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Characteristics of the 2011 Chao Phraya River flood in Central Thailand

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Abstract:

A massive flood, the maximum ever recorded in Thailand, struck the Chao Phraya River in 2011. The total rainfall during the 2011 rainy season was 1,439 mm, which was 143% of the average rainy season rainfall during the period 1982–2002. Although the gigantic Bhumipol and Sirikit dams stored approximately 10 billion m^3 by early October, the total flood volume was estimated to be 15 billion m^3. This flood caused tremendous damage, including 813 dead nationwide, seven industrial estates, and 804 companies with inundation damage, and total losses estimated at 1.36 trillion baht (approximately 3.5 trillion yen).

The Chao Phraya River watershed has experienced many floods in the past, and floods on the same scale as the 2011 flood are expected to occur in the future. Therefore, to prepare of the next flood disaster, it is essential to understand the characteristics of the 2011 Chao Phraya River Flood. This paper proposes countermeasures for preventing major flood damage in the future.

KEYWORDS the 2011 Chao Phraya River flood; the Chao Phraya River; record-high rainfall; evaporation; gentle river gradient; the Bhumipol and Sirikit Dam reservoirs

INTRODUCTION

A massive flood, the maximum ever recorded in Thailand, struck the Chao Phraya River during August through December 2011. This flood caused tremendous damage, including 813 dead and 3 missing nationwide (as of Jan. 8, 2012; Thai Ministry of Interior, 2012). The area of damaged agricultural land throughout Thailand peaked on Nov. 14 at 18,291 km^2 (Thai Ministry of Interior, 2012), and the total flood volume was estimated to be 15 billion m^3. In the industrial sector, 7 industrial estates and 804 companies suffered inundation damage, and of those, 449 companies were Japanese (Japan External Trade Organization, 2011). The World Bank (as of Dec., 2011) estimates 660 billion baht in damage to property such as real estate, and 700 billion baht in opportunity loses, for a total loss of 1.36 trillion baht (approximately 3.5 trillion yen) due to this flood. The real economic growth rate in 2011 is expected to decelerate from 3.7% to 0.1% (National Economic and Social Development Board, 2012). Many floods have been experienced in the past in the Chao Phraya River watershed, and floods on the same scale as the 2011 flood are expected to occur in the future. In developing proper assessments and flood control measures to prepare for the next flood disaster, it is important to develop a solid understanding of the actual situation surrounding this flood, and get to the root causes of the flood damage.

OVERVIEW OF THE CHAO PHRAYA RIVER

Figure 1 shows a diagram of the Chao Phraya River watershed, and the inundation situation on Oct. 18, 2011. The area of the Chao Phraya River watershed is approximately 160,000 km^2, which is 30% of the total area of Thailand. The Chao Phraya River watershed is divided into an upper watershed and lower watershed by the narrowed section at Nakhon Sawan.

In the upper watershed, the Ping River (watershed area 33,900 km^2), Wang River (watershed area 10,800 km^2), Yom River (watershed area 23,600 km^2), and Nan River (watershed area 34,300 km^2) flow down from the northern mountain system and join together at Nakhon Sawan. The total area of the upper watershed is approximately 110,000 km^2. For the purposes of irrigation and power generation, the Bhumibol Dam (reservoir capacity 13.5 billion m^3, catchment area 26,000 km^2, built in 1964) was constructed on the Ping River, and the Sirikit Dam (reservoir capacity 9.5 billion m^3, catchment area 13,000 km^2, built in 1974) was constructed on the Nan River. Another 5 dams have been constructed for the Ping, Wang, and Nan River watersheds, bringing the total reservoir capacity including the Bhumibol and Sirikit Dam reservoirs to 24.7 billion m^3. In the Yom River watershed, plans have been made to build the Kaeng Sua Ten River Dam (1.15 billion m^3) and a conduit to the Sirikit Dam reservoir, but these are yet to be constructed.

