ASIA-PACIFIC NETWORK FOR
GLOBAL CHANGE RESEARCH

CAPaBLE Programme Final Report



Project Reference Number: CBA2016-07SY-Shrestha

Adaptation to groundwater vulnerability of Asian cities to climate change: developing capacity to bridge the science and policy interface

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"Adaptation to groundwater vulnerability of Asian cities to climate change: developing capacity to bridge the science and policy interface"

Final Report submitted to APN

OVERVIEW OF PROJECT WORK AND OUTCOMES

1. Project Information

Project Duration	**:**	1.5 years (including 0.5 year no cost extension)
Funding Awarded	**:**	US$ 40,000 for Year 1
Key organisations involved	**:**	Asian Institute of Technology (AIT), Thailand: Dr. Sangam Shrestha, Associate Professor Institute for Global Environmental Strategies (IGES), Hayama, Japan: Dr. Binaya Raj Shivakoti Department of Groundwater Resources (DGR), Thailand: Dr. Oranuj Lorphensri Brawijaya University, Indonesia: Dr. Dian Sisinggih Division of Water Resources Planning and Investigation for the South of Vietnam, Vietnam: Dr. Bui Tran Vuong International Waterlogging and Salinity Research Institute, Pakistan: Dr. Muhammad Basharat

2. Project Summary

Today, 54% of the world's population live in urban areas, a proportion that is expected to increase to 66% by 2050. Major cities and municipalities in the region rely either fully or partially on groundwater. Four highly relevant Asian cities (Bangkok, Bandung, Ho Chi Minh and Lahore) were selected which bear groundwater dependency in the range of 45% to 100%. We assessed the current and future climate, quantify changes in climatic drivers, analyse vulnerability of groundwater recharge systems to the changes, and then formulate adaptation strategies to reduce the vulnerability of groundwater resources in these cities. The methodology included modelled backed analysis of groundwater (recharge) vulnerability which is then discussed with stakeholders (policy-makers, scientist, and local water users) via project events for prescribing possible adaptation options in the four cities. The results show Ho Chi Minh city and Bandung to receive lesser rainfall and Lahore and Bangkok to get more rainfall. Bangkok is the only city to have minor fluctuation in future temperature while all others have significant increase (up to 3.1^{0}C). In line with the rainfall projections, Ho Chi Minh and Bandung are projected to have decrease in groundwater recharge while the other two cities are expected to get boosted recharge rates. The project results are useful for groundwater management under climate change scenarios in the cities. Moreover, the e-conferences and regional workshops were found to be effective modes of capacity building.

Outputs:

- Multi model climate change projections for four Asian cities
- Water balance/ hydrological model setup for the project cities
- Completion of groundwater recharge vulnerability to climate change in four Asian cities
- Organization of two Regional level workshops
- Organization of e-conference for project participation and brainstorming ideas
- Formulation of adaptation strategies for reducing the vulnerability of groundwater recharge

Outcomes:

- Trained project collaborators and a dozen participants including young researchers
- Capacity building of project collaborators and knowledge transfer via the regional workshops and e-conference
- State-of-the-art methodologies shared with project collaborators and event participants

Keywords: climate change, groundwater recharge, capacity building, Asian cities, adaptation options

3. Activities Undertaken

E-conferences: Communications over the Internet between the partners and collaborators for finalizing the detailed methodological approach of the project

Climate change projections: The future climate (near, mid and far future) of four Asian cities was projected using multiple RCM under RCP 4.5 and RCP 8.5 scenarios.

Groundwater recharge modelling and climate change impact assessment on groundwater recharge: Hydrological models were developed to estimate the groundwater recharge in four Asian cities. Climate change impact on future groundwater recharge was estimated using the future climate data obtained from above activities in four Asian cities.

1st regional workshop, AIT: The event covered discussion over the climate change analysis for the four cities and further modifications to the methodological approach for groundwater vulnerability analysis. The time and effort demand of the modified approach (extensive modelling) led to extension of the project by 6 months.

2nd regional workshop, AIT: The event covered discussion over the climate change and resulting groundwater recharge exposure for the four cities and the adaptation options based on the results.

4. Key facts/figures

- The project has trained project collaborators from 4 Asian cities viz Lahore (Pakistan), Ho Chi Minh City (Vietnam), Bangkok (Thailand) and Bandung (Indonesia) and a dozen of participants including graduate degree students, post-graduate degree students, young researchers.

- There were 2 regional workshops organized as a part of the project. The two workshops enabled capacity building of project collaborators and knowledge transfer. The discussions involved helped to shape the project methodology and interpret the results from analysis.

- The project also organized e-discussions wherein all the project partners and collaborators got involved in rigorous discussions on the project methodology. This web-based practice for correspondence was found to be highly effective which in the end accumulated a thread of 17 detailed emails.

- The project carried out state-of-the-art methodologies for estimating climate change projections for the 4 cities using 4 regional climate models (RCMs) under 2 representative concentration pathways (RCPs). The RCM output were first corrected using 2 bias correction methods before analysis.

- Using state-of-the-art model backed approach, the project estimated the future groundwater recharge for the 4 cities under the 2 RCP scenarios with the ensemble of the 4 RCM climatic output. There were 2 recharge estimation model applied during the process.

5. Potential for further work

The project has helped in capacity building of the partners in two aspects – 1) methodological knowledge transfer of climate change and groundwater vulnerability evaluation, 2) results based discussion of adaptation options. One potential area for further work is to carry out detailed capacity building including hands-on training on the methods utilized in this project. Numerical evaluation of the discussed adaptation options could be the second potential area for further work. Whereas evaluation of climate change impact on groundwater via numerical modelling using groundwater models could be another way forward for model backed scientific analysis of groundwater vulnerability of the Asian cities.

6. Publications

Proceedings of 1st Regional workshop on Adapting groundwater of Asian cities to climate change: bridging the science and policy interface. Asian Institute of Technology, Thailand, December 13-14, 2016

Proceedings of 2nd Regional workshop on Adapting groundwater of Asian cities to climate change: bridging the science and policy interface. Asian Institute of Technology, Thailand, September 8-9, 2017

Aslam, R. A., Shrestha, S., & Pandey, V. P. (2018). Groundwater vulnerability to climate change: A review of the assessment methodology. Science of The Total Environment, 612, 853-875.

7. **Pull quote**

"*One of the main lessons I have learned during one year as project's partner is that broad partnerships are the key to solving broad challenges and creating a better project requires good teamwork, partnerships, and collaboration*"

Dr. Bui Tran Vuong, DWRPIS, Vietnam

"*The project enabled us to better understand selected cities in South and Southeast Asia from the perspective of sources and extent of groundwater vulnerability to climate change and identify context-specific adaptation strategies in those cities through collaborative approach*"

Dr. Vishnu Prasad Pandey, IWMI, Nepal

"*The project provides an effective platform to facilitate the knowledge sharing and learning on integrated approaches to adaptation planning across countries having different socio-economic perspectives and climate hazards*"

Dr. Duc Hoang Nguyen, AIT, Thailand

"The lesson which I have learned from the outcomes of this project is that there are some factors other than climate change that need to be considered for better assessment and adaptation planning of groundwater vulnerability in the project cities"

Rana Ammar Aslam, AIT, Thailand

"*Challenges faced by more and more Asian countries in their struggle for adapting with negative impacts of climate change on groundwater resources. APN project not only assisted selected Asian cities in their endeavors to evaluate the vulnerability and risks of groundwater under future climate, but also proposed the adaptation methods to address the issues in a sustainable way. Scientific base analysis and information exchange from corroborative partners are valuable sources for future planning and investigation at four selected cities as well as other Asian cities."*

Hoàng Thị Ngọc Anh, AIT, Thailand

"*The project gives very clear insights of Climate variability and change directly affects the groundwater quantity through change in precipitation, evapotranspiration, recharge rates, and indirectly through human activities and provides actionable adaptation measures within the Asian cities*."

Binod Bhatta, AIT, Thailand

8. **Acknowledgments**

We are grateful to several researchers, government officials, and non-governmental organizations who participated in this project directly and indirectly by providing valuable time, experiences and expertise, datasets, including being part of the workshops, and e-consultations conducted in this project. Special thanks goes to Dr. Jariya Boonjawat, [Advisor, Atmospheric Research Group, Southeast Asia START Regional Center, Chulalongkorn University] and Dr. Jayakumar Ramasamy [Chief of Natural Science Sector, UNESCO, Bangkok Office] for their speech in the opening session of the 1st Regional workshop. We are also thankful to Dr. Winai Chaowiwat from Hydro and Agro Informatics Institute, Thailand for his presentation during the event. Our team is also obliged to Dr. Madan Lal Shrestha [Member, Scientific Planning Group, Asia Pacific Network for Global Change Research (APN) & Academician, Nepal Academy of Science and Technology(NAST)] for his seminar presentation in the opening session of 2nd Regional workshop.

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1. Introduction

1.1. Background

Around two billion of the rural/urban population obtain drinking water from groundwater, which accounts for around 32% of the total drinking water supply (Morris et al., 2003). Today, 54% of the world's population live in urban areas, a proportion that is expected to increase to 66% by 2050. Projections show that urbanisation, combined with the overall global growth could add another 2.5 billion people to urban populations by 2050, with close to 90% of the increase concentrated in Asia and Africa. Major cities and municipalities in the region rely either fully or partially on groundwater as a part of the water supply network, where it is also used by small-scale rural or town water supply systems. For example, groundwater dependency is 70% for domestic and 60% for industrial water demand in Bandung-Indonesia (2007 estimate; Tirtomihardjo, 2015), 45% in Ho Chi Minh – Vietnam (2012 estimate; Vuong et al., 2015) and 100% in Lahore – Pakistan (Basharat, 2015). Despite the significance of groundwater for sustainable development, it has not always been properly managed, which has often resulted in depletion and degradation of the resource. Due to various pollution sources and climate change in urban areas, the quality and quantity of groundwater have become important issues for urban groundwater environments (Collin and Melloul, 2003). The strategic importance of groundwater for global water and food security will probably intensify under climate change as more frequent and intense climate extremes (droughts and floods) increase variability in precipitation, soil moisture and surface water (Taylor et al., 2013). The predicted impacts of climate warming on groundwater include changes in the magnitude and timing of recharge (e.g. Hiscock et al., 2012), typically with a shift in seasonal mean and annual groundwater levels depending on changes in the distribution of rainfall (Liu, 2011) and snow melt (Jyrkama and Sykes, 2007 and Okkonen and Kløve, 2010). The predicted changes in recharge may be larger than the changes in precipitation (Ng et al., 2010).

In this project, we assessed the current and future climate, quantify changes in climatic drivers, analyse vulnerability of groundwater recharge systems to the changes, and then formulate adaptation strategies to reduce the vulnerability of groundwater resources in selected Asian cities (Bangkok, Bandung, Ho Chi Minh and Lahore) through a collaborative effort of scientists, policy-makers and relevant stakeholders (e.g. users). The project also developed the capacity of policy-makers to assess vulnerability of groundwater recharge system though customization and application of several models. Through e-conferences and regional workshops, communications among policy-makers, scientist, and local stakeholders (water users) were enhanced. The assessment results are useful for groundwater management under climate change scenarios.

1.2. Project Research Value

The project has included four highly relevant Asian cities (Bangkok, Bandung, Ho Chi Minh and Lahore) in terms of groundwater dependency/ issues. The groundwater dependency of these selected cities ranges from 45% to 100%. Thus, assessment of groundwater vulnerability in the context of changing climate is no doubt the highly on demand investigation for groundwater management in these four cities. Moreover, the project includes capacity building of policy-makers to assess vulnerability of groundwater recharge system though customization and application of several models. In addition, communications among policy-makers, scientist, and local stakeholders (water users) were enhanced through e-conferences and regional workshops. The assessment results are useful for groundwater management under climate change scenarios in the cities.

The project and its activities complement to at least first three goals (i.e., Support regional cooperation; Enhance capabilities in science-based decision-making; and Strengthen interactions among scientists and policy-makers) outlined in the APN's Fourth Strategic Plan (2015-2020). Similarly, the project encompasses three of the APN's research agenda (2015-2020):

- Agenda-1 (Strengthen capacity in one of the five thematic research areas): The proposed project aims to strengthen capacity in three thematic research areas: 1 (climate change and variability), 4 (resource utilization and pathways for sustainable development), and 5 (Risk reduction and resilience)
- Agenda-4 (Continue capacity development efforts): It is a continuation of earlier project (CBA2013-06NSY-Shrestha) as an effort to continue capacity development in the areas closely related to the project accomplished earlier.
- Agenda-5 (Continue to emphasize partnership approach by securing investment from other stakeholders): Out of US$ 58,980 estimated budget, US$18,980 is secured from other sources.

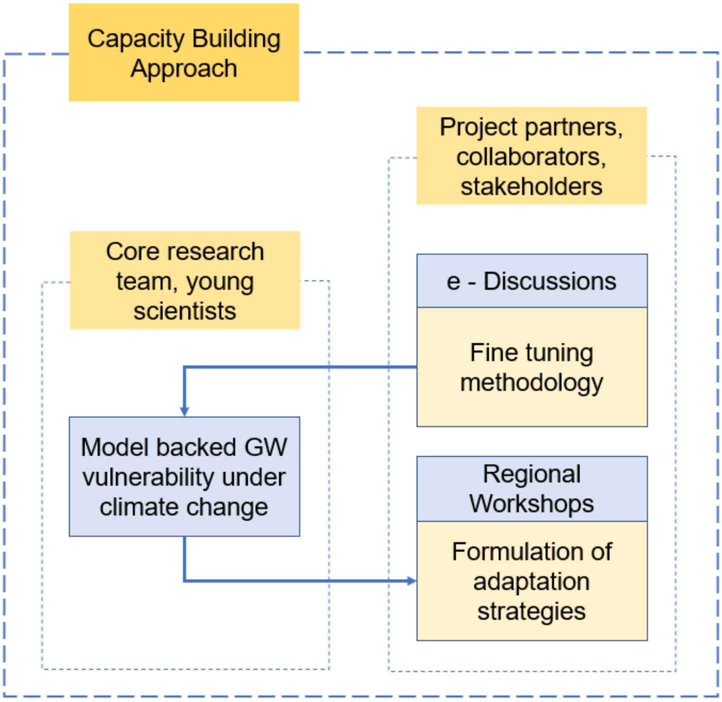
1.3. Objectives

The overall objective is to build capacity of the policy-makers and relevant stakeholders in assessing vulnerability of groundwater resources to climatic and non-climatic changes and device adaptation strategies by engaging them in joint research activities and workshops for bridging the science and policy interface. Specific objectives are outlined hereunder;

1. To assess the current and future climate and their trends in the selected Asian cities
2. To assess the vulnerability of groundwater recharge systems in those cities to climatic changes
3. To formulate the adaptation strategies for reducing the vulnerability of groundwater recharge
4. To develop the understandings and capacity of groundwater managers and relevant stakeholders for assessing groundwater vulnerability and developing adaptation strategies.

