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Open Data Flood Mapping of Chao Phraya River Basin and Bangkok Metropolitan Region

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Author's contribution

This whole work was carried out by the author RTC.

Original Research Article

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ABSTRACT

Aims: To examine the utility of open data for flood mapping of the Bangkok Metropolitan Region and Chao Phraya River basin. The region is particularly vulnerable to flooding, having experienced recurrent major flooding events, including the some of the most extensive and prolonged in 2011.
Study Design: Novel methodologies were innovated utilising open spatial data and open source geographical software to generate flood extent/hazard maps of the Bangkok Metropolitan Region and Chao Phraya River basin. Key geospatial data were sourced from the Thai Geo-Informatics and Space Technology Development Agency and NASA's Shuttle Radar Topography Mission.
Methodology: Given limited resources for conducting detailed hydrological-hydraulic analyses, two alternative approaches were examined for flood extent/hazard mapping of the basin and city. The first method made use of publicly available historical flood data to produce an up-to-date composite flood extent/hazard map. The second approach, using the latter output as a reference source, examined the utility of a modified topographic index for delineating flood-prone areas, as integrated into the r.hazard.flood module of the open source GRASS GIS application.
Results: Compilation of multi-year historical data enabled generation of a relatively fine-scale (~100m spatial resolution) flood extent/hazard map for the basin and city. The optimal tau threshold for delineating flood exposed cells from the modified topographic index was linearly related to the sub-basin mean slope. The four most northerly sub-basins of the Chao Phraya basin, those with higher mean slopes, gave lowest total errors, ranging from 17.5 to 35.9 percent.
Conclusions: Open data in the form of multi-year spatial flood layers were effectively

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combined to generate a relatively fine-scale flood extent/hazard map for the Chao Phraya River basin and Bangkok Metropolitan Region, and the modified topographic index showed promise as an alternative means for identifying flood exposed areas.

Keywords: Open data; disaster risk reduction; climate change adaptation; flood mapping; flood hazard; flood risk; digital elevation model; GRASS GIS.

1. INTRODUCTION

Flooding is an increasing hazard for low-lying coastal megacities of Southeast Asia. Climate change is projected to bring increased precipitation and frequency of intense rainfall events, increased extreme rainfall events linked to tropical cyclones and sea level rise [1]. The densely inhabited mega delta regions in the Asia-Pacific region are described as being at most risk from increased flooding from the sea and in some areas by rivers [2].

1.1 Increasing Flood Potential of Chao Phraya River Basin

The Bangkok Metropolitan Region (BMR), situated at the mouth of the Chao Phraya River, is vulnerable to both riverine and coastal flooding. The area is low-lying, with Bangkok City mostly less than 2.5 meters above mean sea level and below mean sea level in some areas [3]. In a recent OECD study, Bangkok was ranked as one of the most vulnerable to future coastal flooding with regard to population and asset exposure in the context of expected urbanisation and economic growth [4]. Coastal erosion in the upper Gulf of Thailand was described as already critical and impeding sustainable development of the BMR, with sea level rise and land subsidence due to excessive water withdrawal likely exacerbating hydrological impacts in the future [5]. Factors that potentially increase the risk of flooding in the BMR, including both human-related development activities within the Chao Phraya River catchment and climate change-related impacts [1,5-9], are shown in Fig. 1.

1.2 Bangkok Flood History

Bangkok has experienced recurrent major flooding, including from the mid-twentieth century: 1942, 1978, 1980, 1983, 1995, 1996, 2002, 2006 and 2011 [6,10-11]. The flood of 2011 was unprecedented in recent times, likely representative of more than a 100-year return period event, resulting from heavy rainfall over the entire Chao Phraya catchment [12-13]. According to DHI [12], the return period is estimated above 100 years, based on modelling conducted of the Chao Phraya River basin since the 1990s, hydrological studies and measured peak water levels, with the latter likely underestimated in 2011 given diversions of upstream flows; observed and estimated peak water levels reproduced as Table A1 in Appendix. Precipitation during the rainy season of 2011 was reported as 143 percent of the average over the 20 year period from 1982 to 2002 [14]. The flood resulted in over 800 mortalities, the displacement of thousands of city residents, an estimated 45 billion USD in damage, and economic repercussions internationally [14-17].

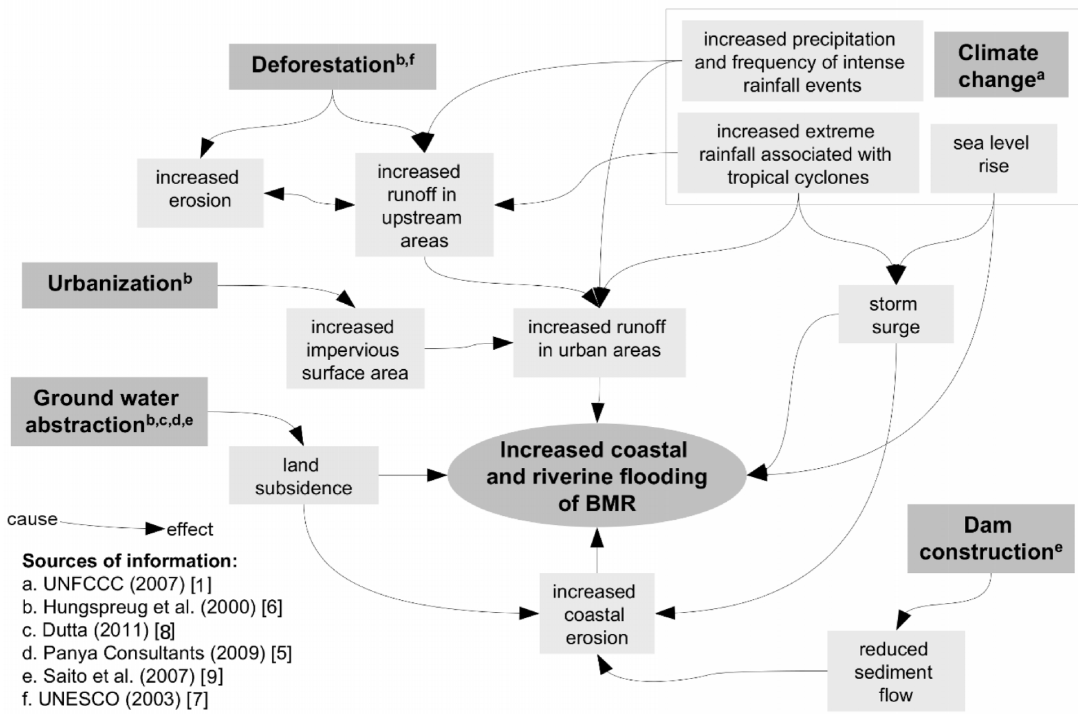

Fig. 1. The overall effect of human activities on increasing flood potential of Bangkok Metropolitan Region [1,5-9]

1.3 Flood Modelling

In order to accurately model flooding in the Bangkok Metropolitan Region, requires a detailed understanding of rainfall and run-off processes in the Chao Phraya River basin and its constituent sub-basins. The Chao Phraya River basin covers an area of approximately 160,000 km^2 (see Table 3, section 3.1) with four northern tributaries (Ping, Wang, Yom and Nan Rivers) that converge at Nakhon Sawan to form the Chao Phraya River, which subsequently branches and flows through the BMR to the Gulf of Thailand (Fig. 2) [7]. Flooding can result from a number of causes including upstream storm run-off, direct precipitation over the city, coastal storm surge and sea level rise, and the extent of flooding influenced by a range of factors such as flood management infrastructure, drainage and sewerage networks, land subsidence, sedimentation, and soil properties [18], as well as measures adopted during flood events such as water diversion (e.g., [12]). Since the mid-twentieth century, in the Chao Phraya basin, 3000 dams have been constructed, the two largest being the Bhumiphol and Sirikit dams which control 22 percent of the run-off of the whole Chao Phraya basin [7]; the latter two dams constructed in 1964 and 1974 respectively [14] (see Fig. 2).

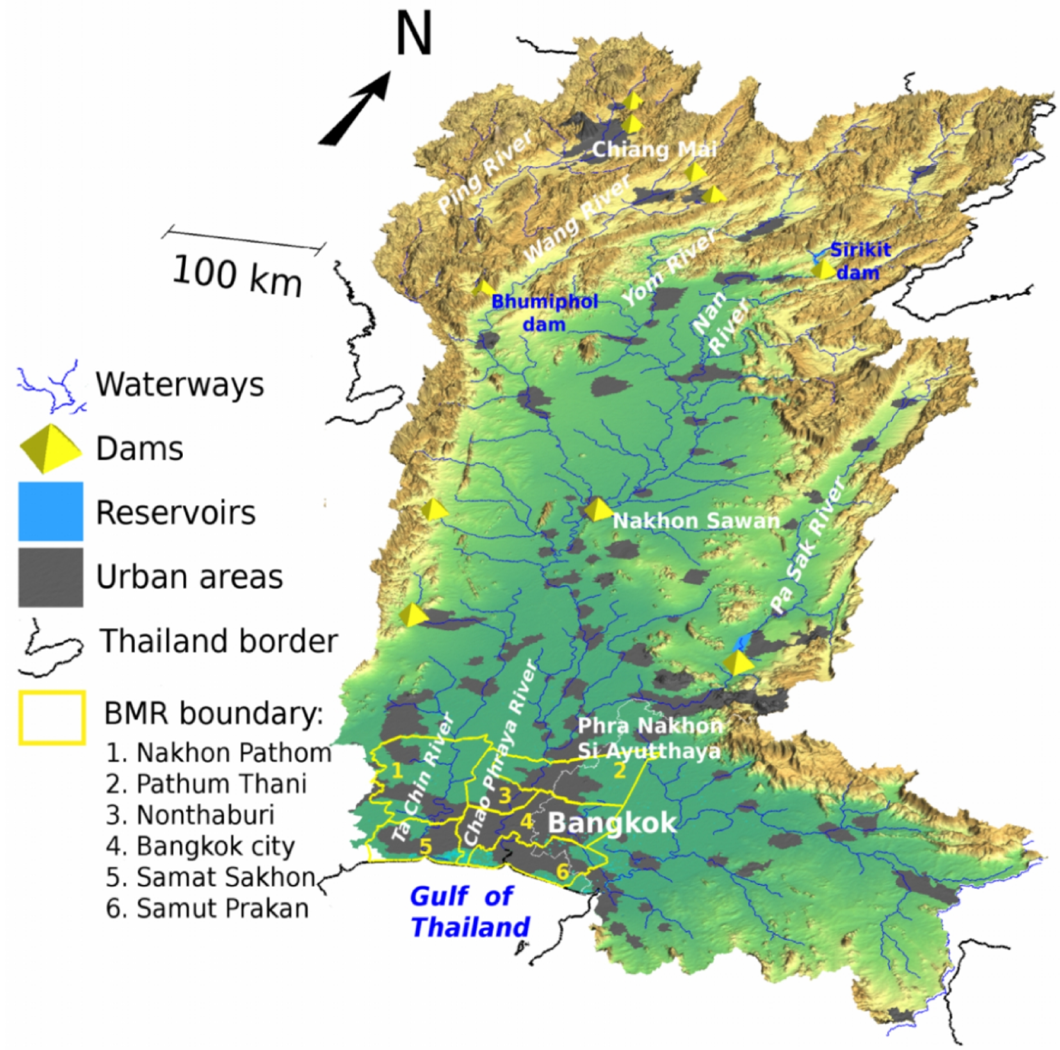

Fig. 2. Three-dimensional view of Chao Phraya River, adjacent Sa Keo sub-basin, and BMR with labelled administrative areas

Note: vertical elevation of image is exaggerated. Open data sources used in figure: digital elevation model [37]; basin/sub-basin boundaries [40]; dams and reservoirs [51]; urban areas [49]; waterways [50]; and BMR administrative areas [46]

Detailed flood inundation modelling efforts in the recent past by Panya Consultants [5] and the World Bank [18] examined the potential impact of climate change on flooding in Bangkok. However, modelling systems used in the latter studies, based on the commercial MIKE FLOOD software package developed by the Danish Hydraulic Institute (DHI), were not accessible, nor the data and financial resources available for the author to conduct an equivalent detailed investigation. Accurate and reliable flood hazard/risk maps were not available for the Chao Phraya River basin nor Bangkok Metropolitan Region. Data management concerns have previously been ascribed to multiple agencies responsible for maintaining water resources data and information [7].

