MSc Thesis – Master Water Science and Management

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Global Changes of Flood Hazard in Cities

Developing a Global Approach to Assess Hydroclimatic Changes in Cities Across a Wide Range of Futures

Jasper van Beveren (8376417)

Utrecht University

Dr. Stefanie Lutz PhD

Deltares

Hans Gehrels

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Abstract
As the climate changes, weather patterns are expected to shift. Stakeholders (e.g. policymakers, investors, water managers and planners) are interested in how strong and how frequent future storm events might become and what this means for the climate hazard cities face. Hence, there is need for a global assessment approach that can aid policymakers and investors in determining the city's most at risk of certain climate hazards. Risk is here defined as the product of the probability of the hazard and a measure of the associated consequence (Risk = Hazard * Exposure * Vulnerability). Climate scientists can estimate changes in climate with global top-down models. However, they can't trust on the reliability of these models on local scales like cities, they often have difficulties determining hydrological extremes which are especially important for stakeholders. This research aims to contribute to the climate risk assessment of cities, by proposing a new approach to contribute to decision making in determining the city's most at risk of flooding under different climate conditions. Adding to the assessment of where climate adaptation is deemed necessary. The approach used in this research moves away from conventional top-down approaches and builds on existing bottom-up approaches, utilizing a new methodology by using global datasets, and hydrological models that can simulate the hydrological extremes stakeholders are interested in.

The results show the developed workflow by testing it on the study area of Bangkok for riverine flooding under historic, climate variability and climate change conditions. Although the approach still requires work when assessing the impact of climate change, it already is in a state in which it can raise many interesting discussions about methodologies for climate risk assessments, and possibly can become an established approach in climate risk assessments. A main achievement related to scientific and management implications is that not only steps have been made to improve the reliability of rapid, global flood hazard methodologies but rather a shift in the approach on how to model climate change has started, addressing city-wide resilience issues from a holistic, global perspective. The constructed approach is a solution for the coarse scale and the misinterpretation of hydrological extremes that comes with top-down approaches. Additionally, when adding the exposure and vulnerability components of risk to the suggested approach it can provides opportunities for cities to explore whether climate disasters could have a major impact on society beyond the immediate knowledge of experts and policymakers. This information will be crucial for stakeholders identifying which cities benefit most from adaptations to climate risk under several climate conditions.

Key Words: *Climate Risk in Cities; Flood Hazard; Global Risk Assessment; Weather Generator; Hydrological Extremes*

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1. Introduction

1.1. Background & Problem description

“It is unequivocal that human influence has warmed the atmosphere, ocean and land” (IPCC, 2021, p. 4). This is one of the first statements you will find reading the last IPCC report. It indicates that, anthropogenic emissions of greenhouse gases (GHG) and human activities are pushing the Earth system towards its limits, likely causing a higher frequency of floods and other extreme weather events around the globe (Masson-Delmotte et al., 2021; Rockström et al., 2009; World Weather Attribution, 2021).

Over the last decade, climate change is accelerating and is now affecting every country on every continent. It is disrupting national economies and affecting livelihoods, particularly through the impact on water and water-related hazards. For city governments, increased climate variability imposes additional challenges to effective urban management, while for residents it increasingly affects their lives and livelihoods due to more frequent floods, and other climate risks (Dickson et al., 2012). With 68% of the world’s population expected to reside in cities and flood risk being exacerbated by climate change (UN, 2018), the interlinkages of cities and climate change were reaffirmed in the Sixth and latest Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2022). The report concluded that heat waves, extreme precipitation events, and drought conditions are more likely to occur in the future and are affecting cities in several ways; Exposure in large cities to cyclones and earthquakes is projected to rise rapidly; Coastal cities are made more vulnerable by the low-lying land they are often built on and are therefore susceptible to sea-level rise, flooding and coastal erosion; Dryland cities suffer from scare water resources due to extended droughts, which is particularly severe on drinking water supplies; Inland an high-altitude cities will be affected by climate change predominantly as a result of changing patterns of precipitation (Dickson et al., 2012; IPCC, 2022).

Cities are the hubs of economic growth and are at the forefront of the climate change debate as cities contribute to greenhouse gas emissions and are places of concentrated human activity (Carter et al., 2017), making urban flooding one of the key global challenges of the twenty first century (O’Donnell & Thorne, 2020). Considering the challenges for different types of cities with their global commitment to climate adaptation, Bates et al. (2021) state that for adapting to these changing conditions, analyses are required that can skilfully, comprehensively, and consistently predict hazard at fine spatial resolution, but can also make robust projections of climate change hazards into the future (Alves et al., 2020; Li et al., 2019; Kaspersen et al., 2017). This includes a need for improved climate predictions over the coming decades under different GHG emissions and urbanization scenarios for different cities (Smith et al., 2014). Hence, there is need for a global assessment approach that not only can assess current flood hazard but in addition also aims to assess future flood hazard for large number of cities.

City governments and policymakers have a direct interest in climate change issues because urban areas are directly and particularly vulnerable to its impact. In particular adaptation has to be thought locally as it requires taking into account the impacts of climate change on the local territory and the elements of vulnerability upon which actions may be taken (Dreyfus, 2015). When conveying flood risk information to the public, engineers, and hydrologists often focus on a small subset of predestined hazard assessments (e.g. depth inundation maps and flood frequency analysis) that are often presented in terms of exceedance levels and are applied to riverine flooding, focusing almost exclusively on peak flow rates. These conventional hazard assessments are rooted in design criteria for creating adaptations and flood control infrastructure (Knighton et al., 2017).

Because rivers are part of the hydrological cycle and often important to cities, climate change has played an important role in river regimes and fluvial patterns in the past, and anticipated climate changes are expected to have major impacts on modern rivers in the future. Climate influences rivers directly by controlling the hydrological inputs of a river basin (Middelkoop, 2008).

1.2. Global Risk Assessment

The Paris Agreement in 2015 highlights the importance of averting, minimizing, and addressing loss and damages associated with the adverse effects of climate change. Risk assessment and management is specifically proposed as a mechanism to address these challenges (Mendoza et al., 2018). The concept of risk helps cities to identify adaptation options and build urban resilience to the changing climate. Despite the assumptions and bias of indicator-based approaches they have been promoted as useful tools to assess and compare the complexity of climate change from local to global scales. However, there is need for a fast-global assessment approach that can give insights and aid to policymakers as well as investors in determining the city's most at risk of certain climate hazards. Which will contribute to the assessment of where climate adaptation measures are most urgently needed (Hagenlocher et al., 2019).

Flood risk is often defined as hazard and its consequences. Hazards can be defined as sudden or slowly occurring events or processes that may cause loss of life, injury, or other health impacts, as well as loss and damages. Climate related hazards can be defined in two categories, the first kind of hazards, stresses, refer to slowly unfolding crises such as drought and prolonged heat. In contrast, shocks are sudden events and only last for a couple days, like the peak flow rates that occur during riverine flooding. During this research the latter climate related hazard was investigated, with a focus on riverine flooding. Flood risk is than defined as the product of the probability of the hazard and a measure of the associated consequence, or according to the United Nations (Oppenheimer et al., 2015):

Risk = **Hazard** * Exposure * Vulnerability

For completion of the risk definition, the second section determining risk is exposure, which refers to the extent to which people, infrastructure and other elements are subjected to hazards and potential losses (Hagenlocher et al., 2018; Sudmeier-Rieux et al., 2019). The third and last section of risk, (social) vulnerability, refers to the attributes of communities and societies, and the circumstances in which they live that make them more susceptible or even unable to cope with the hazards occurring (Sudmeier-Rieux et al., 2019).

Although global assessments of climate change impact can provide a rough indication of trends and expected impacts, the local conditions define how vulnerable the communities are to these water security threats. Adaptation to climate change is therefore a local process that requires the design of tailored solutions (Ray & Brown, 2015). Mendoza et al (2018) states that "Estimating future climate impacts has proven to be particularly contentious and frustrating, and in many cases effective solutions have been largely dependent on the skills and experience of a few individuals rather than systematic and reproducible approaches" (p.12). Hence, water planners and managers need guidance that helps them move away from what we do not know about the future to what they do know (Mendoza et al., 2018).

1.3. Climate Change Assessment

Current global assessments to estimate changing hydroclimatic conditions follow a conventional top-down approach of climate projections (Balica et al., 2012; Bertilsson et al., 2019). Following a sequence of selecting climate change projections from a Global Circulation Models (GCM), climate downscaling and then estimating potential climate change impacts using hydraulic models (Brown et al., 2011). However, there is no consensus about the means of doing so, nor a methodology that has yet been generally accepted for assessing the significance of climate risks. The need for such an approach has recently been elevated by the World Bank (Mendoza et al., 2018; Ray & Brown, 2015), were a recent study found that climate models have been more useful for setting context than for informing investment and policy choices. The lack of success in the use of climate projections to inform decisions is not due to the lack of effort in translating model outputs but rather to a fundamental and unavoidable issue limiting these approaches. The issue could be classified as a risk assessment problem. The uncertainty associated with future climate is largely irreducible in the temporal and spatial scale that are relevant to water resource management. Perhaps most important, several authors (Cloke et al., 2013;

Smith et al., 2014; Stainforth et al., 2007) state that GCMs lack skill in generating variables that are most important for decision making, such as hydrological extremes like peak discharges (Ray & Brown, 2015), meaning they do not sufficiently describe the range of potential future conditions that may occur. Additionally, these projections mispresent climate drivers such as multiyear droughts or monsoon patterns (Stainforth et al., 2007). Hence, a top-down approach is useful for evaluating responses to particular emission scenarios, but a knowledge gap exists for exploring and evaluating risk from local climatology and socioeconomic conditions at a fine resolution level as cities (Wilby & Dessai, 2010).

The recognized limitations of GCMs, including the misrepresentation of climate drivers, imply that GCM based projections may have difficulties providing valuable risk analysis (Brown & Wilby, 2012). Brown et al. (2011) suggest that to address the limitations of the top-down approach, a bottom-up approach can be used, by moving away from climate model predictions and instead focusing on reducing vulnerability to climate uncertainty and improving robustness against climate hazards. Vulnerability refers here to the degree to which a system or in this case a city is susceptible to or unable to cope with the adverse effects of climate change (Johnson et al., 2016). The bottom-up approach starts with understanding the cause of vulnerability and creating plausible climate condition using weather generators that are able to simulate possible timeseries that plausibly could occur in the future.

A stochastic weather generator is a model capable of generating daily weather patterns that statistically resemble the observed historical patterns at a site (Steinschneider & Brown, 2013). Additionally, weather generators allow to extend the simulation of weather timeseries to unobserved locations, through interpolation of the weather generator parameters obtained from running the models at neighbouring sites. It is worth noting that a stochastic weather generator is not a predictive tool that can be used in weather forecasting but is simply a means of generating timeseries of synthetic weather statistically “identical” to the observations (Semenov & Barrow, 2002).

