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# An Assessment of the Coupled Hydrology and Management of Northern Thailand's Water Resources in Extreme Climate Conditions

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## Abstract

*The Chao Phraya basin of central Thailand is prone to both flooding and drought and optimal means to mitigate those hazards are nonobvious. In 2011, Thailand experienced some of the worst flooding in its history in a year of record rainfalls, though a number of factors besides exceptional rainfall contribute to regional water-related problems. In the weeks leading up to the 2011 overtopping of the country's largest dam, the Bhumibol, the managers unwaveringly released only a fraction of each day's incoming water until the impending disaster struck. In part of this assessment, a simple System Dynamics model is constructed of the coupled hydrology and human decisionmaking in the operation of the Bhumibol reservoir. Counterintutitively, the model shows that the simple dam management policy employed likely minimized the severity of flooding during the 2011 season. However, in a future climate with differing levels of rainfall, the dam management policy would need to be modified. Another simple model was constructed to examine the governance of Thailand's second-largest dam, the Sirikit, during the drier conditions of 2014. Likewise, no evidence of dam mis-management was found for this facility. These models were combined and extended to include the entirety of the Chao Phraya river basin. This extended version of the model was used as a 'learning laboratory' to examine the effects of several policy options on water management in flood and drought conditions.*

## 1. Introduction

Climate change is altering urban areas around the world, especially coastal regions like Bangkok, Thailand, that are undergoing rapid economic growth coupled with a wave of urbanization, but which are also exposed to extreme weather hazards. In 2011, for example, Thailand experienced the heaviest rainfalls and worst flooding in the previous 50 years, claiming more than 800 lives, displacing millions of people and disrupting the Thai economy. The flood's most severe damage was in the Chao Phraya River Basin, where rivers originate in northern part and flow southward toward the Gulf of Thailand. Along the way, they provide irrigation water to the country's central valley that supplies 30% of the world's exported rice crop, hydroelectric power to Thailand's rapidly industrializing economy and household water to 23 million people, 15 million of whom live in the Bangkok urban area. [Demographia, 2015]

The Chao Phraya river basin has a tropical climate, making it susceptible both to flooding in the rainy season (May – October) and to water shortages at other times of the year. A number of factors besides rainfall also contribute to recurrent flooding and to the 2011 floods in particular. Physical factors played a role, such as deteriorated waterways, insufficient infrastructure and equipment for water control and deforestation in watershed areas. Also, management issues contributed to water problems, including scattered and insufficient data on water resources, lack of long-term plans and financial support, and incoherence among the more than 30 agencies concerned with water management. [Kumpa, 2013]

When a disruption hits, causes and effects are not always closely related in either time or space. So, to reduce vulnerability and build resilience, the Chao Phraya River Basin should be seen in totality using a systems approach. This can give us a clear perspective on the scale, complexities and uncertainties of climate change hazards. Various disciplines define resilience in different ways, but in this work we follow the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report's definition of resilience as 'The capacity of … systems to cope …. responding or reorganizing in ways that maintain their essential function, identity, and structure, while also maintaining the capacity for adaptation, learning, and transformation' [IPCC, 2014]. The ability a system has to survive in a changing environment depends on the rich structure of a number of feedback loops to restore or rebuild the system. [Meadows, 2008]

The purpose of this study is to assess the climate resilience of the upper Chao Phraya basin. We use DNV GL's Systems & Urban Resilience Framework (SURF) to guide the assessment. [Christiansen, 2015] This framework offers a structured and systematic process that provides guidance about the scale, complexities and uncertainties associated with urban areas and climate-change-related hazards in order to enhance long-term decision making. The framework directs attention to aspects that will strengthen resilience in the long term from an integrated systems perspective, by considering the synergetic performance between Ecological systems, Physical systems (like infrastructure), Social systems and Governance systems. Even in simple systems non-intuitive behavior is often observed. Therefore, to further develop the field of resilience, sound principles are needed, including models and simulations.

In this assessment, a simple System Dynamics model is first constructed of the coupled hydrology and human decisionmaking in the operation of the major reservoirs of northern Thailand. In the months leading up to the 2011 overtopping of Thailand's largest dam, the Bhumibol, reservoir managers released only a fraction of each day's incoming water, virtually guaranteeing that a disastrous level of flooding would occur. Our model shows that, non-intuitively, this dam management policy likely minimized the severity of flooding during the 2011 season. In future climate scenarios with differing levels of rainfall, however, the dam management policy would need to be modified.

We then extend the model to consider the entirety of the upper Chao Phraya river basin. We use this extended model as a sort of 'learning lab' in both flooding and drought conditions for exploring not only alternative dam management policies, but also wider options, such as further infrastructure development, forest management, wetland preservation, and related issues.

## 2. Background

The Chao Phraya river basin is the largest in Thailand, encompassing about 160,000km$^2$. The northern part of the basin is mountainous and the rivers that originate there – the Ping, Wang, Yom and Nan – converge at Nakhon Sawan where they form the Chao Phraya river that flows southward to Bangkok and out to the Gulf of Thailand. The Bhumibol Dam, located on the Ping River, represents more than 55% of the reservoir capacity of northern Thailand and has been operating since 1964. The Sirikit Dam, built in 1972 on the Nan River, constitutes an additional 39%. Together, these two dams contain more than 93% of the reservoir capacity of northern Thailand. [Thaiwater, 2016] The primary purpose of these dams is domestic and industrial water supply and hydropower. The dams also function as flood protection. The Yom River has no major dam, although debate surrounding a controversial proposal to dam the river was rekindled by the devastating flooding in 2011.