2. Methodology

Broadly, the project methodology includes modelled backed analysis of groundwater (recharge) vulnerability which is then discussed with stakeholders (policy-makers, scientist, and local water users) via project events for prescribing possible adaptation options in the four cities. The discussions (e-discussions and regional workshops) work as platform for capacity building of the stakeholders in terms of knowledge transfer of the existing methods for quantification of groundwater vulnerability under climatic change. Additionally, it also acts as a forum for formulating adaptive strategies for various ground condition/ preparedness situation versus climatic projection scenarios. The methodology is broadly illustrated in figure below.

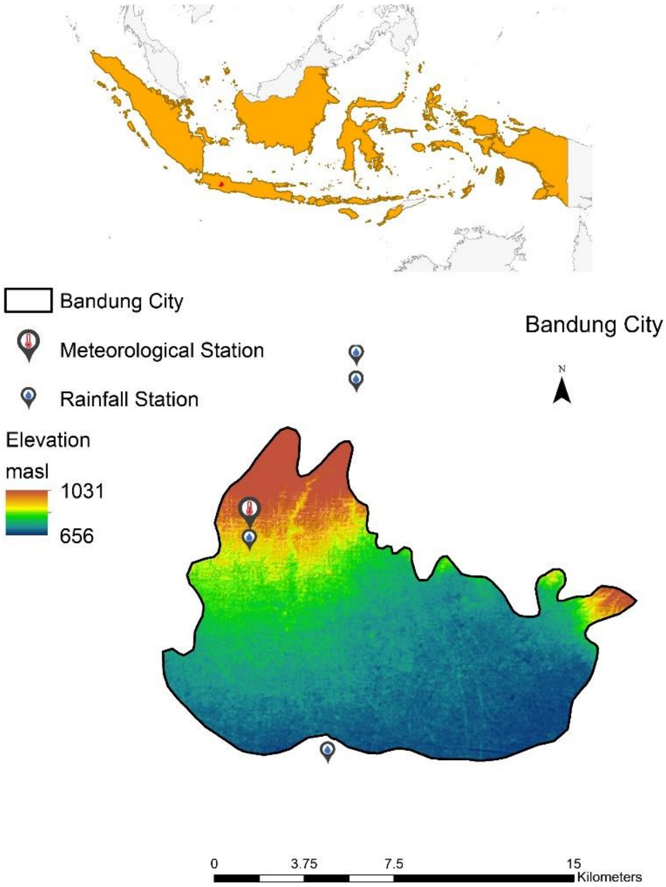


2.1. **Project Cities**

2.1.1. Bandung

Bandung is the capital of West Java province in Indonesia. It's the nation's third most populous city, with over 2.6 million populations (2015). The city lies on a river basin surrounded by volcanic mountains.

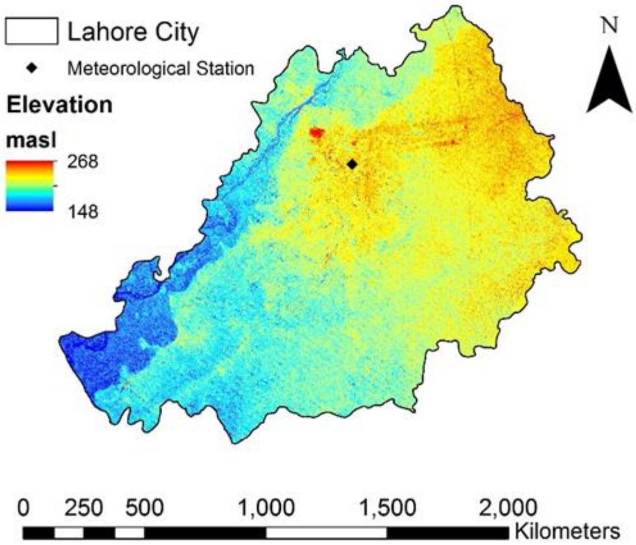
As a rapidly developing metropolitan region, the Bandung Basin is experiencing growing problems with groundwater, where there is an imbalance between discharge and recharge. The groundwater levels have dropped by more than 50 meters from its original level, forming a cone of depression in the water table and creating a critical zone, especially in industrial areas.



2.1.2. Lahore

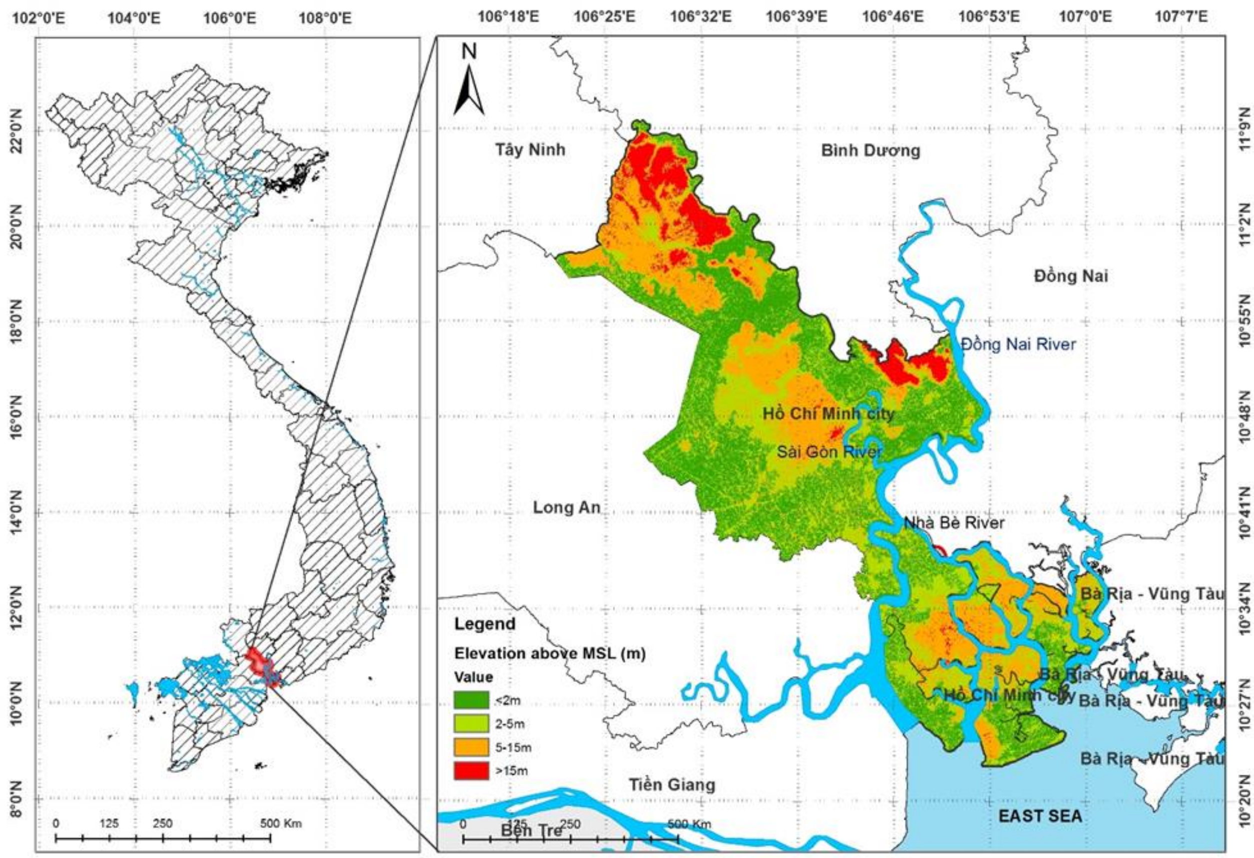
Lahore is the capital of Punjab province in Pakistan. It's the nation's second most populous city, with over 11 million populations (2017). The city lies on a river basin surrounded by agricultural lands and other relative less populous cities.

As a rapidly developing metropolitan region, the Lahore city is experiencing growing problems with groundwater, where there is an imbalance between discharge and recharge. The groundwater levels have dropped on an annual rate of 0.45 to 1.50 m by more than 45 meters from its original level, forming a cone of depression in the water table and expanding the critical zone.



2.1.3. Ho Chi Minh City

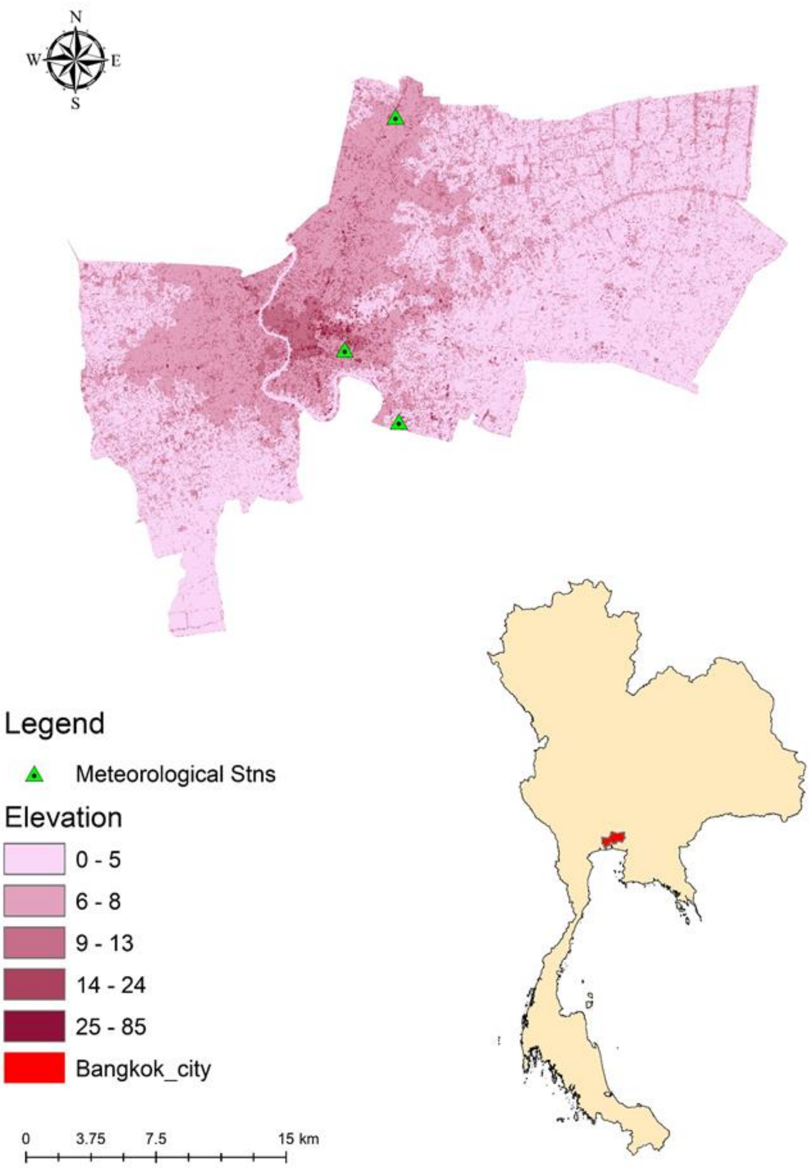
Ho Chi Minh City (HCM City) is the economic capital of Vietnam. It is situated in a transition zone from hilly areas of the middle of Vietnam to lowland of Mekong delta. HCM city is enclosed by Tay Ninh and Binh Duong provinces in the north, Dong Nai and Ba Ria - Vung Tau provinces in the east and Long An Province in the west. The south of HCM city is bounded by the East Sea with a stretch of 30 km coastline.



The city covers an area of 2095 km^2, extended in the NW–SE direction, with a maximum length of 100 km and a maximum width of 45 km. It is crisscrossed by the canals and tributaries of Dong Nai-Sai Gon river system with elevation decreasing from North to South. Most of the city area has a low elevation from 0 to 2 m above MSL as seen in Fig. 1. HCM City is currently the most important economic center of Vietnam. In 2012 its GDP was around 30 billion USD, making up 21.7% of the total national GDP (HCMC, 2012). The present population of the city is 7.7 million, which has increased quickly with the growing net emigration rate as well as the increasing urbanization, construction activities, and groundwater use. The number of wells in HCM City was 257216 and the total extraction rate reached 717246 m^3/d.

2.1.4. Bangkok

Bangkok is the capital of Thailand, and it is the most populated city in the country. City has been providing home for more than 13% of country population. City is the hub for most of the commercial and economical activities of the kingdom. At the same time, the City is very famous and appreciated by visitors for its versatility and multiple points of interests. The economy of the Thailand has been rising dramatically during recent 50 years; Bangkok has huge contribution on that. Bangkok is located in southern part of the Thailand with very low altitude i.e. 12m from msal. The total area occupied by the city is 1570 km^2.