1.4 Flood Extent/Hazard Mapping

This study specifically addresses creation of *flood extent/hazard* maps. In general, the term 'flood hazard map' refers to a spatial information product that illustrates geographical areas that are flood-prone or susceptible to flooding, which differs from a 'flood risk map' which indicates potential negative impacts of a flood, such as the number of people and kind of economic activities affected [19]. More specific requirements of hazard maps, as defined by the European Flood Directive (EFD) definition [19], includes identification of those areas at low, medium (return period ≥ 100 years) and high probabilities of flood, including components of extent, depth, and flow velocity where relevant. The emphasis here is on mapping the geographical extent of flooding, plus indication of flooding frequency based on historical data, with outputs to be integrated subsequently with socio-economic and health data to better understand risk and resilience as part of the Coastal Cities at Risk (CCaR) project.

1.5 International Coastal Cities at Risk Initiative

Improved knowledge of flood risk is an important focus of the ongoing five-year, 2011-2016, international Coastal Cities at Riskinitiative, being co-implemented by Chulalongkorn University, Thailand, and the University of Western Ontario, Canada [20-21]. CCaR's aim is to improve knowledge and capacity of megacities to adapt to climate change-related impacts in the context of rapid urban growth. CCaR is part of the International Research Initiative on Adaptation to Climate Change (IRIACC) of the Canadian International Development Research Centre (IDRC), and funded by the three research councils of Canada: 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).

CCaR supports research in the megacities of Bangkok, Manila, Lagos and Vancouver, of which a central output is development of a spatial system dynamics simulator to model city resilience (Coastal Megacity Resilience Simulator) [22], of which developing a measure of flood risk is a key component, together with other economic, social and health inputs. However, the unavailability of flood hazard data became apparent during implementation of project in Bangkok, and thus critical that alternative approaches identified for flood mapping. Hence the focus of this paper to describe approaches taken, challenges encountered, and to share findings with wider research and practitioner communities. Moreover, with two major floods each decade since the 1980s, flooding poses a substantial climate-related risk to the livelihood of Bangkok residents. The need for accurate, accessible and up-to-date flood maps is clearly evident to facilitate decision making, whether for government disaster preparedness planning, investment by the business community, or residents wanting to better understand their potential vulnerability.

1.6 Study Objectives

The chief objective of the study was to examine the utility of open data for flood mapping of the BMR and its wider basin. While there is no single definition of 'open data' [23-24], for the purpose of this study, the broad opendefinition.org was adopted, where: 'a piece of data or content is open if anyone is free to use, reuse, and redistribute it - subject only, at most, to the requirement to attribute and/or share-alike' [25]. In this study all of the data used in the analyses were freely accessible online, apart from one set of administrative boundaries supplied by the BMA ([26-30], Table A2). However, only one dataset considered for use, NASA's Shuttle Radar Topography Mission (SRTM) data, was released and distributed without restriction; its derivative created by Consultative Group for International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI) was actually used in this study, but is more restrictive with regard to data distribution (see section 2.1 and Table A2 for more details).

Key open datasets used in the study included eight years of historical inundation data, and application of a modified topographic index (TI_m) based on SRTM digital elevation model data using methodology developed by Manfreda and colleagues [31-32]. According to the Manfreda et al. [31], the TI_m-based method 'may represent a useful and rapid tool for a preliminary delineation of flooding areas in ungauged basins and in areas where expensive and time-consuming hydrological-hydraulic simulations are not affordable or economically convenient'.

Historical data and outputs from TI_m will indicate at a relatively fine scale the spatial extent of flood-prone areas. Multi-year historical data can also provide a spatio-temporal indication of flooding occurrence for hazard mapping (section 3.1). Though eight consecutive years of historical data is a relatively short time-span, the period includes two major flood episodes, including the most recent of 2011, estimated as having a return period of more than 100 years (see section 1.2); and based on discharge data from the Chao Phraya River basin, the 2006 flood had an estimated return period of 10 years [12]. Moreover, the pattern of recent historical inundation should reflect current flood management infrastructure and efforts, potentially useful given the current lack of available modelling capacity. Flood-prone areas derived from the TI_m are based on the compiled eight-year historical flood map; given that 2011 likely reflected an above 100-year flood event, outputs from the TI_m analysis were considered roughly correspondent with this return period. Data from all eight years were used in the TI_m analysis, and not 2011 coverage alone, as collectively this should capture more areas susceptible to flooding, thereby addressing spatial variability of precipitation across the basin. Findings will be directly used for examining city resilience though the Coastal Megacity Resilience Simulator (section 1.5), and should also prove beneficial for other efforts investigating and developing risk maps for the basin and city.

The study's secondary aim is to provide a quantitative historical assessment of the impact of recent flooding events in terms of area inundated, including the above 100-year event of 2011. Additionally, open source software is used in the analyses, with the aim of presenting methods that could be adopted by researchers or practitioners working outside an institutional setting with limited access to commercial GIS software, key issues which in the opinion of this author pose barriers to the uptake and application of geospatial technologies.

The *r.hazard.flood* add-on module of the open source GRASS GIS (Geographic Resources Analysis Support System Geographic Information System) [32-33] offers potential for generating flood maps based solely on the properties of a digital elevation model (DEM). The *r.hazard.flood* module is a python-based script that can be readily integrated into the main GRASS software suite, accessed through a graphical user interface window, and enables creation of flood map rasters based on a modified topographic Index (TI_m) derived from DEM physical properties. Research on applying TI_m- based flood mapping is well documented on river systems in Italy [31], and in this study, its utility further evaluated as a practical open source mapping tool by applying to the Chao Phraya River basin in Thailand.

2. MATERIALS AND METHODS

Two approaches were examined for creating flood extent/hazard maps based on the availability of open data. Firstly, multi-year spatial historical inundation data (see section 2.1) were used to create a GIS composite layer of the entire Chao Phraya basin and BMR, and the latter then used as a reference layer to assess the utility of the modified topographic index, as integrated in the GRASS GIS module *r.hazard.flood*, for delineating flood-prone areas. Open source desktop GIS and command line utilities were used, including GRASS GIS and associated add-on modules [33], and GDAL/OGR command line utilities [34]. Before examining these methods, open data sources used are highlighted in the next section.

2.1 Open Data Sources and Quality Assessment

A variety of data sources were utilised and are detailed below, together with any data quality issues encountered.

2.1.1 Historical flood inundation layers

Historical spatial flood data were obtained from the Thailand Flood Monitoring System of the Geo-Informatics and Space Technology Development Agency (GISTDA) [35]. Flood inundation area maps were downloaded as ESRI shapefiles from the latter site, with annual flood data accessible from 2005 to 2012 inclusive. The flood maps were derived from synthetic aperture radar (SAR) imagery acquired during the rainy season [GISTDA, personal communication].

2.1.2 Digital elevation data

Post-processed digital elevation data from the Shuttle Radar Topography Mission (SRTM) [36] were used in the study to create the modified topographic index (TI_m). SRTM data used were of 3 arc second spatial resolution and processed to fill no-data regions by the Consortium for Spatial Information (CSI) of the Consultative Group for International Agricultural Research (version 4.1) (CGIAR) [37-38]. ASTER Global Digital Elevation Model (ASTER GDEM) [39] data were also examined for use, but quality appeared variable in the lower Chao Phraya basin which precluded theiruse on this occasion; a linear artefact was apparent in two tiles: ASTGTM2_N14E099_dem_tif and ASTGTM2_N14E100_dem.tif.

2.1.3 Chao Phraya river basin and sub-basin boundaries

The Chao Phraya River basin and sub-basin boundaries for the study were defined using the ESRI shapefile - '*Hydrological basins in Southeast Asia (Derived from HydroSHEDS)'* - accessible from the UN FAO's GeoNetwork portal [40]. The data set was published under FAO's AQUASTAT programme, and derived from the HydroSHEDS initiative of the World Wildlife Fund (in partnership with the U.S. Geological Survey (USGS) and other organisations) [41]. While basin boundaries have been derived elsewhere (as briefly mentioned below), boundaries for both basin and sub-basins are provided, all of which are named; however, some sub-basins were incorrectly labelled in the latter resource and have been re-labelled[1] to reflect main rivers/waterways as shown in Fig. 3.

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[1]*Sub-basins re-labelled as indicated in parentheses: Mae Nam Wang (Mae Nam Ping); Mae Nam Yom (Mae Nam Wang); Mae Nam Nan (Mae Nam Yom); Mae Nam Ping (Mae Nam Nan); Noi (Mae Nam Pa Sak); Mae Nam Pasak (Khlong Kriangkrai).*

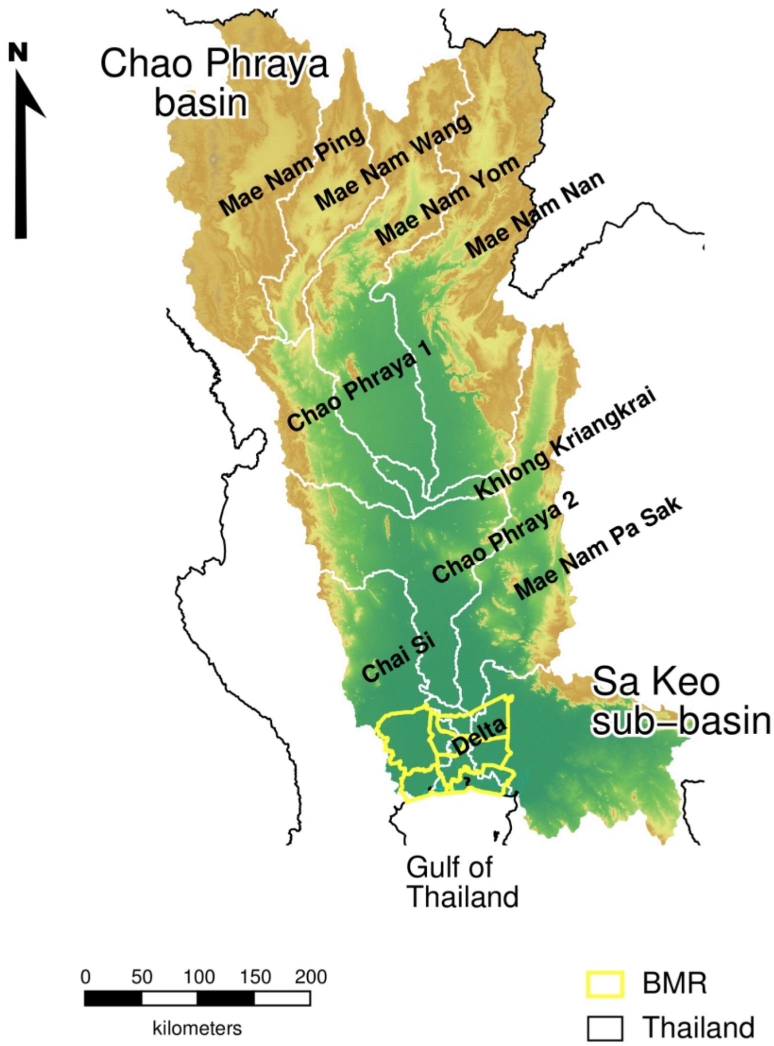

Fig. 3. Chao Phraya River basin and sub-basins and adjacent Sa Keo sub-basin

Coordinate reference system: EPSG 32647 (UTM47N WGS84). Basin boundaries (white lines) as per FAO AQUASTAT hydrological basins data set [40]. Other open data used in figure: CGIAR-CSI SRTM digital elevation model [37]

HydroSHEDS data are primarily based on elevation data acquired from NASA's Shuttle Radar Topography Mission [36] as well as the Digital Chart of the World (DCW), ArcWorld data set, and the Global Lakes and Wetlands Database (GLWD) [42]. Unlike HydroSHEDS, the basins/sub-basins are named in the FAO-amended dataset, and the boundary of the Chao Phraya basin closely matches that in HydroSHEDS, apart from some differences in the southern part of the basin, such as inclusion of the Chai Si sub-basin and small differences near the coast. The technical literature for HydroSHEDS describes the drainage basins as not yet finalised, though generally they have better accuracy than the earlier HYDRO1k elevation derivative database, ArcWorld and DCW, and there may be issues concerning the accuracy of river networks in low relief areas [42].