Figure 1 depicts a schematic representation of the major water stocks and flows in northern Thailand. Various river gauging stations, of which a few important ones are shown, record daily average flow rates. The Thai government provides publicly accessible records of the water volume and flow rates at key points in the country's water infrastructure. Station C.2 at Nakhon Sawan effectively marks the beginning of the Chao Phraya river. This study and other published studies use the flow rate at C.2 station as a proxy for flood and drought severity. [Wongsa, 2014; Wichakul, 2015] Here, we consider a C.2 flow rate above 3500 m$^3$/s to be a flooding situation and below 500 m$^3$/s to indicate a critically low rate. [Thaiwater, 2016]

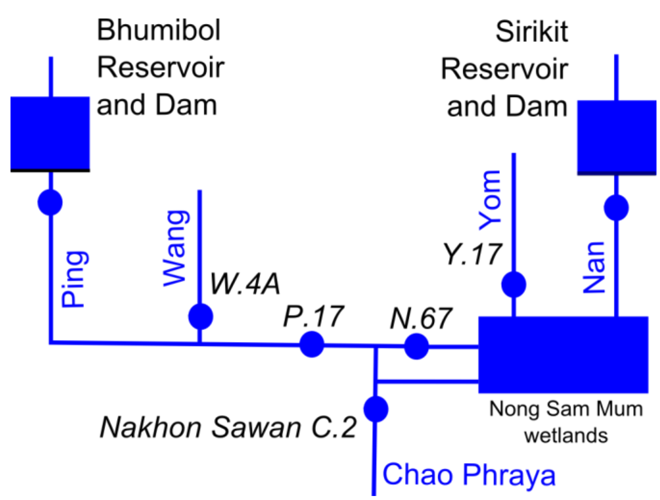


**Figure 1: Schematic diagram of major water stocks and flows in northern Thailand.** The blue dots mark some important river flow gauge stations.

The year 2011 was the rainiest year in decades, with the cumulative annual rainfall being more than 140% of the average level from 1950-1997. [IMPAC-T, 2016] Five major tropical storms contributed to this record season, including Haima in June, Nock-ten in August, Hai Tang and Nesat in September and Nalkae in October. However, the 2011 season was unusually wet from the start. The rainfall in March was more than three times the normal March level and the accumulated rainfall in every month throughout the year thereafter was well above the 1950-1997 average level and also well above the levels in recent years.

The chaotic 2010 season, which saw the Bhumibol and Sirikit reservoirs approach extraordinarily low levels in the summertime followed by a rainy autumn which brought conditions NASA described as "the worst floods in decades", might have also had an effect on water management in 2011. [NASA, 2010] By the end of 2010, cumulative rainfalls were above the 1950-1997 annual average, however, the amounts of water in storage at both major reservoirs at the beginning of 2011 were still at the lower end of both reservoirs' target storage range.

These reservoirs both reached their minimum storage levels for the year in mid-May 2011, where they were then substantially below target storage levels. Throughout an unusually wet summer, managers at the Bhumibol and Sirikit dams retained almost-continually increasing volumes of water until both dams overtopped in early October. The cumulative 2011 water inflow was a record-high value for both dams since their construction.

Thailand is prone not only to flooding, like in 2011, but also to droughts. In recent years, El Niño–Southern Oscillation (ENSO) conditions in the Pacific have favored drier conditions in Southeast Asia, including Thailand. Accumulated rainfalls in 2014 throughout the upper Chao Phraya basin were about 85% of the 1950-1997 average level. In 2015, they were only about 75% of the average, comparable to the drought year of 1993 and about one-half of the level seen in 2011. [IMPAC-T, 2016]

We conduct this assessment using System Dynamics modelling (SD) as it is uniquely suited to understanding strategic problems in complex systems and to giving insight into feedback processes. System Dynamics has been widely used to study urban areas [Forrester, 1961] and, in the last decades, increasingly to study climate change [Sterman *et al.*, 2013]. More recently SD has been used to quantify resilience in systems exposed to climate-related hazards [Simonovic, 2013]. Water resources in Thailand have been studied before and after the 2011 flooding. Some have used SD to study reservoir operations, for example in Canada, but not Thailand. [Ahmad, 2000] A number of other studies have been conducted using hydrological models that consider landscape topology [Cham, 2015; Wongsa, 2014]. Others have looked at long-term socioeconomic recovery in Thailand. [Thongsawas, 2013]

To help build understanding of the dynamics of flooding and drought and the capacity of management policies to minimize the effects of water variability, several related System Dynamics models were constructed and are described in greater detail below.

# 3. Models and Results

To create a platform from which the 2011 flooding event and subsequent drier years could be examined in greater detail, a System Dynamics model was built in STELLA in several variations, including a version that considered only the Bhumibol Dam, one concerned with the Sirikit Dam, and a larger version concerned with the entire basin north of Nakhon Sawan. The purpose of the smaller versions were to assess (and, potentially, improve) the quality of dam management decisions during flooding and drought conditions and to test the robustness of dam management policies under alternative future climate scenarios. The larger version of the model was to be a basis to explore further social, economic, environmental and technical options for mitigating the risk of both flood and drought in central Thailand.

### The Bhumibol Reservoir and Dam Management in 2011

One model is concerned only with the functioning of the Bhumibol reservoir and dam, depicted in the upper-left portion of the schematic diagram in Figure 1 above. We model the flow rate out of the Bhumibol dam and use it to calculate the flow rate at C.2 station.

It is not obvious that the operation of the Bhumibol dam contributed substantially to the 2011 flooding situation. Depite being the largest dam in northern Thailand, only roughly 22.5% of the flow through C.2 station (in the period 1980-1996) came from there. Also, flooding was first reported in the Nakhon Sawan area as early as August 2011, two months before the Bhumibol dam (and Sirikit dam) overtopped.

