6TH INTERNATIONAL CONFERENCE ON FLOOD MANAGEMENT
September 2014 - São Paulo - Brazil

# FLOOD MANAGEMENT IN BANGKOK: ADVANCING KNOWLEDGE AND ADDRESSING CHALLENGES

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**ABSTRACT**: The Bangkok Metropolitan Region (BMR) is increasingly at risk from the impacts of climate change. The Southeast Asia region is projected to experience heavier precipitation, increased monsoon-related precipitation extremes, and greater rainfall and wind speed associated with tropical cyclones. In terms of population and assets exposed, Bangkok is projected to be one of the top ten cities globally exposed to the impacts of coastal flooding. Flooding is considered the most critical hazard for the city, both from coastal and inland flooding, with potential for peak river run-off, high tide, and heavy cyclone-associated rainfall to coincide towards the end of the year. Flooding caused by riverine run-off and rainfall is a reoccurring phenomenon, as recently experienced in 2011, when one of the worst flooding events in Thai history caused hundreds of mortalities, widespread displacement, and severe economic damage. This paper examines development of a research strategy and presents preliminary findings for assessing the impact of climate change on coastal and inland flooding of the BMR, which forms a central component of the five-year international Canadian-funded Coastal Cities at Risk project. Key challenges included the lack of spatial data, requiring development of creative methodologies for flood mapping and modelling impacts. Coastal flooding was modelled by integrating projected absolute sea level rise, land subsidence, and plate tectonic movement; inland flooding was mapped from multi-year historical radar data; and the utility of a digital elevation model (DEM) derived modified topographic index examined for delineating flood-prone areas. Future research will examine the impact of storm surge, rainfall-runoff modelling, and integrate flood hazard and other data into a system dynamics model to provide measures of city resilience.

Key Words: climate change adaptation, disaster risk reduction, coastal flooding, riverine flooding, sea level rise

## 1. INTRODUCTION

The severity of flooding in the Bangkok Metropolitan Region (BMR) (or Greater Bangkok) can be attributed to a variety of hydrometeorological and development-related factors. Factors that cause flooding in the BMR include upstream runoff, locally heavy rainfall over Bangkok and its surroundings, such as caused by tropical cyclones, and high tide (Hungspreug et al. 2000; Tingsanchali 2000; Panya Consultants 2009; Trisirisatayawong et al. 2011). Flooding caused by these natural processes have been exacerbated by land use and land cover changes in the Chao Phraya River Basin (CPRB) including deforestation, ground water abstraction, urbanization, and dam construction (Hungspreug et al. 2000; UNESCO 2003; Saito et al. 2007; Panya Consultants 2009; Dutta 2011). Furthermore, projected climate change impacts for Southeast Asia look set to increase future flood risk. The Fifth IPCC Assessment Report (AR5) reports that it is *very likely* that monsoon-related precipitation extremes will increase in the region (IPCC 2014), and there is *medium confidence* in a moderate increase in rainfall, though due to

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complex terrain, sub-regional variations are expected (Christensen et al. 2013). While both global mean tropical cyclone maximum wind speed and precipitation rates are *likely* to increase, there are *likely* regional variations but currently *low confidence* in regional projections (Christensen et al. 2013). With regard to population and asset exposure, Bangkok was ranked as being one of the most vulnerable to future coastal flooding (Nicholls et al. 2008).

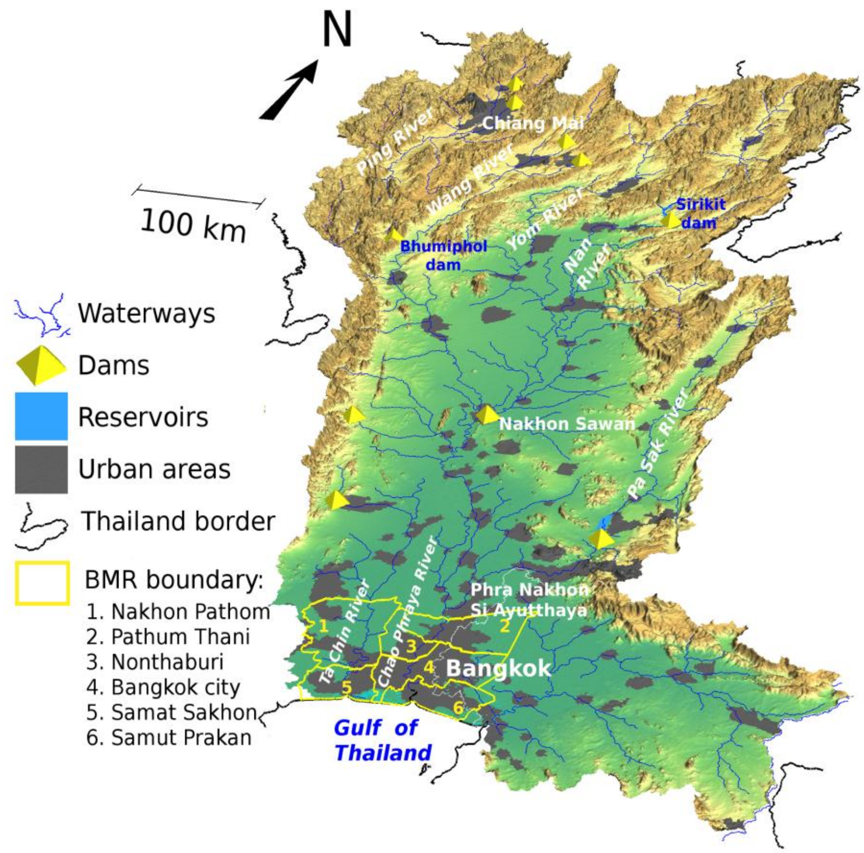

Figure 1. Three-dimensional view of BMR located in the Chao Phraya River basin and adjacent Sa Keo sub-basin (basin boundaries derived from AQUASTAT programme of UN FAO (2009)) (by Cooper 2014, under review).