After creating timeseries a climate stress test can be executed over the synthetic weather. A climate stress test is designed to demonstrate the limits of performance in an existing system under a variety of plausible future conditions (Brown & Wilby, 2012). In other words, “envelopes” could be created containing a range of possible climate changes by adjusting precipitation and temperature values. Additionally, different sources of information like climate projections can be examined to determine the plausibility of problematic conditions (Brown et al., 2011).

In a bottom-up approach future conditions are generated parametrically or stochastically based on spatial resolutions for local climatology and socioeconomic conditions, in contrast to the top-down approach that only considers a limited set of scenarios from climate projections over large areas. While the bottom-up approach has reached broader recognition it still requires a methodology that links global datasets with hydroclimatic hazards, on a fine spatial resolution like cities (Mendoza et al., 2018; Ray & Brown, 2015).

Considering the challenges for cities and their global commitment to climate adaptation there is need for an approach that can estimate the flood hazard a city is facing and make projections about fluvial flooding “inundation of the areas close to waterways/bodies after these have exceeded their storage capacity (Muthusamy et al., 2019)” under multiple climate conditions. As water managers are most interested in hydrological extremes like floods (for example, what future flow and inundation will result from a 100-year return period storm event) it is from high importance that hydrological processes are better represented. However, the conventional top-down approach lacks the skill to tackling climate risks at an urban scale. Hence, there is need for a methodology that can help stakeholders to assess the climate risk in cities while better representing hydrological responses. Current bottom-up approaches lack the possibility to assess large number of cities through a methodology that can simulate hydrological processes under several climate conditions at a spatial scale relevant for cities.

1.4. Aim and Research Questions

This research aimed to contribute to the climate risk assessment in cities by proposing a flood hazard methodology designed to contribute to policymakers as well as investors in determining the city's most at risk of riverine flooding under different climate conditions. Adding, much needed value to the assessment of where climate adaptation measures are most urgently needed. The approach builds on existing bottom-up methodologies to climate change and utilizes a new approach by using global datasets and integrating hydrological extremes through hydrological models that include catchment processes (e.g. evapotranspiration, runoff, river channel flow) in a spatially distributed manner. Additionally, the approach will compliment flood models by integrating hydrological extremes, such as the 100-year return period storm event. This methodology is applicable where any risk of flood hazard is deemed not acceptable under historical and future climate conditions.

These objectives will be achieved by answering the central research question:

"How can historic, climate variability and future climate conditions be used through a bottom-up approach, resulting in a global assessment framework that explores fluvial flood hazards on a city scale?"

The central research question will be supported by the following sub-research questions:

RSQ1: How can a bottom-up approach be linked to global datasets and hydrological models that can estimate fluvial flood hazards under historic, climate variability and future climate conditions?
RSQ2: How do flood hazards under climate variability and climate change conditions compare to historic fluvial flood hazards at a city level?

2. Theoretical background

To improve understanding of the complex interactions of the climate system, ecosystems, and human activities and conditions it is helpful to have a background about how the research community develops and uses scenarios regarding climate change (Moss et al., 2010). Scenarios form an essential part of climate change research and assessment (Riahi et al., 2017). Their creation contributes to the understanding of long- term consequences of near- term decisions and enables researchers to explore different possible futures in the context of fundamental future uncertainties (Riahi et al., 2017).

Socioeconomic and emission scenarios are used in climate research to provide plausible descriptions of how the future could evolve with respect to a range of variables such as socioeconomic change, technological change, energy and land use, and emissions of greenhouse gases and air pollutants (van Vuuren et al., 2011). These variables are used as input for climate model runs and as a basis for assessment of possible climate impacts, mitigation options and associated costs.

A number of approaches that have been used to determine future scenarios are the scenarios by the Intergovernmental Panel on Climate Change (SA90, IS92, and SRES), the Representative Concentration Pathways (RCPs) (Moss et al., 2010; van Vuuren et al., 2011) and The Shared Socioeconomic Pathways (SSPs) (O'Neill et al., 2014). O'Neil et al. (2014) defines the SSPs as reference pathways describing plausible alternative trends in the evolution of society and natural systems over the 21st century at a global and large regional level. Because SSPs do not include the effects of climate change and climate policy, they do not describe plausible assumptions for the future on their own. Hence, combining the SSPs with RCPs makes it possible to explore socio-economic trends under different level of climate forcing (O'Neill et al., 2014; van Vuuren et al., 2014).

3. Materials and Methods

The proposed approach was executed through a workflow, which consists of several individual components that together were able to simulate flood hazard maps of hydrological extremes for cities under historic, climate variability and climate change conditions. First, the models and software are described which were needed to construct the workflow. Next, a study area was defined were the workflow was built around, followed by a climate change narrative. The climate change narrative was used to estimate the amount of climate change needed for the creation of future climate conditions. The last sections consist of creating and connecting the individual parts of the workflow.

3.1. Materials

3.1.1. Models and Software

Spatial environmental models such as hydrological, hydrodynamic, groundwater, flooding, water quality and water demand models require large amounts of data and data manipulations. HydroMT was the core of the workflow to facilitate the processes of building a model input data, connecting models and analysing model output data based on a python ecosystem (Deltares, 2022; Eilander & Boisgontier, 2022). HydroMT is a modular Python package that allows the use of (global climate forcing, and geographical) datasets within the Deltares environment, reads them through a data adapter, and generates models through a set of common methods. The research will be carried out with models and software provided by Deltares. Models that are supported by HydroMT and other software that was used in the research are the following:

- **Weather Generator**, consisting of a set of scripts coded in R based on the existing work by (Steinschneider & Brown, 2013), was used for decision-centric vulnerability assessment under climate change. The tool was envisioned to be useful for a wide range of socio-economic and biophysical systems sensitive to different aspects of climate variability and change. Parameters can be altered to enable the generation of realistic timeseries of climate variables that exhibit changes to lower-order and higher-order statistics at long-term (interannual), mid-term (seasonal), and short-term (daily) timescales. When coupled with hydrological models in a bottom-up assessment the tool can efficiently add to the exploration of potential climate changes under which a system is most vulnerable;
- **Wflow** (Eilander et al., 2022; van Verseveld et al., 2022): is Deltares’ solution for modelling hydrological processes, allowing users to account for hydroclimatic processes in a fully distributed environment. Wflow contains multiple distributed model concepts, which maximizes the use of open earth observation data, allowing the user to model in data scarce environments. Based on gridded topography, soil, land use and climate data, Wflow calculates all hydrological fluxes at any given point in the model at a given time step;
- **Super-Fast INundation of CoastS** (SFINCS) (Leijnse et al., 2021): is the reduced complexity model designed for fast modelling of compound flooding events in a dynamic way at limited computational cost and good accuracy. Floods are often driven by different forcing mechanisms occurring simultaneously. Therefore, SFINCS include fluvial, pluvial, tidal, wind- and wave driven processes.

3.2. Study Area

The aim was to create a global assessment approach that can be used for large amounts of cities to support decisionmakers in determining the city's most at risk of riverine flooding under different climate conditions. For creating and testing the approach through a workflow, the methodology was developed around a single study area. The selected city of interest was Bangkok, located on the Chao Phraya River delta in the central plains of Thailand, with an average elevation of 0-2 m above Mean Sea Level (MSL) (Figure 1). The lower portion of the Chao Phraya River flows through urban areas before discharging into the Gulf of Thailand in Samut Prakarn Province (Singkran & Kandasamy, 2016). It is worth noticing that in this research Bangkok was solely used as a case study to develop the workflow around, meaning this research did not try to assess nor compare the result to the local situation.

Bangkok was a suitable case study due to its location close to the Gulf of Thailand and the Chao Phraya River that flows through the city, making Bangkok sensitive to the interaction of high sea levels, with large river discharges and precipitation which can cause extreme fluvial, pluvial and coastal flooding (Bates et al., 2021). Additionally, Bangkok is a city where floods are frequently occurring, meaning that large amounts of literature is available which could benefit the study when fine tuning the approach.

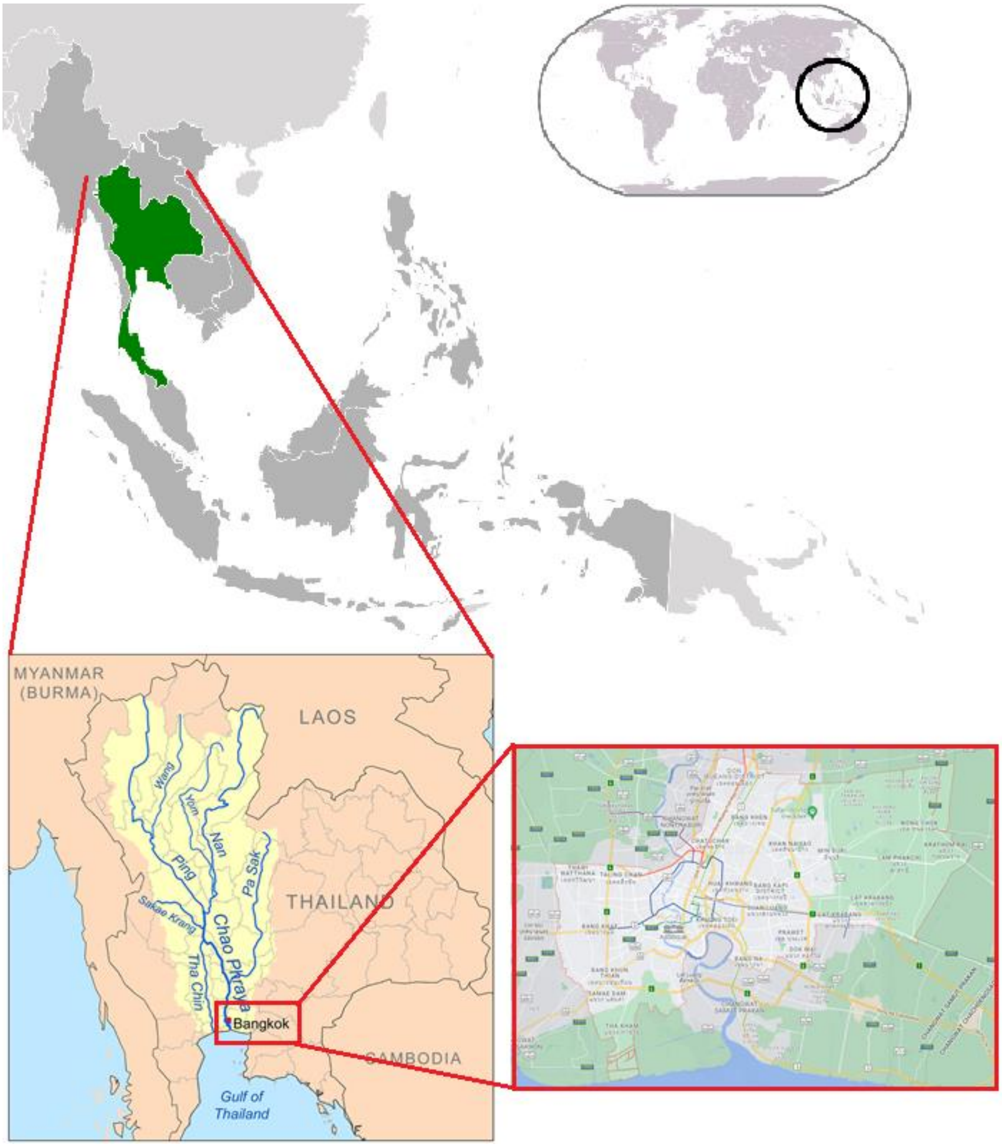

Figure 1 Study Area. Bangkok, Thailand

3.3. Climate Change Narrative

The workflow was developed around a climate change narrative. For realizing historic, climate variability and future climate scenarios the proposed approach uses the climate change quantities and scenarios that are based on the IPCC Working Group 1 Interactive Atlas. The Interactive Atlas is a new component of the Sixth Assessment Report (AR6) being a tool for flexible spatial and temporal analyses of much of the observed and projected climate change, including the regional synthesis for Climatic Impact-Drivers (CIDs) (*IPCC WGI Interactive Atlas*, 2021).The interactive Atlas allows regional exploration of observed and projected climate data by focusing on key atmospheric and oceanic variables navigated by global and regional information of future projections using global warming, scenarios and future periods, based on the latest Coupled Model Intercomparison Project phase 6 (CIMP6) that uses the combination of SSPs with RCPs.