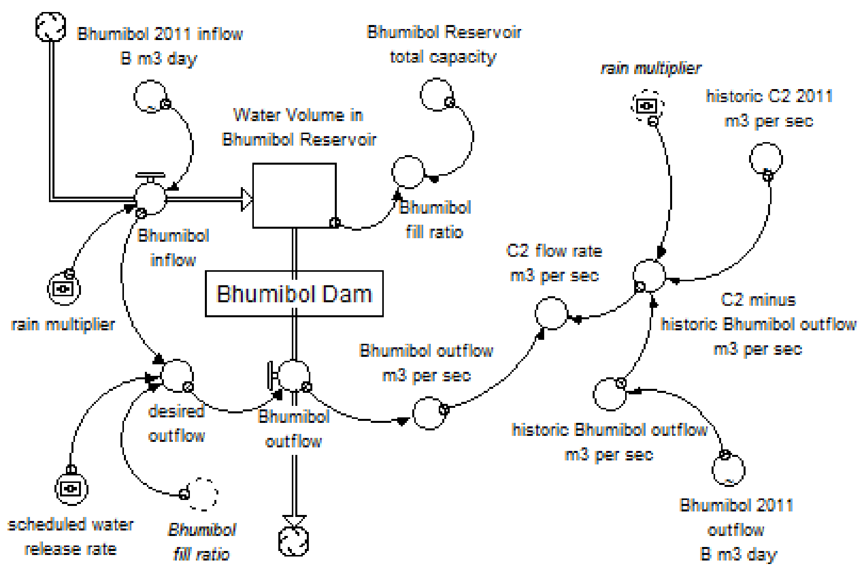


**Figure 2: Stock-and-flow diagram of the Bhumibol Reservoir and Dam in the 2011 season.** The label 'Bhumibol Dam' is only for visual reference.

In this model, shown in Figure 2, there is only one stock, the 'Water Volume in the Bhumibol Reservoir'. Water runs into the reservoir at a rate determined from the measured daily inflow rates observed in 2011. A 'rain multiplier' parameter allows the inflow rate to the Bhumibol reservoir (and the flow rates of all other waterways in northern Thailand) to be scaled up or down by a constant factor to test alternative rainfall scenarios. For the first pass of analysis, this parameter was simply left as '1', thus exactly reproducing the specific pattern of rainfall seen in 2011.

At the actual dam, water outflow is set based on the water level in the reservoir (in meters above sea level), shown in Table 1. Effectively, this policy embodies a balancing feedback loop, as a higher reservoir water level results in a higher scheduled reservoir outflow rate, thus acting to decrease the reservoir level.

| **Bhumibol Reservoir water level** (meters above mean sea level) | **Scheduled water release rate** (percentage of inflow rate) |
|---|---|
| 256.0 | 30% |
| 257.0 | 50% |
| 258.0 | 70% |
| 259.5 | 100% |

**Table 1: Scheduled water release rate as a function of water level in the Bhumibol Reservoir.** *Source:* Hoshikawa, 2015

The graph in Figure 3 below depicts the actual historical water release rate from the Bhumibol Dam during 2011 by day of the year. The early portion of the year is discarded because very low water inflow rates during that time mean that the outflow (as a percentage of the inflow) is frequently an extremely large number or, in some cases, is mathematically undefined due to division by zero.

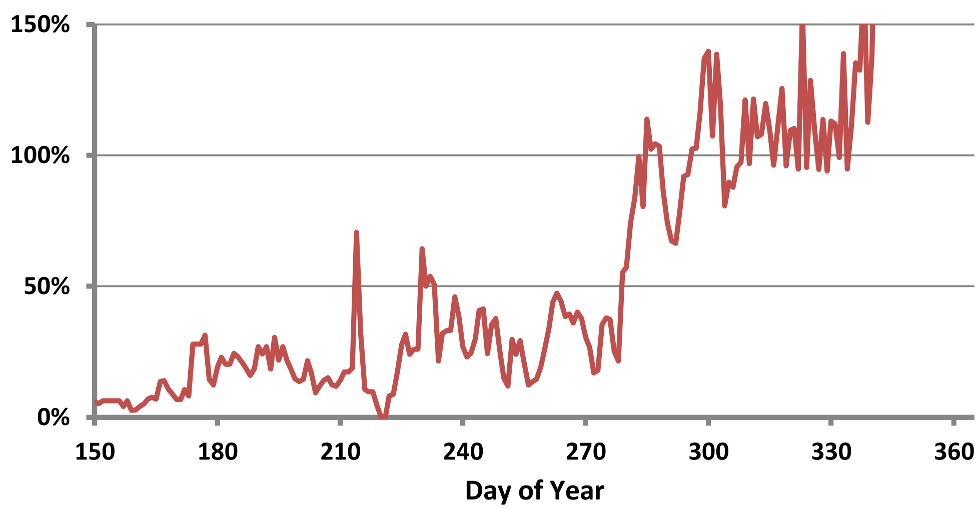


**Figure 3: Daily water outflow as a percentage of inflow at the Bhumibol reservoir in 2011.** A value of 100% means that outflow equals inflow. Values less than 100% mean that the outflow rate was less than the inflow.

We can see in Figure 3 that the outflow rate from the Bhumibol reservoir in 2011 was always less than the inflow rate (that is, less than a value of 100%) until about Day 283 (9 October 2011), when the reservoir was completely full. In the two months leading up to the overtopping of the dam, from the time of storm Nock-ten (just after day 210), the outflow rate averaged about 30% of the inflow rate. That is, every day as water flowed into the reservoir, about 30% of that inflow was released from the dam and the remaining 70% retained in the reservoir. It was literally only in the last few days before the reservoir reached full capacity that the inflow rate was stepped up to 50% and then 70% of the inflow rate.

When the reservoir reaches its peak capacity, all of the incoming water is released immediately as the reservoir had no more ability to store water. Thus, even though the water authorities specified a table of scheduled release rates whose value depends on the amount of water in the reservoir, in practice, from the time of the Nock-ten storm until the time the Bhumibol reservoir was at its capacity, the authorities essentially only used two values: 30% when the reservoir was not completely full and 100% when it was.

We start our simulation at Day 210 (29 July 2011), just as the rains from tropical storm Nock-ten were about to reach the Bhumibol reservoir and the dam's release rate started its two month period of averaging about 30% of the daily inflow. The volume of water in the reservoir was 8.46 Billion $m^3$ at that time, compared to a reservoir capacity of 13.46 $Bm^3$, leaving about 5 $Bm^3$ of usable reservoir space.