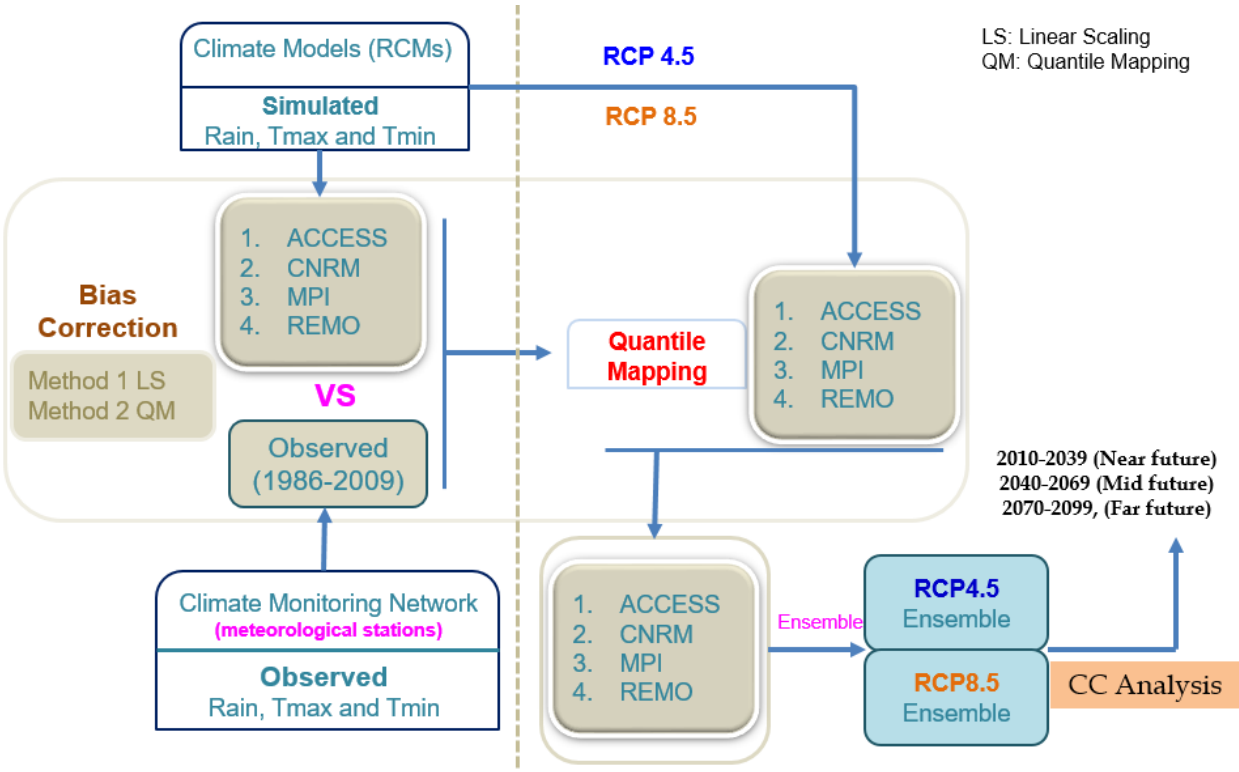


There are a couple of rivers which form a system of waterways in the city. They flow from the north to the Gulf of Thailand, and the Chao Phraya River is the main river that cuts through the city of Bangkok. City has tropical climate with distinct two season, first four (J, F, M, A) and last two (N, D) months are considered as dry season and middle six (M, J, J, A, S, O) are considered as wet season. As city is located in low altitude from Mean sea level, in future city might have waterlogged problems because of seawater intrusion. Decreasing rainfall and increasing temperature is the current climate scenario of the city. As we have several example that raising sea level and seawater intrusion are being biggest problem of the city, during future Bangkok might have the same. Excessive and illegal ground water withdrawal is the biggest problem of the city for Ground water recharge.

2.2. **Research/ Modelling component**

2.2.1. Climate Change Analysis

The groundwater vulnerability analysis component of the methodology consists of two parts – climate change analysis (CCA) for projecting the future climate of the cities, followed by groundwater recharge modelling based on the future climate projections. The methodology for climate change analysis is as shown in figure below.

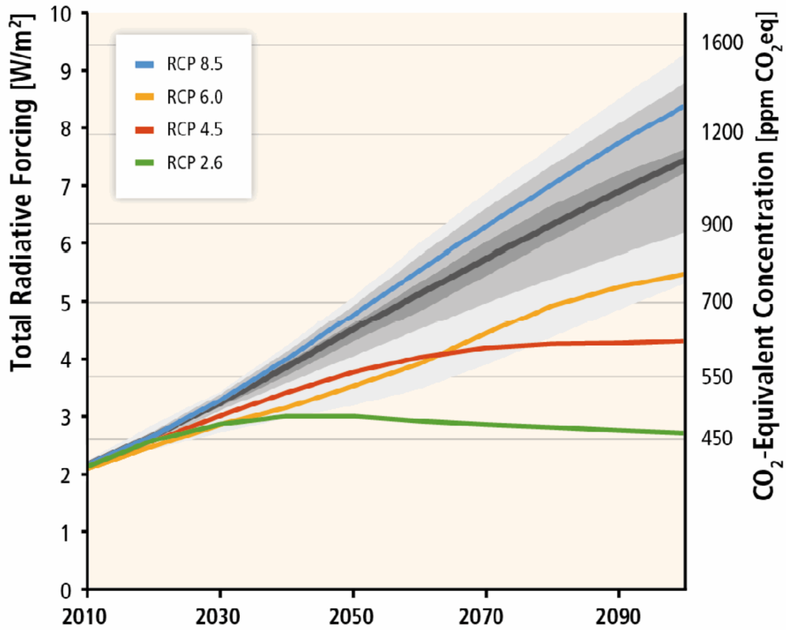


Selection of Climate Model output and Climate Change Scenarios

At first the regional climate models' (RCMs) output are selected based on experience/ literature. Since three out of four project cities were from South East Asia, we selected the climate model results which have been proven to be better suited for CCA studies in the region. McSweeney et al. (2015) had studied the suitability of downscaling General Climate Models (GCMs) over multiple regions of the world. Out of the 28 GCMs evaluated, they found ACCESS 1-0, CNRM-CM5 and MPI-ESM-LR to be among the "satisfactory" performing models. Based on this, we selected four RCMs output which were run under lateral boundary conditions under these three GCMs. The models selected and their brief information is tabulated in table below.

RCM	Parent GCM	Resolution (degree)	Hindcast	Forecast	Developer
CCAM	ACCESS1.0	0.5	1970-2005	2006-2099	Australian Bureau of Meteorology, Australia
CCAM	CNRM-CM5	0.5	1970-2005	2006-2099	National center for Meteorological Research, France
RCA4	MPI-ESM-LR	0.5	1970-2005	2006-2099	Max-Planck-Institute for Meteorology, Germany
REMO 2009	MPI-ESM-LR	0.5	1970-2005	2006-2099	Climate Service Center, Germany

In 2014, the International Panel for Climate Change (IPCC) released its Fifth Assessment Report (AR5). The report adopted four greenhouse gas concentration trajectories called Regional Concentration Pathways or simply RCPs (figure below). RCP8.5 represents *Rising radioactive forcing* pathway leading to 8.5W/m^2 (~1370 ppm CO_2 equivalent by 2100). RCP6.0 represents *stabilizing without overshoot* pathway to 6W/m^2 (~850 ppm CO_2 equivalent) at stabilization after 2100. RCP4.5 gives *stabilization without overshoot* pathway to 4.5W/m^2 (~650 ppm CO_2 equivalent) at stabilization after 2100. Whereas, RCP2.6 gives a *peak in radioactive forcing* at 3W/m^2 (~490 ppm CO_2 equivalent) before 2100 and then decline. We included two RCPs – RCP4.5 and RCP8.5 – one each for optimistic and pessimistic future scenarios.



Downscaling and Bias Correction

After the selection of the RCMs, the climatic variables from the models were downscaled to meteorological stations i.e. gridded data was converted to point data. The spatial criteria for downscaling followed was the *station embracing grid* approach wherein grid containing the station were used for data extraction and representation.

The downscaled, point time series of climate model output were then tallied with the observation data at the locations to check for bias. Then further bias correction techniques were utilized to minimize bias. The bias correction techniques applied are linear scaling (LS) and a comparatively complex distribution based method of quantile mapping (QM). A brief description of the two methods is as follows –

Linear Scaling (LS)

Linear scaling is the simplest bias correction technique applied in various studies (Ines and Hansen, 2006; Teutschbein and Seibert, 2012; Shrestha et al., 2015) and is used to adjust the RCMs mean value. The difference between the monthly mean observed and model data is applied to the model data to obtain bias corrected climate data. Data analysis relied on Linear Scaling bias correction (V.1.0) (Shrestha, 2015) was used for the application of this method. The following equations are used for the linear scaling technique:

$$P_{his}(d)^* = P_{his}(d).\,[\mu_m(P_{obs}(d)) / \mu_m(P_{his}(d))] \quad (1)$$

$$P_{sim}(d)^* = P_{sim}(d).[\mu_m(P_{obs}(d)) / \mu_m(P_{his}(d))] \quad (2)$$

$$T_{his}(d)^* = T_{his}(d) + [\mu_m(T_{obs}(d)) - \mu_m(T_{his}(d))] \quad (3)$$

$$T_{sim}(d)^* = T_{sim}(d) + [\mu_m(T_{obs}(d)) - \mu_m(T_{his}(d))] \quad (4)$$

Where, P = precipitation, T = temperature, d = daily, μ_m = long term monthly mean, * = bias corrected, his = Raw RCM data, obs = observed data, sim = Raw RCM future data

Quantile Mapping (QM)

The main objective of quantile mapping is to correct the quantiles of RCM data to match with the quantile of observed data by creating a transfer function to shift the quantile of precipitation and temperature. Distribution based QM (Gudmundsson et al., 2012; Teutschbein and Seibert, 2012) as well as Empirical QM (Gudmundsson et al., 2012) are used in correcting precipitation and temperature. In this study, Empirical QM is used with the 99-percentiles table generated and linear interpolation between them. The QM method was implemented in R language (Venables and Smith, 2012) using package "qmap" (Gudmundsson, 2014). The following equations are used for the quantile mapping technique:

$$P_{his}(d)^* = F^{-1}_{obs,m}[F_{his,m}(P_{his,m})] \quad (5)$$

$$P_{sim}(d)^* = F^{-1}_{obs,m}[F_{sim,m}(P_{sim,m})] \quad (6)$$

$$T_{his}(d)^* = F^{-1}_{obs,m}[F_{his,m}(T_{his,m})] \quad (7)$$

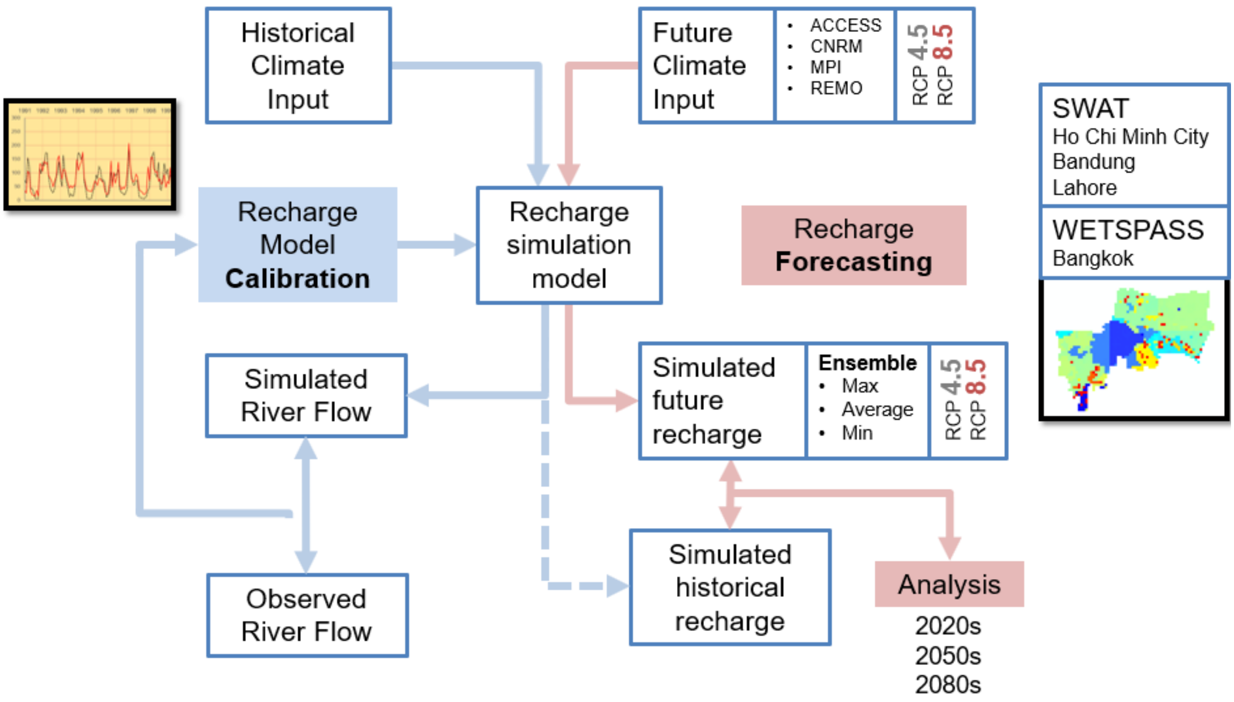
$$T_{sim}(d)^* = F^{-1}_{obs,m}[F_{sim,m}(T_{sim,m})] \quad (8)$$

Where, F = Cumulative Distribution Function (CDF), F^{-1} = inverse of CDF

It is elaborated in *Results & Discussion* section on how evaluation showed QM to outperform LS in all the four cities. The so prepared bias corrected climatic projections were then used for further analysis i.e. groundwater recharge modelling.

2.2.2. Groundwater Recharge Analysis

The methodology for groundwater recharge modelling is as shown in figure below.



Recharge Models

The recharge models used in this study are Soil and Water Assessment Tool (SWAT) and Water and Energy Transfer between Soil, Plants and Atmosphere under Steady State condition (WETSPASS). SWAT is a semi-distributed hydrological model which forms a hydrological domain to model. We applied SWAT for Lahore, Ho Chi Minh City and Bandung. In case of Bangkok it was difficult to cover the city within a hydrological catchment and thus WETSPASS was used instead. WETSPASS uses cell by cell water balance approach and thus doesn't require the model domain to be a hydrological catchment.

SWAT Model

SWAT is a physically based hydrological model widely used to evaluate the impact of land management practices and climate change impacts on water availability, sediment and nutrient yields of a watershed. SWAT is freely available and widely used across the world due to its comprehensive nature to simulate various processes and components of watershed. We used SWAT through Arc-SWAT extension in ArcGIS. Arc-SWAT is the most popular GUI for controlling SWAT incorporated into the ArcGIS interface.

The basic data required to set up a SWAT model are DEM, landuse, soil map and climate data such as rainfall, temperature (max and min), relative humidity, solar radiation and wind speed. However, climate data in many regions may not be always available or have low quality or missing values. In this case, SWAT model consists of built in stochastic weather generator model WXGEN to generate and fill missing data in the measured data. Therefore, SWAT model can also be used to simulate the hydrology in an ungauged or data scare area.

The model catchments were first divided into number of sub basins and then further divided into Hydrological Response Units (HRUs). SWAT forms HRUs based on the similar landuse, soil type and slopes (Shrestha et al., 2016) which are the areas in the watershed which respond similarly to given inputs such as rainfall and temperatures (Neitsch et al., 2011). Elevation data, landuse and soil data are used to drive discharges and direct sub-basin routing (Easton et al., 2010). All the hydrological processes are simulated in HRUs.