HYDRO1k Elevation Derivative Database is derived from the Global 30 Arc-Second Elevation (GTOPO30) data set, a 30 arc second (~1 km) digital elevation model of the world created by USGS in 1996 [43-44]. Layers created as part of the data set include derivatives for hydrological analysis including basin boundaries, streams, slope, aspect, flow direction and accumulation.

Another data set delineating the Chao Phraya basin is the Global Runoff Data Centre (GRDC) '*Major River Basins of the World*' [45], derived from HYDRO1k. The chief differences between the latter and FAO's data set concerns the inclusion of the Mae Nam Moei (Salween basin) and the Sa Keo (Gulf of Thailand Coast) sub-basins into the Chao Phraya River basin in the GRDC layer.

For the purpose of this study, FAO's delineation of the Chao Phraya basin was adopted [40], where the Bangkok Metropolitan Region (BMR) crosses two major basins - the Chao Phraya and Gulf of Thailand Coast basins. The BMR extends from the Chao Phraya basin into the Sa Keo sub-basin of the latter. The BMR and entire Chao Phraya basin are located in the UTM47N zone and all results are presented based on this projection.

2.1.4 Administrative boundaries and urban areas

The BMR, or Greater Bangkok, comprises the city of Bangkok (special administrative area) and conterminous provinces of Samut Prakan, Samut Sakhon, Nakhon Pathom, Nonthaburi, and Pathum Thani. The BMR boundary can be freely accessed from the GADM database of Global Administrative Areas [46]. The BMR covers an area of approximately 7652 km^2 (calculated from GADM) with a population of 10.5 million in 2012 [47], though the population varies by several million more in consideration of unregistered residents and commuters [48]. A BMR boundary layer supplied by the Bangkok Metropolitan Administration proved to be mostly congruent with the GADM-derived data with a total BMR area of 7689 km^2; some minor boundary differences are apparent generally with the largest differences in Samut Sakhon and Samut Prakan provinces. The BMA-supplied layer was used for determining flooded areas for each BMR administrative area, as reported in Tables 1 and 2 (Results and Discussion). Urban areas flooded in the BMR were based on open data from the Global Rural-Urban Mapping Project (GRUMP) by CIESIN et al. [49].

Other open data sets accessed include those used for displaying rivers and water bodies in Fig. 2 above [50-51].

2.2 Creation of Composite Historical Flood Map

The method adopted for creating the composite flood map is summarised diagrammatically in Fig. 4. Shapefiles were clipped and transformed from EPSG 4326 to EPSG 32647 (UTM 47N/WGS84) and rasterized to a spatial resolution of 100m using GDAL command line utilities - ogr2ogr and gdal_rasterize; the appropriate spatial resolution was determined following consultation with GISDTA. After rasterizing, a single compiled raster image was created from the series of eight flood inundation images (2005 - 2012 inclusive) by summing cell values using the GRASS *r.series* module [52]. The output layer contained cell values ranging from 1 to 8 representing areas with the lowest to highest occurrence of flood; areas unflooded during the 8 year period were assigned a value of zero. Based on the accuracy of the input inundation maps, identification of flooded areas should be approximately 80 to 90% correct, though the error might be higher in urban areas [53].

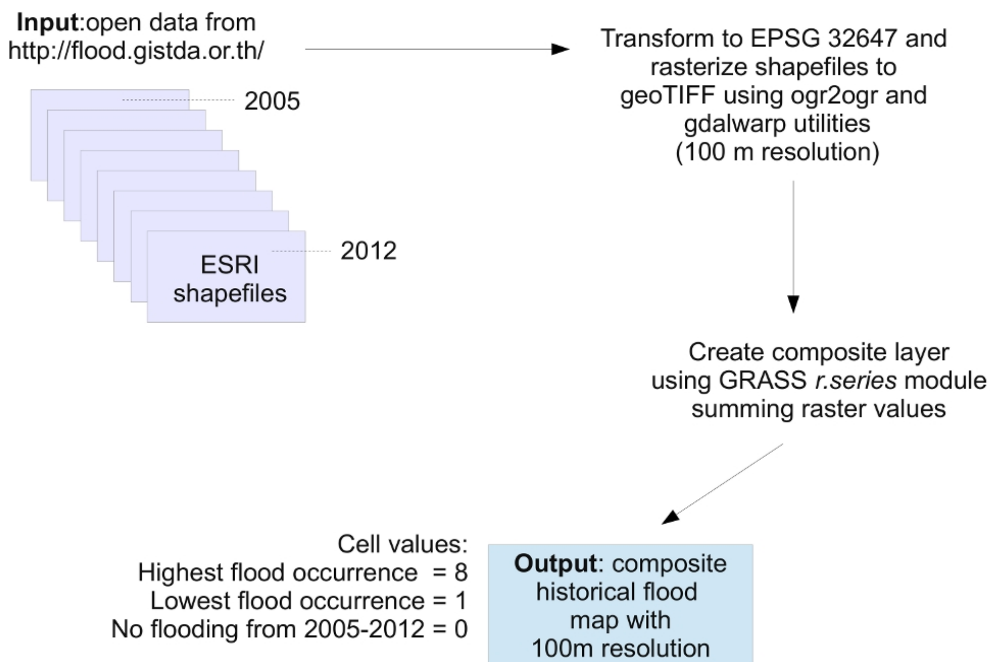

Fig. 4. Schematic diagram showing creation of composite historical flood map

2.3 Development of Flood Map Using Modified Topographic Index and Error Analysis

The second approach examined the utility of the modified topographic index (TI_m), a procedure developed by Manfreda et al. and incorporated into the GRASS *r.hazard.flood*add-on extension module [31-32,54-55]. The module delineates flood-prone areas by calculating a modified topographic index from a digital elevation model (see formula below), and categorises those cells above a given threshold value as exposed to flooding [31]. In other words, flood-prone areas are derived from topographic parameters, the supposition being that physical surface features can reveal areas exposed to flood inundation given that the land surface is shaped by hydrological processes [31]. Areas susceptible to inundation are determined by a value above a calculated threshold (*tau*, τ).

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

The TI_m is based on the Topographic Index (TI), also called the Topographic Wetness Index (TWI), which reflects the quantity of water flowing to a particular location and accumulation in low slope areas (e.g., [56]), but differs only by the inclusion of an exponent, n [57]. The TI_m is a function of the specific upslope contributing area (a_d) (determined by multiplying accumulation x cell size), the local slope (β), and the exponent n is a function of DEM cell size.

The threshold *tau* and exponent n values incorporated into the *r.hazard.flood* module were derived from research conducted in the Arno River basin in Italy [31], employing a calibration procedure based on error analysis of TI_m outputs compared to reference flood maps generated from an ensemble of historical flood maps, geomorphological and hydraulic studies [31,57]. The TI_m threshold value used in *r.hazard.flood* corresponds to the minimum total error with reference to the higher 500-year return period of the reference maps, where $\tau = 10.89n + 2.282$ [31]. The exponent n was found to be strongly correlated to DEM cell size, where a plot of n against DEM cell size could be expressed as $n = 0.016x^{0.46}$ [31]. Additional findings in the Italian study showed that good results were possible using DEM's with resolutions of up to approximately 100m, including reliable results from NASA's SRTM 90m DEM. For example, using this expression, a DEM of 90m cell size will give a threshold of 3.6627, with cells above this value defined as being exposed to flooding.

The method adopted in this study was to use the CGIAR-CSI SRTM 90m DEM 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 (see Fig. 5). Error estimation is based on the approach by Manfreda et al. [31] (see Fig. 6). 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 (as used in the Arno River basin study by Manfreda et al. [31]) were not available.

Additional potential constraints to error analysis of the TI_m layer include land use/land cover changes in the Chao Phraya basin, including urbanisation and flood infrastructure (e.g., construction of dikes), and water diversion during a flooding event (e.g., [12]), which could modify the extent of flooding in the reference layer. For instance, greater flood protection given to key commercial and business districts of the BMR (located in the Delta sub-basin). Furthermore, an appropriate tau threshold needs to be determined to identify flood-prone areas based on the reference historical flood map. The reference map likely represents more than a 100-year flood (see comments above concerning the 2011 flood) and thus if the default threshold in r.hazard.flood were applied, it would give an overestimation of area delineated by the module as flood-prone. The optimal tau value, corresponding to minimum total error, was interpolated from error analysis of each sub-basin, as summarised in Fig. 6.