With the model we can assess the wisdom of the Bhumibol dam authority's decision to maintain that (relatively) constant release rate of 30%. In the model, the 'scheduled water release rate' is a user-defined constant which defaults to 0.30 (30%). (The actual ratio of cumulative water outflow from the dam from Day 210 until it overtopped on Day 282 was 29.7% of the cumulative inflow.)

The ratio of the current 'Water Volume in the Bhumibol Reservoir' to the 'Bhumibol Reservoir total capacity' is referred to as the 'Bhumibol fill ratio'. When this ratio is equal to 1 (that is, the reservoir is full), the outflow from the dam ('Bhumibol outflow') is set equal to the inflow ('Bhumibol inflow'). Otherwise, the outflow is simply the inflow multiplied by the 'scheduled water release rate'.

The structure on the right-hand side of Figure 2 is concerned with the Bhumibol dam's contribution to the flow rate at C.2 station at Nakhon Sawan. From historical flow records it is seen that it takes about 7 days for water that departs the Bhumibol dam to reach the C.2 river gauge. Figure 4 below shows the historical reported flow rates at Nakhon Sawan C.2 river flow gauging station and from the Bhumibol dam. This historical record of dam outflow rates (delayed by 7 days) was subtracted from the C.2 station flow values to get the values of 'historic C2 minus Bhumibol outflow m3 per sec'. This way, the modeled values of the Bhumibol outflow could be added to 'historic C2 minus Bhumibol outflow m3 per sec' to obtain what the C.2 flow rate might have been under alternate dam management policies.

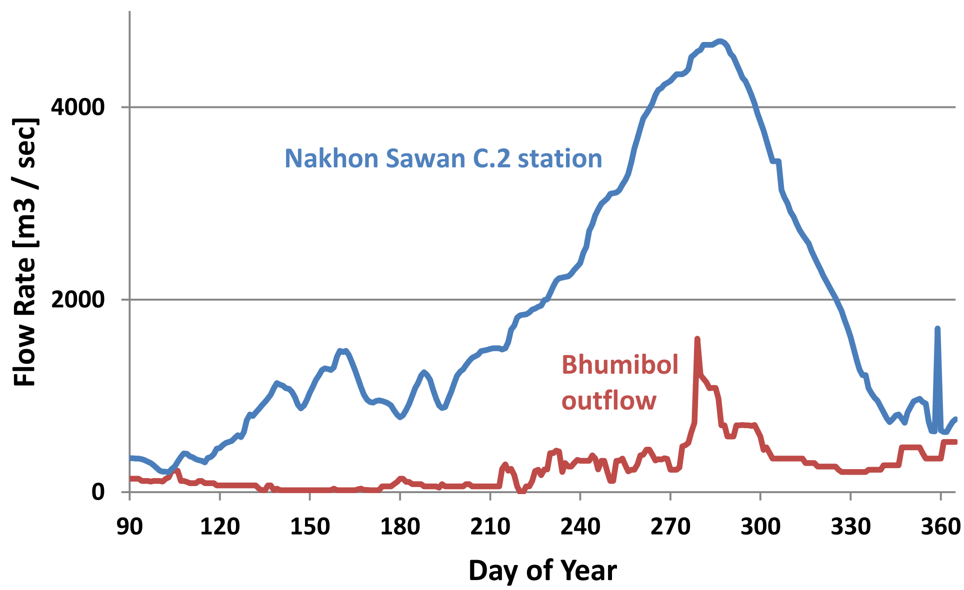


**Figure 4: Historical reported flow rates at Nakhon Sawan C.2 river flow gauging station (blue) and from the Bhumibol dam (red) in 2011.**

In 2011, the maximum flow limit at C.2 was 3500 $m^3/s$, beyond which flooding occurs, a value that was exceeded from mid-September (roughly Day 260) until the end of October (roughly Day 300), reaching a reported peak value of 4686 $m^3/s$ in mid-October (Day 287).

Figure 5 below shows simulation results depicting the peak C.2 station flow rate (that is, its maximum value at any day during the simulated year) as a function of the 'scheduled water release rate'. In the simulation, the C.2 flow rate was smoothed using the SMTH1 (first-order smoothing function) with an averaging time of 7 days, to avoid single-day peak values skewing results.

The 'rain multiplier' of 1.0 corresponds to the case where the actual 2011 historical sequence of daily rainfall volumes was used. At very low values of the 'scheduled water release rate', the Bhumibol dam fills quickly, resulting in the dam losing its ability to store water when the rainy season arrives. This causes the maximum flow rate at C.2 station to be higher than it would have been had water instead been released. Conversely, large values of the 'scheduled water release rate' result in the reservoir never reaching its capacity and therefore having unused space behind the dam that could have been used to retain water, thus also increasing flood severity.

The marked point corresponds to the actual 2011 average water release rate, which was about 30%. For the amount of rain that fell that year, this value is close to minimizing the maximum flow rate at C.2 station.