SWAT model consists of hydrological, sedimentation/erosion, weather, plant growth, nutrients, land management, channel routing and pond/reservoir routing components. The water cycle in the SWAT model is based on the water balance equation as shown below –

$$SW_t = SW_o + \sum (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (9)$$

Where, SW_t is the final soil water content, SW_0 is the initial soil water content, t is time in days, R_{day} is the amount of precipitation, Q_{surf} is the amount of surface runoff, E_a is the amount of evapotranspiration, W_{seep} is the amount of water entering the vadose zone from the soil profile, and Q_{gw} is the amount of return flow. All are expressed in mm

An exponential decay weighing function proposed by Venetis (1969) and used by Sangrey et al (1984) in a precipitation/groundwater response model is utilized in SWAT to account of the time delay in aquifer recharge once the water exits the soil profile. The delay function accommodates situations where the recharge from the soil zone to the aquifer is not instantaneous. The recharge to the aquifers on a given day is calculated as –

$$w_{rchrg,i} = \left(1 - exp\left[-\frac{1}{\delta_{gw}}\right].w_{seep} + exp\left[-\frac{1}{\delta_{gw}}\right].w_{rchrg,i-1}\right) \quad (10)$$

Where, w_{rchrg} (output variable name: GW_RCHG) is the amount of recharge entering the aquifers on day i (mm H_2O), δ_{gw} is the delay time or drainage time of the overlying geologic formations (days), w_{seep} is the total amount of water exiting the bottom of the soil profile on day i (mm H_2O), and $w_{rchrg,\, i-1}$ is the amount of recharge entering the aquifers on day i-1 (mm H_2O).

WETSPASS Model

WETSPASS (Water and Energy Transfer between Soil, Plants and Atmosphere under Steady State condition), a spatially distributed water balance model tested successfully to evaluate the impact land cover change to water flux at basin scale (Batelaan and Woldeamlak, 2003). It calculates water balance in each raster cell based on various land cover types and total water balance in the model domain is the sum of the same in each independent cell. The total water balance of a raster cell can be expressed mathematically as following equations:

$$ETraster = av.ETv + as.ETs + ao.ETo + ai.ETi \quad (11)$$
$$Sraster = av.Sv + as.Ss + ao.So + ai.Si \quad (12)$$
$$Rraster = av.Rv + as.Rs + ao.Ro + ai.Ri \quad (13)$$

Where ETraster, Sraster, Rraster are the total evapotranspiration, surface runoff, and groundwater recharge of a raster cell respectively. av, as, ao, and ai are the vegetated, bare-soil, open-water and impervious area fractions of a raster cell, respectively.

Calibration of Recharge Model

SWAT consists of numerous parameters that govern the response of the model. These parameters are process based and must be within a realistic uncertainty range (Arnold et al., 2012). Sensitivity analysis was performed to determine the most sensitive parameters for a given watershed. Sensitivity analysis of the catchments was performed using SWAT CUP tool. The sensitive parameters were then used to calibrate the model against the observed discharge data. Then auto-calibration was performed using SWAT-CUP followed by fine tuning via manual calibration. Model validation was conducted to ensure that the model is capable of simulating accurately using new sets of input data. Based on this *hydrological calibration* of the model, it was concurred that the spatially varied recharge output is also validated.

In case of WETSPASS, the initial groundwater levels were interpolated at each cell from the groundwater measurement stations for the initialization of the model.

Future Recharge Projection and Baseline comparisons

After the calibration of the model, future bias corrected climate is input to get future groundwater recharge projections. Altogether there were eight probabilities of future groundwater recharge coming from four RCMs and two RCP scenarios. An ensemble (average) between the RCMs was considered to be the representative projection for each RCP 4.5 and 8.5.

2.3. **Projection based Adaptation Options**

First, potential adaptation strategies, both structured and non-structured, for groundwater sector were identified from literature review. It resulted in the options as indicated in figure below. Their meaning, suitability, and limitations were presented to the participants of 2nd Regional Workshop held in AIT during September 8-9, 2017. Discussion session helped to deepen the understanding of the participants about different types of adaptation options.

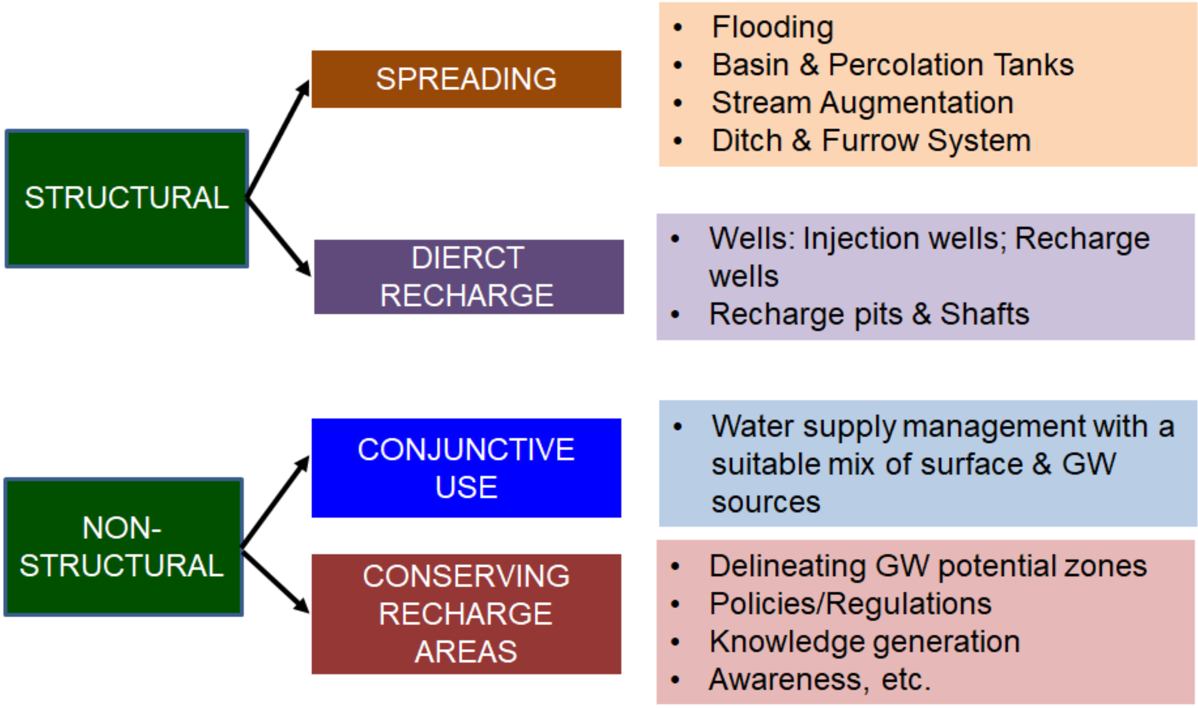


Figure: Potential adaptation options identified from literature review.

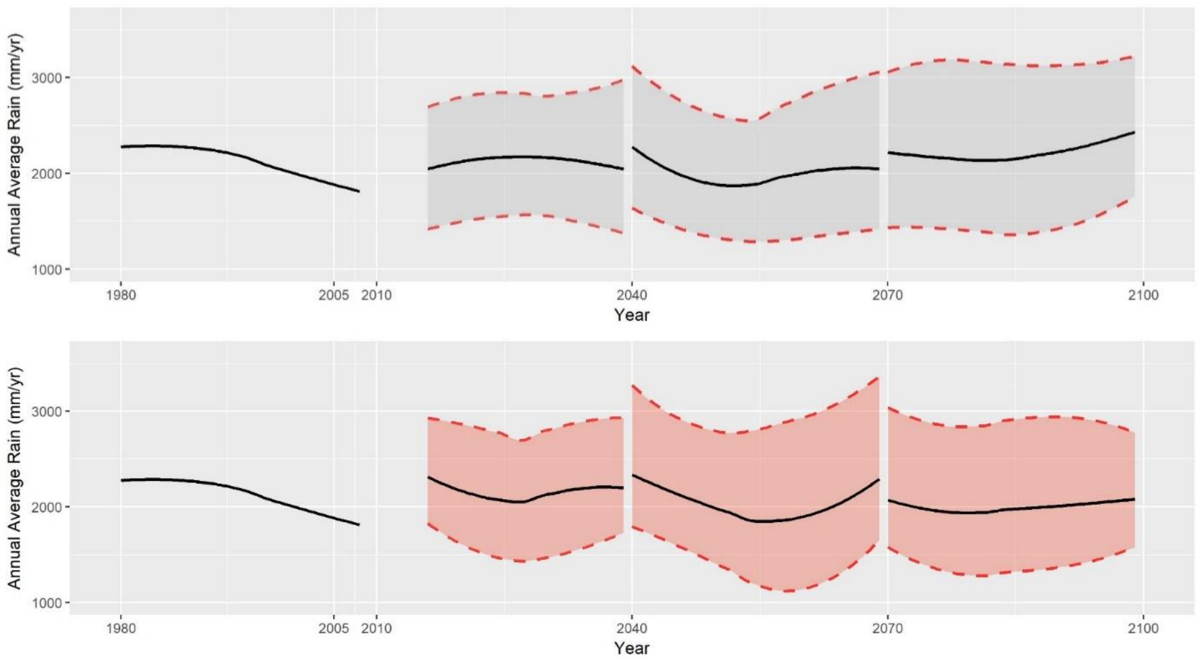
Group discussion session then discussed various characteristics of the cities, including projected changes in climatic variables and subsequent impacts on groundwater recharge obtained from model-based study. Then, based on typical characteristics of the participating cities, together with collaborator of the cities, suitable adaptation options for the participating cities were identified and prioritized. They are presented in the following sub-sections.