For this project, future flood hazards were assessed by assuming an increase in mean-temperature and mean-precipitation over a Long-Term scenario (2081-2100), relative to the present climate (1981-2010), for the entire region of South-East Asia, under the SSP5-8.5 (strong emission) scenario. SSP5 stands for a case with high challenges to mitigation in combination with low challenges to adaptation and RCP8.5 stands for exploring the consequence of high emission trajectories (Riahi et al., 2017; van Vuuren et al., 2011). Following this scenario, the CIMP6 multi-model ensemble projected a continuous and significant increase in the mean temperature and precipitation over the South-East Asian region. Adapted from the Interactive Atlas, Table 1 shows the combination of SSP5 with RCP8.5 and the projected consequences for temperature and precipitation.

*Table 1 is combining a different socio-economic reference as described by SSPs with different future levels of climate forcing. The SSP numbers correspond to five different storylines as further discussed in O'Neill et al. (2014). The forcing levels are chosen to correspond to the forcing level reached by the RCPs, see also van Vuuren et al. (2011). Together, representing a possible long-term scenario that combines mitigation and adaptation for the region of South-East Asia under climate change conditions. Adapted from: (*IPCC WGI Interactive Atlas*, 2021)*

Period	**Scenario**	**Median (degrees ℃)**	**Total Precipitation Change %**
Long Term (2081-2100)	SSP5-8.5	4.4	12

In summary, for generating future climate conditions this MSc thesis worked with an increase of 4.4 ℃ and 12% for temperature and precipitation respectively. It is important to mention that the storyline above was used as a reference to a possible emission scenario under strong GHG emissions. The current work did not try to compare results but uses an IPCC narrative as a direction of creating the workflow and create understanding of the amount of climate change on a fine spatial resolution like cities.

3.4. Development of the workflow

This thesis proposes an approach that can be executed through a workflow. The general approach of the research can be found in the framework displayed in Figure 2. To answer the overlaying question of a climate risk assessment in cities, I propose an explorative bottom-up approach to assess historic, climate variability and climate change flood hazards using open global climate forcing data with the city of Bangkok as study area. To conclude, the approach is applied to explore possible fluvial flood hazards under historic, climate variability and climate change timeseries.

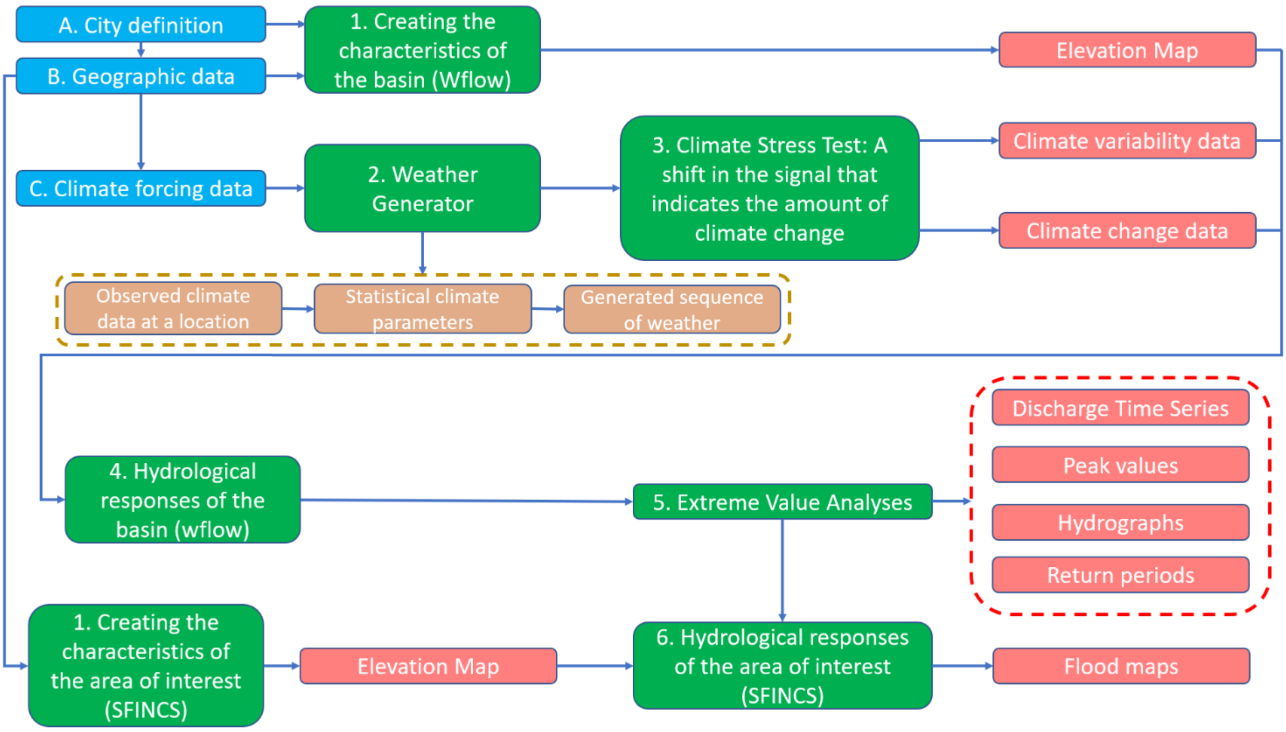

Figure 2 Research Framework. Each color indicates a different section of the methodology whereas the number/character refer to specific tasks explained in the method section of the workflow with the corresponding number/character. Steps that have the same number can/will be executed at the same time. The Blue colored boxes refer to the inputs needed to execute the workflow; the Green boxes are referring to the application that was needed to create outputs indicated in the Red boxes. The Weather Generator box shows a simplification of the process with a more elaborated explanation shown in the orange boxes. To conclude, the Blue arrows show the process of creating the workflow and connecting data, inputs/outputs, and models.

A major part of this thesis was creating an approach that can be executed through a workflow. To do so HydroMT was used; The best way to provide data to HydroMT is by using a data catalogue. The goal of the data catalogue is to provide simple and standardized access to (large) datasets. It supports many drivers to read different data formats and contains several pre-processing steps to unify the datasets. The data catalogues can be accessed through *yaml files*, which contain all required information to read and pre-process a dataset. Additionally, HydroMT provides functionalities for setting-up models from raw data or adjust the models created. The exact process of building or updating a model can be configured in a *.ini file*. These files describe the full functionality of model methods and their arguments. For more details, like the *yaml* & *.ini* files, and *scripts* that cover the technical aspects of the constructed methodology there can be referred to the GitHub created for this research: https://github.com/jaspervbeveren/MSc-Thesis.git. The GitHub contains a *ReadMe file* which will link the files and scripts to the methodology steps as shown in the framework (Figure 2). For additional information regarding building or updating models there can also be referred to the *ReadMe file* in the GitHub repository which contains links to the models used with their online documentation.

Next, Table 2 provides explanation of each individual component created and contributing to the workflow, which was realised using the models, software and configuration files previously referred to.

Together this part of the methodology will consist of the components that will answer the first and second research question of the research.

Table 2 presents and describes all the components of the workflow that I have created to assess fluvial flooding under historic, climate variability and climate change conditions. Additionally, the table indicates the parts that were created or adjusted by linking the several models used in the realization of this approach. After each description files/scripts are shown in bullet points and refer to the matching steps in the research framework / GitHub.

<table>
<tr><td>RSQ1: "How can a bottom-up approach be linked to global datasets and hydrological models that can estimate fluvial flood hazards under historic, climate variability and future climate conditions?</td><td>Rationale: This method seeks to assess historic, climate variability and future climate flood hazards conditions on a city scale by combing global datasets with a weather generator complimenting hydrological models (Wflow & SFINCS).</td></tr>
<tr><td colspan="2">Inputs
Step A. City definition
A geographic area, in which the city of choice was located, can be selected through coordinates for which HydroMT automatically determines the boundary conditions. To assess a specific area in the city additional coordinates of the desired area were needed to simulate flooding. The time period used contains 30-years of historical climate forcing data, ranging from 1981-2010.
<u>Documentation in github:</u>
– Deltares_data.yml

Step B. Geographic data
Geographical datasets were needed to build the hydrological models. The data was automatically extracted with HydroMT and forms a foundation for the processes of the hydrological cycle when climate forcing data was added. If not connected to the Deltares network users can setup their own datasets that covers the area of interest, further explained in the Wflow documentation by Eilander et al. (2022). Although, the study area was Bangkok, to assess the impact of climate change the hydrological model needed to cover the whole Chao Phraya River Basin as most of the increased flood inflow from climate variability and change were situated in the upper basin.
<u>Documentation in github:</u>
– Deltares_data.yml

Step C. Climate forcing data
The main purpose of this task was retrieving and pre-processing of present historical climate data (1981-2010) that was used as input for the weather generator. I created a script that can accesses Climate forcing datasets (in this case ERA5) and extracts timeseries of weather variables for the selected study area. The data was extracted from the dataset for the coordinates regarding the geographic area of interests. The final data was outputted in a single netCDF format containing the climate forcing like precipitation and temperature.
<u>Documentation in github:</u>
– Deltares_data.yml
– Extract_era5_original.ipynb

Application

Step 1. Creating the characteristics of a basin and of the areas of interest
This task will execute the software component that builds the Wflow and SFINCS models. The component will extract data from global geographical datasets (amongst others soil types, landcover, digital elevation model). I have setup input files that include the base map of the area and in this map, I added rivers, lakes, glaciers, and reservoirs within the study area including a default gauge map, based on basin outlets and additional gauge maps. The suggested approach through a workflow still misses the ability to account for sea-level rise and tidal differences. Hence, a fixed water level is set at mean sea level which is not changing under the future climate conditions.
<u>Documentation in github:</u></td></tr>
</table>

- Build_subbasin_bangkok.ipynb
- Update_bangkok.ipynb
- Build_bangkok_sfincs.ipynb
- Update_sfincs_model.ipynb
- Sfincs_bangkok_fab.ini
- Sfincs_forcing_wg_historic.ini
- Sfincs_forcing_wg_variability.ini
- Sfincs_forcing_wg_climx.ini
- Wflow_build_bangkok.ini
- Wflow_update_bangkok_wg_historic.ini
- Wflow_update_bangkok_wg_variability.ini
- Wflow_update_bangkok_wg_climx.ini

Step 2 & 3. Creating climate variability and climate change data

The aim was to produce synthetic weather series that contains samples of natural variability and plausible climate changes in weather variable statistics. Meaning several plausible timeseries that could occur in the future were generated. The weather generator can generate many climate permutations, each of which can exhibit a different type of climate alteration. Plausible climate changes were achieved through altering the statistical parameters of temperature and precipitation. For example, you could create so called "envelopes" that contains a range of possible climate changes in precipitation and temperature: (-10% , 0 , +20% , +30% precipitation) & (-1, 0, +1, +2, +3, +4 ℃). Based on an IPCC narrative, explained in Paragraph 3.3, I selected one plausible envelope to execute the workflow on. I adjusted the script of the weather generator according to these changes by changing the statistical parameters of temperature (+4.4 ℃) and precipitation (+12%) to the desired value. Now multiple stochastic weather realizations will be generated based on the outputs of the climate forcing data. Next, I selected different stochastic weather realization, two for a climate variability timeseries and one for a climate change timeseries.