In the lower watershed, the Chao Phraya River joins with the Sakae Krang River (watershed area 5,000 km^2) from the right bank between Nakhon Sawan and the Chao Phraya Dam (built in 1957), which was constructed 96 km downstream from Nakhon Sawan. This dam controls the discharge of the Chao Phraya River, and irrigation water is diverted to the left and right banks of the river. The Tha Chin River and the Noi River branch off from the right bank upstream of the dam. The Tha Chin River flows down to

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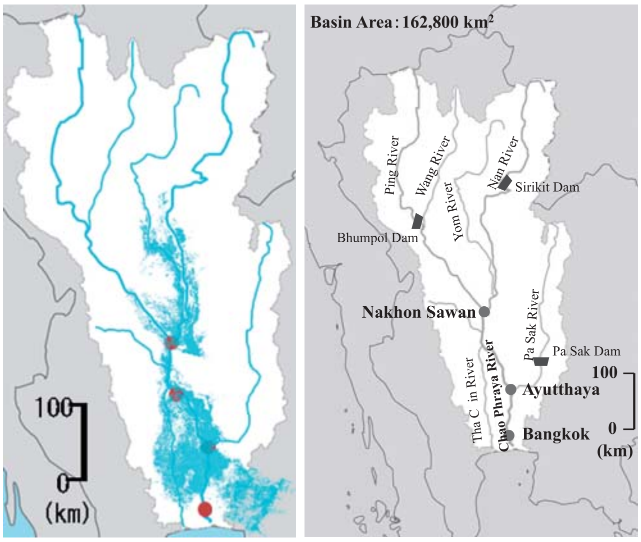

Figure 1. Diagram of the Chao Phraya River watershed (right), and the inundation situation as of Oct. 18, 2011 (left).

the sea, but the Noi River joins the Chao Phraya River south of Ayutthaya. Downstream of Ayutthaya, the Chao Phraya River joins with the Pa Sak River (watershed area 14,300 km^2). The Pa Sak River Dam (960 million m^3) was constructed on the Pa Sak River in 1999, and another 2 dams (total 409 million m^3) have been built on the right bank of the Tha Chin River.

Rivers in Thailand are generally gently sloped rivers, with gradients in the aforementioned lower watershed of the Chao Phraya River and the downstream parts of the Nan and Yom Rivers, particularly gentle. For example, the elevations in the lower watershed of Chao Phraya River are 15 m in the area around the Chao Phraya Dam located 186 km from the river's mouth, 7 m in the area around Ayutthaya located 90 km from the river's mouth, and 5 m around Bangkok, giving river gradients of around 1/10,000 to 1/15,000. Generally, discharge capacity increases on the downstream side where rivers come together, but the Chao Phraya River lacks downstream discharge capacity (Figure S1). For this reason, the flooding from upstream makes water levels rise downstream, dispersing flooding onto the floodplain. By the same token, in many tributaries which flow into the Chao Phraya River, floodwater from their own watersheds cannot flow into the Chao Phraya river due to elevated water levels in the Chao Phraya River itself, and the flooding is dispersed onto floodplains around the tributaries. That is, in the lower watershed, flooded areas naturally expand along the river, and mitigate the severity of flood disasters in the downstream sections of the Chao Phraya River.

Historically, Thailand has taken advantage of these river characteristics to control flooding of the Chao Phraya River. Flooding is controlled by storing water in the dam reservoirs in the upper watershed of the Chao Phraya River, and by expanding the flood area to decrease the floodwater level in the lower watershed. Since the flood flow is slow, due to the gentle gradient of the Chao Phraya River watershed, flooding seldom causes real damage to human life if the inundation level is below the knee. In addition, floodwaters can also be effectively evaporated by widely expanding the flood area. According to a flood survey report by the Japan International Cooperation Agency (JICA) released in 1999, the discharge capacity of the Chao Phraya River at Bangkok is only about a 3-year probability river discharge if there is no flooding from the Chao Phraya Dam to Bangkok (JICA, 1999). However, floods have not occurred frequently in Bangkok because most of the excess water is stored upstream in floodplains of the Chao Phraya River lower watershed.