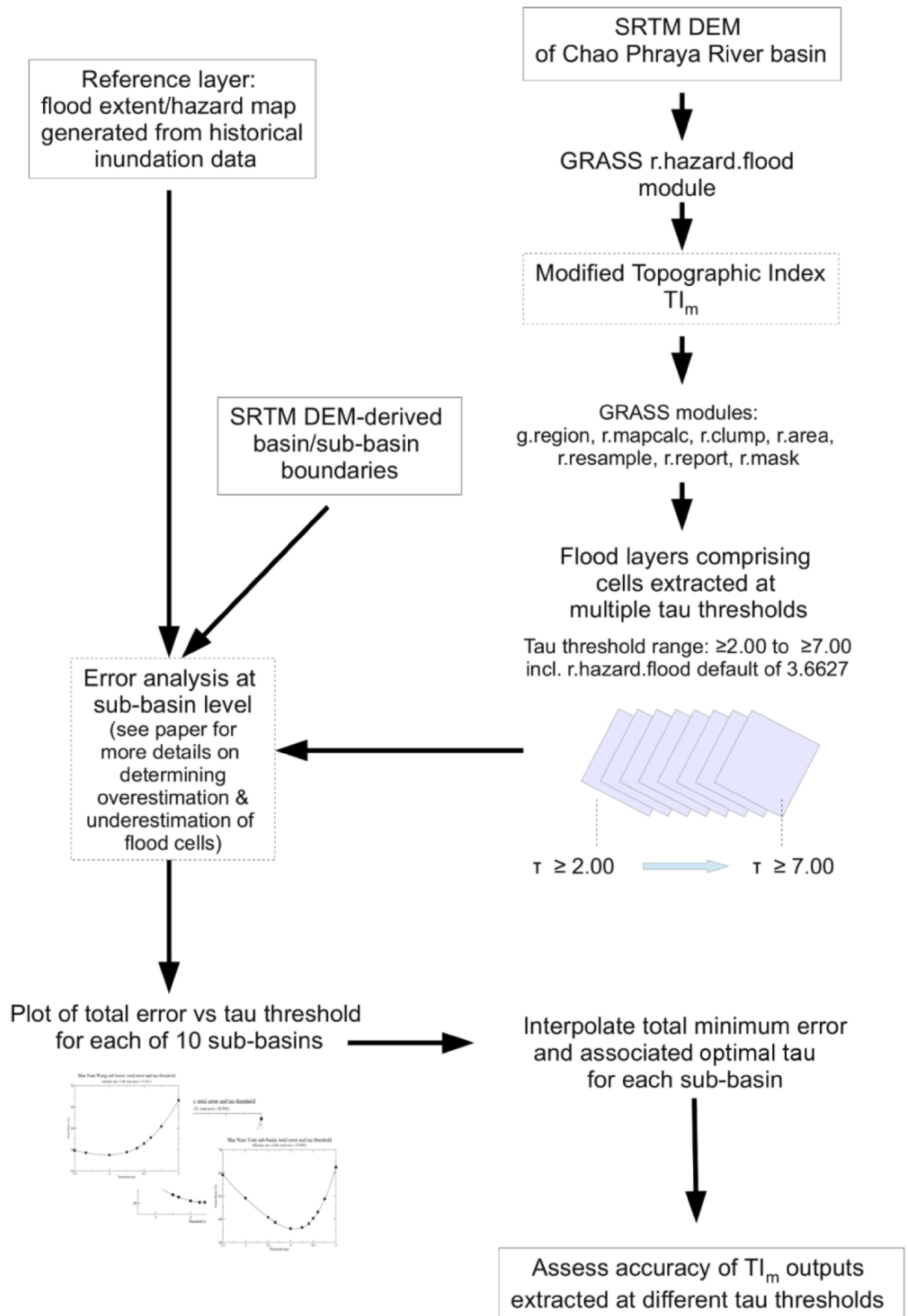

Fig. 5. Flow chart of methodology for assessing utility of modified topographic index for generating flood map

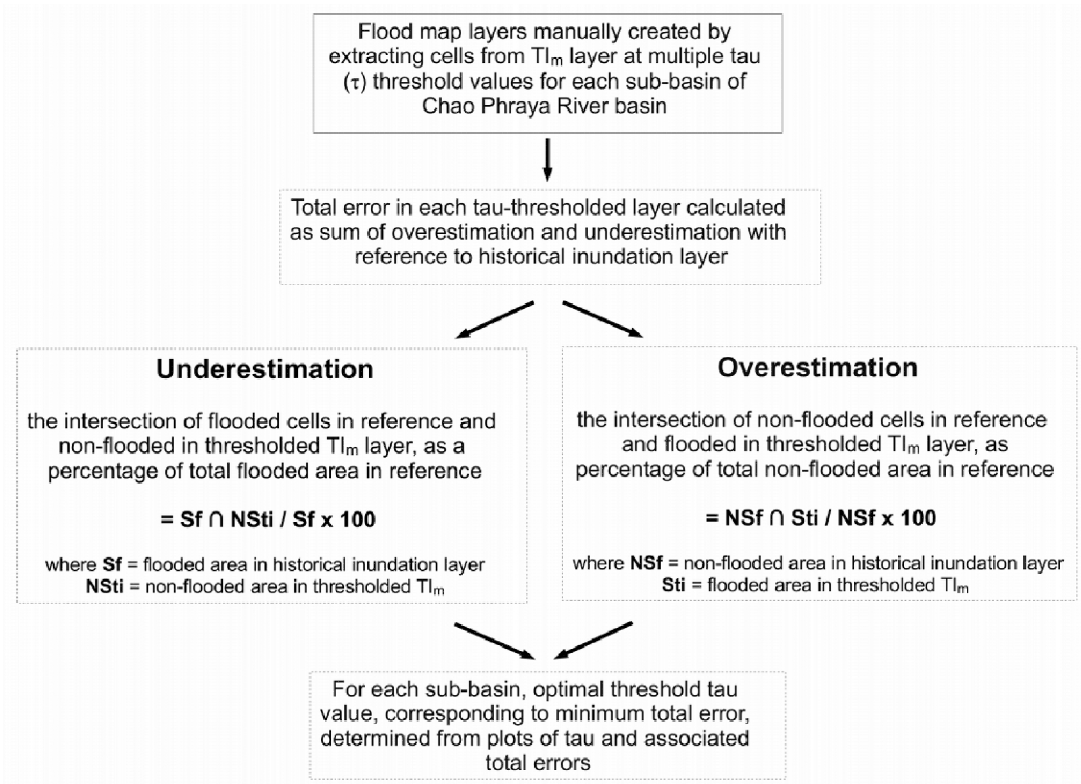

Fig. 6. Error analysis of TI_m –based flood rasters to derive optimal tau threshold values

Error estimation based on the approach by Manfreda et al. [31]

A DEM of the entire Chao Phraya River basin was created by patching together SRTM tiles downloaded from CGIAR-CSI [58] and this input to the *r.hazard.flood* add-on module to generate the TI_m layer, with flood output layers subsequently manually generated using selected tau thresholds between 2.0 and 7.0 (including the *r.hazard.flood* default of 3.6627 which corresponds to a 90m resolution DEM based on a 500-year flood return period) (Fig. 5). Selected tau thresholds and total errors were plotted for each sub-basin and the minimum threshold interpolated using a cubic spline (using GRACE 2D plotting software[2]). The mean slope of each sub-basin was also determined (output from *r.slope.aspect* [59]) and plotted against minimum total errors and tau thresholds to assess potential correlation.

3. RESULTS AND DISCUSSION

3.1 Composite Historical Flood Map

Based on historical data, flood extent/hazard maps were generated for the entire Chao Phraya River basin (Fig. 7) and Bangkok Metropolitan Region (Fig. 8). Areas of highest flood occurrence are displayed in red and least risk coloured yellow, and those areas not flooded in the eight year study period remain uncoloured. Cumulative historical inundation (i.e.,

[2] *GRACE 2D plotting tool: http://plasma-gate.weizmann.ac.il/Grace.*

maximum extent of flooding derived by overlaying all annual inundation layers) are presented for: the entire BMR, Bangkok City and constituent provinces (Table 1); urban areas (Table 2); and entire Chao Phraya River basin and sub-basins (Table 3). Stacked bar charts showing the annual extent of flooding for the BMR (Bangkok City and its contiguous provinces) and the entire Chao Phraya basin (all 10 sub-basins) are displayed in Figs. A1 and A2 respectively (see Appendix). Key statistics of the 2011 flood disaster indicate that approximately 4200 km^2 (56 percent) of the BMR was inundated, and at the basin level over 26,000 km^2 (17 percent) was flooded.

Table 1. Total land area flooded within BMR (data combined from 2005 to 2012)

Administrative area	Total area[1]	Land area[2]	Land area flooded[3]	
	(km^2)	(km^2)	(km^2)	(%)
BMR	7689.0	7483.1	4460.2	59.6
Bangkok city	1569.3	1519.0	829.4	54.6
Samut Sakhon	864.3	837.2	76.7	9.2
Samut Prakan	960.2	904.8	301.3	33.3
Nakhon Pathom	2141.2	2127.5	1408.6	66.2
Nonthaburi	633.4	617.4	479.4	77.6
Pathum Thani	1520.4	1477.2	1364.6	92.4

[1]*Total area: land and river/waterways/water bodies*
[2]*Land area: excluding river/waterways/water bodies;*
[3]*flood pixels overlaying river/waterways/water bodies omitted from flood area calculations*

Overall, at some time during the eight year period from 2005 to 2012, nearly 60 percent of the BMR's land area and 50 percent of its urban area was flooded. The province of Pathum Thani was the most flood-prone province with 92 percent of its land area inundated and 95 percent of its urban area. The provinces of Nonthaburi and Nakhon Pathom were also especially vulnerable with 78 and 66 percent of land inundated respectively. Bangkok City (the special administrative area), experienced flooding mainly in its eastern and western regions, while the coastal provinces of Samut Sakhon and Samut Prakan experienced flooding to a lesser extent, though not insubstantial; however, coastal flooding caused by tidal and storm surge may not be captured in the GISTDA inundation layers as they were derived from SAR data during the rainy season and focused on flooding caused by precipitation and downstream run-off (GISTDA, personal communication).

The results clearly indicate that millions of residents are vulnerable to flooding in the BMR: with a total population of over 10 million and some 50 percent of its urban area inundated on one or more occasions between 2005 and 2012 (see Table 2). It should also be noted that past historical inundations may not indicate the frequency and extent of present and future flooding events in the context of climate change and land cover/land use changes in the basin. However, given the lack of existing hydrological-hydraulic modelling data, these data do provide some indication of spatial vulnerability to flooding.

Table 2. Urban areas flooded within BMR (data combined from 2005 to 2012)

Administrative area[1]	Urban area[2]	Population[3]	Urban area flooded	
	(km^2)	Persons	(km^2)	(%)
BMR	4039.1	10,455,800	1973.0	48.8
Bangkok city	1280.9	5,673,560	636.8	49.7
Samut Sakhon	511.1	508,812	64.1	12.5
Samut Prakan	616.6	1,223,302	178.4	28.9
Nakhon Pathom	681.4	874,616	300.5	44.1
Nonthaburi	373.3	1,141,673	244.0	65.4
Pathum Thani	575.8	1,033,837	549.1	95.4

[1]Administrative boundaries derived from data supplied by BMA to CCaR project

[2]Urban area calculations using data from CIESIN, IFPRI, WB, CIAT (2011) [49] and excluding river/waterway/waterbodies.

[3]2012 population data from BMA (2012) [47]

Table 3. Flooded areas within Chao Phraya River basin and sub-basins (data combined from 2005 to 2012)

Drainage basin	Total area	Area flooded	
	(km^2)	(km^2)	(%)
Chao Phraya (entire basin)	157,633.3	31,919.3	20.2
Sub-basins			
Mae Nam Ping	26,269.8	708.4	2.7
Mae Nam Wang	10,736.7	838.3	7.8
Mae Nam Yom	24,582.1	6,099.2	24.8
Mae Nam Nan	33,293.0	4,280.2	12.9
Chao Phraya 1	9,440.8	1,600.6	17.0
Khlong Kriangkrai	2,122.3	1,143.5	53.9
Mae Nam Pasak	19,527.7	3,844.8	19.7
Chao Phraya 2	16,400.6	7,021.5	42.8
Chai Si	12,912.3	5,363.6	41.5
Delta	2,348.8	1,019.1	43.4

3.2 Modified Topographic Index (TI_m)

For each Chao Phraya sub-basin, the optimal threshold tau value, corresponding to minimum total error, was interpolated from a plot of calculated total errors and associated tau threshold values used for extracting the flood raster from the TI_m layer. Fig. A3 (Appendix) presents total error and tau threshold plots of each Chao Phraya sub-basin, and Table 4 shows the interpolated minimum total errors and associated optimal tau thresholds, as well as area and mean slope for each sub-basin.