Documentation in github:

- Gws_script_bangkok.R

Step 4. Hydrological responses basin

The main purpose of this task was executing hydrological model runs to generate timeseries of discharge outputs at the boundaries of the area of interest. Within this task, the Wflow model was executed for each weather realization to generate an associated hydrological response, resulting in a discharge timeseries. In total four weather realizations were simulated, one realization based on the historical extracted climate forcing data and three stochastic weather realization containing two times climate variability and one-time climate change.

Documentation in github:

- Era5_wg.yml
- Wflow_sbm_historic.toml
- Wflow_sbm_variability.toml
- Wflow_sbm_variability_2
- Wflow_sbm_climx.toml

Step 5. Extreme Value Analyses of the basin

The purpose of this task was to generate a series of informative plots to understand the response of the hydrological models, by using a historical, climate variability and climate change timeseries as input. I've done this by creating a python script that executes an extreme value analyses over the four discharges timeseries that were retrieved from Wflow (one historic, two-times a climate variability and one-time a climate change discharge-series). Below, I suggest a few informative visualizations that in addition contribute as input for the next part of the workflow:

- Discharge timeseries with peak maxima;
- Flow Frequency Curve;
- Normalized Peak Hydrographs;

- Return periods.

Referring to the introduction which stated that water managers were most interested in hydrological extremes, I wanted to know which historical or future waterflows result from several return periods or storm events. Hence, the discharge timeseries are used to create Flow Frequency Curves containing the annual peak maxima over a 30-year period. The frequency curves were used to construct Normalized Peak Hydrographs which show the interaction of the rainfall-discharge processes in the catchment resulting from 30 annual peak maxima. By combining the 30 annual peak maxima the script constructed a mean hydrograph. Next, I calculated the mean discharges of the different peak maxima and divided this by the mean hydrograph to calculate the magnitudes of the events or in other words the return period. The plots were generated using an appropriate plotting framework in python and will aid in the response of hydrological model SFINCS, to provide the possibility of several inputs in the form of return periods, ranging from 2, 5, 10, 25, 50, 100, 250 and 500 year floods.

Documentation in github:

- Design_events.ipynb
- Update_design_events.ipynb

Step 6. Hydrological responses area of interest based on return periods

First, a flood model (SFINCS) was updated through an input file and thereafter executed, based on a return period from a 100-year storm event, creating four flood maps under a historic, two-times climate variability and climate change conditions. SFINCS is applicable for any of the suggest return periods if desired.

Documentation in github:

- Floodmaps.ipynb
- Sfincs_historic_rp100.inp
- Sfincs_variability_rp100.inp
- Sfincs_variability_2_rp100.inp
- Sfincs_climx_rp100.inp
- Sfincs_log_historic_rp100.txt
- Sfincs_log_variability_rp100.txt
- Sfincs_log_variability_2_rp100.txt
- Sfincs_log_climx_rp100.txt

RSQ2: *"How do flood hazards under climate variability and climate change conditions compare to historic fluvial flood hazards at a city level?"*	**Rationale:** The developed workflow was tested for several amounts of climate change using the same bottom-up approach to assess flood hazard under historical, climate variability and future climate conditions.

Applying the approach

I selected three different stochastic weather realizations from the climate change "envelope" I used to create the workflow. Two realizations containing climate variability and the other realization containing climate change. Next, I executed the steps using the same method previously described, over the same study area and time period. Additionally, I included the historical timeseries and ran this through Wflow to compare the climate variability and climate change outcomes to the present climate data.

3.5. Ethical Issues

All data was retrieved from public open source global data. Data will not be stored on personal/portable storage media but on the Deltares server or publicly available servers instead. All results obtained from the current research was stored in a project folder in the Deltares archive which can be accessed by Deltares employees. Because, this research is conducted in cooperation with Utrecht University, results and means will be shared with the appointed supervisors and if possible, to everyone who is interested. GitHub is used for the publicly available methods and results. No further ethical issues were expected.

4. Results

The results comprise a section related to the workflow, which was further divided into the individual processes of the workflow. In the first section the hydrological processes creating the characteristics of the models Wflow and SFINCS were created presenting elevation maps, followed by a section related to the simulation of climate variability and climate change data using the weather generator. The last two sections show the hydrological response of executing the flood models through an Extreme Value Analyses under historic, climate variability and climate change conditions.

4.1. Application of the workflow

The application of the developed workflow was illustrated using the case study of Bangkok. The structure of the workflow is as shown in the research framework in Figure 2 and executed according to the number/character of the indicated steps.

4.1.1. Creating the characteristics of the hydrological models

The elevation maps in Figure 3 displays the catchment of the Chao Praya river and the city of Bangkok built by the hydrological models Wflow and SFINCS using the global datasets available within the Deltares network and the created scripts/input documents that can be found on GitHub. The legend of the hydrological basin (left) presents the rivers, reservoirs, and gauges within the model. The legend of the area of interest (right) shows model boundaries, observation points, and the river flowing through the city of Bangkok. The area of Bangkok (right) adjacent to the one major river in the area has the highest elevation levels. Elevation decreases as the river flows towards the Gulf of Thailand or when going further away from the river.

4.1.2. Weather Generator

Five timeseries of stochastic weather realizations were generated by the weather generator and one historical realization was used extracted from a global dataset (ERA5). Out of these five realizations three realizations were picked of which two realizations include climate variability and one was stressed with the amount of climate change from the “envelope” based on the narrative in Paragraph 3.3.

To evaluate the performance of the proposed weather generator it was applied to the study area of Bangkok with data available between 1 January 1981 and 31 December 2010, according to the narrative explained in the Third Chapter. Figure 4 shows the mean and standard deviation for daily precipitation and mean temperature for the stochastic and observed timeseries. The standard deviation is a measure of how dispersed the data is in relation to the mean. Each point presented in the plots is similar to one year, together showing 10950 points of weather observations.

The results suggest a positive association between the observed and stochastic timeseries for both precipitation and temperature; it also illustrates a strong linear relationship between the two timeseries, indicating that the stochastic timeseries match the observed ones. In general, good performance was shown for the precipitation variables and statistics, however, temperature shows a more scattered view of points under the standard deviation, indicating that in relationship to the mean, temperature was underestimated. However, the proposed weather generator places an emphasis on altering precipitation patterns in the climate system because this variable often dominates the performance of biophysical and socio-economic systems. Hence, temperature gets underestimated because the current weather generator was calibrated to getting precipitation right.

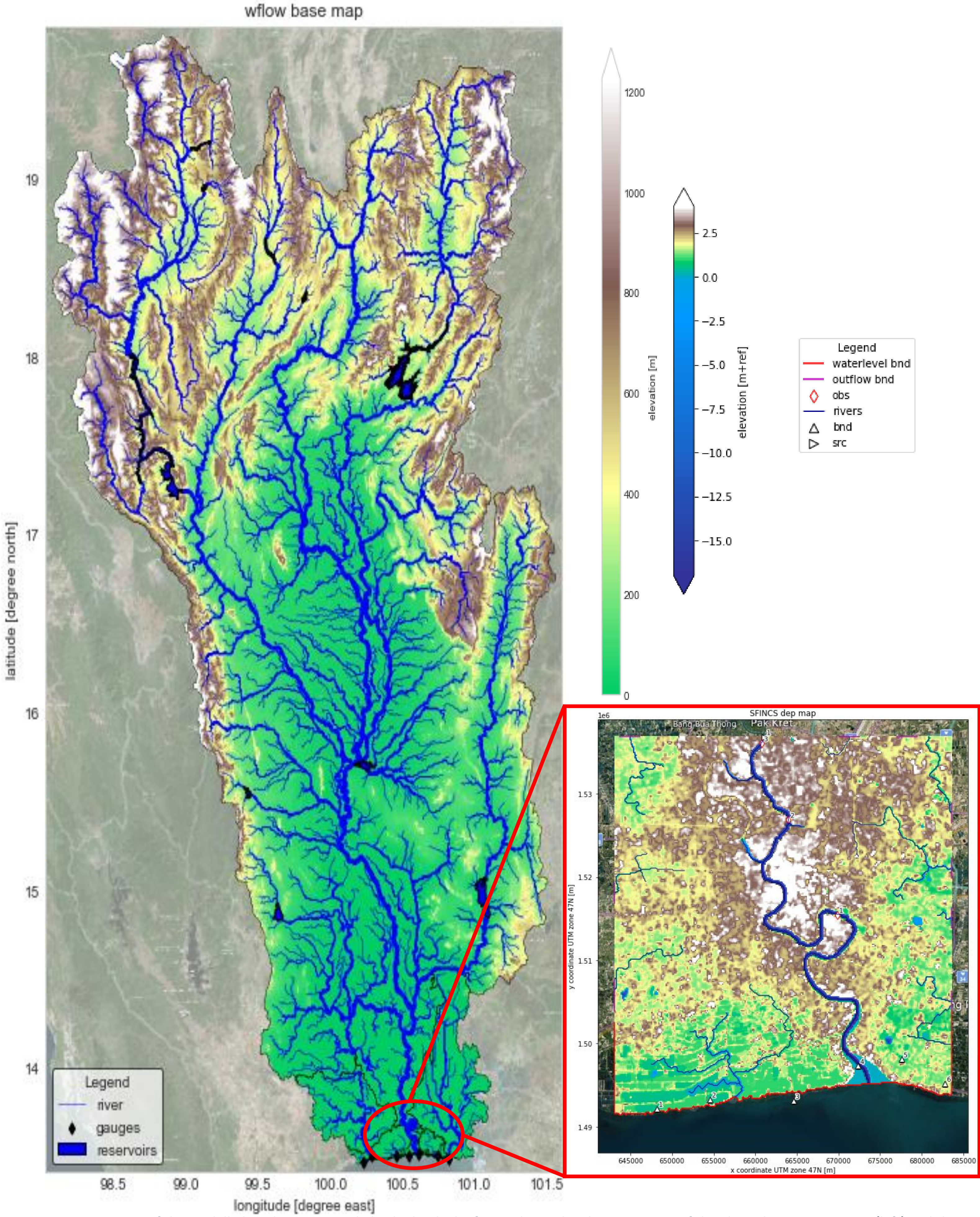

Figure 3 Location of the modelled study area. Bangkok, Thailand. The figure shows the elevation maps of the Chao Phraya River Basin (left) and the city of Bangkok (right). Created with input from global geographical datasets. The first elevation indicator refers to left figure and the second indicator to the smaller right figure.