3. Results & Discussion

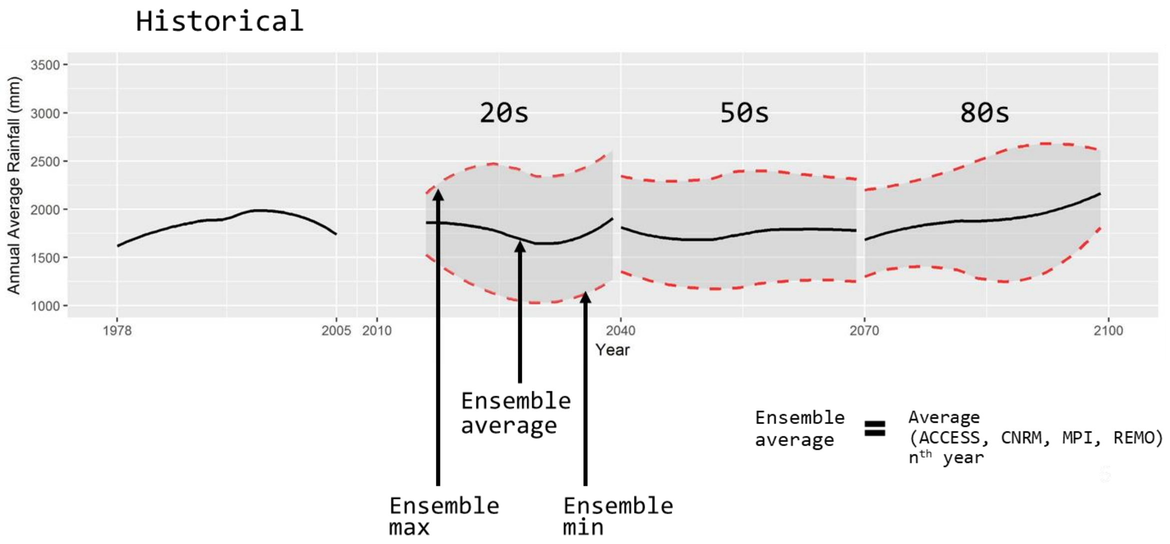
3.1. Bandung, Indonesia

3.1.1. Climate Change Projections

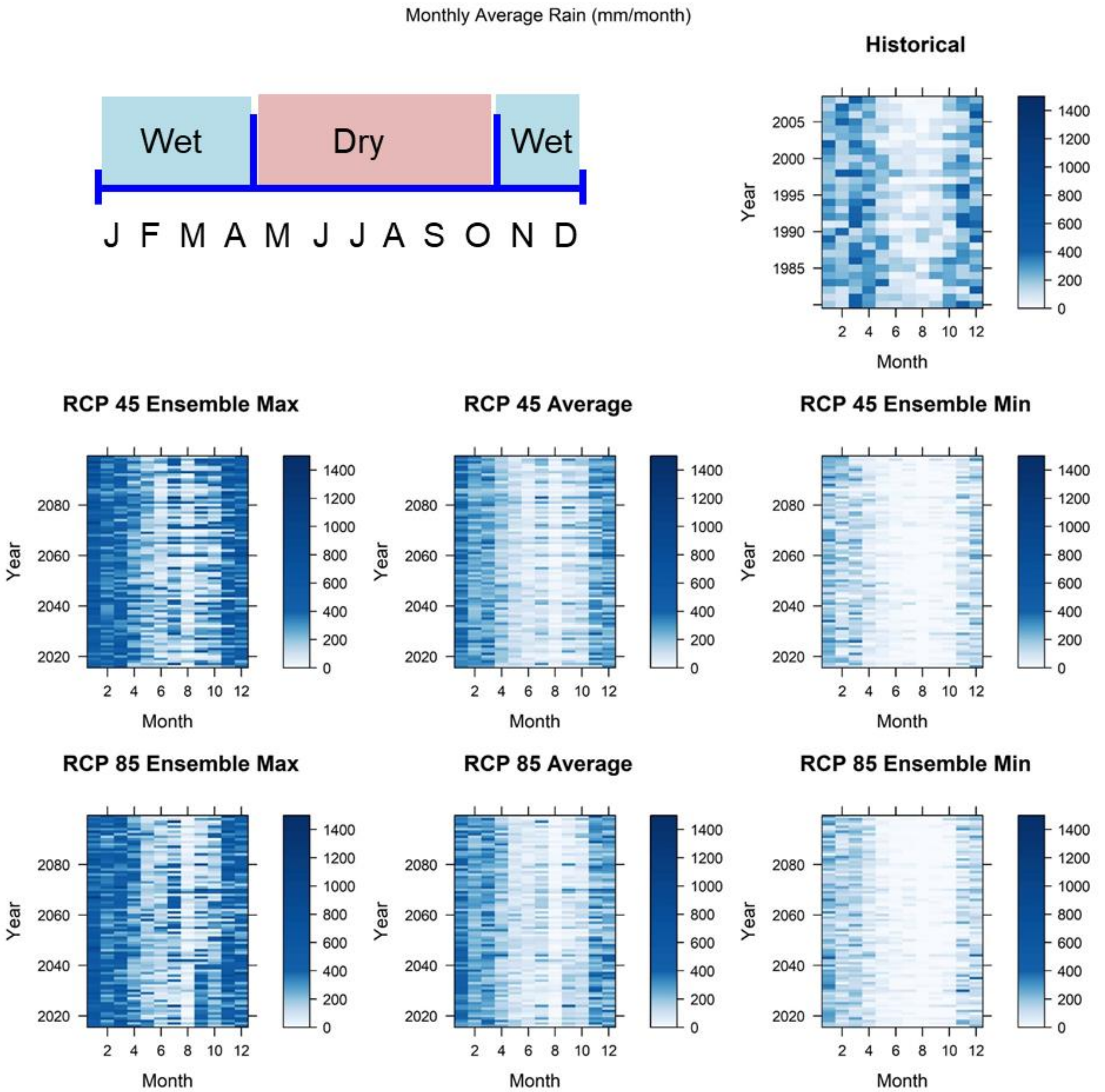
Annual Trend of Rainfall



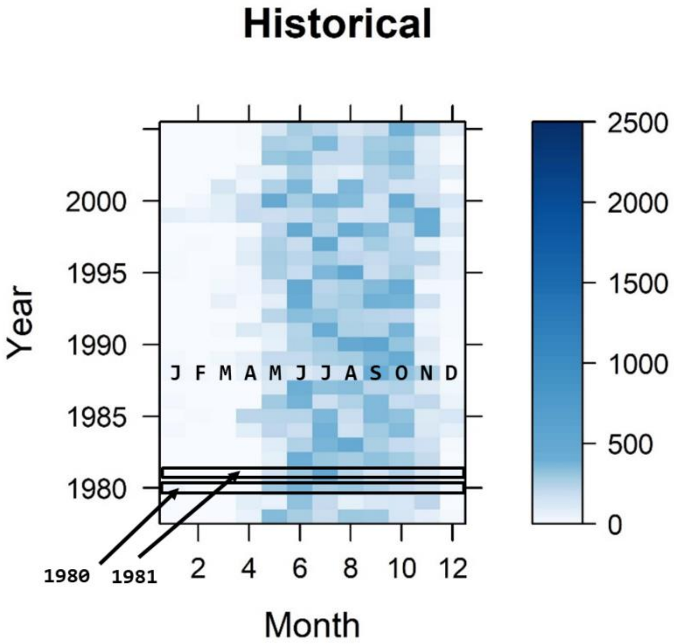
In Bandung, the past trend shows decrease in rainfall in recent years. Compared to that, RCP4.5 ensemble (average) projects an overall slight decrease with an increase in 80s. While with RCP8.5 there is overall decrease with average plunging below 2000 mm per year. The components of the trend graph are indicated in figure below for clarity –



Seasonality of Rainfall



Bandung has a tropical monsoon climate. The above level plots show that in the past the maximum rainfall occurred in the months of March and December. In both RCP4.5 and 8.5, however, the wettest month shifts to January. Some dry months (July, September) are seen to become wetter and some wet months (April, October) turn drier than observed in the past. The following figure describes the meaning of the level plot and its interpretation –

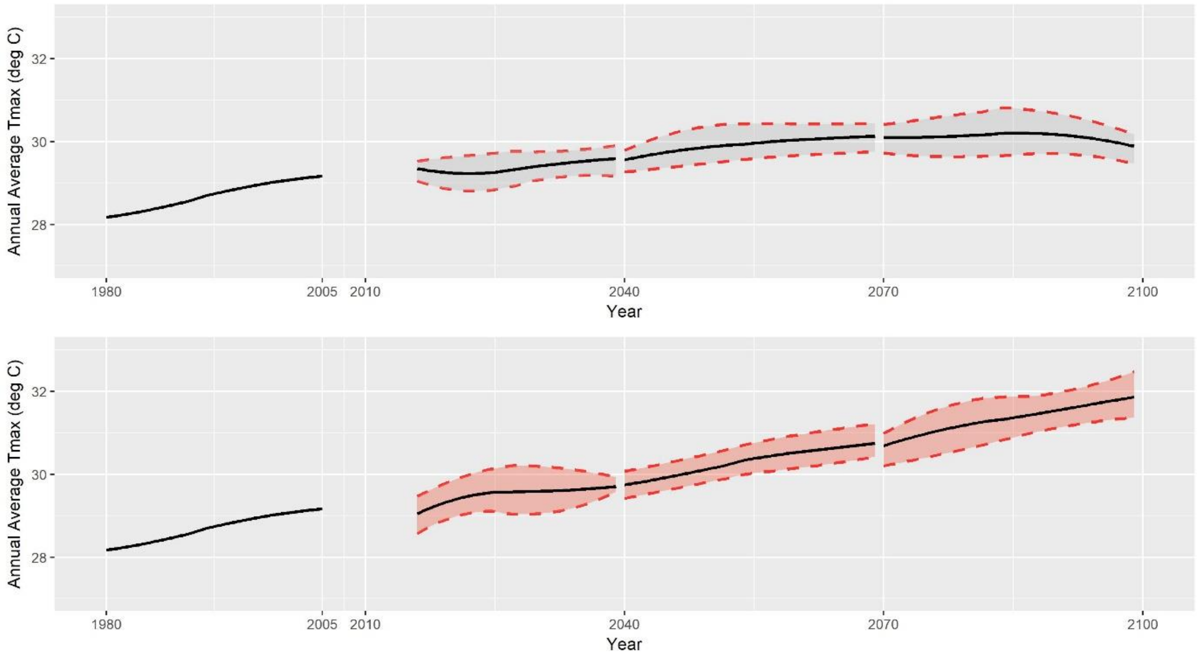


Rainfall Summary

In summary, Bandung future climate projections tell us that the rainfall is going to decrease in the dry season and increase slightly in the wet season. The overall decrease however is negligible for RCP 4.5 and -3.5% for RCP 8.5.

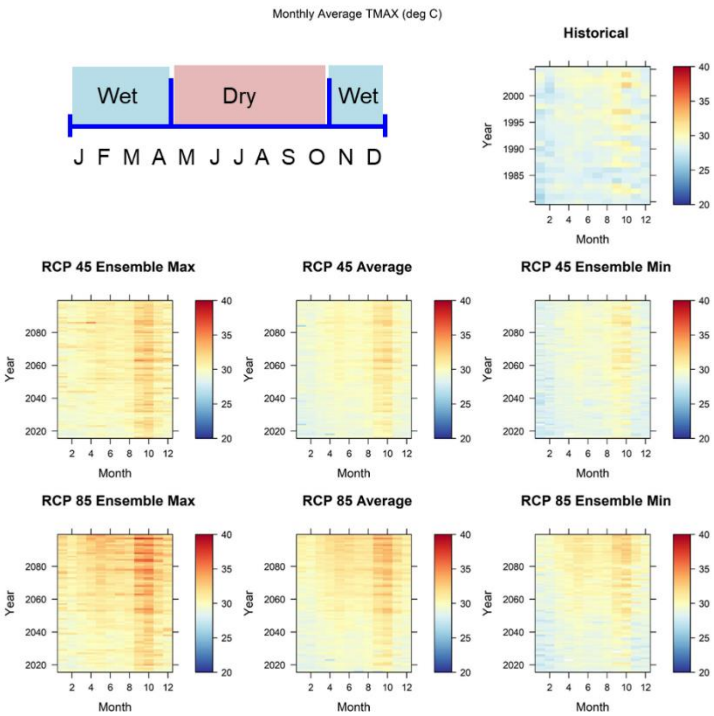
Bandung, Indonesia		ANNUAL					**DRY**					**WET**				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Rainfall (mm/yr.)	2142					629					1513				
RCP 4.5	Average Rainfall (mm/yr.)		2120	2124	2011	2226		526	516	472	587		1586	1608	1529	1626
	Change (mm)		-22 **-1%**	-18 **-0.8%**	-131 **-6.1%**	84 **+3.9%**		-103 **-16.4%**	-113 **-18%**	-157 **-25%**	-42 **-6.7%**		+73 **+4.8%**	+95 **+6.3%**	+16 **+1.1%**	+113 **+7.5%**
RCP 8.5	Average Rainfall (mm/yr.)		2067	2172	2051	1999		475	531	504	400		1585	1640	1533	1592
	Change (mm)		-75 **-3.5%**	30 **+1.4%**	-91 **-4.2%**	-143 **-6.7%**		-154 **-24.5%**	-98 **-15.4%**	-125 **-19.9%**	-229 **-36.4%**		+72 **+4.8%**	+127 **+8.4%**	+20 **+1.3%**	+79 **+5.2%**

Annual Trend of Maximum Temperature



The Past trend of maximum temperature in Bandung gives us an increasing trend in the recent years. According to RCP4.5, there will be an overall increase by 1^0 at the end of the century, with plateau in the 80s [comparison to 2005 value]. Whereas, for RCP8.5 the overall increase will be almost 3^0 at the end of the century, with constantly increasing trends over 20s, 50s and 80s [comparison to 2005 value].

Seasonality of Maximum Temperature



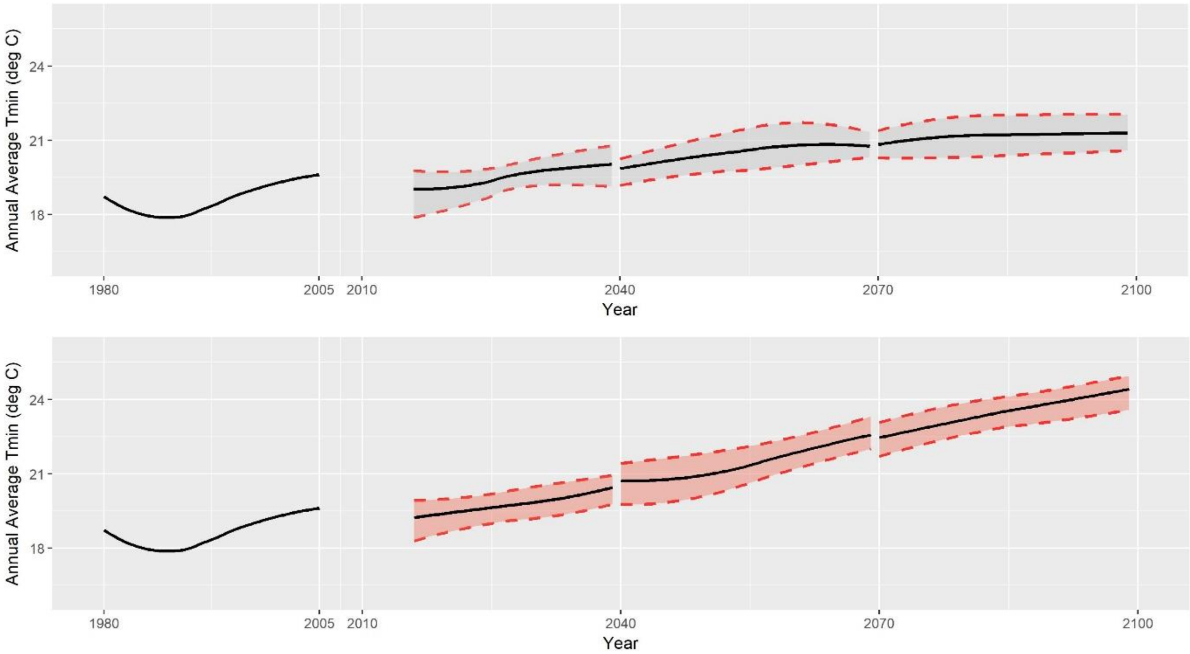
In Bandung, the maximum temperature (Tmax) used to exceeded 30^{0}C intermittently in the months of September and October i.e. ending months of dry season. But in RCP4.5, Tmax (ensemble average) is seen to regularly cross 30^{0}C in Sep and Oct. On the second half of the century, the trend is seen in starting months of dry season as well, mainly in May. RCP8.5 shows similar contrasts with year round increase in temperature. This can be especially significant on the second half of the century where the hottest months will observe Tmax nearing to 40^{0}C and the values will stay above 30^{0}C year round.

Summary of Maximum Temperature

In short, the maximum temperature for Bandung will increase in future under both the RCP scenarios. The increase in the 21st century (ensemble average) is projected to be 1.1^{0}C for RCP 4.5 and 1.7^{0}C for RCP 8.5. The inter seasonal comparison of the changes were showed almost comparable increase between the wet and dry months.

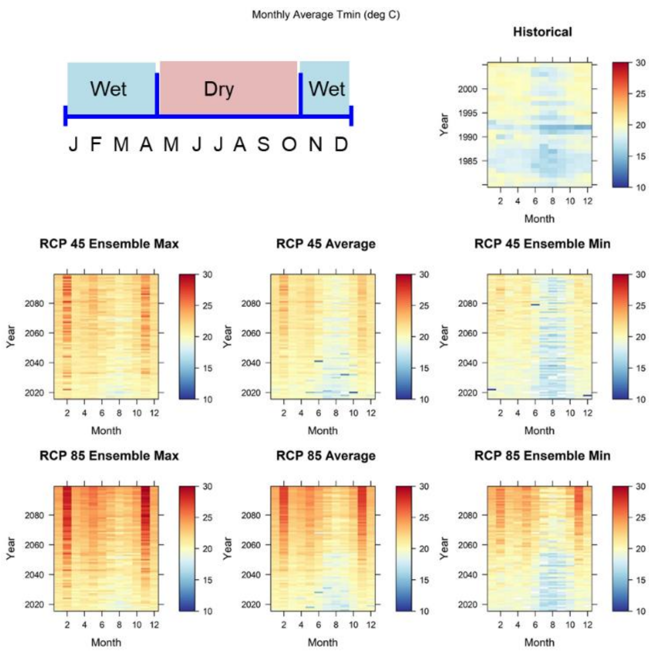
Bandung, Indonesia		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmax (ºC)	28.7					29					28				
RCP 4.5	Average Tmax (ºC)		29.8	29.4	29.9	30.1		30.2	29.8	30.3	30.5		29.4	28.9	29.5	29.7
	Change (ºC)		+1.1	+0.7	+1.2	+1.4		+1.2	+0.8	+1.3	+1.5		+1.4	+0.9	+1.5	+1.7
RCP 8.5	Average Tmax (ºC)		30.4	29.5	30.3	31.3		30.8	29.9	30.7	31.9		29.9	29.1	29.8	30.8
	Change (ºC)		+1.7	+0.8	+1.6	+2.6		+1.8	+0.9	+1.7	+2.9		+1.9	+1.1	+1.8	+2.8

Annual Trend of Minimum Temperature



The minimum temperature (Tmin) in the past shows an increasing trend in recent years. In future, RCP4.5 based projection shows an overall increase by >1^0 at the end of the century, with smaller trend by the time we reach the 80s [comparison to 2005 value]. Whereas by RCP8.5, the overall increase would spike up to around 3.5^0 at the end of the century, with constantly increasing trends over 20s, 50s and 80s [comparison to 2005 value].