HYDROMETEOROLOGICAL SETTING OF THE CHAO PHRAYA RIVER

Thailand has a tropical savanna climate and basically two seasons: the rainy season (May–October) and the dry season (November–April). Figure 2 shows monthly and total rainfall for the watersheds. Due to the limited availability of data, monthly and total rainfalls were calibrated from 15 weather stations of the Thai Meteorological Agency from May to October in 1982–2002 and in 2011 using the Thiessen method. In flood years (1983 and 1995) when Bangkok was inundated (Somkiat, 2009), monthly rainfall in July and August exceeded the monthly average for the period 1982–2002. In 1983, rainfall was also higher than average in October, being the highest recorded during 1982–2002. The highest August rainfall during 1982–2002 was recorded in 1995. Total rainfall in the rainy season exceeded the average total rainfall (1,003 mm) in both flood years, being 1,147 mm and 1,153 mm in 1993 and 1995, respectively. In 2011, monthly rainfall exceeded the average monthly rainfall for the entire rainy season, with the higher July and September rainfall than recorded during 1982–2002. The total rainfall during the 2011 rainy season was 1,439 mm, which is 143% of the average rainy season rainfall during 1982–2002. In addition, 5 typhoons made landfall in Thailand in 2011. The average number of typhoons per year during 1951–2011 was 1.5, with 5 or more typhoons making landfall in Thailand in a year only three times: 1964, 1971 and 1972. The prevalence of typhoons strongly influenced the rainfall in 2011.

On the other hand, it can be assumed that there was no major difference in rainy season evaporation and infiltration rates between the flood year and other years, because rice paddies, namely wet surface, are consistently the major type of land use in Thailand. Taking, for example, observation data (1971–2000) by the Thai Meteorological Department (Phitsanulok observatory; 16°47'N, 100°16'E; 45 m above mean sea level) in the Yom River watershed, which has many rain-fed paddies, the normal values of cumulative rainfall and pan evaporation in the rainy season were, respectively, 1,192 mm and 842 mm. Considering the water budget, the 350 mm difference is regarded simply as runoff, which flows into rivers. Assuming there is almost no change in evaporation rates, it is estimated that runoff was approximately 860 mm during 2011, which is 246% of normal values.

Figure 3 shows the total discharge of the Chao Phraya River at Nakhon Sawan from June to October in 1956–1999 and 2011. The total discharge in 2011 was 32.6 billion m^3, which was 232% of the average value for 1956–1999. This is a similar value to previous estimates of runoff at the