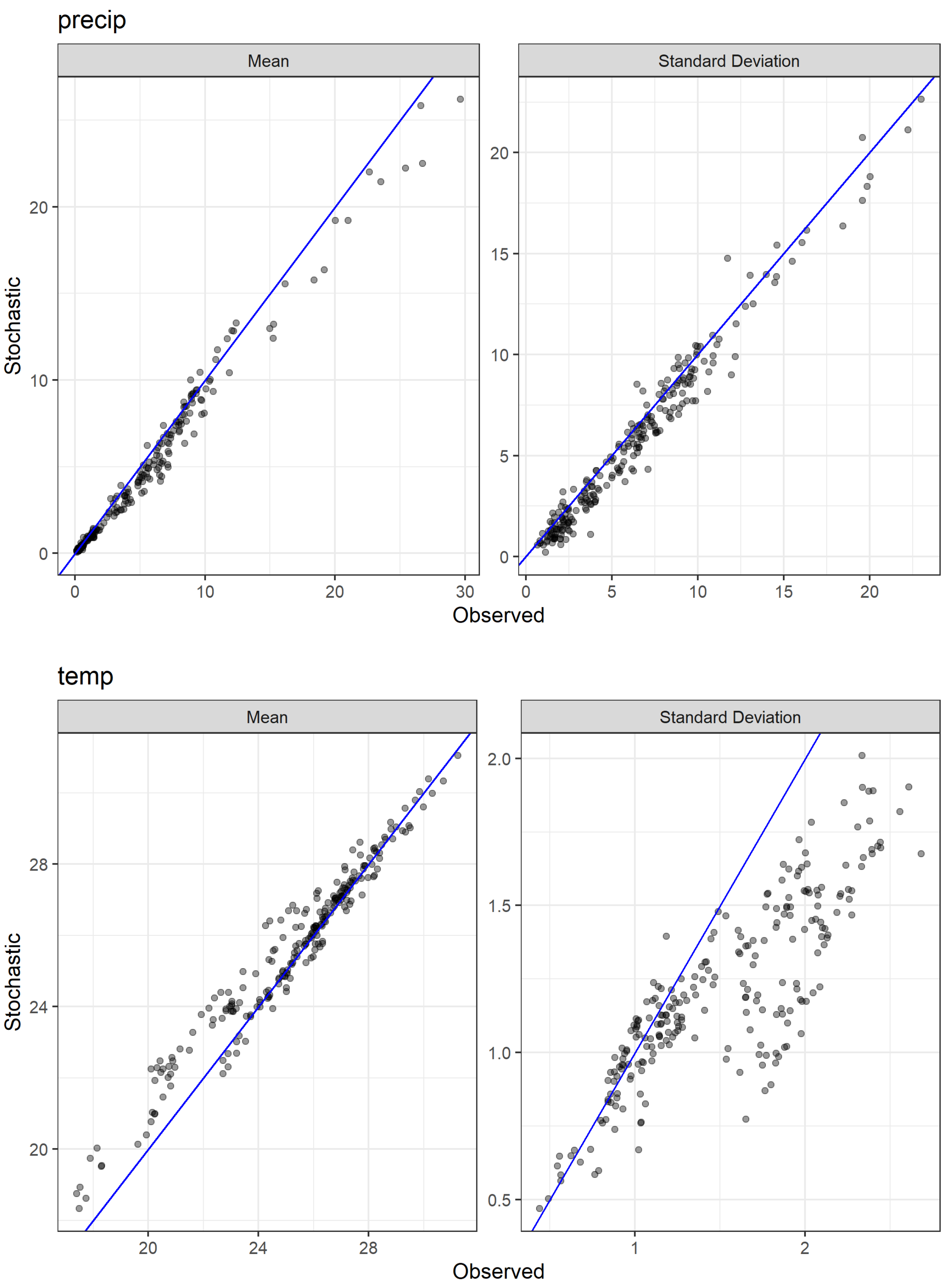

Figure 4 Daily performance statistics for all grid cells and months, including the mean, standard deviation of precipitation and temperature. Median values are shown against the observed values.

4.1.3. Hydrological Responses and Extreme Value Analyses

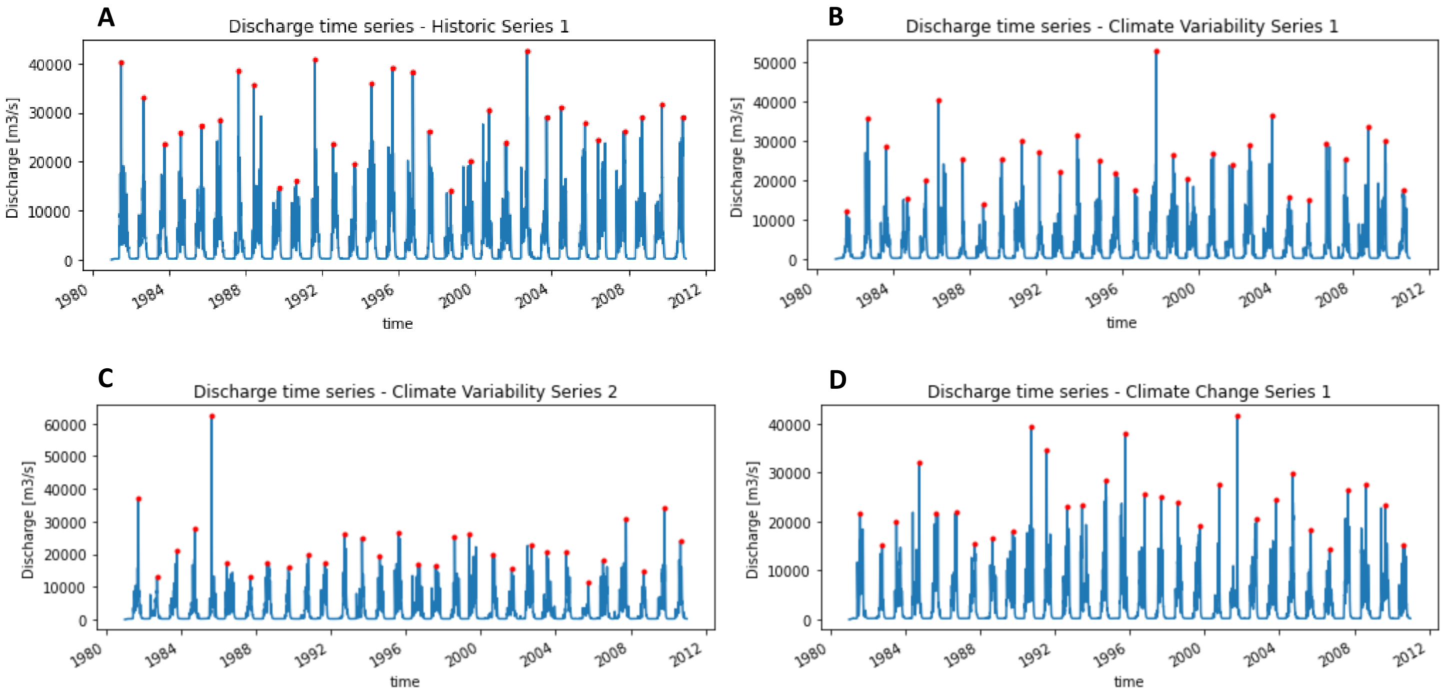

Figure 5 Hydrological responses of the Wflow model resulting in discharges of the Chao Phraya River Basin under (A) historic, (B & C) climate variability, and (D) climate change conditions. The red dots indicate the maxima annual peaks of discharge and are independent when separated by at least 14 days.

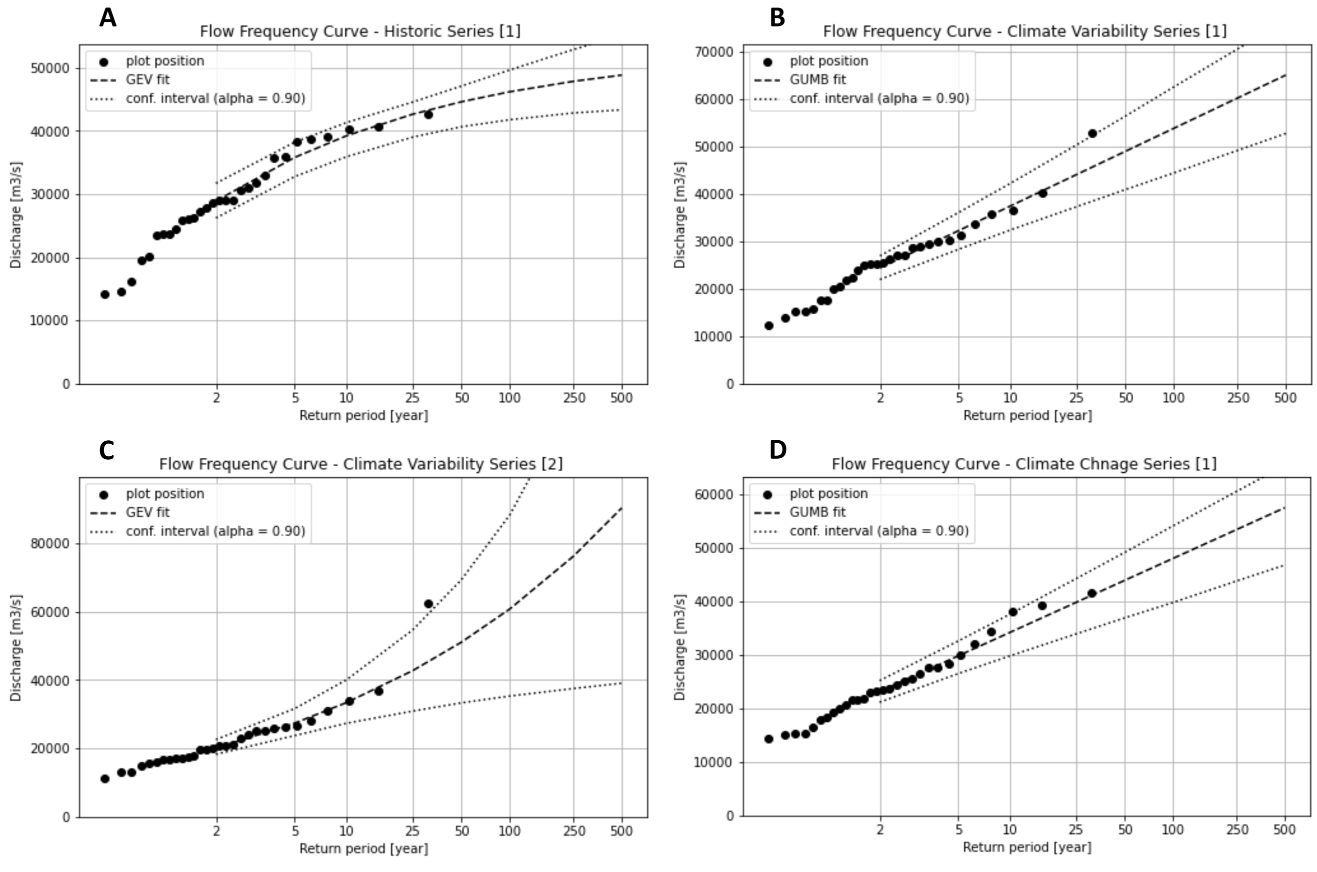

Figure 6 Flow Frequency Curves estimating design floods based on discharge amounts under (A) historic, (B & C) climate variability, and (D) climate change conditions.