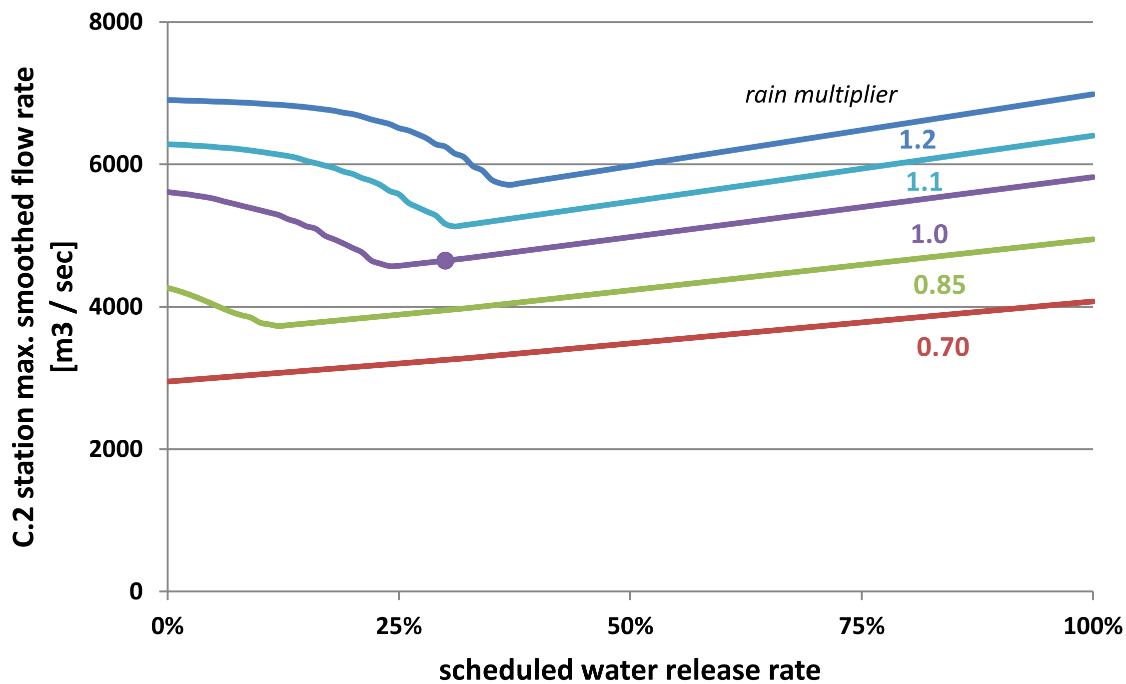


**Figure 5: Maximum flow rate at Nakhon Sawan C.2 river flow gauging station as a function of the 'scheduled water release rate' policy.** Included are graphs for the actual 2011 record of daily rainfall (multiplier = 1.0) and for cases of lower and higher rainfall amounts.

The simulations show that, for 2011 rainfalls, no value of the 'scheduled water release rate' was found to generate a maximum C.2 flow rate below the 3500 $m^3/s$ value that signifies flood conditions. Simulations were conducted in which the historical sequence of 2011 rainfall volumes was scaled up or down according to the value of the rain multiplier. Since the rainfall in 2011 was about 140% of an average year, the rain multiplier of 0.70 roughly corresponds to the average year's case in 1950-1997 (0.70 ~ 1/1.4). The Fifth IPCC Assessment Report, AR5, concludes that it is very likely that monsoon-related precipitation extremes will increase in the region in coming decades. [IPCC, 2014] Figure 5 shows that, for two hypothesized future scenarios where the daily rainfall rates were 10% or 20% higher than in the 2011 season, the flooding severity, understandably, is expected to increase and also that the optimal 'scheduled water release rate' would increase as well.

A simulation was also conducted in which the Bhumibol reservoir was emptied on Day 250 (just prior to the start of flooding at C.2 station) to its 'dead water' level of 3.7 billion $m^3$ and then all incoming water retained until the reservoir filled. Even in this case, the maximum flow rate for 2011 at C.2 station would still have been above 3500 $m^3/s$. Since 'C2 minus Bhumibol outflow' is greater than 3500 $m^3/s$, there is no water management policy at the Bhumibol dam for 2011 that would have prevented the flooding on the Chao Phraya.

**The Sirikit Reservoir and Dam Management in 2014**

Reservoir management in drought conditions differs from management in times of excessive water. Figure 6 below shows the reported outflow-to-inflow ratio for the Sirikit dam, on the Nan river, as a function of the absolute inflow rate (in millions of $m^3$ per day), on a log-log scale.

There are two distinct 'regimes' in outflow policy. In the early portion of the year (January - July), there is a linear relationship between the outflow-to-inflow ratio and the inflow to the reservoir. In the later portion of the year (September - November), there is a different relationship, though still linear. In periods around the months of August and December, transitional policies are used. (The Bhumibol reservoir shows a similar behavior pattern for 2014. That is, the dam's release rate is not simply a constant fraction of the inflow rate – which would appear as a simple horizontal pattern – as it was in the 2011 flood year.)

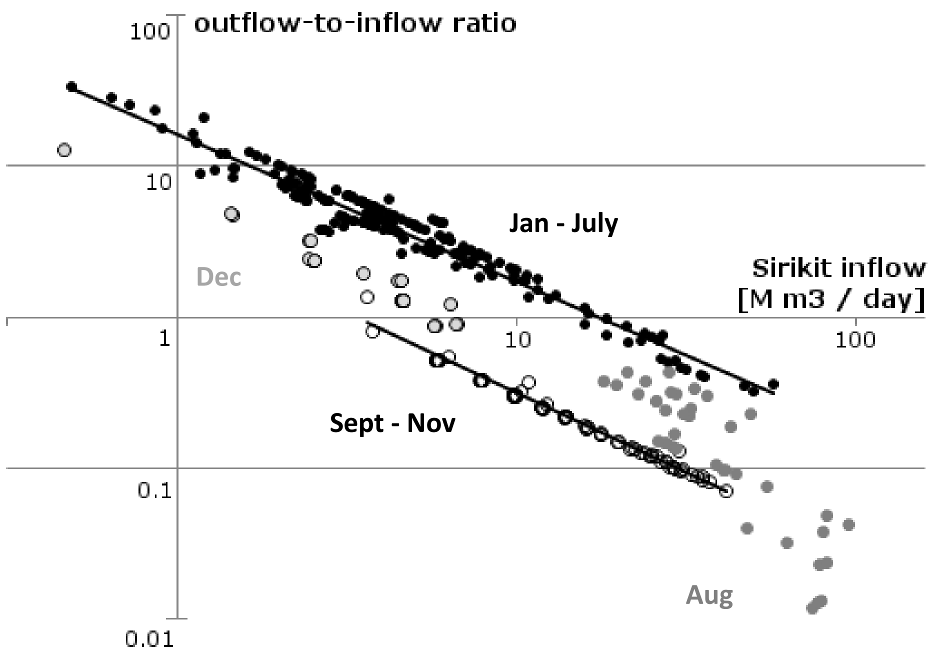


**Figure 7: The outflow-to-inflow ratio at the Sirikit Dam in 2014 as a function of the absolute water inflow rate (in millions of $m^3$ per day).** The early portion of the year and late portion of the year follow a linear log-log relationship, with roughly month-long transitional periods in August and December.