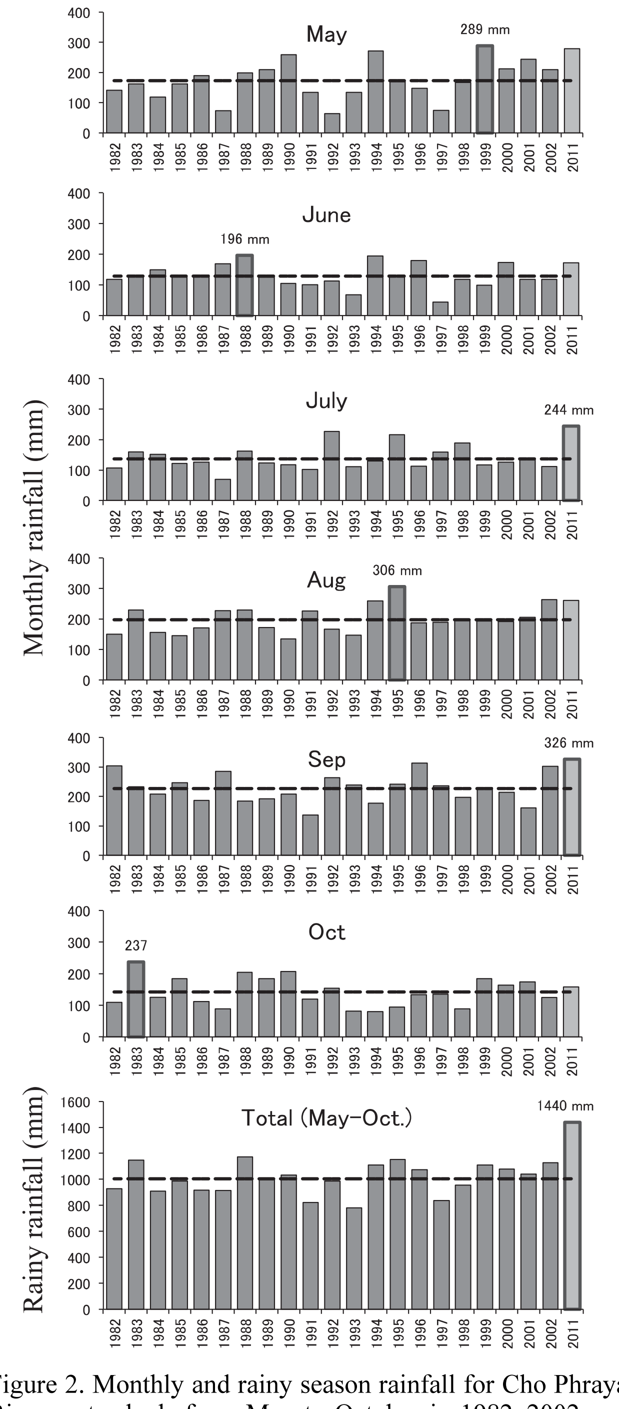

Figure 2. Monthly and rainy season rainfall for Cho Phraya River watersheds from May to October in 1982–2002 and 2011. Dashed line indicates the average for the period 1982–2002, bar frame and amount of rainfall indicates the highest rainfall in 1982–2002 and 2011. Monthly and total rainfalls were calibrated from 15 weather stations of *the Thai Meteorological Agency* using the Thiessen method. (Data source: *GaME-T2 Data Center*)

Phitsanulok Observatory. Total discharge recorded in the flood year of 1995 was 23.5 billion m^3, which is 167% of the average during 1956–1999. Applying runoff estimation from the Phitsanulok Observatory, runoff is estimated to have been 151% in 1995. Again, this agrees with estimates above. On the other hand, although there was high rainfall in the rainy season of 1983 (Figure 2), the total discharge was 11.0 billion m^3, which is only 79% of 1956–1999 average. Similarly, total discharge in 1988 was 69% of the 1956–1999 average even though total rainfall was high in the rainy season (117%). According to the survey report by JICA released in 1989, peak discharge at the Chao Phraya Dam during the 1983 flood was 4,100 m^{3}s^{-1} (JICA, 1989). Such discrepancies will need to be reviewed in the future, including consideration of the precision of data, to determine whether major flooding occurred between Nakhon Sawan and the Chao Phraya Dam, and how flooding occurred in Bangkok.

The top 5 events in terms of total discharge during 1956–1999 and 2011 at Nakhon Sawan occurred in 2011, 1970 (28.4 billion m^3), 1961 (24.8 billion m^3), 1975 (24.1 billion m^3), and 1995. According to the Royal Irrigation Department, which is responsible for the operation of the Chao Phraya Dam, the threshold discharge capacity of the lower watershed of the Chao Phraya River (Figure S1) above which flooding occurs is 2,000 m^{3}s^{-1}. Cumulative discharges exceeding the threshold at Nakhon Sawan are shown in Table I for the 5 largest events. The discharge in 2011 exceeded the threshold in the middle of August, as well as in the middle of September (See Figure S2). In Nakhon Sawan, flooding of the city center was prevented through flood prevention actions such as sandbagging, but on October 21 a small boat moored on the river smashed through the sandbagging and the entire city center was inundated with about 150 cm of water. A peak discharge of 4,698 m^{3}s^{-1} was recorded on October 13. Later, by the end of October, the discharge dropped below the discharge capacity of Nakhon Sawan, and was below the threshold in late November. Just as in 2011, the discharge in 1970 exceeded the threshold in the middle of August, and the discharge capacity of Nakhon Sawan in the middle of September, but the discharge dropped below the discharge capacity of Nakhon Sawan in the middle of October, and below the threshold by the beginning of November. In other years, the discharge exceeded the threshold at the beginning of September, and the discharge capacity of Nakhon Sawan at the end of September, but the discharge dropped below the discharge capacity of Nakhon Sawan from the middle of October to the middle of November, and below the threshold in the middle of November. These results show that flooding in 2011 continued about 1 month longer than in other years, and that the cumulative excess discharge estimated to have flooded downstream was an extremely large 12 billion m^3.