Additionally, storm surge generated by tropical cyclone systems have potential to increase flood risk. Megacities such as Bangkok, located on river deltas in Asia, are particularly at risk to increased flooding from the impacts of climate change. IPCC's AR5 (IPCC 2014) reports that low-lying coastal areas of Asia, home to a considerable proportion of the population, are especially vulnerable to climate change-related hazards including typhoons, storm surge and sea-level rise.

It is within this context of climate change and rapidly growing low-lying coastal megacities, that this paper presents ongoing research and findings on the impacts of coastal and inland flooding on the BMR, a key component of the five-year Canadian-funded Coastal Cities at Risk (CCaR) project that integrates research and capacity building across four cities of Manila, Lagos, Vancouver and Bangkok (McBean 2014). CCaR aims to build knowledge and capacity of megacities to adapt to climate change-related impacts in the context of rapid urban development, and is one of the projects supported under the *International Research Initiative on Adaptation to Climate Change* (IRIACC) of the Canadian International Development Research Centre (IDRC). A central output of CCaR is development of a Coastal Megacity Resilience Simulator to model city resilience, of which developing a measure of flood risk is a key component, together with economic, social, health and organizational inputs (Simonovic & Peck 2013). The system dynamics model is based on Vensim simulation software and is designed to visualize and analyze adaptation options with the aim of advancing megacity resilience to the impacts of climate change (Simonovic & Peck 2013).

## 1.1 Flood history

Flooding is not a new phenomenon for Bangkok, the city is situated on the Chao Phraya River flood plain (Figure 1) and historically has frequently experienced significant flooding episodes going back to the late eighteenth century. Past notable events include 1785, 1819, 1831, 1942, 1975, 1978, 1980, 1983, 1986, 1995, 1996, 2002, 2006 and 2011, with reports attributing heavy upstream runoff, as well as locally heavy rainfall over Bangkok and environs, and high tides as chief causes (Yong et al. 1991; Enters 1995; Hungspreug et al. 2000; Suvanpimol 2004; Sroikeeree & Bannatham 2005; Panya Consultants 2009; DHI 2011; Hill 2011; Gemenne et al. 2012). However, the most recent flood of 2011 was unprecedented in terms of losses and damage, resulting in over 800 mortalities, millions of displaced people, and economic losses estimated at almost 46 billion USD (World Bank 2011, Asia Foundation 2012). Whereas flood heights in 1785 and 1819 were reported as perhaps at least twice that of 2011 (Hill 2011), the key difference nowadays results from extensive development and urbanization of the river basin, significantly increasing exposure and vulnerability to flooding, and culminating in 2011 with the most expensive disaster on record for Thailand and seventh most costly natural disaster globally since 1980 (Economist 2012).

### 1.2 Hydrometeorological factors influencing flooding

The impacts from upstream river discharge, heavy rainfall over the city and its environs, and high tides are responsible for frequent major flooding of Bangkok, with heightened risk toward the end of the year when all of these phenomena have potential to co-occur (e.g., Engkagul 1993, Tingsanchali 2000, Dutta 2011). Thailand's climate is dominated by the southwest monsoon (May to October) and northeast monsoon (October to February) (Phantuwongraj et al. 2013), and influenced by the El Niño/La Niña Southern Oscillation (ENSO), Indian Ocean Dipole (IOD) and aerosol pollution (Bridhikitti 2013). Approximately 90 percent of the annual rainfall in the CPRB occurs during the southwest monsoon (Hungspreug et al. 2000), with the average annual rainfall over the basin of 1,130 mm (Panya Consultants 2009), varying from 1,200 to 1,600 mm in the upper basin and 1200 mm in the north and west areas of the lower basin (Wattayakorn 2006), and 1500 mm in Bangkok (Dutta 2013). Peak river discharges at Nakhon Sawan occur during September to October (Mikhailov & Nikitina 2009; JICA 2013), peak flow usually reaches Bangkok in November (Weesakul & Thammasittirong 2000), and combined with high tide at this time, may contribute to serious flood damage (e.g. Weesakul & Thammasittirong 2000; Panya Consultants 2009).

The maximum tidal range of the Chao Phraya River delta is 2.3 to 2.8 m (Chaimanee et al. 2000 cited in Tanabe et al. 2003) and the tide is highest from November to December (Weesakul & Thammasittirong 2000). Monsoonal winds drive a difference in sea level in the Gulf of Thailand of approximately 0.4 m in height between monsoon seasons, increasing above mean sea level during the northeast monsoon and decreasing during the southwest monsoon (Phantuwongraj et al. 2013).

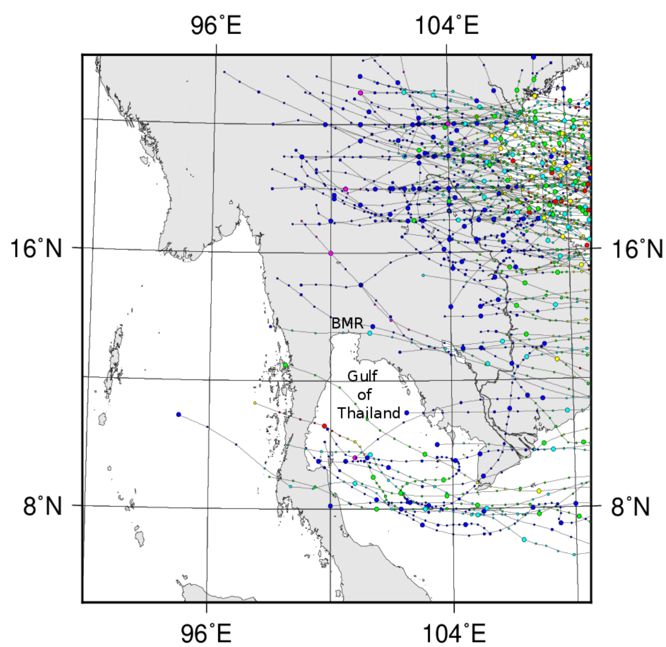


Figure 2. Tracks of cyclonic systems tracking across mainland Southeast Asia and Gulf of Thailand since 1951. Map and data output from Digital Typhoon (circle colours: red, typhoon; yellow, severe tropical storm; green tropical storm; blue, tropical depression; cyan, unknown). Data source and image generated from http://www.digital-typhoon.org