For the simulation results shown below, the outflow-to-inflow ratio for the Sirikit reservoir ('Sirikit outflow fraction') was treated as $Y = m_e x + b_e$ (with $m_e = -0.84$ and $b_e = 1.167$) before Day 210 and $Y = m_l x + b_l$ (with $m_l = -1.02$ and $b_l = 0.501$) after Day 210. These values were found to reproduce the historical Sirikit reservoir levels to within a small error for most of the year.

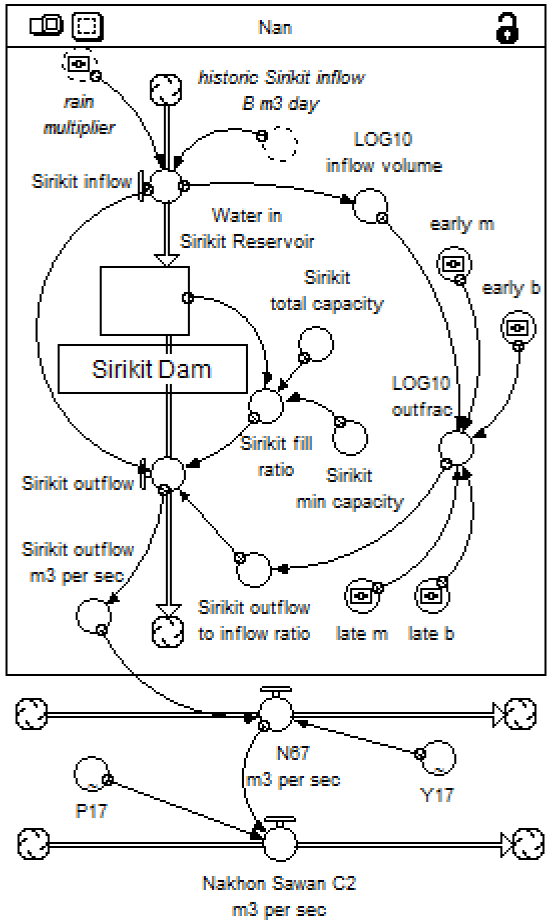


**Figure 8: Stock-and-flow diagram of the Sirikit Reservoir and Dam in the 2014 season.** The label 'Sirikit Dam' is only for visual reference.

The model of the Sirikit reservoir and dam is constructed similarly to the model of the Bhumibol. The 2014 historical record of rainfall determines the inflow rate to the reservoir ('Sirikit inflow'). A 'rain multiplier' allows this historical record to be scaled up or down each day by a fixed amount.

The calculation of the 'Sirikit fill ratio', which equals 0 when it is at its minimum 'dead water' level and 1 when the reservoir is at its capacity, allows the outflow from the dam to be shut off (or set equal to the inflow) depending on if the reservoir is full (or empty).

The outflow from the reservoir ('Sirikit outflow') is simply the inflow multiplied by the 'Sirikit outflow to inflow ratio', whose value follows the piecewise log-log linear relationships seen in Figure 7 and described in the text above. Representing the outflow relationship in this manner allows alternative policies for the governance of the dam to be tested by simply adjusting the values of the outflow-governing parameters.

The flow rate at C.2 station is calculated by adding the historical records of the Y.17 station and the P.17 station to the simulated outflow from the Sirikit reservoir. Again, the flow rate through C.2 station can serve as a metric of quality of overall river management, as a minimum flow rate is necessary to provide irrigation water, drinking water, and other water for human use, but also as water is needed naturally for the wetlands near Nakhon Sawan and wildlife along the river. For this analysis, we would like to find policies that maximize the number of days, after Day 90, in which the flow rate exceeds 500 $m^3$/s. (Day 90 was chosen as the staring date for measuring as the river naturally has a very low flow rate in the earliest months of the year. Even in March 2011, the wettest March on record, the average flow rate for the month was around this value and actually exceeded 500 $m^3$/s for only 12 days in the month.)

The one noteworthy parameter that affects the number of days where the C.2 station exceeds 500 $m^3$/s is 'early m', or $m_e$, the slope of the log-log outflow relationship in the portion of the year before Day 210. Figure 9 shows the number of such days for the case of the best-fit value for the 'early m' parameter (-0.84) compared to other values near this best-fit value.

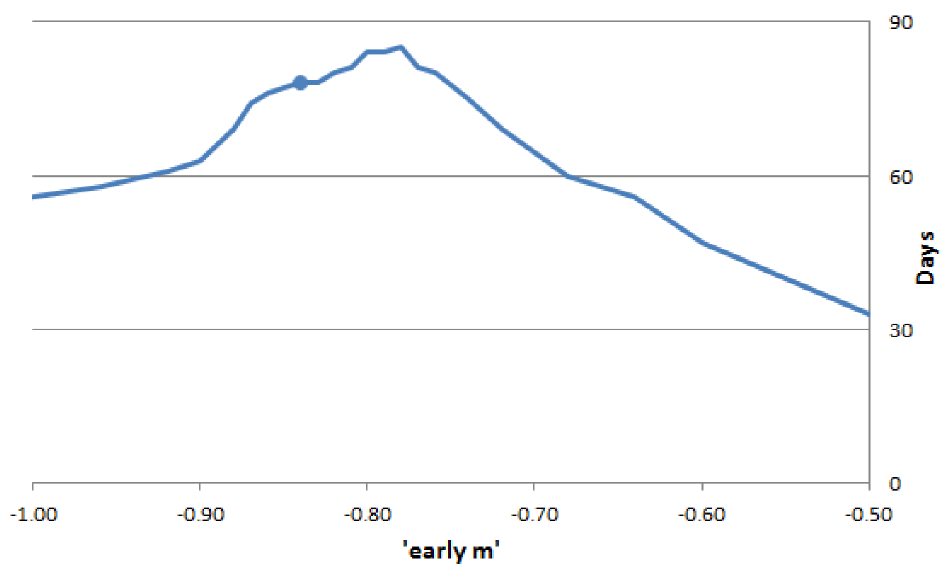


**Figure 9: Number of days (after Day 90) that the flow rate at C.2 station exceeds 500 $m^3$/s, as a function of 'early m' ($m_e$).** The dot marks the value that is the best fit (-0.84) for the historical record of outflow ratios.