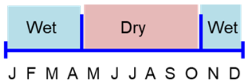
Seasonality of Minimum Temperature



The monthly seasonality of Tmin in Bandung in the past showed the values seldom crossing over 20^{0}C till the mid-1990s. Since then the wet months usually are seen to have Tmin around 20^{0}C. In contrast, RCP4.5 ensemble average projection shows Tmin regularly crossing the 20^{0}C threshold throughout the year, apart from July - Sep. This is especially true in the 50s and 80s. RCP8.5 illustrates similar effect with a much larger amplification. In this scenario, Tmin increases drastically in most of the 50s and 80s with year round average monthly Tmin of > 20^{0}C with values shooting 30^{0}C+ in months of Feb and Nov.

Summary of Minimum Temperature

In summary, the minimum temperatures in Bandung over the 21st century is projected to increase, even more than the maximum temperatures. By the end of the century, its projected that Tmin increases by 1.9^{0}C and 3.1^{0}C under RCP 4.5 and 8.5 respectively. However, seasonal values reveals wet months to be affected more in terms of increase in Tmin.



Bandung, Indonesia		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmin (ºC)	18.6					18.1					19.1				
RCP 4.5	Average Tmin (ºC)		20.5	19.5	20.5	21.2		19.8	18.8	19.9	20.6		21	20.2	21.1	21.8
	Change (ºC)		+1.9	+0.9	+1.9	+2.6		+1.7	+0.7	+1.8	+2.5		+1.9	+1.1	+2	+2.7
RCP 8.5	Average Tmin (ºC)		21.7	19.8	21.4	23.5		20.9	19.2	20.8	22.7		22.2	20.4	22	24.3
	Change (ºC)		+3.1	+1.2	+2.8	+4.9		+2.8	+1.1	+2.7	+4.6		+3.1	+1.3	+2.9	+5.2

3.1.2. Groundwater Recharge Projections

Model Performance

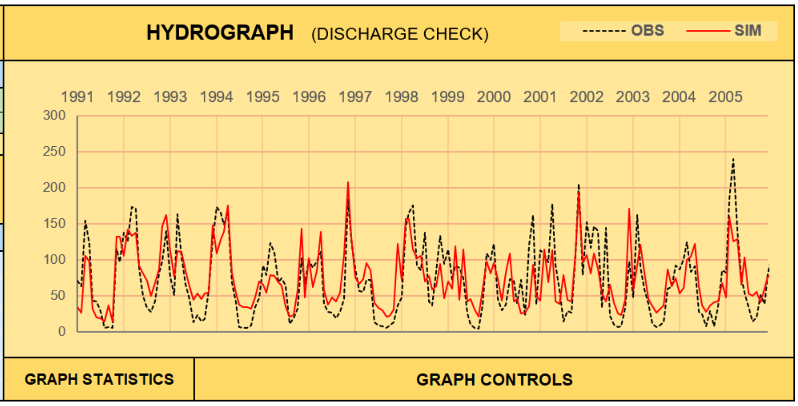
With climate input at 8 rainfall stations and 1 temperature station, calibration of the SWAT model for Bandung was carried out for the years 1991 to 1999. The comparison of discharge at outlet station at Nanjung showed a match of 0.66 Nash Sutcliffe Efficiency (NSE) and a volume bias of +7.0%. Validation of the model (2000 – 2008) showed NSE of 0.57 and volume bias of -4.3%. The hydrograph match between the observed discharge at Nanjung and the SWAT simulated discharge is shows in the following figure.

INPUT

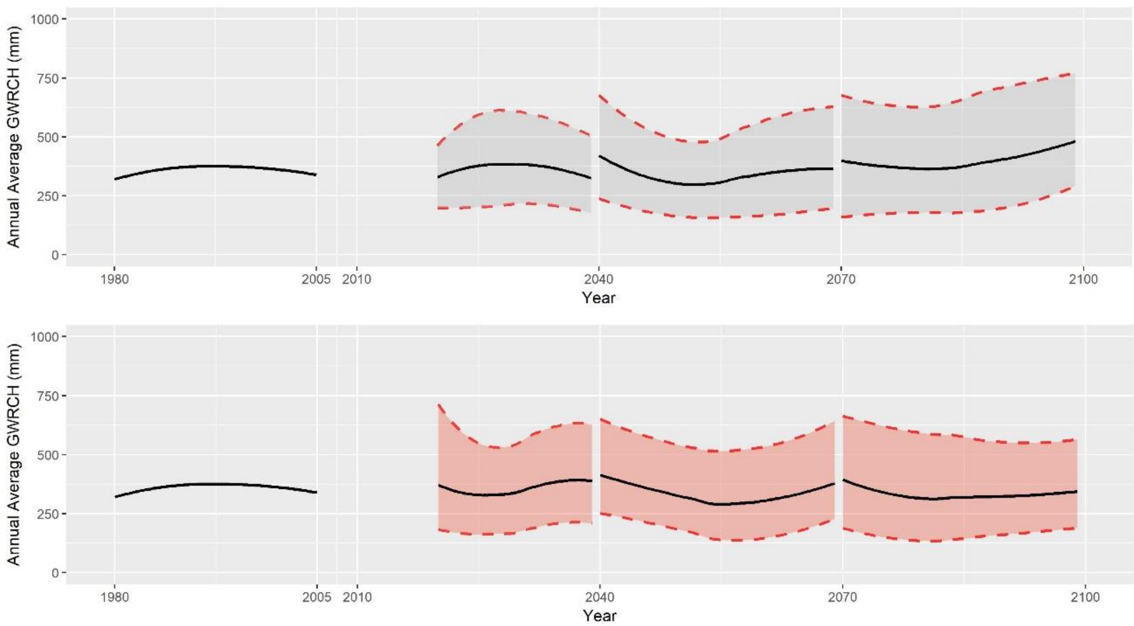
Calibration		Validation	
Start Date	Jan-91	Start Date	Jan-00
End Date	Dec-99	End Date	Dec-08

OUTPUT
(entire model period statistics)

Calibration		Validation	
NSE	0.66	NSE	0.57
NSE_{rel}	-2.92	NSE_{rel}	-0.85
R^2	0.67	R^2	0.58
wR^2	0.67	wR^2	0.51
RSR	0.58	RSR	0.66
PBIAS	+7.0%	PBIAS	-4.3%



Annual Trend of Groundwater Recharge

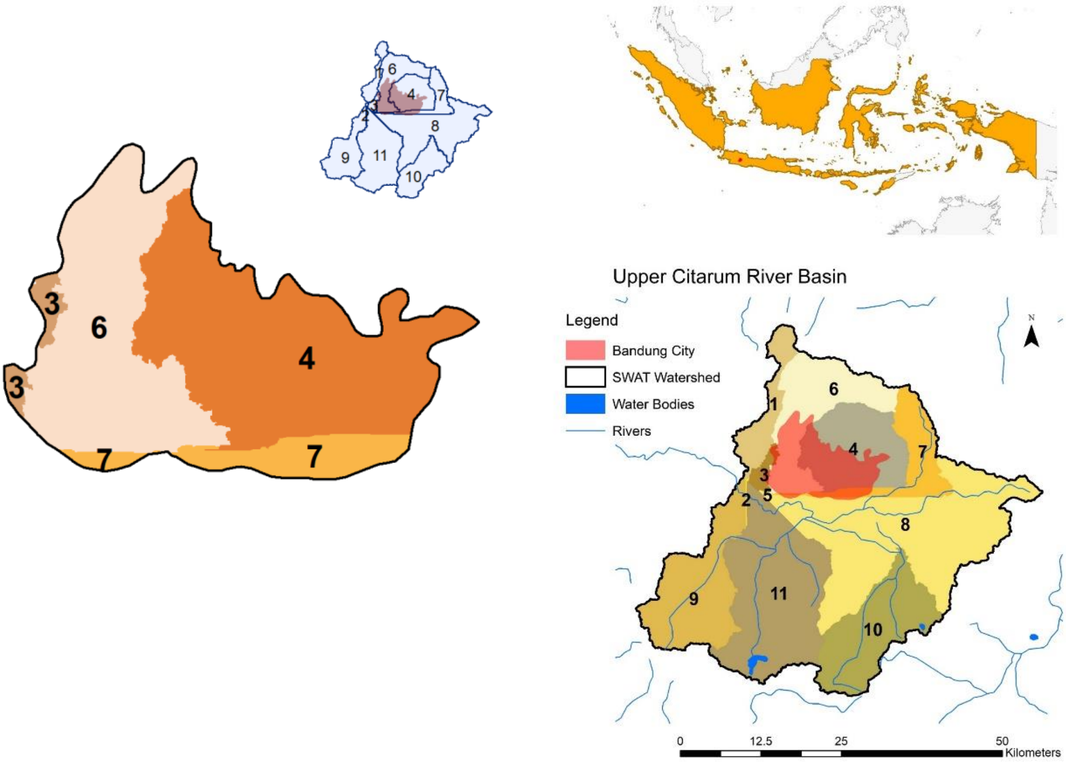


In the recent years, Bandung's groundwater recharge (GWR) is seen to have a decreasing trend in recent years. RCP 4.5 also shows the same trend as there will be overall decrease in

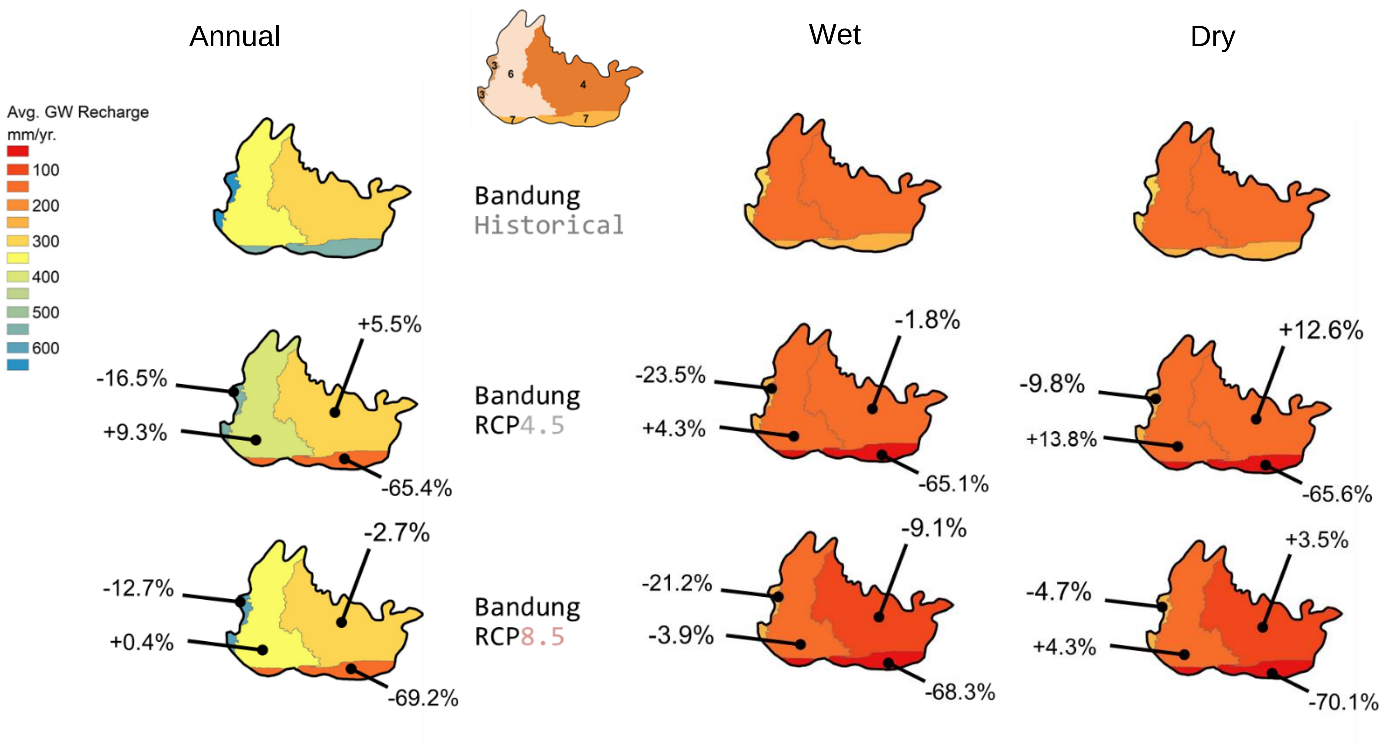
GWR with better recharge observed in the 80s. In case of RCP 8.5 the dip is even larger compared to RCP 4.5.

Spatial Variation and Seasonality of Groundwater Recharge

The SWAT model domain of Bandung alongside the zonation of the city for spatial variation analyses is as depicted in the figure below. The zonation is based on the hydrological sub-division of the watershed into sub-basins. There were 11 sub basins delineated in the SWAT model for Bandung, out of which the city encompasses sub-basins 3, 4, 6 and 7.

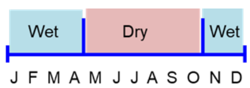


Looking at the GWR results, Zone 6 to be the safest area in terms of climate change impact (CCI) on GWR. There is big reversal of GWR in Zone 7 making it the hardest hit area with large GWR decline due to CC. In spite of large percentage decline, Zone 3 is still the most well recharged area in the city.



Summary of Groundwater Recharge

In summary, the GWR in Bandung is projected to decrease by -2.9% and -10.0% based on RCP 4.5 and 8.5 respectively. The larger proportion of the decrease is seen in the dry season with -8.2% and -14.7% decrease in the dry season in comparison to +2% and -5.6% fluctuations in wet season for RCP 4.5 and 8.5 respectively.