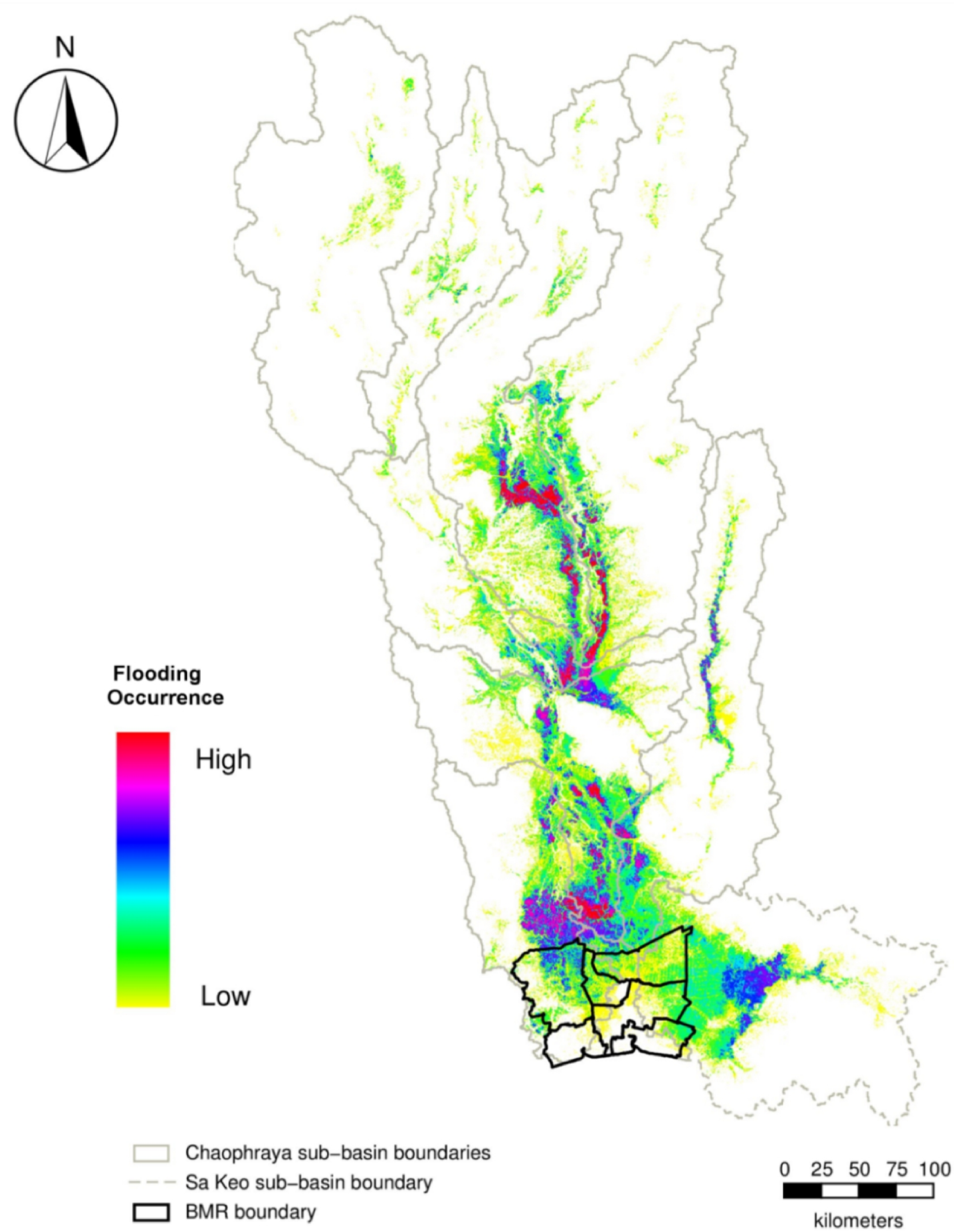

Fig. 7. Flood extent/hazard map of Chao Phraya River basin and adjacent Sa Keo sub-basin

Map shows spatial extent and frequency of past flood events from 2005 to 2012 inclusive. Coordinate reference system: EPSG 32647 (UTM47N WGS84). Spatial resolution of 100m. Areas of highest flood occurrence indicated as red

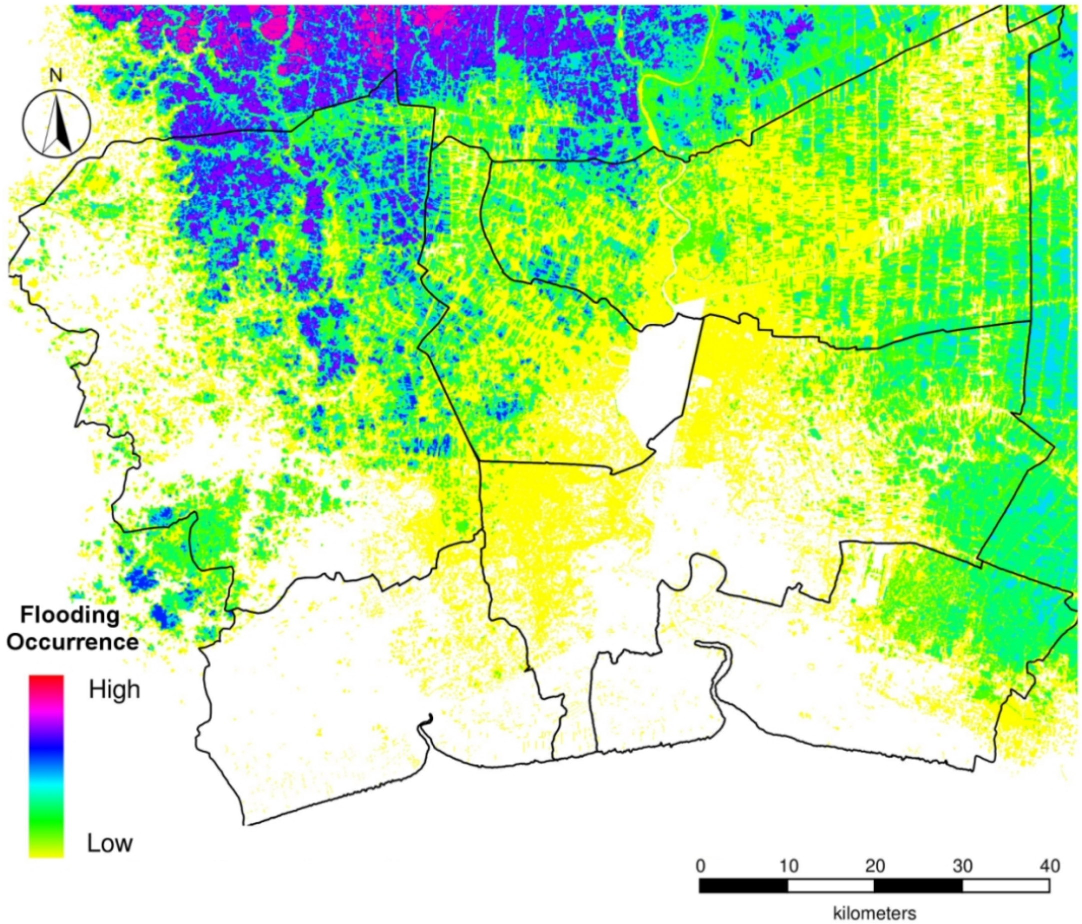

Fig. 8. Flood extent/hazard map of Bangkok Metropolitan Region

Map shows spatial extent and historical occurrence of flood events from 2005 to 2012 inclusive. Coordinate reference system: EPSG 32647 (UTM47N WGS84). Spatial resolution of 100m. Areas of highest flood occurrence indicated as red. Note: flooding is likely underestimated in region of BMR in 2005, as apparent from abrupt linear boundaries on flood polygons to north and east of BMR; perhaps related to incomplete imagery or subsequent processing

Optimal tau threshold values varied from 3.96 (Mae Nam Ping) to 5.23 (Delta). It was anticipated that the estimated tau threshold would be higher than the 3.6627 calculated using the linear function derived by Manfreda et al. [31] (see Fig. 6); at the latter threshold, much of the error in the sub-basins is attributable to overestimation of flooded areas. The reference layer used in this study was derived from eight years of inundation data, with the 2011 flood likely reflecting more than a 1-in-100 year flood, whereas the tau threshold derived by Manfreda et al. [31] was based on a considerably higher return period of 500 years.

Total minimum error decreased with increasing sub-basin mean slope. Accuracy was substantially lower when applied to areas of lower topographic relief, with minimum total error increasing linearly from approximately 10 to 70 percent for a mean slope decreasing from 20 to 2.5 percent respectively. A linear regression of minimum total error and mean sub-basin slope shows a correlation (correlation coefficient -0.9449) between increasing mean slope and reducing total error; such a linear correlation does not appear present in Manfreda et al. [31] data. The minimum total error (y) can be estimated from the linear function: $y = 78.174 - 3.3377x$, where x is the mean slope (Fig. 9). Thus, minimum total errors of 10, 25 and 50 percent correspond to mean slopes of approximately 20, 16 and 8% respectively. Significant error may be introduced into low relief areas given that the SRTM DEM comprises integer and not floating point data [31]. Unfortunately, it was not possible to further examine whether this error was related to using SRTM DEM given artefacts evident in the higher resolution ASTER DEM for the region. Overall, the four most northerly sub-basins of the Chao Phraya basin, those with higher mean slopes, gave lowest total errors, ranging from 17.5 to 35.9 percent (see Fig. 10). All the remaining sub-basins had errors ranging from 45.8 to 87.2 percent.

Table 4. Interpolated minimum total errors and associated optimal tau thresholds for each sub-basin and basin/sub-basin areas, urban extents and mean slopes

Drainage basin	Total area (km^2)	Urban area (km^2)[1]	Urban Area (% of basin/ sub-basin)	Mean slope (%)	Minimum total error (%)	Optimal threshold (tau)
Chao Phraya (entire basin)	157,633	13,652	8.7	11.70	34.07	4.50
Sub-basins						
Mae Nam Ping	26,270	1,475	5.6	20.67	17.53	3.96
Mae Nam Wang	10,737	634	5.9	14.68	35.90	4.06
Mae Nam Yom	24,582	1,284	5.2	10.78	30.50	4.50
Mae Nam Nan	33,293	1,197	3.6	15.28	20.50	4.32
Chao Phraya 1	9441	548	5.8	9.43	45.82	4.76
Khlong Kriangkrai	2,122	35	1.7	2.19	69.40	4.64
Mae Nam Pa Sak	19,528	2,750	14.1	8.40	46.65	4.67
Chao Phraya 2	16,401	1,329	8.1	4.45	58.79	5.05
Chai Si	12,912	2,846	22.0	2.82	69.30	5.18
Delta	2,348	1,553	66.1	1.24	87.16	5.23

[1]*Data derived from CIESIN, IFPRI, WB, CIAT (2011) [49]*

The optimal tau threshold representing minimum total error appears related to sub-basin mean slope. The four northernmost sub-basins, with highest mean slope values, presented optimal tau thresholds ranging from 3.96 to 4.50, with thresholds from 4.64 to 5.23 for the remaining sub-basins (Table 4). A linear relationship between optimal tau threshold and mean slope is given by the function: $y = 5.1912 - 0.06162x$, where y is the optimal threshold (Fig. 11). It is interesting to note that Manfreda et al. also noted improved performance of the TI_m method in basins of lower order [31]. Given that tau appears related to mean slope in this study, more accurate representation of flooding using TI_m may be best obtained by customising the threshold to the mean slope of each sub-basin; in this study a single tau value does not appear practicable for accurately delineating flood exposed areas.