Figure 5 presents four discharge timeseries, one based on (A) historic weather data, and three timeseries resulting from stochastic weather that include (B & C) climate variability and (D) climate change respectively. Each of the timeseries include 30 years of annual peak maxima. The historic series shows several peak maxima around 20.000 m3/s and 40.000 m3/s. The climate variability timeseries shows, as expected, a different realization in timeseries compared to the historic series. The peak maxima indicate a greater variance between peak maxima with the lowest value located just above 10.000 m3/s and the highest peak around 50.000 m3/s. A first impression of the second climate variability timeseries shows a similar trend to the first climate variability series, however, an obvious outlier (> 60.000 m3/s) can be observed. This peak possibly could indicate a so called "deep uncertainty" event that plausibly could occur. Deep uncertainty in this case means the uncertainty about the mechanisms and functional relationships being studied. Neither the functional relationship nor the statistical properties are known, and there is little scientific basis for placing believable probabilities on scenarios. Hence, this outlier was a product captured in the form of wide range of plausible scenarios. Lastly, the climate change timeseries shows similar discharges as the historic series but the overall discharge seems to be going down when climate change was included. Based on this one "envelope" of climate change over a 30-year period, streamflow appears to become less when amounts of climate change were included.

Figure 6 presents the 30 annual peak maxima in a flow frequency curve, with the y-axis showing discharge and the x-axis showing several return periods ranging from 2 to 500 years. Based on a Generalized Extreme Value (GEV) distribution and a Generalized Extreme Value Distribution Type-I (GUMB), the best fit depends on the behaviour of the distribution of the sequence of independent and identical distributed random variables, being the discharge peak maxima. Hence, the different behaviour of the plots in Figure 6. Starting with the historical series, the plot show that the highest concentration of peak maxima can be found within the 2 and 5-year return period, after surpassing these return values the peak maxima indicated that larger return periods occur with only a slight increase in flow rate. Between 45.000 m3/s and 52.000 m3/s the return periods between 5 and 50-years. According to the plot of the (A) historic series the largest return period being 500-years occurs around a flow rate of 50.000 m3/s. Next, the first (B) climate variability curve shows a linear behaviour, the highest concentration was still visible at the 2 to 5-year return period, from there a more scattered view can be seen with a jump to a small outlier having a discharge larger than 50.000 m3/s. According to the fit of the plot the largest return period of 500-years occurs around a discharge of 65.000 m3/s. The second (C) climate variability plot shows that the highest concentration of peak maxima was located between a return period of 0 and 10-years. Observing the plot, it also shows a large outlier around 60.000 m3/s, this being the possible deep uncertainty event. The flow frequency curve that includes (D) climate change, shows like the first (B) climate variability plot, a linear behaviour but less steep, indicating that adding climate change in this realization decreases discharges. Overall, the concentration in discharges were generally of comparable magnitude, only showing a small decrease when looking at the timeseries that include (D) climate change. However, largest peak maxima indicate something interesting. The largest discharges being 42.000 m3/s, 52.000 m3/s, 60.000 m3/s and 40.000 m3/s for the (A) historic, (B) climate variability, (C) climate variability, and (D) climate change series respectively, show large deviation between the peaks. Additionally, this indicates that the different realizations have different return-periods. For example, the second (C) climate variability series has a maximum peak discharge of 60.000 m3/s with a return period of 25-years. However, looking at the same amount of discharge for the first (B) climate variability series a 60.000 m3/s discharge has a return period of 250-years. Based on this it can be indicated that only a change in climate variability was already enough to result in a large variety of return periods. However, more realization will be needed to see a trend that proves or disapproves this indication.

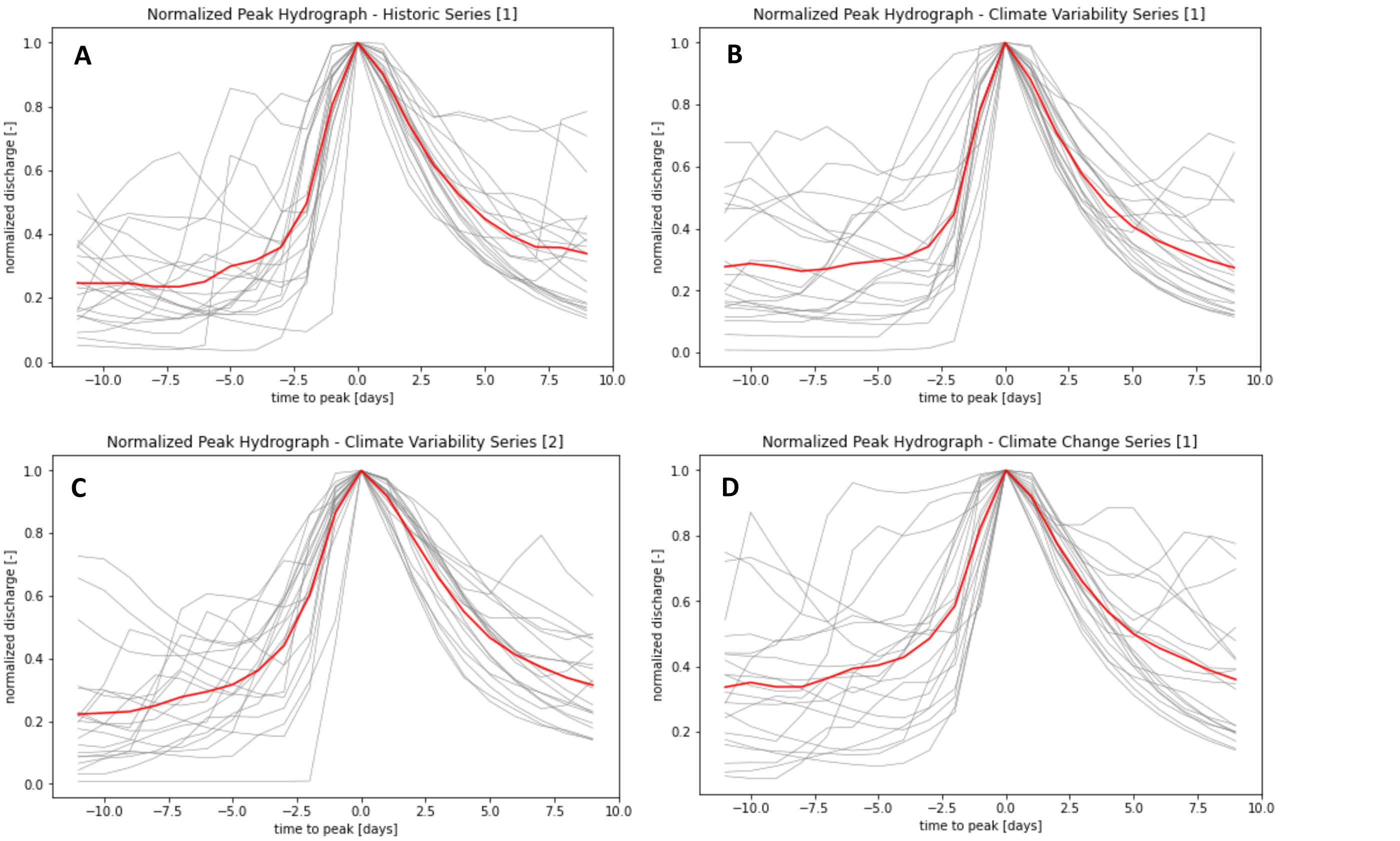

Figure 7 Normalized Peak Hydrographs of the rainfall-discharge processes in the catchment under (A) historic, (B & C) climate variability, and (D) climate change conditions. The lines indicate 20 different peak discharges with the bold line in red indicating the mean hydrograph