Bandung, Indonesia		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average GWR (mm/yr.)	380					184					196				
RCP 4.5	Average GWR (mm/yr.)		369	364	343	400		169	166	157	183		200	198	186	217
	Change (mm)		-11 **-2.9%**	-16 **-4.2%**	-37 **-9.7%**	20 **+5.3%**		-15 **-8.2%**	-18 **-9.8%**	-27 **-14.7%**	-1 **-0.5%**		+4 **+2%**	+2 **+1%**	-10 **-5.1%**	+21 **+10.7%**
RCP 8.5	Average GWR (mm/yr.)		342	360	339	331		157	160	158	154		185	200	182	178
	Change (mm)		-38 **-10%**	-20 **-5.3%**	-41 **-10.8%**	-49 **-12.9%**		-27 **-14.7%**	-24 **-13%**	-26 **-14.1%**	-30 **-16.3%**		-11 **-5.6%**	+4 **+2%**	-14 **-7.1%**	-18 **-9.2%**

3.1.3. Adaptation Options

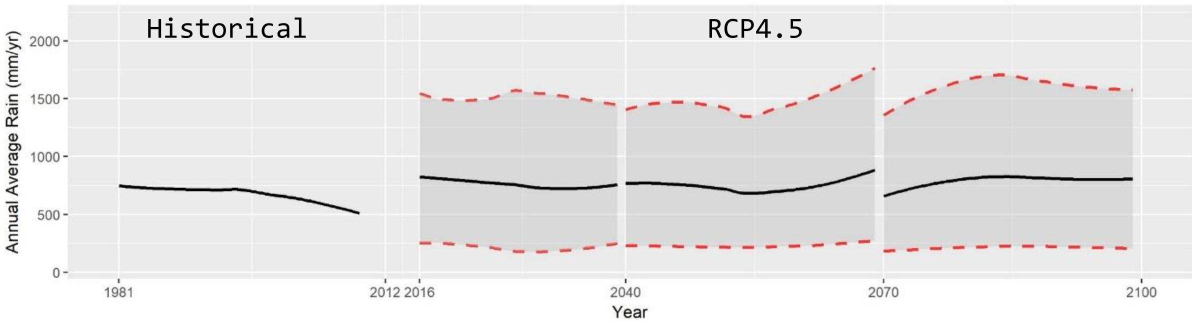
Groundwater recharge (annual as well as seasonal values) in Bandung is projected in decrease in general. Following adaptation options are expected to be useful to deal with climate change impacts on groundwater resources.

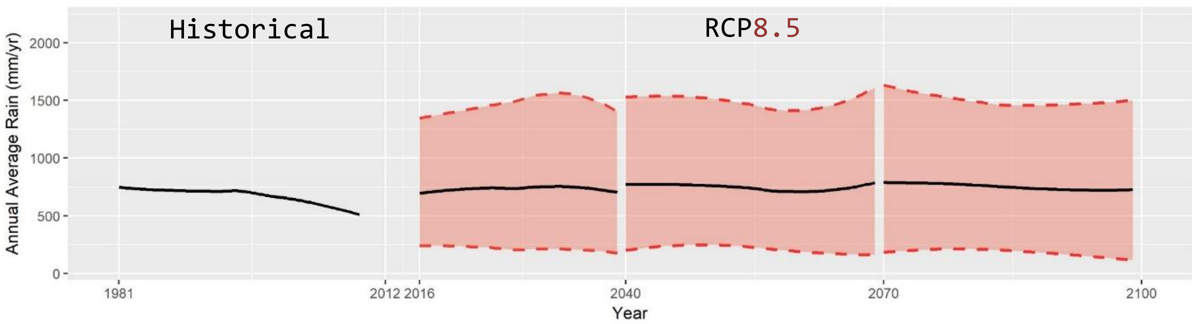
- Estimating safe yields as well as groundwater potential/critical zones and adopt them in groundwater planning and regulations
- Conjunctive use of surface and groundwater sources
- Stream augmentation by means of constructing check dams
- Integrating recharge agenda with flood control agenda and vice-versa
- Strengthening groundwater monitoring networks
- Arranging regulatory provisions for groundwater abstractions
- Mainstreaming groundwater issues in resilient cities or other similar city-wide adaptation initiatives

3.2. **Lahore, Pakistan**

3.2.1. Climate Change Projections

Annual Trend of Rainfall

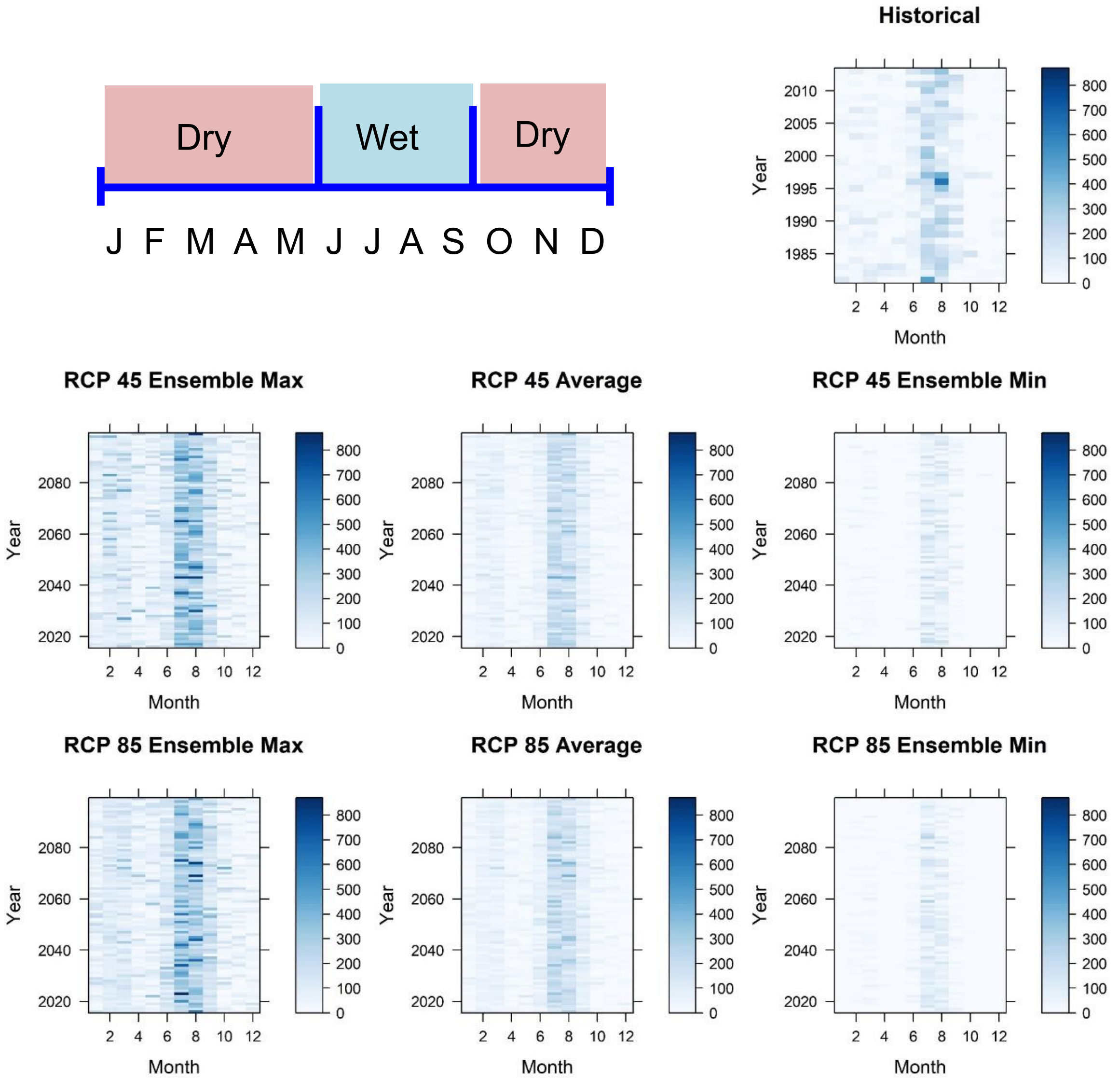




In Lahore, the past trend shows decrease in rainfall in recent years. Compared to the year 2005, RCP4.5 ensemble (average) projects an overall slight increase with a variation in 50s and 80s. While under RCP8.5 there is overall increase throughout the 21st century with slight decrease in 80s.

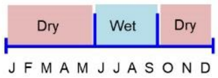
Lahore has a subtropical monsoon climate. The below level plots show that in the past the maximum rainfall occurred in the months of July, August and September. For both RCP4.5 and RCP8.5, however, the wettest months remain wet. Some dry months (January to March) are seen to become wet than observed in the past.

Monthly Average Rain (mm/month)



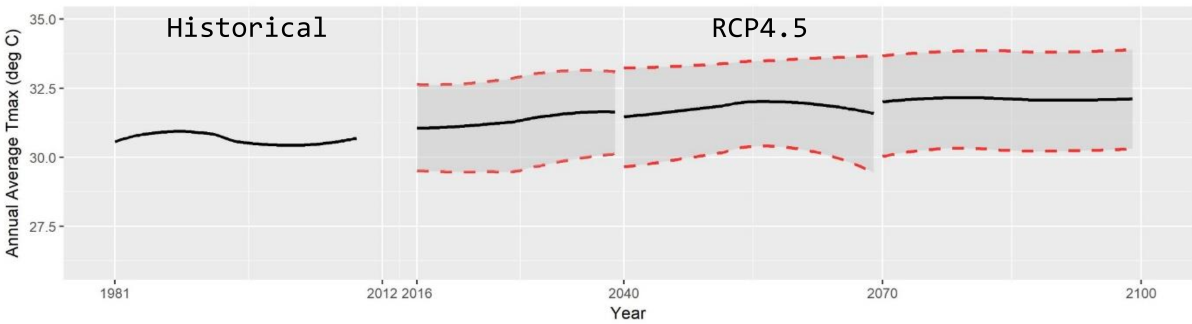
Rainfall Summary

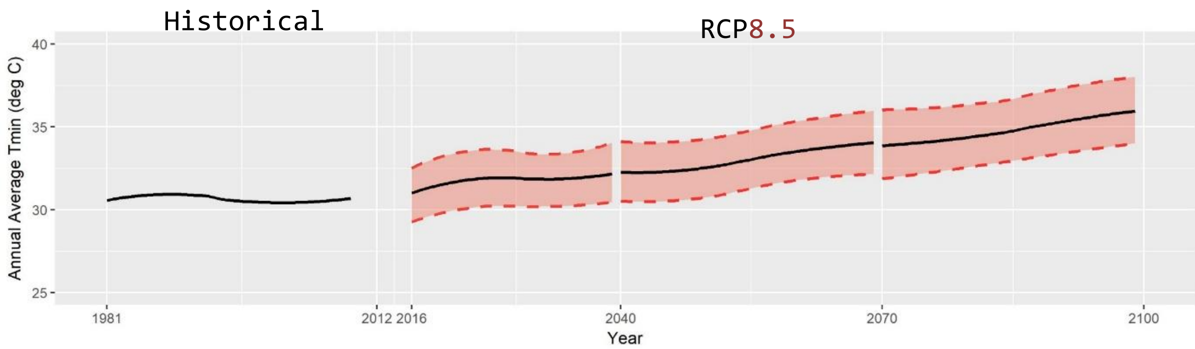
In summary, Lahore future climate projections tell us that the rainfall is going to increase with large increase in the dry season and slightly in the wet season. Average rainfall will likely to increase by 11 to 14.5% in 21st century for RCP 4.5 and RCP 8.5 respectively.



Lahore, Pakistan		ANNUAL Past (1980 – 2005)	ANNUAL 21st century	ANNUAL 30s (2010 – 2039)	ANNUAL 50s (2040 – 2069)	ANNUAL 80s (2070 – 2099)	DRY Past (1980 – 2005)	DRY 21st century	DRY 30s (2010 – 2039)	DRY 50s (2040 – 2069)	DRY 80s (2070 – 2099)	WET Past (1980 – 2005)	WET 21st century	WET 30s (2010 – 2039)	WET 50s (2040 – 2069)	WET 80s (2070 – 2099)
Base-line	Average Rainfall (mm/yr.)	671					166					505				
RCP 4.5	Average Rainfall (mm/yr.)		768	760	759	783		251	235	241	273		518	525	519	510
	Change (mm)		97 +14.5%	89 +13.3%	88 +13.1%	112 +16.7%		85 +51.2%	69 +41.6%	75 +45.2%	107 +64.5%		13 +2.6%	20 +4%	14 +2.8%	5 +1%
RCP 8.5	Average Rainfall (mm/yr.)		743	738	743	749		238	222	237	254		505	516	506	495
	Change (mm)		72 +10.7%	67 +10%	72 +10.7%	78 +11.6%		72 +43.4%	56 +33.7%	71 +42.8%	88 +53%		0 +0%	11 +2.2%	1 +0.2%	-10 -2%