DAM RESERVOIR AND FLOODING SITUATION IN THE CHAO PHRAYA RIVER

The following describes the weather and dam reservoir storage situation in 2011 in Thailand.

MAR: Precipitation began at the end of March. It was 2 months earlier than a typical year.

APR: Low rainfall rate continued, in line with a normal year.

MAY: Monthly rainfall was recorded at a very high level relative to the past 30 years (Figure 2). Water storage in the reservoirs of the two large dams (Bhumibol and

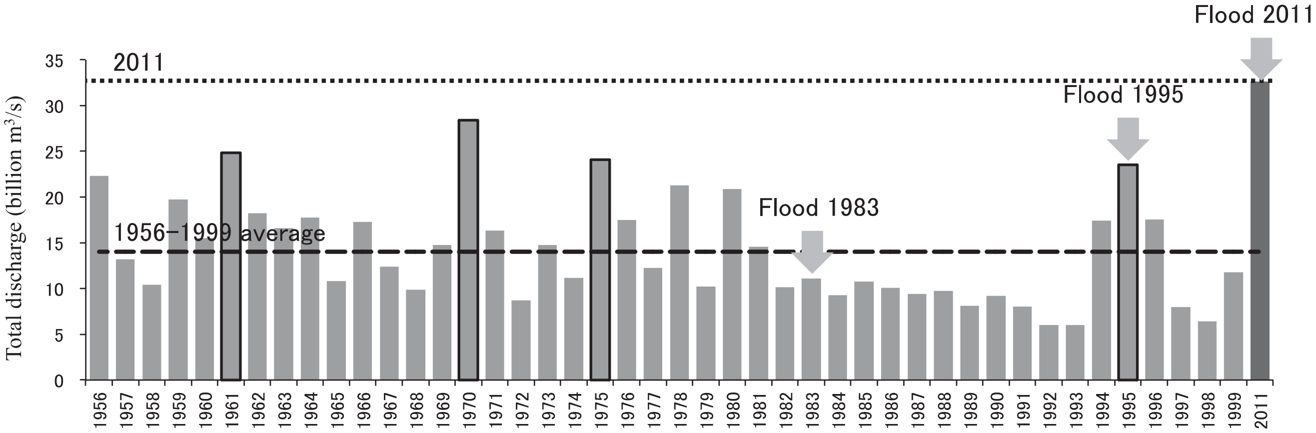

Figure 3. Total discharge of the Chao Phraya River at Nakhon Sawan from June to October in 1956–1999 and 2011. Dashed line indicates the average for the period 1956–1999, and dot line indicates total discharge in 2011. Bar frame indicates the top 5 total discharge events in 1982–2002 and 2011. (Data source: *GaME-T2 Data Center* and *the Royal Irrigation Department*)

Table I. Cumulative discharge and the period it exceeded 2,000 m^3/s at Nakhon Sawan. Data provided from *the Royal Irrigation Department*.

Year	2011	1970	1961	1975	1995
Cumulative discharge (Million m^3)	11,900	7,400	9,500	7,600	7,000
Exceeded period (Days)	96	77	78	64	69

Sirikit) was at a level far below the lower dam operation curve (See Figure S3).

JUN: In late June, heavy rain fell due to the effects of Typhoon "HAIMA," and water storage in both reservoirs began to recover to a large extent (See Figure S3).