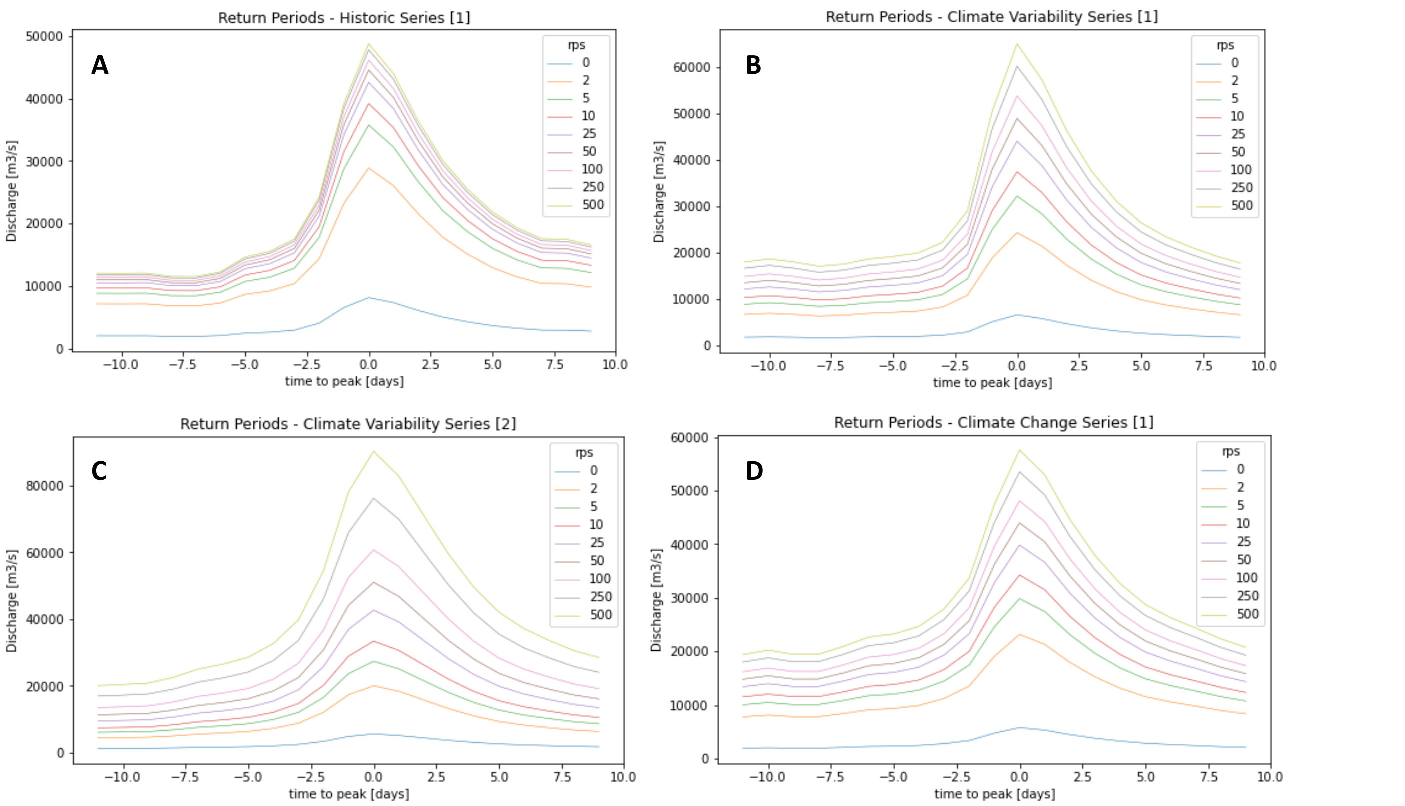

Figure 8 Return Periods simulated from discharges by combining the extreme value analyses with the shape of the hydrographs under (A) historic, (B & C) climate variability, and (D) climate change conditions.

Figure 7 presents the normalized peak hydrographs of the four timeseries, with the y-axis ranging from 0 to 1 and the x-axis showing the time in days to the peak event. The hydrographs contain 20 out of the 30 peak maxima to keep the figure clear. These discharge hydrographs were the result of all the rainfall-discharge processes in a catchment and therefore offers valuable information on the Chao Phraya River catchment processes. The higher values indicate lower return periods whereas the lower values simulate large return periods. Overall, a mean hydrograph was constructed around 0.3 with the (B & C) climate variability plots having a steeper rising limb which graduates into a less steep falling limb like the (A) historic and (D) climate change graphs. However, the (B & C) climate variability graphs show a horizontal or almost horizontal line with a value around 0 which presents the outliers indicated before.

The last four graphs (Figure 8) of the Extreme Value Analysis presents the return periods for each timeseries, being (A) historic, (B & C) climate variability and (D) climate change. First impression shows that the historic timeseries start somewhere around 10.000 m3/s whereas the others start between 10.000 m3/s and 20.000 m3/s. However, the figure becomes interesting when looking at the discharges that match the return periods, large variety of values can be found matching the flow frequency curves.

4.1.4. Flood maps

During this research it was reapididly mentioned that watermanagers and decisionmakers were interested in hydrological extremes. Figure 9 on the next page, presents the flood maps of a 100-year storm event under (A) historic, (B & C) climate variability, and (D) climate change conditions. The legend shows the *src* point where the river enters the boundary of the SFINCS model and the observation point of the presented peak discharges occuring during a 100-year stormevent under several climate conditions. First impression indicates that innudation of the area of interest were similar for a 100-year return period under different climate conditions. However, when observing the discharges presented in the floodmaps different discharges match the 100-year return period and looking at the waterdepth a difference in innudation can be observed. Flood map (B) and (C) both containing climate variability, were having a higher concentration of yellow areas, indicating that the water levels were higher in these maps compared to the flood maps with (A) historic and (D) climate change return periods. These result indicate that climate variability has a higher impact on inuddated areas compared to climate change.

All the flood maps suggest that the flooding begins at the point where the river enters the boundary conditions of the SFINCS model and from there spread across the area making its way to the gulf of Thailand. When following the river downwards the water level becomes less deep, possibly indicating an increase of capacity of the river, or more likely, that the areas that are less inundated are higher. This might result from the inclusion of built area in the elevation, giving a biased view of the real inundation situation.

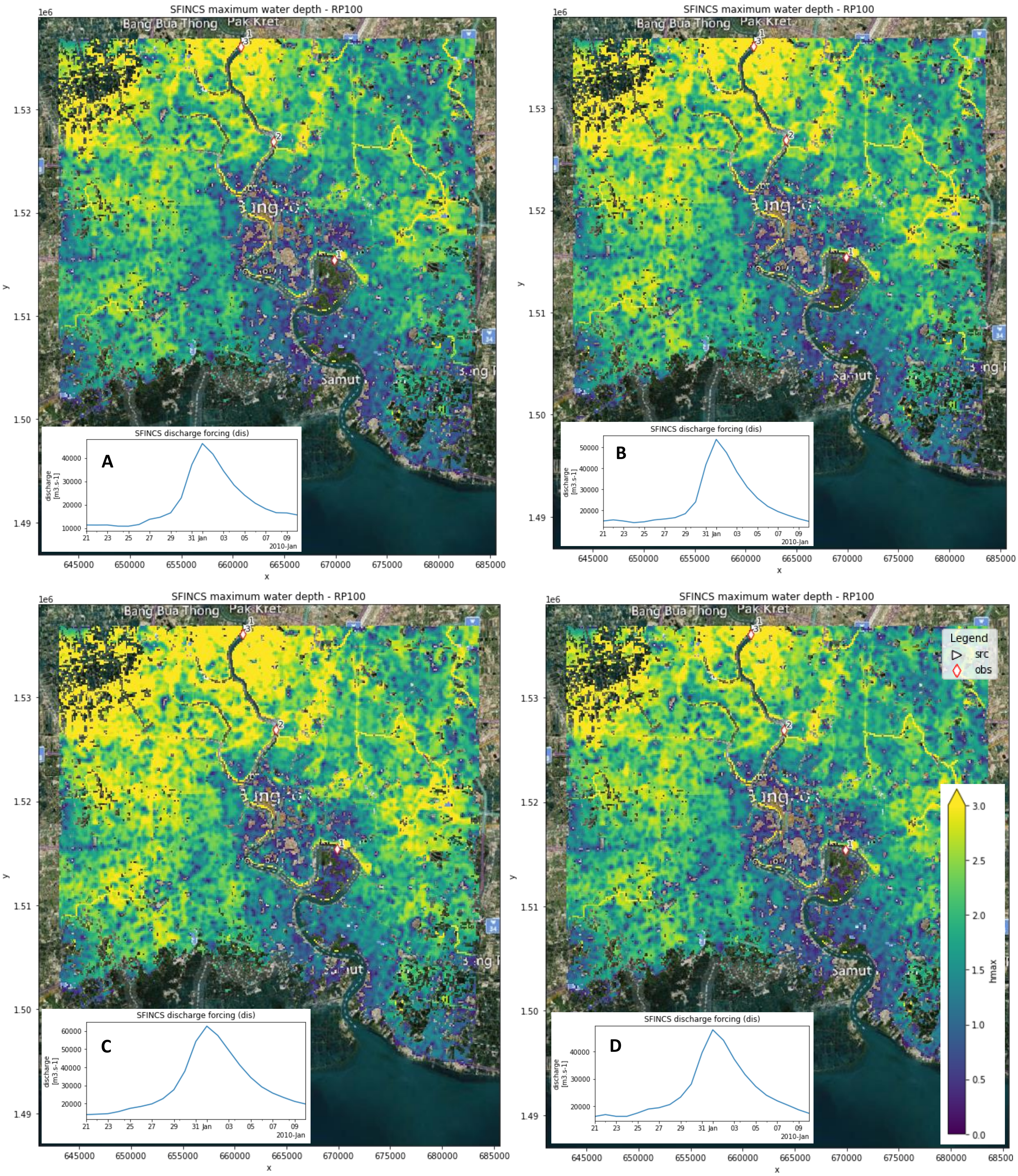

Figure 9 Projected flood dept for a 100-year return period under (A) historic, (B) climate variability 1, (C) climate variability 2, and (D) climate change conditions.

5. Discussion

First, a general discussion of the approach is presented in the next section, followed by the application of the workflow. Finally, the limitations are explained, and recommendations are given for future research along with the scientific and management implications.

5.1. General discussion

This research aimed to contribute to the climate risk assessment of cities. This thesis provided a first step in the assessment of climate risk by constructing a global flood hazard methodology designed to contribute to policymakers as well as investors in determining the city's most at risk of riverine flooding under several climate conditions. Adding insights of where climate adaptation measures are most urgently needed. The methodology builds on existing bottom-up methodologies and utilizes a new approach by integrating hydrological extremes through hydrological models that include catchment processes of the hydrological cycle (e.g. evapotranspiration, runoff, river channel flow) in a spatially distributed manner, complimenting flood models triggered by hydrological extremes, such as the 100-year return period storm event. The methodology is theoretically applicable where any risk of flood hazard is deemed not acceptable. The approach differs from the conventional top-down approaches because it takes into account the multiple climate conditions scenarios for different cities. Additionally, it contains analyses that are required for simulating fluvial hazards at the fine spatial resolution needed for cities. Comparing the approach to existing bottom-up climate change assessments such as the Decision Three Framework (Ray & Brown, 2015) and the Climate Risk Informed Decision Analyses (CRIDA) (Mendoza et al., 2018) it is able to include hydrological extremes through the use of global dataset under several climate change conditions in one single approach. This helped to pave the way for flood risk assessments under several climate conditions that plausibly could occur in the (nearby) future.

5.2. Application of the workflow

The floodplain of the Chao Phraya River Basin is hydraulically complex. Resulted flood depths and extent may differ from reality due to simplified assumptions on hydrodynamical processes on the watershed. It is recommended that the projected floodplain areas need to be continually updated to account for land cover changes developments, floodplain developments and infrastructure and natural changes to the landscape and hydrologic systems (Jamrussri & Toda, 2017). The discharges obtained when executing the workflow seem relatively high. Observing Figure 5 the largest peak discharge is above 60.000 m3/s under the (C) climate variability conditions. In contrast, the threshold discharge capacity for flooding of the lower watershed of the Chao Phraya River during the 2011 flood in Bangkok was much lower (Komori et al., 2012). However, along the Chao Phraya River dams are located, and Sayama et al. (2015) showed a considerable impact of the dam reservoir operations on river flow simulations (Wichakul et al., 2015). Currently, this research doesn't account for the inclusion of physical structure like dams. Hence, for future river flow projections, to suppose the current dam operations and inundation situation is an additional hydrologic modelling scenario to be considered.

Although the workflow currently only assesses fluvial flooding, Bangkok remains an interesting study area due to it sensitivity to fluvial, pluvial, and coastal flooding and the interaction of high sea levels, large river discharges and precipitation (Bates et al., 2021; Singkran & Kandasamy, 2016). Hence, Bangkok remains a location that can be used further to incorporate pluvial and coastal flooding in the workflow. However, only assessing one flood hazard at the time (in this case fluvial) could give biased results as most often flood is an interaction of several flood drivers.

