000. Retrieved from www.std.cpc.ku.ac.th/delta/deltacp/home.htm in August 2012.

35. Strategic Committee for Water Resource Management. Master Plan on Water Resource Management. January 2012. Retrieved from http://www.rlcps.com/download/rlcps_com/Master%20Plan%20on%20Water%20Resource%20Mngt%20[Eng].pdf.

36. Suiadee, W. and Tingsanchali, T. (2007), A combined simulation-genetic algorithm optimization for optimal rule curves of a reservoir: a case study of the Nam Oon Irrigation Project, Thailand, Hydrological Processes, 21, 3211-3225, 2007. DOI: 10.1002/hyp.6528

37. Thai Meteorological Department (2011). Rainfall and severe flooding over Thailand in 2011. Climatological Center, Meteorological Development Bureau, Nov 2011. Retrieved from www.tmd.go.th/en/event/flood_in_2011.pdf

38. Tospornsampan, J., I. Kita, M. Ishii, Y. Kitamura (2005), Optimization of a multiple reservoir system operation using a combination of genetic algorithm and discrete differential dynamic programming: a case study in Mae Klong system, Thailand. Paddy Water Environ, 3: 29-38, 2005. DOI 10.1007/s10333-005-0070-y.

39. Tospornsampan, J., I. Kita, M. Ishii, Y. Kitamura (2005), Optimization of a multiple reservoir system operation using a simulated annealing: a case study in Mae Klong system, Thailand. Paddy Water Environ, 3: 137-147, 2005. DOI 10.1007/s10333-005-0010-x.

40. Visutimeteegorn, S., Likitdecharote, K., Vongvisessomjai, S. (2007). Effects on the upstream flood inundation caused from the operation of Chao Phraya Dam. Songklanakarin Journal od Science and Technology, 2007, 29(6) : 1661-1674

41. World Bank. Rapid Assessment for Resilient Recovery and Reconstruction Planning. Bangkok, Thailand, 2012. (Joint Publication of World Bank and Global Facility for Disaster Reduction and Recovery (GFDRR)).

42. Yamazaki, D., S. Kanae, H. Kim, T. Oki (2011). A physically based description of floodplain inundation dynamics in a global river routing model. Water Resources Research , vol. 47, no. 4, 2011, DOI: 10.1029/2010WR009726.

43. Yamazaki, D. , T. Oki, and S. Kanae (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, 2009

44. Yatagai, A. O. Arakawa, K. Kamiguchi, H. Kawamoto, M. I. Nodzu and A. Hamada (2009): A 44-year daily gridded precipitation dataset for Asia based on a dense network of rain gauges, SOLA , 5, 137-140, DOI:10.2151/sola.2009-035.