Storm surge caused by tropical cyclones has been reported on a few occasions along the Thailand coast since the 1960s (Harriet in late October 1962, typhoon Gay in early November 1989 and typhoon Linda in early November 1997) (Phantuwongraj et al. 2013; Digital Typhoon 2014[1]), including an estimated surge of about 0.61 m at the Chao Phraya river entrance due to Typhoon Linda (Panya Consultants 2009). October is the peak month for cyclonic storms closest to Bangkok tracking from the east across mainland Southeast Asia and the Gulf of Thailand (Figure 2).

A combination of factors are seen responsible for past floods. The recent and unprecedented 2011 flood, described as being a 100-year, or more than a 100-year event (DHI 2011, JICA 2013), was attributed to above average rainfall over the CPRB, with a total of 1,439 mm during the rainy season, representing 143% of the average for the period 1982–2002 (Komori et al. 2012). In 2011, rainfall began at the end of March (two months earlier than usual), was the heaviest for 30 years for the months of May, July and September, and two typhoons, Haima and Nock-Ten, strongly influenced rainfall in June and July (Komori et al. 2013). The flood's duration was one month longer than previous events and total river discharge (from June to October) at Nakhon Sawan, located toward the centre of the basin, was 232 percent of the mean value for 1956–1999 (Komori et al. 2011).

Other recent major floods include those of 1983, 1995 and 2006. The flood of 1983 was attributed to a culmination of heavy rainfall upstream, two tropical storms over the basin's floodplain, runoff from the east, a high spring tide, and unusually heavy rainfall over Bangkok (Panya Consultants 2009, Hungspreug et al. 2000). The 1995 flood, described as a 25 year event, caused extensive city-wide flooding and was a consequence of heavy rain upstream caused by multiple storms from July to September, heavy rain over Bangkok, with high water levels resulting from peak flows intersecting with spring high tide in October (Panya Consultants 2009, Hungspreug et al. 2000).

### 1.3 Current status of flood management in the basin

An outcome of Bangkok's long flooding experience has been the step by step development of flood defences across the CPRB, including construction of dams and reservoirs, canals, dikes (levees) and polder systems, installation of pumps and other infrastructure to reduce impacts (e.g., Hungspreug et al. 2000, Panya Consultants 2009). Following the 2011 flood, further structural and non-structural recommendations were proposed from the "*Project for the Comprehensive Flood Management Plan for the Chao Phraya River Basin*" (JICA 2013). The collaborative project engaged the Japan International Cooperation Agency (JICA) and Thai government agencies, including the Office of National Economic and Social Development Board (NESDB), Royal Irrigation Department (RID), Ministry of Agriculture and Cooperatives (MOAC), Department of Water Resources (DWR) and Ministry of Natural Resources and Environment (MNRE) to prepare a comprehensive flood management plan for the CPRB (JICA 2013). The suite of structural and non-structural measures recommended as the most cost efficient for protecting the lower Chao Phraya basin are shown in Table 1. The estimated total cost for structural measures alone, ranges from 143 to 190 billion Thai Baht (4.8 to 6.3 billion USD) (depending on the capacity of the outer ring road diversion channel). Alternative measures were also evaluated by the latter authors, including construction of new dams, improving retention areas, and a 223 km western diversion channel, but their flood reduction impact was considered limited and the combined proposal valued much greater at 508 billion Thai

Table 1. Priority recommendations proposed in JICA (2013) study for protecting lower Chao Phraya basin

| **Structural measures** | **Non-structural measures** |
|---|---|
| Effective operation of existing dams | Reforestation |
| Bypass channel at Ayutthaya | Land use control of inundation areas |
| Outer ring road diversion channel (500 or 1000 $m^3$/s) | Flood forecasting system |
| Improvement of river channel and dikes | |

[1] http://www.digital-typhoon.org

Baht. The Thai government has allocated substantial financial resources for major flood protection works, but as of writing no decision had been made as to when and which projects are to be implemented.

It should be noted that the JICA (2013) study based flood modelling on an equivalent 2011 flood, calculated as a 100-year return event, a similar benchmark used in other countries, but did not evaluate potential climate change-related effects on rainfall intensity and variability. Furthermore, the JICA (2013) study considered the effect of storm surge based on historical typhoon Linda, which entered the Gulf of Thailand in 1997, and the 2011 flood, indicating that the combined impact of a 2m storm surge would be considerable, requiring infrastructural investment including construction of sea walls, elevated roads and river improvements. This finding demands future study and is a focus of ongoing CCaR research.