JUL: At the end of July, there was intense rainfall due to the effects of Typhoon "NOCK-TEN." Monthly rainfall was the highest in the past 30 years (Figure 2). Flooding occurred at the confluence of the Yom River lower watershed and the Nan River downstream from the Sirikit Dam. Water storage in both reservoirs recovered at a steady rate (See Figure S3).

AUG: There was a lot of rain in August, and water storage in reservoirs began to exceed the higher dam operation curve (See Figure S3). However, flooding had begun in the area near Nakhon Sawan at this time, and it was no longer possible to increase preliminary release to prevent flooding downstream from both reservoirs.

SEP: The highest monthly rainfall in the past 30 years (Figure 2). The Sirikit Dam reservoir almost became full (See Figure S3). Discharge of the Chao Phraya River exceeded its discharge capacity from Nakhon Sawan to Ayutthaya (See Figure S1), and began to overflow. In the middle of the month, water gates on the right bank were destroyed by the flood, and massive flooding occurred. At the end of the month, levees on the left bank broke one after another, and there was flooding of around 5 billion m^3 which was estimated from the difference in the hydrograph between the upstream and downstream parts at the levee breakage location.

OCT: Rainfall was in line with an average year. The Bhumibol Dam reservoir almost became full (See Figure S3). The flooding of the left bank in late September moved to the South, inundating a series of industrial estates on the left bank.

By early October the two dam reservoirs stored approximately 10 billion m^3, which is an amount equivalent to two-thirds of the total flood volume, and this effectively mitigated the flooding. If flooding due to rain from the typhoon at the end of June was not stored and released, it may have been possible to store about 1 billion m^3 extra at the Sirikit Dam reservoir. Similarly, if flooding due to rain from the typhoon at the end of July was not stored and released, it may have been possible to store about 1 billion m^3 extra at the Bhumibol Dam reservoir in September (See Figure S3). However, at that time, water storage was within the scope of both upper and lower dam operation curves (See Figure S3), and thus it may have been impossible to make the judgment to release water at the beginning of the rainy season in order to save water for the dry season. Seasonal weather forecasting is useful for such dam operation; however, such forecasting is still within a research phase and is difficult to incorporate into operational use.

CONCLUSION

The following facts regarding the 2011 Chao Phraya River Flood can be gleaned from Figure 1.

1) Flooding occurred at the downstream parts of the Nan and Yom Rivers in the upper watershed of the Chao Phraya River.
2) All floodwater at the upper watershed flowed into the lower watershed from the narrow section at Nakhon Sawan.
3) Flooding occurred over a wide area in the downstream part of the Chao Phraya River.

1) is strongly related to the fact that the downstream parts of the Nan and Yom Rivers have a particularly gentle slope. In terms of 2), due to the gentle slope of the downstream parts of the Nan and Yom Rivers, the flooded area became large, and a high flood discharge was supplied to the lower

watershed from the narrow section at Nakhon Sawan over a long period. As a result, 3) occurred: water gates and levees broke due to the high water level of the Chao Phraya River, and flooding over a broad area inundated into the lower watershed. Further investigation of other flood cases are required to fully understand the characteristics of the Chao Phraya River flood.

Considering the water budget of the upper watershed, total dam reservoirs water storage, evaporation and total discharge at Nakhon Sawan are subtracted from the total rainfall during from June to October, resulting in an estimate of approximately 17 billion m^3. It is important to reduce flood discharge into the lower watershed of the Chao Phraya River by increasing the flood control capacity of dam reservoirs and other facilities.