The largest peak discharge described was indicated as an outlier and a deep uncertainty event. These events are often defined as Black Swan events and can be described as an event that lies outside the realm of regular expectations, carries an extreme impact, and is explainable only after the event happened (Walker et al., 2010). Additionally, the comparison of the extreme value analysis and the return periods indicates that adding a certain amount of climate change reduces the discharge. This comes as a surprise as the magnitude and frequency of hydrological events are expected to increase in coming years due to climate change (Shrestha et al., 2017). However, this research only applied the methodology on the area of Bangkok to test whether the approach was working. During the general applicability of bottom-up approaches many climate realizations are often realised, therefore often containing multiple stochastic weather realizations that include several amounts of climate change. On the other hand, Hasan et al. (2018) state that understanding the sensitivity of river discharge to precipitation, or simply called; precipitation elasticity, is helpful to show how responsive the streamflow in the basin is to precipitation changes. The concept of runoff elasticity relies on the fact that energy available for evapotranspiration plays a large role in determining whether the precipitation received within a catchment generates runoff. Hence, Climate elasticity of runoff is an important indicator for evaluating the effects of climate change runoff (Hasan et al., 2018). It can be defined as, the percent change of streamflow resulting from a 1% change in precipitation or other climate variables. Meaning, the concept of precipitation to runoff elasticity provides a possible option on why the influences of climate change are not significantly visible.

The flood maps presented in Figure 9 of the results show a very similar impression of inundated areas, even under several discharges. However, the boundaries of the SFINCS model are currently working as a “wall” meaning that the water will not flow out of these boundaries but flows to the lower laying areas, creating a biased view of the actual situation that could occur. This need to be adjusted in future cases when applying the workflow.

Based on the performance of the hydrological models the results suggest a decrease in streamflow under future climate conditions compared to the historic climate forcing data. While the lower streamflow is a product of complex combinations in the physical processes of a catchment, Alodah & Seidou (2019) indicates a possible reason of such projected changes in flow rate can be attributed to enhanced evapotranspiration due to the increases air temperature. From the model results, it was difficult to achieve reliable estimates of peak flow under changed climate conditions. Peak flows largely diverse under climate variability conditions and this indicates that under climate change conditions a greater number of realizations were needed to make good estimations about peak flows. The best hydrological estimations can be made when considering more stochastic weather generator realizations to ensure a thorough evaluation (Alodah & Seidou, 2019). Additionally, to overcome high computational requirements, future research is needed to determine the right amount of realizations that are needed to represent observed data in climatic and hydrological modelling (Alodah & Seidou, 2019; Steinschneider & Brown, 2013). Additionally, applying the workflow for multiple cities gives better insights in applicability of the approach.

5.3. Limitations

The workflow created was designed to support decision-centric climate change studies by exploring a system under a wide range of plausible climate scenarios and identify potential fluvial flood hazard. According to Steinschneider et al. (2013) this raises two immediate questions, i.e., what constitutes plausible climate change and how large should the range of climate change be? In which the important factor is how far the climate must change before the system no longer functions properly, spreading awareness to the stakeholder of the potential climate hazard to see where climate adaptations are needed. The historic amount of climate change, for the purpose of creating the workflow, was based on IPCCs SSP5-8.5 strong emission narrative. As stated in the introduction, Wilby & Dessai (2010) mentioned that a top-down approach, like the Interactive Atlas, is useful for evaluating responses to particular emission scenarios, but not accurate to explore changes on a fine spatial resolution like Bangkok, or even Thailand. Hence, Steinschneider et al. (2013) states that for bottom-up approaches a promising strategy is to identify the climate variables and time scales that influence the performance of the system and then extend the range of climate changes for those variables wide enough to stress the system to failure. When the failures emerge, decisions can be made regarding the plausibility of the conditions causing them. However, the aim of the current research was developing and testing an approach that can help decision makers determining the city's most at risk of flooding under different climate conditions and not focusing on the uncertainty of the system or city.

The proposed weather generator places an emphasis on altering precipitation patterns in the climate system because this variable often dominates the performance of biophysical and socio-economic systems. Middelkoop (2018) agrees that precipitation is the most important driving force of the fluvial system, as changes in precipitation will be the primary cause of runoff changes and can be affected by either climate variability or climate change. However, the author deems temperature as the second most import driving force as it effects evapotranspiration and snow melt. Since, climate "envelopes" generally include rising temperatures it is recommended that with the development of weather generators a similar level of emphasis is laid on temperatures as for precipitation to assess the hydrological processes in river catchments. For this research precipitation was still deemed the most important factor as riverine flooding is determined by the magnitude and occurrence of extremes. While the weather generator used in this study can simulate multiple forms of climate variability at several timescales, the model has some challenges regarding future climate changes. A resampling algorithm drives the model, meaning that at the daily times scale the tool implicitly assumes that the spatial correlation structure of the weather variables is stationary. This may not be the case under future climate changes, yet such a change cannot yet be simulated (Steinschneider & Brown, 2013). Additionally, the current weather generator aims at creating long timeseries with focus on long term statistics and is not designed, but can be used for the purpose of assessing flooding, meaning there is still a lot of room for changes regarding the assessment of extreme values regarding flooding.

When applying a hydrological model to assess the hydrological implications of climate and land-use changes, it is recommended that the model is able to predict the relations between climate inputs, basin characteristics and runoff correctly under changed conditions (Middelkoop, 2008). For this research the assumption is made that the hydrological model calibrations hold under future climate conditions. The hydrological model Wflow uses parameters that were based on catchment and soil properties that may also change in the future (Sperna Weiland et al., 2021). Concerning the global applicability of the framework, the primary data issue is the reliability of a global Digital Terrain Model. When building a base model, it was quickly recognized that parts of the built areas were included in the elevation models. Although this aspect of the model will improve when improved dataset come available, there is also a possibility to change the resolution of the model to fit the dataset to make sure the models simulate the situation on the same resolution as the dataset. However, this changes computational time. For the first iteration of a rapid assessment tool which desires to obtain most reliable results as rapidly as possible for anywhere in the world the computational time is "relatively" long. Currently, it takes around two days to execute every step of the workflow and obtain results. It is therefore recommended to continue to prioritize the developments of hydrological models and limit the uncertainties in flood projection modelling to get insights with increasing computational time.

5.4. Scientific and Management Implications and Future Research

This thesis provided a first step in the assessment of climate risk by constructing a global flood hazard methodology designed to contribute to decisionmakers in determining the city's most at risk of riverine flooding under historical, climate variability, and climate change conditions. The workflow can explore the potential riverine flood hazards due to climate changes under which a city is most vulnerable.

The current workflow was solely developed for fluvial flooding of a hazard assessment as some individual parts of the workflow are still under development and not yet able to comprehend, for example, timeseries of precipitation as an hourly pattern that is needed to assess pluvial flooding (Steinschneider & Brown, 2013). Regarding coastal flooding, the suggested approach through a workflow still misses the ability to account for sea-level rise and tidal differences. Finally, it can be stated that the flood model for fluvial flood hazard still has some flaws when assessing the impact of climate change but has also demonstrated that there is potential to analyse historic, climate variability and future climate flood hazards based on global datasets and modelling tools alone. The outcome consists of a flexible workflow that in theory can be applied for a large number of cities and simultaneously can be improved over time when either data sources improve, model settings are revisited, or better assumptions are made.

Relatively few examples of bottom-up approaches informing stakeholders are known because these studies include multiple drivers of climate change. Additionally, many bottom-up approaches seek to produce contextualised information of whatever levels of climate impacts are plausible (Conway et al., 2019). The assessment of risk has been dominated by top-down approaches and is challenging as climate projections and impacts are highly uncertain, even in the near term, and frequently do not match user requirements for specific detail and levels of confidence that are sufficient to influence decisions. Resolution of these issues has the potential to contribute to the demands of international and national adaptation policy. Whilst bottom-up approaches generate complementary insights into who and what is at risk, integrating the results, however, is a much-needed step towards developing information to address the needs of immediate adaptation decisions (Conway et al., 2019). Hence, as the range of the several climate variability and climate change realizations can be very wide. This is primarily due to uncertainty in the climate scenarios (Middelkoop, 2008). A way to limit these concerns is to combine the suggested bottom-up approach with the different sources of the conventional top-down approaches to determine the plausibility of the problematic conditions and thereby limiting the amount of climate change “envelopes” that are needed (Brown et al., 2011).

A main achievement related to scientific and management implications is that not only steps have been made to improve the reliability of rapid, global flood hazards but rather a shift in the approach on how to model climate change has started, addressing city-wide resilience issues from a holistic, global perspective. Although the approach still needs some work, it already is in a state in which it can get involved in many interesting discussions about methodologies for climate risk assessment. Further validation is required before the approach can be used globally and applied for the purpose of decision making; analyses on the uncertainty considering the models and observations is needed. Additionally, the ability to include pluvial and coastal flood hazard is recommended when data sources are improved, and better model calibrations and better assumptions are made. On top of that, the current research focused on climate change, a first step that could be undertaken is to limit the applicability of the approach to present historical climates and compare the outcome to local situations. When accurate enough extend the research again to assess future scenarios and risk.

The major contributing of this research is to the climate risk assessment of cities. However, the research still needs to be expanded to a full risk assessment. As Risk is defined as: Risk = Hazard * Exposure * Vulnerability, it is important that all three sections that define risk are included. The current research solely focusses on the hazard section, hence, before this research can be used to answer the bigger question of which cities are most at risk of climate change, the remaining sections of exposure and vulnerability need to be included as the calculation of risk is directly dependent on the occurrence and magnitude of hazard events, but also on the number of people exposed to climate hazard and the resilience of the city and its habitants (Oppenheimer et al., 2015).

To conclude the discussion, the constructed approach is a solution for the coarse scale and the misinterpretation of hydrological extremes that comes with top-down approaches. Additionally, the suggest approach provide opportunities for cities to explore whether climate disasters could have a major impact on society beyond the immediate knowledge of experts and policymakers. Knowing this information is crucial for decision makers identifying which cities benefit most from adaptations to climate risk under several climate conditions (Dreyfus, 2015).

6. Conclusion

This research is part of a MSc thesis and tries to answer the question, which cities are most at risk due to climate change. The research will achieve this by proposing a flood hazard methodology designed to contribute to stakeholders in determining the city's most at risk of riverine flooding under several climate conditions. Adding to the assessment of where climate adaptation measures are most urgently needed. To realise the suggested approach, a main research question has been formulated:

"How can historic, climate variability and future climate conditions be used through a bottom-up approach, resulting in a global assessment framework that explores fluvial flood hazards on a city scale?"

To answer this question, this study presented a methodology that moves away from conventional top-down approaches and build on an existing bottom-up approach, using global datasets, and hydrological models that can create the hydrological extremes that are needed for decision making; such as the inundation resulting from a 100-year return period storm event. Based on the main result, this workflow can explore potential riverine flooding under several climate change simulations. While validation of the approach is required, this research could grow into an established methodology on how to model climate change, addressing city-wide resilience issues from a holistic, global perspective.

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