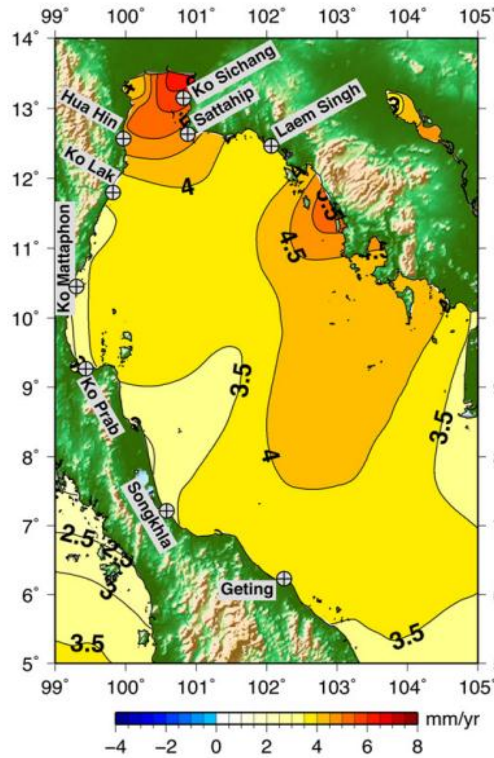


Figure 3. Geographical distribution of absolute sea level rise rates derived from 1993–2009 multi-satellite altimetry (by Trisirisatayawong et al. 2011)

## 2. MODELLING COASTAL AND INLAND FLOODING

The overall aim of CCaR project-related flood research is to assess the impact of climate change on coastal and inland flooding of the BMR. Specifically, to identify areas affected by flood caused by sea level rise and rainfall runoff/local precipitation; classify the affected areas by flood depth and duration; and integrate these physical hazard data with socio-economic, health and organisational data into the Coastal Megacity Resilience Simulator to examine city resilience and explore possible adaptation options. Preliminary research, as presented in this paper, examines the impact of sea level rise on coastal flooding, and generation of a flood extent/hazard map based on historical radar data collected during the rainy season, and explores the utility of a modified topographic index for mapping flood-prone areas. Ongoing and future research will examine the impact of storm surge on sea level, hydrological impacts of climate change over the CPRB, and city resilience modelling.

### 2.1 Modelling coastal flooding caused by sea level rise

Coastal flooding impacts focused on the southern part of the BMR, with modelling of sea level rise (termed the *SLR model*) integrating a number of factors, including absolute sea level rise, plate tectonic motion following the 2004 Sumatra–Andaman earthquake, land subsidence resulting from groundwater abstraction, and monthly mean sea level.

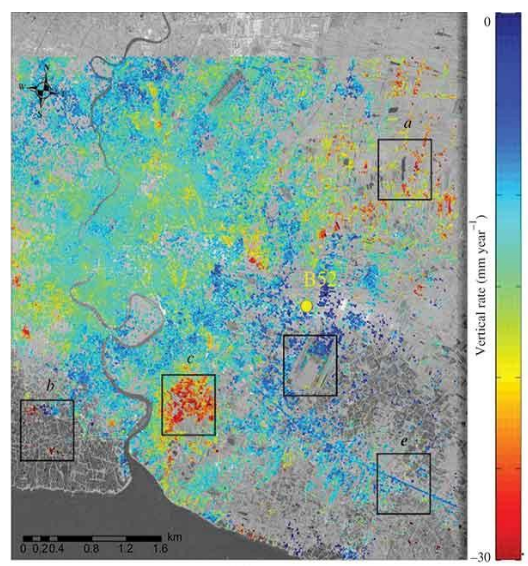


Figure 4. Subsidence rate (mm/year) from InSAR time-series analysis (by Aobpaet et al. 2013)

An absolute rate of sea level rise of 5mm/yr was incorporated into the SLR model (Trisirisatayawong and Cheewinsiriwat 2013). Compared to the global average, sea level is rising significantly more in the Gulf of Thailand (Trisirisatayawong et al. 2011). In the northern part of the

Gulf, the rate of absolute sea level rise was calculated as 4.5 to 5.0 ±1.3 mm/yr (Trisirisatayawong et al. 2011) compared to the global average of 1.8 ±0.3 mm/yr (Church et al. 2004) (Figure 3). According to IPCC's Fifth Assessment Report (AR5), it is described as *likely* that from the early 20$^{th}$ century the rate of global sea level rise has accelerated (Church et al. 2013).

Relative sea level rise could be significant in the near-term for the coastal BMR following the Sumatra-Andaman earthquake. Post downward plate motion of −3.9 ± 2.1 mm/yr and −12.7 ± 4.2 mm/yr were recorded at two stations in the Gulf following the earthquake (Trisirisatayawong et al. 2011). According to Satirapod et al. (2013), post-seismic movement should continue for the next couple of decades at a reducing rate and not exceed 10 cm in the Bangkok area. The SLR model incorporates predicted future vertical subsidence for periods of the seismic cycle equal to 500 years from a visco-elastic model (see Satirapod et al. 2013), the plate downthrow diminishing with time from 1.9 mm/yr in 2010 to -0.2 mm/yr in 2060, and assumed to be uniform over the study area.

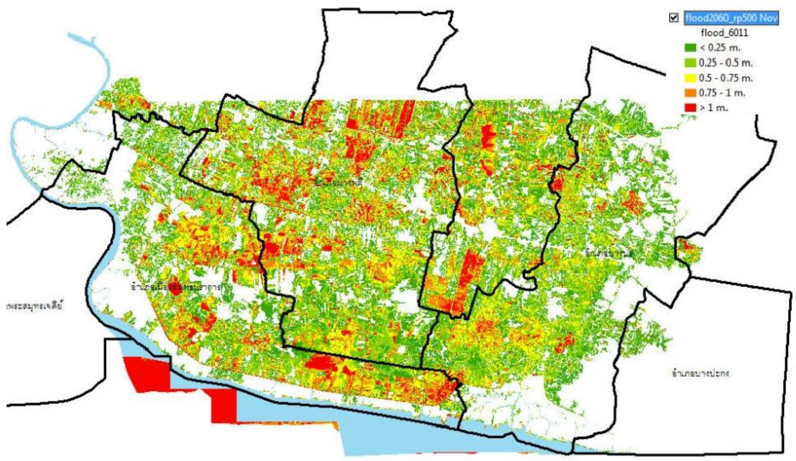

Figure 5. Projected flooding for the peak high tide month of November 2060. Red colour is greater than 1 m depth.