It is seen that the 'early m' value of -0.84, the value that corresponds to the Sirikit reservoir outflow values which were actually recorded in 2014, nearly maximizes the number of days where the C.2 station's flow is above 500 $m^3$/s, though a value of about -0.78 results in about 10% more such days. Though authorities have been criticized for mis-management of water resources in these drier conditions, we again find no evidence supporting these claims pertaining to the Sirikit dam.

**Integrated model of water dynamics in northern Thailand**

Numerous policies have been suggested to make Thailand more resilient in the long term to these extremes in climate conditions, including construction of additional dams (for example, a proposed 1.15 billion $m^3$ reservoir at Kaeng Suea Ten on the Yom River), reforestation (or halting of deforestation) and alternate dam management policies in the Ping and Nan basins. [Cham, 2015] As even simple systems can exhibit non-intuitive behaviors, the Bhumibol and Sirikit models above were combined and extended to include all four river basins north of Nakhon Sawan, as is seen in Figure 9 below.

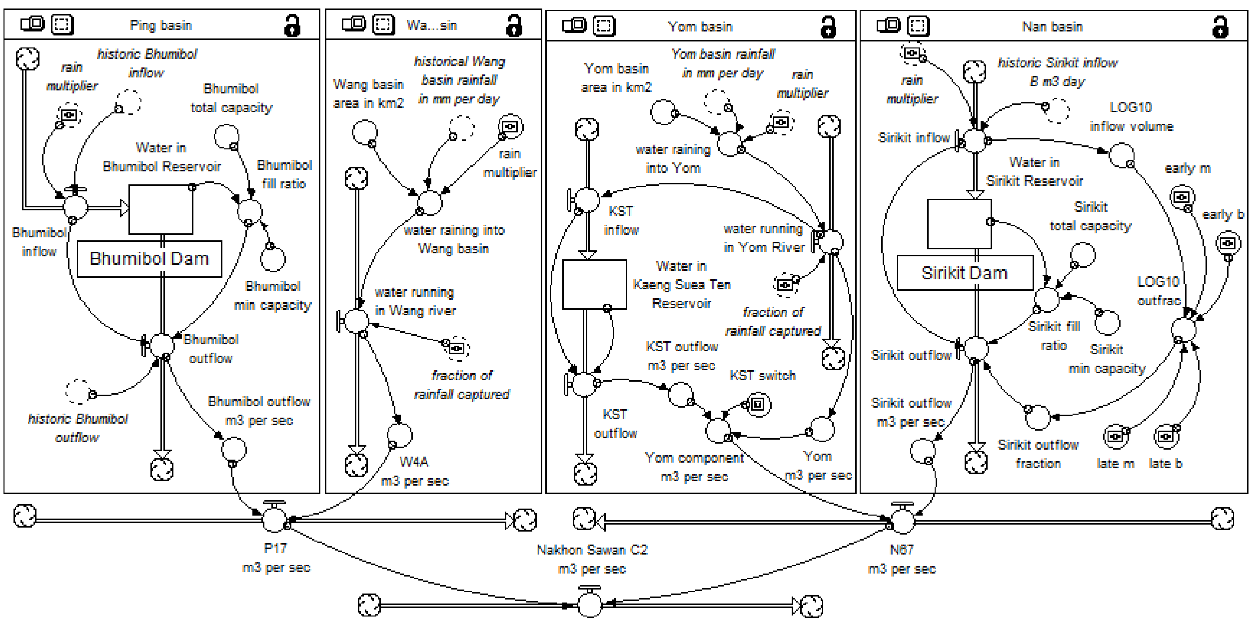


**Figure 10: Model of water dynamics in northern Thailand.** The sub-model dealing with the Bhumibol reservoir is depicted at far left; the Sirikit, at right.

This integrated model provides a 'learning laboratory' type environment where these policies can be tested. For example, a hypothetical dam on the Yom River can be switched 'on' or 'off' to see the impact of its existence on flood severity and drought impacts. The effect of deforestation is incorporated in the form of a 'fraction of rainfall captured' parameter that takes on higher or lower values depending on amount of forest cover in each sub-basin. The rain multiplier can be adjusted on a subbasin-by-subbasin basis to change both the overall level of rainfall and also its distribution across northern Thailand depending on various climate scenarios. Or, any combination of these factors can be simulated.

Additionally, the model serves as a basis to be extended for specific investigations, currently be conducted, concerning the effects of (and on) agriculture, industry, wildlife, groundwater usage and related issues.

# 4. Summary

In this study we constructed a simple model of the operation of the Bhumibol dam, the largest dam and reservoir in northern Thailand. The historical records of water flow rates out of the Bhumibol dam were subtracted from historical records of the flow rate through the C.2 river gauge station to obtain an estimate of the 'baseline' flow rate at C.2 that was not attributable to the Bhumibol dam. Flow rates at C.2 station are used as a proxy for flood and drought severity. The flow rates out of the Bhumibol dam were then simulated for various alternative dam management policies and various alternative rainfall scenarios. These simulated values were combined with the baseline historical value to obtain estimates of the C.2 flow rate under these alternative scenarios.

These simulations indicate that the policy used in 2011 in the months leading up to the Bhumibol dam's catastrophic overtopping (that is, the policy of releasing a constant 30% of the daily reservoir inflow) was, counterintuitively, close to the policy that would minimize flooding. Additionally, it was found that flow rates at C.2 station above 3500 $m^3$/sec, which is the value identified by the Thai government as the river's maximum flow rate, would have occurred under any policy for managing the Bhumibol dam, including draining the reservoir to its minimum 'dead water' value just prior to storm Nock-ten and then retaining all of the incoming water until the Bhumibol dam overtopped.