In the case of the lower watershed, if it is assumed that the total flood discharge from Nakhon Sawan (Table I) floods the entire lower watershed, then it is estimated that the water level of the flooded area will be 0.29 m. If it were possible to control flooding by artificially expanding the flood area and lowering the floodwater, this would have been more effective at mitigating flood damage. However, uncontrollable flooding occurred in 2011 due to water gate destruction and levee failure, especially in the upstream sections of the Chao Phraya Dam. The inundated water on the left bank of the Chao Phraya River was returned to the Pa Sak River by the emergency embankment on the left bank, which has a height of 1.8 m, and then the floodwater made the river water level in the Chao Phraya River increase at the confluence of both rivers (see Figure S4). The high water level in the Chao Phraya River caused back flow into the irrigation cannels at the left bank of the Chao Phraya River, and subsequent overflow (see Figure S4). On the left bank of Chao Phraya River, the railroad and National Route 1 play the role of secondary levees for both rivers (see Figure S4). Other National Roads also play the role of dikes for both rivers. On the other hand, when floodwater inundates the left bank, the railroad and national route stop the floodwater, and this prevents expansion of the flood area to the east (see Figure S4). Furthermore, there is a danger that the detained floodwater will flow intensely between the national route and railroad where many industrial estates have been constructed (see Figure S4). Therefore if a large flood occurs on the left bank side, it will be necessary to take a response which quickly broadens the flood area to the east side by, for example, artificial breaking the levees and dikes.

In the area around Bangkok, the Royal Irrigation Department and the Bangkok Metropolitan Administration have installed drainage pump stations to pump floodwater into the Chao Phraya River. The stations on the left bank have a capacity of approximately 710 m^3s^{-1}, and the stations on the right bank have a capacity of approximately 220 m^3s^{-1}. On the other hand, pumping stations with a capacity of only approximately 100 m^3s^{-1} have been installed on the east side of Bangkok to pump floodwater into the Bang Pakong River, and stations with a capacity of only approximately 150 m^3s^{-1} have been installed on the west side to pump water into The Tha Chin River. During the approximately 3 weeks from Oct. 14 to Oct. 31 during recent flooding, the water level of the Chao Phraya River exceeded the parapet height, and it was difficult to pump water back into the Chao Phraya River. Since it is impossible to construct large flood control basins near Bangkok, pumping is one of the most important solutions to deal with flooding. It is inevitable that the water level of the main river will rise during flooding, and thus there is a need to consider measures for pumping floodwater which do not rely on only the main river.

The 2011 Chao Phraya River flood was caused by high seasonal rainfall. Increased rainfall by 143% over doubled runoff. The resulting flood destroyed water gates and broke levees, especially at the left bank of the upper Chao Phraya Dam, and led to uncontrollable flooding. This resulted in significant damage to industrial estates on the left bank of the Chao Phraya River. The recent major flood damage was not just a domestic problem for Thailand, but also a problem for the world due to its impact on industrial supply chains. Improving the Master Plan for future major floods in the Chao Phraya River watershed is an extremely important aspect of the national infrastructure of Thailand, and must be considered a priority.

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SUPPLEMENTS

Supplement 1: This includes Figures S1 to S4.

Figure S1. Discharge capacity in lower watershed of the Chao Phraya River. Squares indicate industrial estates, with colored squares those that were inundated by the Chao Phraya River Flood in 2011. Data provided by *The Royal Irrigation Department*.

Figure S2. Daily discharge hydrograph at Nakhon Sawan from June to December for the top 5 events in terms of total discharge. Dashed lines indicate 2,000 m^3/s, which is threshold of flood occurring in the lower watershed, and 3,590 m^3/s, which is the discharge capacity at Nakhon Sawan. Data provided by *The Royal Irrigation Department*.

Figure S3. Transition of water storage in the Bhumibol (left figure) and Sirikit (right figure) Dams. Dashed curves indicate the lower and upper dam operation curves. The water storage of both dam reservoirs is controlled with these operation curves. Data provided by *The Royal Irrigation Department*.

Figure S4. Diagram of the canal network in the area of the left bank of the Pa Sak and Chao Phraya rivers. Bold line indicates National Route 1, and thin lines indicate other National Routes. Numbers indicate the National Route numbers, dashed line indicates the railway, and squares indicate the industrial estates. Arrows indicate the inundated water flow in 2011. The map provided by *The Royal Irrigation Department*.

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