Additionally, subsidence caused by groundwater withdrawal was integrated into the SLR model, varying spatially from -2 to -28 mm/yr, and assumed to be constant over time. Groundwater withdrawal is attributed as being a major cause of subsidence and coastal erosion over the last few decades in Bangkok (e.g., Dutta 2011). According to Aobpaet et al. (2013) subsidence at locations in the BMR reached up to 30 mm/yr between 2005 and 2010 (Figure 4); subsidence rates of up to 120 mm/yr. from 1978 to 1981 were reported from levelling studies. Subsidence also extends sub-tidally, facilitating wave-induced coastal erosion (Saito et al. 2007). The latter authors estimated a total subsidence of 1 m at the Chao Phraya River mouth and coastal erosion of greater than 1 km over the last 50 years.

The fourth component of the SLR model estimates future monthly average sea level, the variation of which is modelled as an annual cycle, from sea level observations from the 1940-2002 time series of Ko Sichang tidal station. The robust fit of iteratively-reweighted least squares is employed in the estimation.

Figure 6. Projected flooding in January 2060 with existing dike (top image) and simulated 0.75 m elevated dike (bottom image). Red colour is greater than 1 m depth (by Trisirisataywong and Cheewinsiriwat 2013).

Current (2010) topography is generated from high resolution LIDAR data and future topography calculated from modelled plate motion and the height of each grid cell reduced by interpolating the subsidence rate from InSAR data. Through proximity analysis, starting from coast, if cells are below sea level, the flood depth is determined.

Preliminary research modelled topography for 2035 and 2060, monthly coastal flooding for 2060, and examined the adaptation option of raising a coastal dike by 0.75 m. Illustrative examples of model outputs, include projected flooding for the month of November 2060, as shown in Figure 5; and the effect of raising coastal dikes by 0.75 m for January 2060, as shown in Figure 6.

## 2.2 Modelling inland flooding

To model inundation patterns and flood depth in the BMR requires assessment of the whole Chao Phraya River basin including the BMR. Given considerable data needs for projecting flood forecasts and financial resources available to the project, the aim initially was to identify and build on existing methodology, models and data sets. One of the most recent and thorough investigations of climate impact and adaptation for the BMR was conducted by Panya Consultants (2009) for the Bangkok Metropolitan Administration (BMA) with financial support from the World Bank. They addressed future basin precipitation (A1FI & B1 scenarios), land subsidence, sea level rise (A1FI & B1 scenarios), and storm surge, utilising MIKE Flood/MIKE11 software and a comprehensive data set comprising river/canal network and cross-sections, water levels and discharges, hydraulic infrastructure, digital elevation model (DEM), rainfall/evaporation, and major (not all given its complicated nature) components of the flood protection system. Unfortunately for this study, neither MIKE software nor the data resources were available for conducting an equivalent detailed investigation and thus critical that alternative and more accessible approaches identified for flood mapping.

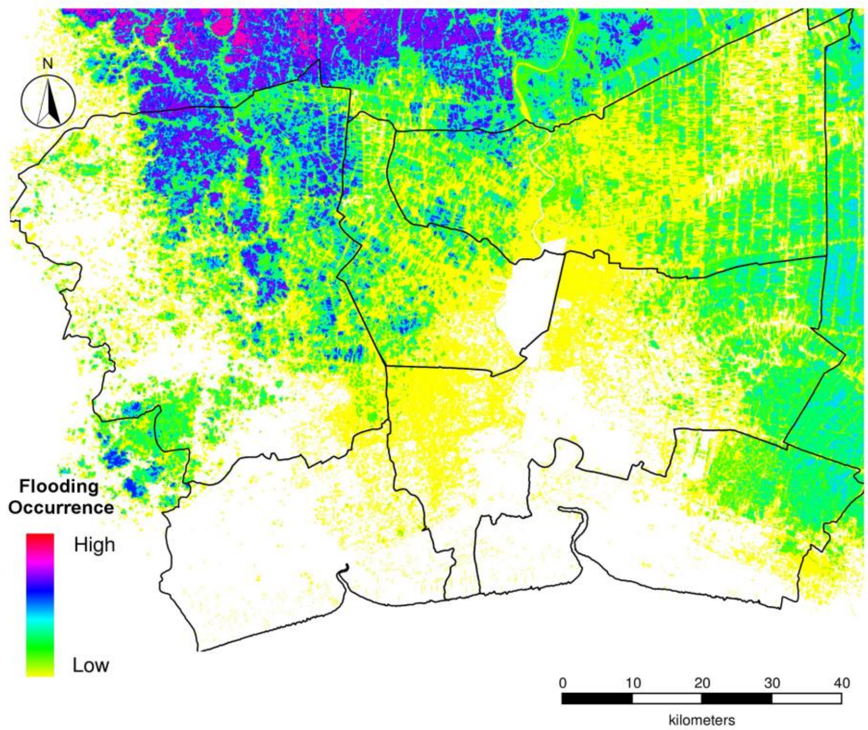


Figure 7. Map shows spatial extent and frequency of past flood events from 2005 to 2012 inclusive. Coordinate reference system: EPSG 32647 (UTM47N WGS84) (by Cooper 2014, under review)

A four step strategy was adopted to address this challenge by making optimal use of open data and open source GIS and modelling software, as follows:

- generate a flood extent/hazard map for the BMR using multi-year historical radar flood data;
- examine the utility of a DEM-derived Modified Topographic Index ($TI_m$) for delineating flood-prone areas;
- rainfall-runoff modelling for assessing climate change impacts at sub-basin level focusing on high resolution/downscaled general circulation model (GCM) data;
- generate inundation extent and depth projections at fine/moderate spatial resolution in BMR (dependent on access to river/canal and hydraulic infrastructure data sets).