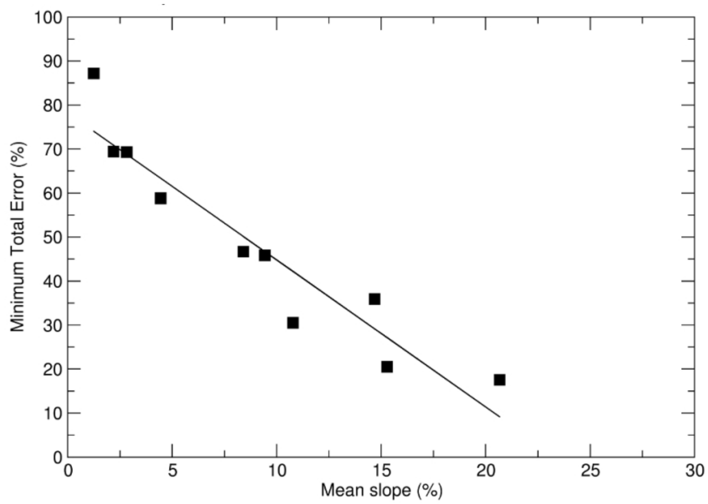

Fig. 9. Plot of minimum total errors and mean sub-basin slopes (y = 78.174 - 3.3377x; correlation coefficient = -0.9449)

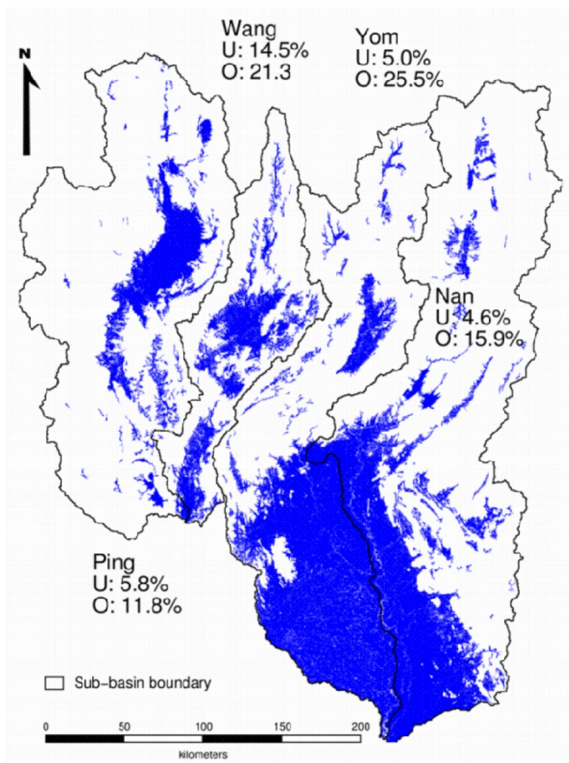

Fig. 10. Flood-prone areas (blue) of the four northern sub-basins generated from TI_m
Flood maps were created using optimal tau thresholds determined from error analysis of each sub-basin. Indicated underestimation (U) and overestimation (O) errors were calculated from the maps extracted with optimal thresholds

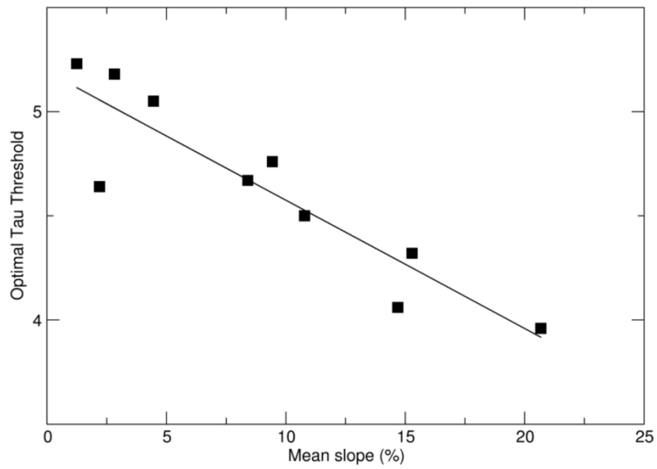

Fig. 11. Plot of optimal tau thresholds and mean slopes (y = 5.1912 - 0.06162x; correlation coefficient = -0.9061)

Potential limitations and constraints to error analysis of the modified topographic index output are depicted in Fig. 12. Limitations include the unavailability of flood data derived from hydrological-hydraulic models of the basin for strengthening the accuracy of the reference data, and more accurate DEM data for generation of the modified topographic index layer. Other potential constraints include accuracy of input historical inundation data, such as underestimation of flooded area in urban settings related to the satellite imagery, and the influence of land cover/land use changes such as urbanisation and flood defence management on flooding extent, e.g., greater flood protection of key commercial and business areas of the BMR (as located in the Delta sub-basin).

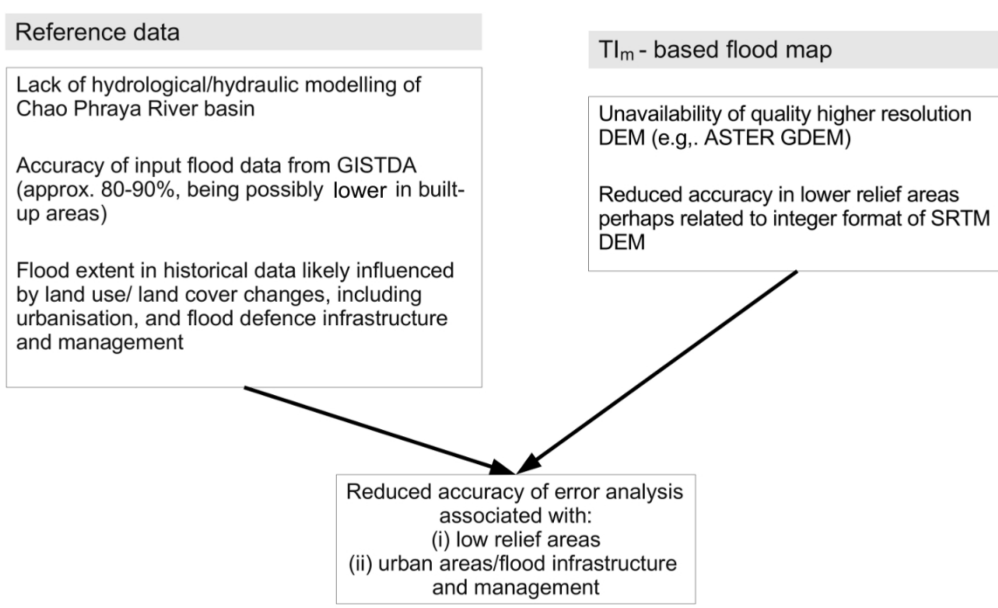

Fig. 12. Potential limitations and constraints to error analysis of TI_m-based flood map

4. CONCLUSION

Open data in the form of multi-year spatial flood layers were effectively combined to generate a relatively fine-scale (~100m spatial resolution) flood extent/hazard map for Thailand's Chao Phraya River basin and Bangkok Metropolitan Region. The maximum flooding extent is likely representative of above a 100-year return period event; however it should be noted that future flooding in the basin may not reflect the past, given new development within the basin and climate change impacts. The flood extent/hazard map offers potential to be updated with more recent data so as to better reflect land cover/land use changes and flood infrastructure developments, as well as climate change impacts. As well as being used for the CCaR project city resilience modelling, the flood maps created in this study will be made available to the Bangkok Metropolitan Administration, requesting that they are added to their existing BMA Web Map Service[4] and also to GISTDA for sharing through their flood monitoring portal [35].

The utility of using a modified topographic index from SRTM DEM for delineating flood-prone areas also offers promise for flood mapping, where other means of assessment, such as detailed hydrological-hydraulic assessments and historical inundation data are unavailable. However, as also noted by Manfreda et al. [31], the index cannot be considered a replacement for more detailed analyses, but as a preliminary assessment of flood-prone areas. For instance, the procedure could be used to identify areas especially at risk from flooding. Findings presented here indicate good correspondence between reference historical inundation data and the results of the TI_m method, at least for the four most northerly sub-basins of the Chao Phraya River basin characterised by higher mean slopes. However, 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 as shown in this study, the mean slope of the sub-basin. No single tau threshold value appears practicable and might be best determined from a sub-basin's slope given the linear relationship observed above.

Performance of the TI_m-based method is reduced in areas of low topographic relief, which may relate to the limited vertical resolution of the SRTM DEM (see section 3.2). The latter observation reflects the comment by Manfreda et al. [31] that the method may be especially useful in basins with marked topography, and greater error may relate to the SRTM DEM used to generate the TI_m. Other potential errors may derive from the accuracy and nature of the reference layer compiled from historical inundation data, where flooding extent may be influenced by land cover/land use changes, such as urbanisation and flood protection measures. The two southernmost sub-basins, characterised by lowest mean slopes and highest urban extents, presented the highest total errors; however, the low mean slope and minimal urbanisation of the central Khlong Kriangkrai sub-basin suggests that mean slope might be the key factor influencing their observed error. Findings indicated that a total error of 20 percent or less required a mean slope of at least 17 percent (~10 degrees).

The modified topographic index is potentially a highly valuable tool for environmental and disaster risk management. To further validate the utility of using the modified topographic index as a tool for delineating flood-prone areas, it is recommended that future studies examine higher resolution DEMs, such as the 30m resolution ASTER GDEM, and other

[4]*BMA Web Map Service: http://203.155.220.230/wms/*

drainage basins as study sites. Moreover, it would be informative to further examine optimal tau thresholds for delineating flood exposed areas and if a linear relationship between the tau threshold and mean slope is observable elsewhere.

The methodology presented here also offers scope to create flood maps representing multiple return periods. For example, according to the report by DHI [12], the 2006 flood was estimated as a 10 year flood and spatial flood data is already accessible from GISTDA. Furthermore, given estimated return periods of 25 and 50 years for the 1996 and 1995 floods respectively [12], there should be scope to derive flood maps for these return periods.

It should also be highlighted that given the emphasis on using open data and open source GIS software, the methods adopted here offer scope for independent non-institutional researchers to conduct further investigations. Open data made generation of Chao Phraya River basin and the BMR flood hazard maps feasible in a reasonable time and with limited financial resources, apart from expertise required to conduct the GRASS-based GIS analyses.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. United Nations Framework Convention on Climate Change (UNFCCC). Climate Change: Impacts, Vulnerabilities and Adaptation in Developing Countries; 2007. Accessed 28 May 2014.
   Available: http://unfccc.int/resource/docs/publications/impacts.pdf.
2. Intergovernmental Panel on Climate Change (IPCC).Climate Change 2007: Synthesis Report; 2007. Accessed 19 September 2013.
   Available: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr.pdf.
3. Royal Thai Survey Department. Map showing dikes and ground level in Bangkok districts and surrounding areas, October 2553 (Prepared by Division of Geodesy and Geophysics, Royal Thai Survey Department; 2010. Thai.