The simulations of the Bhumibol version of the model also found that the water release schedule would need to be modified for future climate scenarios where different levels of rainfall occurred.

Similarly, a model was constructed of water management dynamics for the Sirikit dam and reservoir, focusing on the drier 2014 conditions. In this case, the outflow policy was more complicated than the simple one employed at the Bhumibol dam in the 2011 flooding season. However, a piecewise linear log-log relationship was found to reproduce historical reservoir levels to within a small error. Alternative outflow management parameter values were tested, in which it was found again that the actual management policy employed in 2014 was nearly optimal as gauged by the number of days in which the flow rate at C.2 station exceeded a certain minimum value (500 $m^3$/s).

Thus, our investigations find no evidence of dam mis-management at either of northern Thailand's two largest reservoirs in the 2011 or 2014 seasons. Policies for improving the resilience of the Chao Phraya basin to future extreme climate scenarios were investigated by use of an extended 'learning laboratory' version of the model that incorporates all of the sub-basins found in northern Thailand.

# 5. References

Data Sources:

- Daily flow rates at river gauge stations were obtained from the Thai Royal Irrigation Department: water.rid.go.th/flood/plan_new/chaophaya/Chao_up07102011.jpg, e.g. is for 07 October 211
- Additional historical river flow rate data is available from: hydro.iis.u-tokyo.ac.jp/GAME-T/GAIN-T/routine/rid-river/disc_d.html and also from hydro-1.net/08HYDRO/HD-04/4-10.html
- Rainfall data came from: impact-www.eng.ku.ac.th/chaophraya-auto/ [IMPAC-T, 2016]
- Reservoir volume, inflow and outflow data were obtained from Thaiwater (www.thaiwater.net/), a website of the Hydro and Agro Informatics Institute of Thailand. [Thaiwater, 2016]


Ahmad, S., Simonovic, S.P., 'System Dynamics Modeling of Reservoir Operations for Flood Management', Journal of Computing Civil Engineering, July 2000

Cham, T.C. and Mitani, Y., Flood control and loss estimation for paddy field at midstream of Chao Phraya River Basin, Thailand. IOP Conf. Series: Earth and Environmental Science 26 (2015) 012022, doi:10.1088/1755-1315/26/1/012022

Chia, C.T., Yasuhiro, M., Hiroaki, I., 'Simulation of Modeling Approach for Flood Condition and Proposed Flood Protection at Midstream of Chao Phraya River Basin, Thailand', American Journal of Environmental Protection, 3(3) 84-94, 2015

Christiansen, A.F. A systems perspective for resilient cities. European Climate Change Adaptation Conference (ECCA), 12.-14. May 2015, Copenhagen, Denmark

Demographia World Urban Areas, 11th Annual Edition 20, www.demographia.com/db-worldua.pdf, 2015

Forrester, J.W., Urban Dynamics. Pegasus Communications: Waltham, MA. 1969

Hanasaki, N., Kanae, S., Musiake, K., 'Simulating the discharge of the Chao Phraya River taking into account reservoir operation', Water Resources Systems—Hydrological Risk, Management and Development, July 2003

Hoshikawa K., 'Phumiphon Dam Operations During the 2011 Floods', in Tamada Y., Hoshikawa K., and Funatsu T. (eds) The 2011 Thailand Floods: Lessons and Records, February 2015 (english translation publication date)

IMPAC-T, Integrated Study on Hydro-Meteorological Prediction and Adaptation to Climate Change in Thailand, impact-www.eng.ku.ac.th/chaophraya-auto/, updated daily, 2016

IPCC, Part A. Global and Sectoral Aspects and Asia, Chapter 24. In: Climate Change 2014: Impacts, Adaptability and Vulnerability. Volume 1, Global and Sectoral Aspects. Fifth Assessment Report of the Intergovernmental Panel on Climate Change. 2014

Komori, D., Nakamura, S., Kiguchi, M., Nishijima, A., Yamazaki, D., Suzuki, S., Kawasaki, A. Oki, K., Oki, T., 'Characteristics of the 2011 Chao Phraya River flood in Central Thailand', Hydrological Research Letters, 6, 41–46, 2012

Kumpa, L., 'Building National Resilience in the Context of Recovery from Thailand Flood 2011', 2013

Kure, S., Tebakari, T., 'Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand', Hydrological Research Letters, doi: 10.3178/hrl.6.53, January 2012

NASA, http://earthobservatory.nasa.gov/NaturalHazards/view.php?id=46693, October 2010

Poaponsakorn, N., Meethom, P., 'Impact of the 2011 Floods, and Flood Management in Thailand', in Sawada, Y. and S. Oum (eds.), Economic and Welfare Impacts of Disasters in East Asia and Policy Responses. ERIA Research Project Report, Jakarta: ERIA. 247-310, 2011

Simonovic, S., Peck, A., 'Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities Quantification Framework', British Journal of Environment & Climate Change, 3(3): 378-401, 2013

Sterman, J., Fiddaman, T., Franck, T., Jones, A., McCauley, S., Rice, P., Sawin, E., Siegel, L. Management Flight Simulators to Support Climate Negotiations. Environmental Modeling and Software, 44: 122-135. 2013

Thaiwater, http://www.thaiwater.net/DATA/REPORT/php/rid_bigcm.php?sdate=2011-01-01, where the last digits determine the year, month and day. Updated daily

Thongsawas, P., Paisarnsrisomsuk, S., Wiratchotisatian, P., 'Flood damage in Bangkok: disaster or an opportunity for creative destruction', Worcester Polytechnic Institute, 2013

Wichakul, S., Tachikawa, Y., Shiiba, M., Yorozu, K., 'River Discharge Assessment under a Changing Climate in the Chao Phraya River, Thailand by using MRI-AGCM3.2S', THA 2015 International Conference on "Climate Change and Water & Environmental Management in Monsoon Asia", Bangkok, Thailand, 28-30 January 2015

Wongsa, S., ‘Simulation of Thailand Flood 2011’, IACSIT International Journal of Engineering and Technology, Vol. 6, No. 6, December 2014

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