A priority need for CCaR project resilience modelling was a flood map of the BMR, and this motivated research for the first step in generating a flood extent/hazard map. Fortunately, historical spatial flood data were available (and publicly accessible) from the Thailand Flood Monitoring System of the Geo-Informatics and Space Technology Development Agency (GISTDA)[2]. Flood maps were derived from synthetic aperture radar (SAR) imagery acquired during the rainy season from 2005 to 2012 inclusive. The accuracy of the GISTDA data was 80-90% (perhaps lower in built-up areas) (GISTDA 2013), with a spatial resolution of approximately 100m. It was technically straightforward to create a composite flood extent/hazard map by combining the multi-year inundation layers (Figure 7). Shapefiles were clipped and transformed from EPSG 4326 to EPSG 32647 (UTM 47N/WGS84) and rasterized to a spatial resolution of 100 m using GDAL command line utilities (ogr2ogr and gdal_rasterize). A single compiled raster image was generated from the series of eight flood inundation images by summing grid cell values using the GRASS r.series module. The output layer contained cell values ranging from 1 to 8 representing areas with the lowest to highest occurrence of flooding; areas unflooded during the 8 year period were assigned a value of zero.

The second approach to mapping flood-prone areas examined the utility of the modified topographic index ($TI_m$), a method developed by Manfreda et al. (2011) and incorporated into the GRASS r.hazard.flood add-on extension module (Di Leo 2014). The module delineates flood-prone areas by calculating a modified topographic index from a digital elevation model (see formula 1 below), and categorises those cells above a given threshold value as exposed to flooding (Manfreda et al. 2011). Areas susceptible to inundation are determined by a $TI_m$ value above a calculated threshold (tau, τ). $TI_m$ is defined as:

$$TI_m = \log\left[\frac{a_d^n}{\tan(\beta)}\right] \quad \text{..................[1]}$$

where $a_d$ represents the drained area per unit contour length; β is slope; and n is a function of DEM spatial resolution. The method adopted in this study was to use CGIAR-CSI SRTM 90m DEM[3] of the Chao Phraya River basin and the composite historical flood map developed previously as a reference for assessing the utility of the modified topographic index for defining areas as exposed to flooding. While the analysis depends on the accuracy of the multi-year flood maps (~80-90% as noted previously), these currently represent the best source of information available for the Chao Phraya River basin; detailed and accurate flood maps based on hydrological-hydraulic mapping were not available.

Findings from the analysis indicated good correspondence between reference historical inundation data and the results of the $TI_m$ method for the four most northerly sub-basins of the Chao Phraya River basin characterised by higher mean slopes. However, performance of the $TI_m$-based method appeared reduced in areas of low topographic relief including the BMR. Total minimum error was observed to decrease with increasing sub-basin mean slope. Selection of an appropriate tau threshold value is critical for generating an accurate flood map - the threshold value reflecting the return period to be presented and the mean slope of the sub-basin. The modified topographic index is potentially a highly valuable tool for delineating flood-prone areas and it is recommended that future research examine higher resolution DEMs and other drainage basins to further evaluate its utility and potential constraints.

The third and ongoing step of research is to assess climate change impacts at sub-basin level through rainfall-runoff modelling. Studies conducted over the last couple of years have examined the use of high resolution GCM data for determining hydrological impacts in the CPRB (e.g., Kure & Tebakari 2012; Hunukumbura & Tachikawa 2012; Champathong et al. 2013) and it is envisaged that similar higher resolution data will be evaluated using open rainfall-runoff model(s). The final fourth step will depend on

[2] http://flood.gistda.or.th/
[3] http://srtm.csi.cgiar.org/index.asp

accessibility of detailed spatial data on canal networks and hydraulic infrastructure; the authors are currently examining possible avenues for acquiring appropriate data and options for analysis.

## 3. SUMMARY

The CCaR project has contributed significantly to modeling of potential climate change-related impacts of coastal and inland flooding, and also generated spatial data layers that can be integrated into the CCaR project system-based Coastal Megacity Resilience Simulator to evaluate city resilience to hazards and explore potential adaptation options. The CCaR SLR model successfully integrated measures of ground subsidence (plate tectonic movement and subsidence caused by groundwater abstraction) into projected topography and flood impacts, and future research aims to model storm surge impacts generated by tropical cyclone systems and spatially extend the model further into the BMR from the coastal fringe. A flood extent/hazard map for the entire BMR based on multi-year historical data from river runoff/rainfall was generated, and future progress on inland flooding will focus on rainfall-runoff modelling of the CPRB to establish a more robust understanding of climate-driven hydrological impacts. The aim is then to develop the latter findings to model flood patterns and depths within the BMR.

## 4. ACKNOWLEDGEMENTS

This work was carried out with the aid of a grant from the International Development Research Centre (IDRC), the Canadian Institutes of Health Research (CIHR), the Natural Sciences and Engineering Research Council of Canada (NSERC), and the Social Sciences and Humanities Research Council of Canada (SSHRC), Ottawa, Canada.

## 5. REFERENCES

Aobpaet A, Cuenca MC, Hooper A, Trisirisatayawong I (2013) InSAR time-series analysis of land subsidence in Bangkok, Thailand. *International Journal of Remote Sensing*, 34:8.

Asia Foundation (2012) Ahead of flood season, Thailand's communities demand greater preparedness, 8 August 2012. URL: http://asiafoundation.org/in-asia/2012/08/08/ahead-of-flood-season-thailands-communities-demand-greater-preparedness.

Bridhikitti A (2013) Connections of ENSO/IOD and aerosols with Thai rainfall anomalies and associated implications for local rainfall forecasts. *International Journal of Climatology* 33: 2836–2845.