4. Nicholls RJ, Hanson S, Herweijer C, Patmore N, Hallegatte S, Corfee-Morlot J, Chateau J, Muir-Wood R. Ranking port cities with high exposure and vulnerability to climate extremes: Exposure Estimates, OECD Environment Working Papers, No. 1, OECD Publishing; 2008.
Available: http://dx.doi.org/10.1787/011766488208.
5. Panya Consultants. Climate change impact and adaptation study for bangkok metropolitan region. Final report. Panya Consultants Co. Ltd; 2009. Accessed 28 May 2014.
Available:http://siteresources.worldbank.org/INTEAPREGTOPENVIRONMENT/Resources/ClimateChangeBangkokMainReport.pdf
6. Hungspreug S, Khao-uppatum W, Thanopanuwat S. 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 Bowl, Kasetsart University, Bangkok Thailand; 2000. Accessed 28 May 2014.
Available:http://std.cpc.ku.ac.th/delta/conf/Acrobat/Papers_Eng/Volume%201/Wirat%20RID.pdf.
7. UN Educational Scientific and Cultural Organisation (UNESCO). The United Nations World Water Development Report 1: Water for People - Water for Life. Chao Phraya River Basin, Thailand. Chapter 16; 2003. Accessed: 29 May 2014.
Available:http://webworld.unesco.org/water/wwap/case_studies/chao_phraya/chao_phraya.pdf
8. Dutta D. 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. Hydrolog Sci J. 2011;56(5):805-823.
Available: http://dx.doi.org/10.1080/02626667.2011.585611
9. Saito Y, Chaimanee N,Jarupongsakul T, Syvitski JPM. 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. Accessed 29 May 2014.
Available: http://staff.aist.go.jp/yoshiki.saito/Saito_INPRINT_2007_2.pdf.
10. Royal Irrigation Department (RID) Flood Mitigation Management in Urban Areas. Expert Group Meeting on Innovative Strategies towards Flood Resilient Cities in Asia-Pacific; 2009. Bangkok, Thailand. Accessed 3 September 2013.
Available: http://www.unescap.org/idd/events/2009_EGM-DRR/Thailand-Flood-Mitigation-Lower-ChaoPhraya-River-Basin.pdf
11. Gemenne F, Brücker P, Ionesco D. The State of Environmental Migration 2011. Institute for Sustainable Development and International Relations (IDDRI) / International Organization for Migration (IOM); 2012. Accessed 31 August 2013.
Available:http://www.iddri.org/Publications/Collections/Analyses/SEM%202011_web.pdf
12. DHI Water & Environment(s) Pte Ltd (DHI). Thailand Floods 2011: The Need for Holistic Flood Management; 2011. Accessed 3 September 2014.
Available: http://www.globalcateye.com/media/861/Thailand_Floods_2011.pdf
13. Global Disaster Alert and Coordination System (GDACS) Orange Flood Alert in Thailand; 2011. Accessed 29 May 2014.
Available: http://www.monitor.czert.info/index.php/gdacs/floods/383-orange-flood-alert-in-thailand

14. 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. 2012;6:41–46.
15. Bangkok Post. Japan investor post-flood wish list. Bangkok Post; 2011. Accessed 29 May 2014.
Available: http://www.bangkokpost.com/learning/learning-from-news/261352/japan-investor-post-flood-wish-list
16. East Asia Forum. Thailand's economy still recovering from devastating floods; 2012. Accessed 29 May 2014.
Available: http://www.eastasiaforum.org/2012/05/01/thailand-s-economy-still-recovering-from-devastating-floods.
17. IRIN. How to move floodwater through Bangkok. IRIN: Humanitarian news and analysis, a service of the UN Office for the Coordination of Humanitarian Affairs; 2012. Accessed 29 May 2014.
Available: http://www.irinnews.org/printreport.aspx?reportid=95680
18. World Bank (2010) Climate Risks and Adaptation in Asian Coastal Megacities: A Synthesis Report. The World Bank. Accessed 19 September 2013.
Available: http://go.worldbank.org/P8IU2IW370
19. European Exchange Circle on Flood Mapping (EXCIMAP). Handbook on good practices for flood mapping in Europe; 2007. Accessed 3 June 2014. Available: http://ec.europa.eu/environment/water/flood_risk/flood_atlas/pdf/handbook_goodpractice.pdf.
20. McBean G. Building resilience. International Innovation. 2014;126.
Available: http://www.research-europe.com/magazine/ISSUE/126/index.html. Accessed 15 May 2014.
21. Coastal Cities at Risk (CCaR). Building Adaptive Capacity for Managing Climate Change in Coastal Megacities at Risk. Project Document. Accessed 27 May 2014.
Available: http://www.start.or.th/iriacc-project/documents/project-document-for-iriacc-ccar-project/at_download/file.
22. Simonovic SP, Peck A. Dynamic Resilience to Climate Change Caused Natural Disasters in Coastal Megacities Quantification Framework. British Journal of Environment and Climate Change. 2013;3(3):378-401. Accessed 29 December 2013.
Available: http://www.sciencedomain.org/abstract.php?iid=267&id=10&aid=2034
23. Open Data Research Network. Early insight 2: Definitions of open data. The Open Data Research Network is a collaborative project, coordinated by the Web Foundation and the International Development Research Centre (IDRC); 2013. Accessed 29 May 2014.
Available:http://www.opendataresearch.org/content/2013/566/early-insight-2-definitions-open-data.
24. Opengovdata.org. The Annotated 8 Principles of Open Government Data. Accessed 29 May 2014. Available: http://opengovdata.org
25. Opendefinition.org. Open Definition. Accessed 29 May 2014.
Available: http://opendefinition.org/od/
26. NASA Jet Propulsion Laboratory. Data products, NASA/NGA Memorandum of Understanding. NASA Jet Propulsion Laboratory, 2005. Accessed 29 May 2014. Available: http://www2.jpl.nasa.gov/srtm/mou.html.

27. NASA & METI/Japan Space Systems. ASTER GDEM Policy. ASTER Global Digital Elevation Model. Accessed 10 August 2013.
Available: http://gdem.ersdac.jspacesystems.or.jp/agreement.jsp.

28. US Geological Survey (USGS). HydroSHEDS. Disclaimer; 2008. Accessed 29 May 2014. Available: http://hydrosheds.cr.usgs.gov/disclaimer.php.

29. Center for International Earth Science Information Network (CIESIN) Columbia University, International Food Policy Research Institute (IFPRI), The World Bank, and International Center of Tropical Agriculture (CIAT). Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Urban Extents Grid. Metadata. Accessed 29 May 2014.
Available: http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents/metadata.

30. Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P, et al. Global Reservoir and Dam Database, Version 1 (GRanDv1): Reservoirs, Revision 01; 2011. Metadata. Accessed 29 May 2014.
Available: http://sedac.ciesin.columbia.edu/data/set/grand-v1-dams-rev01/metadata.

31. Manfreda S, Di Leo M, Sole A. Detection of flood-prone areas using digital elevation models. J Hydrol Eng. 2011;781-790. DOI: 10.1061/(ASCE)HE.1943-5584.0000367

32. Di Leo. Description: r.hazard.flood Implementation of a fast procedure to detect flood prone areas; 2014. Accessed 29 May 2014.
Available:http://svn.osgeo.org/grass/grass-addons/grass6/raster/r.hazard.flood/description.html

33. Geographic Resources Analysis Support System (GRASS) GIS. Accessed 29 May 2014. Available: http://grass.osgeo.org.

34. Geospatial Data Abstraction Library (GDAL). Accessed 29 May 2014.
Available: http://www.gdal.org

35. Geo-Informatics and Space Technology Development Agency (Public Organization) (GISTDA). Thailand Flood Monitoring System. Accessed 29 May 2014.
Available: http://flood.gistda.or.th.

36. NASA Jet Propulsion Laboratory. Shuttle Radar Topography Mission. Accessed 28 May 2014. Available: http://www2.jpl.nasa.gov/srtm/index.html.

37. Consultative Group for International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI). SRTM 90m Digital Elevation Data; 2008. Accessed 28 May 2014. Available: http://srtm.csi.cgiar.org/index.asp

38. Jarvis A, Reuter HI, Nelson A, Guevara E. Hole-filled seamless SRTM data V4, available from the CGIAR-CSI SRTM 90m Database (http://srtm.csi.cgiar.org); 2008. Accessed 29 May 2014: Available: http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-database-v4-1.

39. ASTER Global Digital Elevation Model (GDEM). Accessed 29 May 2014.
Available: http://gdem.ersdac.jspacesystems.or.jp/download.jsp.

40. UN Food and Agriculture Organization. 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; 2009. Accessed 29 May 2014.
Available: http://www.fao.org/geonetwork/srv/en/metadata.show?uuid=ee616dc4-3118-4d67-ba05-6e93dd3e962f&currTab=simple

41. US Geological Survey (USGS). Overview, HydroSHEDS. Hydrological data and maps based on SHuttle Elevation Derivatives at multiple Scales; 2008. Accessed 29 May 2014. Available: http://hydrosheds.cr.usgs.gov/overview.php.
42. Lehner B, Verdin K, Jarvis A. HydroSHEDS, Technical Documentation, Version 1; 2006. Accessed 29 May 2014. Available: http://hydrosheds.cr.usgs.gov/webappcontent/HydroSHEDS_TechDoc_v10.pdf.
43. US Geological Survey (USGS). HYDRO1K; 2012. Accessed 29 May 2014. Available: https://lta.cr.usgs.gov/HYDRO1K.
44. US Geological Survey (USGS). Global 30 Arc-Second Elevation (GTOPO30); 2012. Accessed 29 May 2014. Available: https://lta.cr.usgs.gov/gtopo30.
45. Global Runoff Data Centre (GRDC) Major River Basins of the World. Koblenz, Germany: Federal Institute of Hydrology (BfG); 2007. Accessed 29 May 2014. Available:http://www.bafg.de/GRDC/EN/02_srvcs/22_gslrs/221_MRB/riverbasins_node.html
46. GADM. GADM database of Global Administrative Areas, version 1. Accessed 26 July 2013. Available: http://www.gadm.org.
47. Bangkok Metropolitan Administration (BMA). Statistical Profile of the Bangkok Metropolitan Administration. Administrative Strategy Division, Strategy and Evaluation Department, Bangkok; 2012. Accessed 29 May 2014. Available:http://office.bangkok.go.th/pipd/05_Stat/08Stat(En)/Stat(En)55/stat%20eng%202012.htm
48. UN Environment Programme (UNEP) Bangkok City State of Environment Report; 2003. URL: Accessed 29 May 2014. Available: http://www.rrcap.ait.asia/pub/soe/bangkoksoe03.cfm
49. Center for International Earth Science Information Network (CIESIN) Columbia University, International Food Policy Research Institute (IFPRI), The World Bank, and International Center of Tropical Agriculture (CIAT). Global Rural-Urban Mapping Project, Version 1 (GRUMPv1): Urban Extents Grid; 2011. Accessed 29 May 2014.Available: http://sedac.ciesin.columbia.edu/data/set/grump-v1-urban-extents.
50. UN Food and Agriculture Organization. Rivers in Southeast Asia (Derived from HydroSHEDS). AQUASTAT - Programme of the Land and Water Division of the Food and Agriculture Organization of the United Nations; 2010. Accessed 24 March 2013. Available: http://www.fao.org/geonetwork/srv/en/main.home?uuid=dc2a5121-0b32-482b-bd9b-64f7a414fa0d.
51. Lehner B, Liermann CR, Revenga C, Vörösmarty C, Fekete B, Crouzet P. et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. Frontiers in Ecology and the Environment. 2011;9:494–502. Available: http://dx.doi.org/10.1890.
52. Geographic Resources Analysis Support System (GRASS). r.series - Makes each output cell value a function of the values assigned to the corresponding cells in the input raster map layers; 2013. Accessed 29 May 2014. Available: http://grass.osgeo.org/grass70/manuals/r.series.html
53. Geo-Informatics and Space Technology Development Agency (GISTDA). Commonly asked questions regarding GISTDA flood data. Accessed 29 May 2014. Available:http://flood.gistda.or.th/flood/y2011/FL82_Extra/ReportQuestion.pdf. Thai

54. Di Leo M. r.hazard.flood.py; 2010. Accessed 6 June 2014. Available: http://svn.osgeo.org/grass/grass-addons/grass6/raster/r.hazard.flood/r.hazard.flood.py.
55. Manfreda S, Sole A, Fiorentino M. Can the basin morphology alone provide an insight on floodplain delineation? WIT Transactions on Ecology and the Environment. 2008;118:47-56. Accessed 6 June 2014.