Chaimanee, N, DiGeronimo SI, Robba E, Sanfilippo R (2000). Modern environments and Holocene evolution on the west coast of the Upper Gulf of Thailand. In: *The Comprehensive Assessments on Impacts of Sea-Level Rise*. Proceedings of the Thai-Japanese Geological Meeting, Department of Mineral and Resources, Thailand, pp. 66–85.

Champathong A, Komori D, Kiguchi M, Sukhapunnaphan T, Oki T, Nakaegawa T (2013) Future projection of mean river discharge climatology for the Chao Phraya River basin. *Hydrological Research Letters* 7(2): 36–41. DOI: 10.3178/HRL.7.36.

Christensen JH, Krishna Kumar K, Aldrian E, An S-I, Cavalcanti IFA, de Castro M, Dong W, Goswami P, Hall A, Kanyanga JK, Kitoh A, Kossin J, Lau N-C, Renwick J, Stephenson DB, Xie S-P,. Zhou T (2013) Climate phenomena and their relevance for future regional climate change. In: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF et al. (eds.)]. Cambridge University Press.

Church JA, Clark PU, Cazenave A, Gregory JM, Jevrejeva S, Levermann A, Merrifield MA, Milne GA, Nerem RS, Nunn PD, Payne AJ, Pfeffer WT, Stammer D, AS Unnikrishnan (2013) Sea level change. In: *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker TF et al. (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Church JA, White NJ, Coleman R, Lambeck K, Mitrovica JX (2004) Estimates of the regional distribution of sea level rise over the 1950–2000 period. *Journal of Climate* 17: 2609–2625.

Cooper RT (2014, under review) Open data flood mapping of Chao Phraya River Basin and Bangkok Metropolitan Region: Utilising historical inundation data and a DEM-derived modified topographic index.

DHI (2011) Thailand floods 2011: The need for holistic flood management. DHI Water & Environment(s) Pte Ltd. URL: http://www.globalcateye.com/media/861/Thailand_Floods_2011.pdf.

Di Leo (2014) Description: r.hazard.flood Implementation of a fast procedure to detect flood prone areas. URL: http://svn.osgeo.org/grass/grass-addons/grass6/raster/r.hazard.flood/description.html.

Dutta D (2011) An integrated tool for assessment of flood vulnerability of coastal cities to sea-level rise and potential socio-economic impacts: a case study in Bangkok, Thailand. *Hydrological Sciences Journal,* 56(5): 805-823. URL: http://dx.doi.org/10.1080/02626667.2011.585611.

Economist (2012) Natural disasters: Counting the cost of calamities. Jan 14th 2012. URL: http://www.economist.com/node/21542755.

Engkagul S (1993) Flooding features in Bangkok and vicinity: Geographical Approach. *GeoJournal* 31(4): 335-338.

Enters T (1995) The economics of land degradation and resource conservation in Northern Thailand: challenging the assumptions, Chapter 5. In: Rigg, J (Edit) *Counting the Costs: Economic Growth and Environmental Change in Thailand*. Institute of Southeast Asian Studies, Singapore.

Gemenne F, Brücker P, Ionesco D (2012) The state of environmental migration 2011. Institute for Sustainable Development and International Relations (IDDRI) / International Organization for Migration (IOM). November 2012. URL: http://www.iddri.org/Publications/Collections/Analyses/SEM%202011_web.pdf

GISTDA (2013) แนวคำถามคำตอบที่มักสอบถามสำหรั บเรื่ องการแปลพืนที่นำท่ วมของ สทอภ Geo-Informatics and Space Technology Development Agency. URL: http://flood.gistda.or.th/flood/y2011/FL82_Extra/ReportQuestion.pdf.

Hill RD (2011) The Bangkok floods – reflections on the waters. NTS Insight November 2011. URL: http://www.rsis.edu.sg/nts/html-newsletter/insight/nts-insight-nov-1101.html.

Hungspreug S, Khao-uppatum W, Thanopanuwat S (2000) Flood management in Chao Phraya River basin. *Proceedings of the International Conference on the Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bow*l, Kasetsart University, Bangkok Thailand, 12-15 December 2000. URL: http://std.cpc.ku.ac.th/delta/conf/Acrobat/Papers_Eng/Volume%201/Wirat%20RID.pdf.

Hunukumbura PB, Tachikawa Y (2012) River discharge projection under climate change in the Chao Phraya River Basin,Thailand, using the MRI-GCM3.1S Dataset. *Journal of the Meteorological Society of Japan*, 90A: 137-150.

IPCC (2014) 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. URL: http://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap24_FGDall.pdf

JICA (2013) Project for the comprehensive flood management plan for the Chao Phraya River basin. Japan International Cooperation Agency (JICA). Final Report Volume 1: Summary Report, September 2013. URL: http://rid-jica.cooperationprojects.rid.go.th/upgrade-flood-management-master-plan-of-the-chao-phraya-river-basin.

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

Kure S, Tebakari T (2012) Hydrological impact of regional climate change in the Chao Phraya River Basin, Thailand. *Hydrological Research Letters* 6: 53–58. DOI: 10.3178/HRL.6.53.

Manfreda S, Di Leo M, Sole A (2011) Detection of flood-prone areas using digital elevation models. *Journal of Hydrologic Engineering*, 781-790. DOI: 10.1061/(ASCE)HE.1943-5584.0000367.

McBean G (2014) Building resilience. *International Innovation*. Issue 126. URL: http://www.research-europe.com/magazine/ISSUE/126/index.html.

Mikhailov VN, Nikitina OI (2009) Hydrological and morphological processes in the Chao Phraya mouth area (Thailand) and their anthropogenic changes. *Water Resources*, 36:6: 613–624.

Nicholls RJ et al. (2008) Ranking port cities with high exposure and vulnerability to climate extremes: exposure estimates, OECD Environment Working Papers, No. 1, OECD Publishing. URL: http://dx.doi.org/10.1787/011766488208

Panya Consultants (2009) Climate change impact and adaptation study for Bangkok Metropolitan Region. Final report. Panya Consultants Co. Ltd. March 2009. URL: http://siteresources.worldbank.org/INTEAPREGTOPENVIRONMENT/ Resources/ClimateChangeBangkokMainReport.pdf.

Phantuwongraj S, Choowong M, Nanayama F, Hisada K-I, Charusiri P, Chutakositkanon V, Pailoplee S, Chabangbon A (2013) Coastal geomorphic conditions and styles of storm surge washover deposits from Southern Thailand. *Geomorphology* 192: 43–58.

Satirapod C, Trisirisatayawong I, Fleitout L, Garaud JD, Simons WJF (2013) Vertical motions in Thailand after the 2004 Sumatra–Andaman Earthquake from GPS observations and its geophysical modelling. Advances in Space Research 51: 1565–1571.

Saito Y, Chaimanee N, Jarupongsakul T, Syvitski JPM (2007) Shrinking megadeltas in Asia: Sea-level rise and sediment reduction impacts from case study of the Chao Phraya Delta. Inprint Newsletter of the IGBP/IHDP Land-Ocean Interactions in the Coastal Zone, 2007(2): 3-9. URL: http://staff.aist.go.jp/yoshiki.saito/Saito_INPRINT_2007_2.pdf.

Simonovic SP, Peck A (2013) Dynamic resilience to climate change caused natural disasters in coastal megacities quantification framework. *British Journal of Environment and Climate Change*, 3(3): 378-401. URL: http://www.sciencedomain.org/abstract.php?iid=267&id=10&aid=2034.

Sroikeeree K, Bannatham R (2006) Flood and flood management in Bangkok, Thailand In: Case Studies of Seven Cities Urban Training Programme 21 November – 8 December 2005 Bonn/Germany Ed. Kastrup U, UNU-EHS, 2006. URL: https://www.ehs.unu.edu/file/get/3721.

Suvanpimol C (2004) Integrated water management in Chao Phraya River basin, Thailand 2003. Proceedings of Asia Pacific Association of Hydrology and Water Resources 2004, APHW 2004. URL: http://rwes.dpri.kyoto-u.ac.jp/~tanaka/APHW/APHW2004/proceedings/FWR/56-FWR-A319/56-FWR-A319.pdf

Tanabe S, Saito Y, Sato Y, Suzuki Y, Sinsakul S, Tiyapairach S, Chaimanee N (2003) Stratigraphy and Holocene evolution of the mud-dominated Chao Phraya delta, *Thailand. Quaternary Science Reviews* 22: 789–807.

Tingsanchali T (2000) Forecasting model of Chao Phraya river flood levels at Bangkok. *International Conference :The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*, Kasetsart University, Bangkok, 12-15 December 2000 URL: http://std.cpc.ku.ac.th/delta/conf/Acrobat/Papers_Eng/Volume%201/Tawatchai%20Paper%20OK.pdf.

Trisirisatayawong I, Cheewinsiriwat, P (2013) Assessment of flooded area from sea level rise in the upper coastal area of Gulf of Thailand, *The 12th South East Asian Survey Congress*, Manila.

Trisirisatayawong I, Chinvanno S, Bunsomboonsakul S, Niemnil S, Snidvongs A (2011) Shortcomings of current knowledge in contributing climatic/non-climatic factors of Bangkok flood hazard. Cities at Risk II, 11-13 April 2011, Taipei, Taiwan. URL: http://start.org/programs/cities-at-risk/carii-workshop-presentations#1a.

Trisirisatayawong I, Naeije M, Simons W, Fenoglio-Marc L (2011) Sea level change in the Gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry. *Global and Planetary Change* 76, 137–151.

UNESCO (2003) Chao Phraya River Basin, Thailand, Chapter 16. In: The 1st United Nations World Water Development Report: *Water for People - Water for Life.* UN Educational Scientific and Cultural Organisation. URL: http://webworld.unesco.org/water/wwap/case_studies/chao_phraya/chao_phraya.pdf.

UN FAO (2009) Hydrological basins in Southeast Asia (derived from HydroSHEDS). Published in the framework of the AQUASTAT programme of the Land and Water Division of the Food and Agriculture Organization of the United Nations. URL: http://www.fao.org/geonetwork/srv/en/metadata.show?uuid=ee616dc4-3118-4d67-ba05-6e93dd3e962f&currTab=simple

Wattayakorn G (2006) Chao Phraya River estuary. LOICZ- Biogeochemical Modelling Node. URL: http://nest.su.se/mnode/Asia/Thailand/ChaoPhraya/cpbud.htm.

Weesakul S, Thammasittirong S (2000) Operational flood forecasting for Chao Phraya River delta. *International Conference: The Chao Phraya Delta: Historical Development, Dynamics and Challenges of Thailand's Rice Bowl*. 12-15 December 2000, Kasetsart University, Bangkok. URL: http://std.cpc.ku.ac.th/delta/conf/Acrobat/Papers_Eng/Volume%201/sutat%20supot%20OK.pdf.

World Bank (2011) The World Bank supports Thailand's post-floods recovery effort. December 13, 2011. URL: http://www.worldbank.org/en/news/feature/2011/12/13/world-bank-supports-thailands-post-floods-recovery-effort.

Yong RN, Nutalaya P, Mohamed AMO, Xu DM (1991) Land subsidence and flooding in Bangkok. Proceedings of the Fourth International Symposium on Land Subsidence, May 1991). IAHS Publ. no. 200.