    Available: http://library.witpress.com/pages/PaperInfo.asp?PaperID=19286
56. Ali G, Birkel C, Tetzlaff D, Soulsby C, McDonnell JJ, Tarolli P. A comparison of wetness indices for the prediction of observed connected saturated areas under contrasting conditions. Earth Surf Process Landforms. 2014;39:399–413.
57. Di Leo M, Manfreda S, Fiorentino M. An automated procedure for the detection of flood prone areas: r.hazard.flood. Geomatics Workbooks, volume 10, FOSS4G-it, Trento; 2011. Accessed 26 June 2014.

    Available:http://geomatica.como.polimi.it/workbooks/n10/GW10-FOSS4Git_2011.pdf
58. Consultative Group for International Agricultural Research - Consortium for Spatial Information (CGIAR-CSI). SRTM Data Selection Options. Accessed 29 May 2014. Available: http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp.
59. Geographic Resources Analysis Support System (GRASS). r.slope.aspect - Generates raster maps of slope, aspect, curvatures and partial derivatives from an elevation raster map; 2014. Accessed 15 July 2014.

    Available: http://grass.osgeo.org/grass70/manuals/r.slope.aspect

APPENDIX

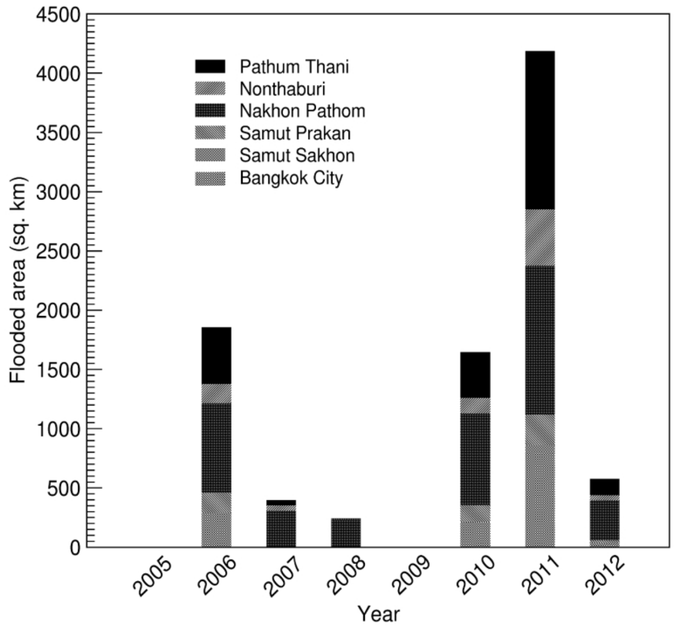

Fig. A1. Historical annual flooding in Bangkok Metropolitan Region: inundation of Bangkok City and constituent provinces

NOTE:for 2005, flooding is possibly underestimated in BMR, as apparent from abrupt linear boundaries of flood polygons to north and east of BMR; perhaps related to incomplete imagery or subsequent processing

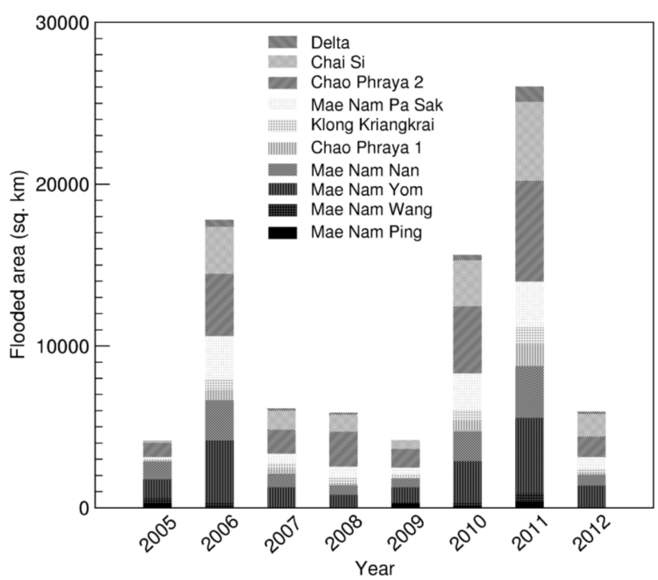

Fig. A2. Historical annual flooding of Chao Phraya River basin: inundation of each sub-basin

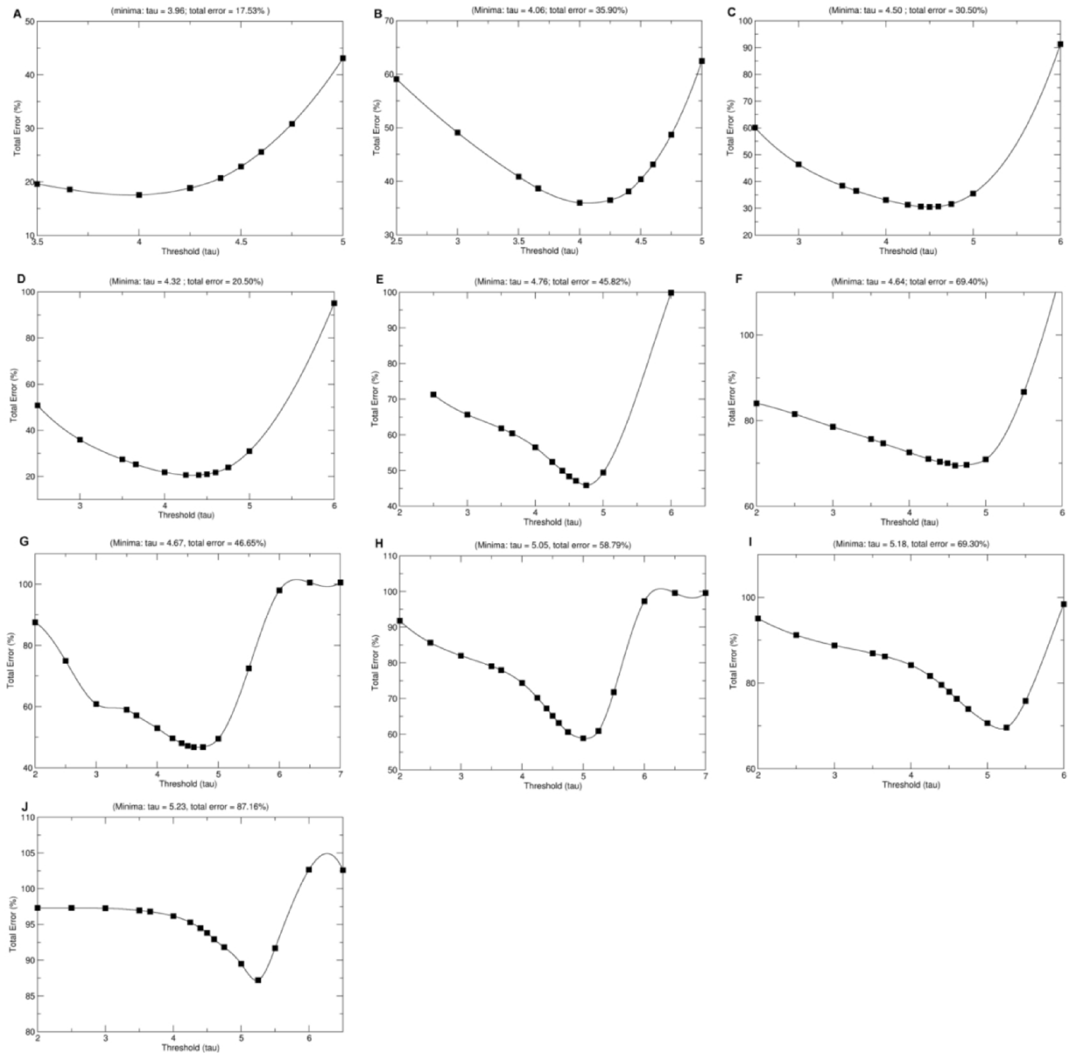

Fig. A3. Interpolation of minimum total errors and optimal tau thresholds for Chao Phraya sub-basins

Plots of total error at given tau thresholds for each sub-basin: A (Mae Nam Ping); B (Mae Nam Wang); C (Mae Nam Yom); D (Mae Nam Nan); E (Chao Phraya 1); F (KlongkriangKrai); G (Mae Nam Pa Sak); H (Chao Phraya 2); I (Chai Si); J (Delta)

Table A1. Peak water levels in Chao Phraya (metres above mean sea level) (reproduced from DHI Water & Environment(s) Pte Ltd [12])

Station	Observed Peaks			Estimated Return Period (years)					
	1983	1995	2011	2	5	10	25	50	100
Ayutthaya	4.7	5.1	5.92	3.4	4.1	4.7	5.1	5.4	5.6
Bang Sai	3.1	NA	4.21	2.6	3.1	3.4	3.7	3.8	4.0
Pakret	2.2	2.6	3.20	2.15	2.61	2.72	2.86	2.96	3.07

Table A2. Openness of data examined in study in terms of availability/access, reuse

and redistribution, and user permission

Data	Availability & access	Reuse & redistribution	User permission	Notes
CGIAR-CSI SRTM 90m Data (version 4.1)	Online [37]	Re-sale/ redistribution not permitted	Commercial use requires prior permission	Data policy bundled with data download.
NASA JPL SRTM Data (version 2-1)	Online [36]	No restriction	No restriction	The CGIAR-CSI version of the SRTM data (see this table) was used in this study. With regard to SRTM data downloaded from JPL: 'Terrain height data greater than or equal to three seconds of arc latitude and longitude (i.e. Level-1 data sets) generated from the SRTM will be released and distributed without restrictions' [26]
ASTER GDEM	Online [39]	Reuse restricted as per policy agreement (see 'Notes' column this table)	Commercial use not apparent.	Downloading data requires registration of site and selecting the policy agreement: 'I agree to redistribute the ASTER GDEM only to individuals within my organization or project of intended use or in response to disasters in support of the GEO Disaster Theme. (Required)' [27]
GADM (version 1)	Online [46]	Redistribution not allowed without prior permission	Commercial use requires prior permission.	'These data are freely available for academic and other non-commercial use. Redistribution, or commercial use, is not allowed without prior permission.' [46]
FAO Hydrological basins (derived from HydroSHEDS)	Online [40]	Re-sale and redistribution requires prior permission (for HydroSHEDS data) (see 'Notes' this table).	Non-commercial use specified (for HydroSHEDS data) (see 'Notes' this table).	Usage constraints of download not apparent on the FAO GeoNetwork metadata catalogue site nor bundled with data. From the HydroSHEDS site: 'Users may apply HydroSHEDS for non-commercial purposes.' [28]
GRDC Major	Accessible	Redistribution	Commercial use	Policy guidelines for

Data	Availability & access	Reuse & redistribution	User permission	Notes
River Basins of the World	from GRDC via email after submitting order form [45]	not allowed without prior permission	requires prior permission.	the dissemination of data accessible at http://www.bafg.de/GRDC/EN/01_GRDC/12_plcy/data_policy_node.html
CIESIN (Global Rural-Urban Mapping Project (GRUMP), v1)	Online [49]	Resale and redistribution not allowed without prior permission.	Non-commercial use only.	'Users are prohibited from any commercial, non-free resale, or redistribution without explicit written permission from CIESIN, IFPRI, The World Bank, and CIAT.' [29]
CIESIN (Global Reservoir and Dam (GRanD), v1)	Online [30]	Re-sale and redistribution not allowed without prior permission	Non-commercial use only.	'The GRanD database is freely available for non-commercial use. Users are prohibited from any commercial resale, or redistribution without explicit written permission from the authors (Lehner et al. 2011) or GWSP.' [30]
GISTDA (Flood data)	Online [35]			No data distribution policy evident at Thailand Flood Monitoring System, but shape file flood data readily accessible online.

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