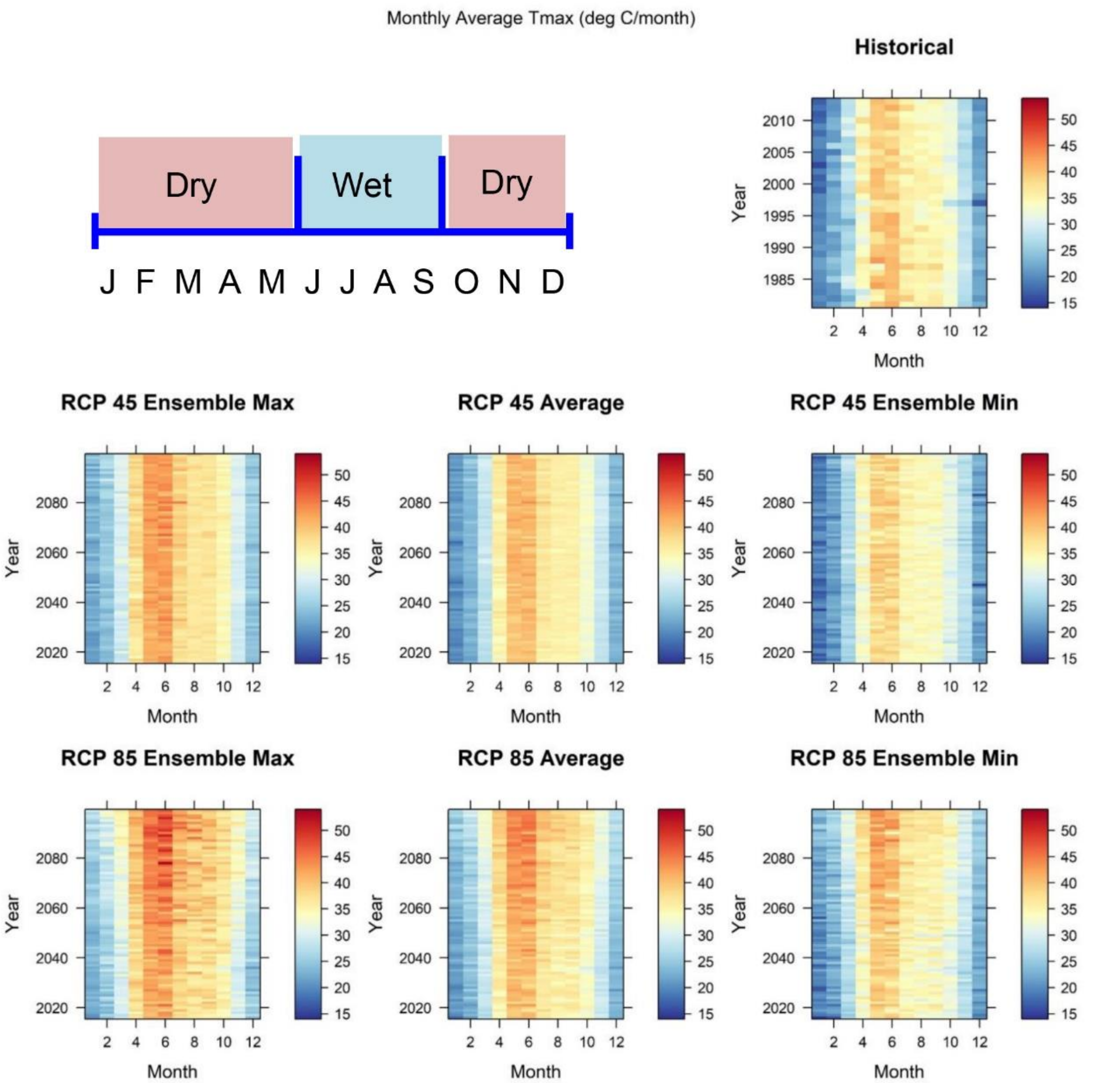
Annual Trend of Maximum Temperature





The Past trend of maximum temperature in Lahore shows mixed patterns of decreasing and increasing trend which set to increase in the recent years. There will be an overall increase in maximum temperature by 1.5^0 and 4.5^0 at the end of the century for RCP4.5 and RCP8.5 respectively. Maximum temperature shows likely variations in 50s for RCP4.5. However, for RCP8.5 it shows consistent increase till end of the 21st century.

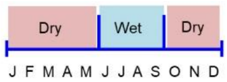
Seasonality of Maximum Temperature



In Lahore, the maximum temperature (Tmax) used to exceeded 35^{0}C intermittently in the months of May and June and 30^{0}C in the starting and ending months of dry seasons. Maximum temperature crosses 30^{0}C regularly in the months from May to September. However for RCP4.5, Tmax (ensemble average) is seen to regularly cross 35^{0}C in Sep and Oct and 30^{0}C in all months from April to October. For RCP8.5 it shows increase in the months from March to November. Especially in the final half of the century where the hottest months will observe Tmax crossing 45^{0}C, whereas it will stay above 30^{0}C in remaining months.

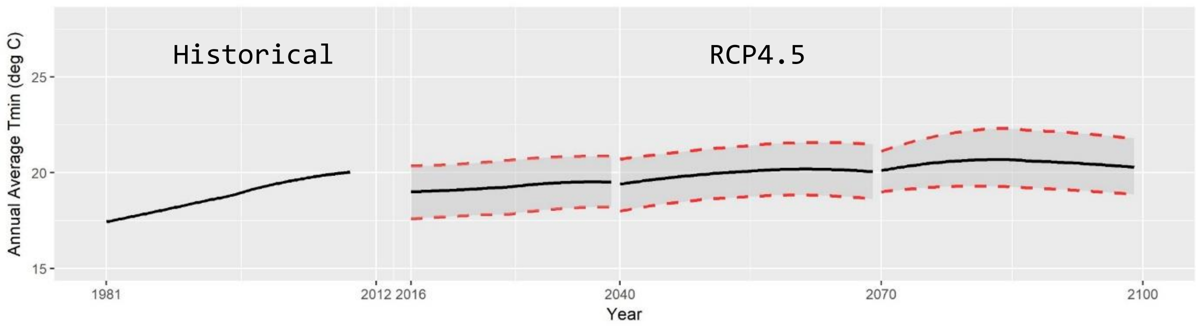
Summary of Maximum Temperature

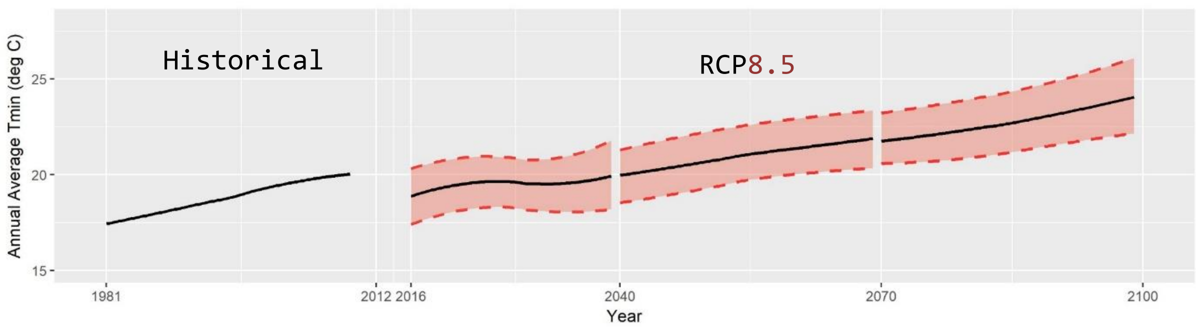
In short, the maximum temperature for Lahore will increase in future under both the RCP scenarios. The increase in the 21st century (ensemble average) is projected to be 1.2^{0}C for RCP 4.5 and 2.6^{0}C for RCP 8.5. The inter seasonal comparison of the changes in maximum temperature shows comparably higher increase in Tmax in dry season compared with wet season.



Lahore, Pakistan		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	30s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	30s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	30s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmax (ºC)	30.6					27.9					36.2				
RCP 4.5	Average Tmax (ºC)		31.8	31.4	31.8	32.1		29.1	28.7	29.2	29.6		37	36.7	37	37.2
	Change (ºC)		+1.2	+0.8	+1.2	+1.5		+1.2	+0.8	+1.3	+1.7		+0.8	+0.5	+0.8	+1
RCP 8.5	Average Tmax (ºC)		33.2	31.8	33	34.9		30.8	29.3	30.6	32.5		38.2	36.8	38	39.7
	Change (ºC)		+2.6	+1.2	+2.4	+4.3		+2.9	+1.4	+2.7	+4.6		+2	+0.6	+1.8	+3.5

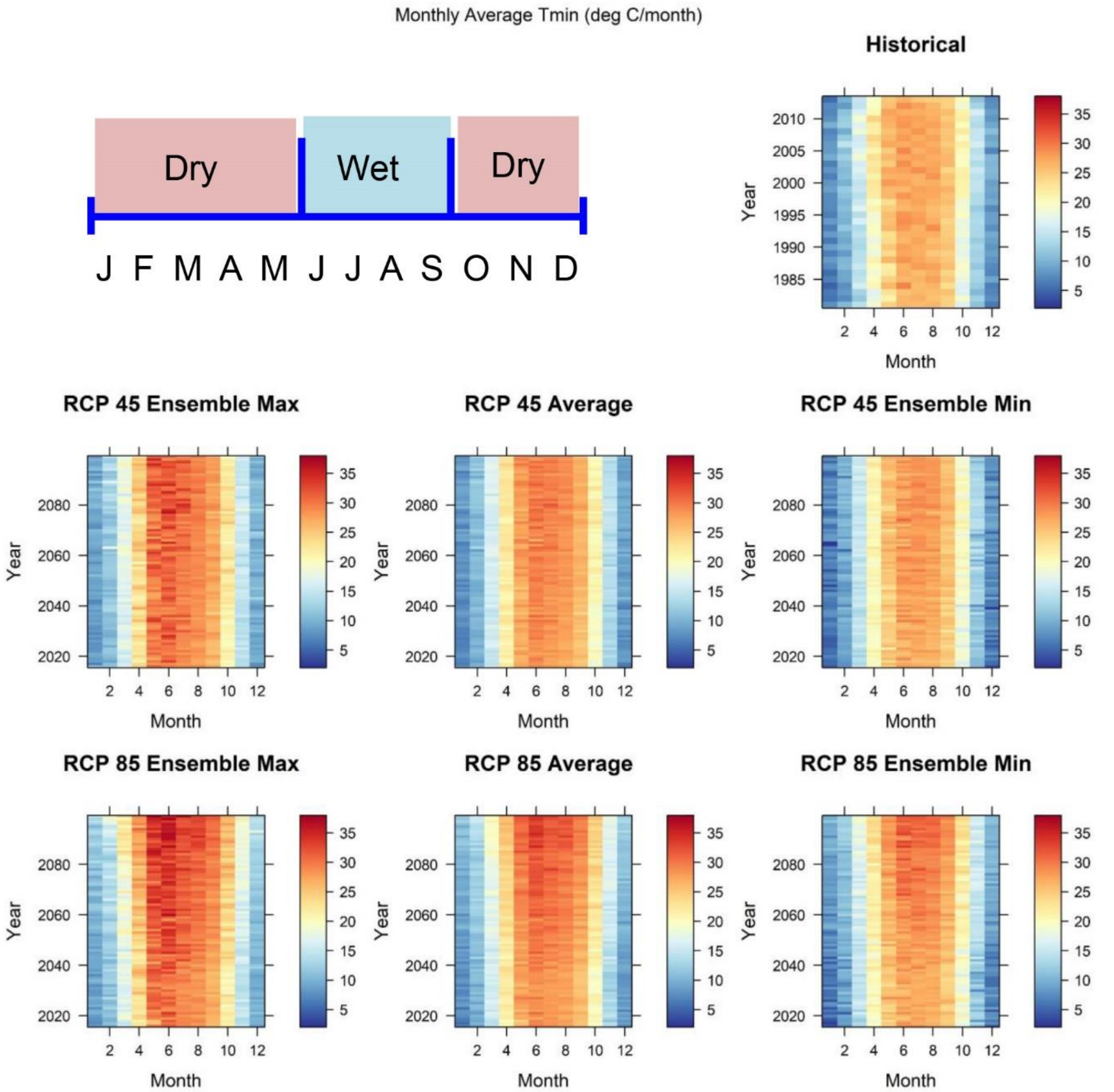
Annual Trend of Minimum Temperature





The minimum temperature (Tmin) in the past shows an increasing trend at nearly constant rate in recent years. Compared to the value of 2005, RCP4.5 based projection shows an overall increase by >1^0 at the end of the century, with smaller trend by the time we reach the 80s. Whereas RCP8.5 shows overall increase by ~ 4^0 at the end of the century, with constantly increasing trends over 20s, 50s and 80s.

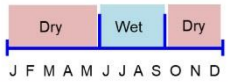
Seasonality of Minimum Temperature



In the past average monthly Tmin seldom crossed 25^0C in wet season months June to September and 20^0C in March and October (i.e. starting and ending months of dry seasons). In contrast, RCP4.5 ensemble average projection shows Tmin intermittently crosses 30^0C from May – July, and regularly crosses 20^0C for month from April to October throughout the 21^{st} century. For RCP8.5 Tmin will likely to approach 35^0C in June and July after 20s. It will cross 25^0C from April to Oct. and will approach 20^0C in March and November, in 20s, 50s and 80s.

Summary of Minimum Temperature

In summary, the minimum temperatures in Lahore over the 21^{st} century is projected to increase in both seasons. Contrary to Tmax, Tmin will observe more increase in wet season compared to dry season. By the end of the century, its projected that Tmin increases by 1.1^0C and 2.2^0C under RCP 4.5 and 8.5 respectively.

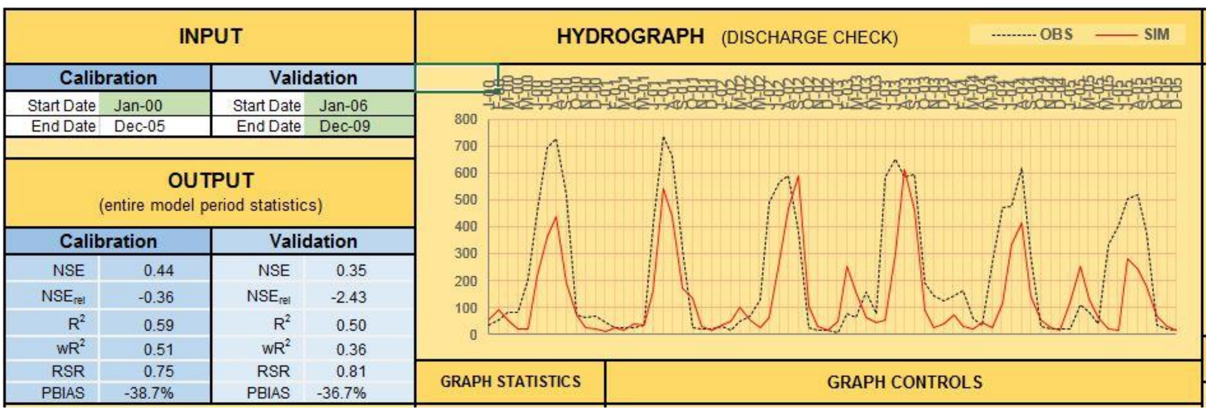


Lahore, Pakistan		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmax (ºC)	18.9					15					26.6				
RCP 4.5	Average Tmax (ºC)		20	19.3	20	20.5		15.8	15.2	15.9	16.4		28.1	27.5	28.2	28.7
	Change (ºC)		+1.1	+0.4	+1.1	+1.6		+0.8	+0.2	+0.9	+1.4		+1.5	+0.9	+1.6	+2.1
RCP 8.5	Average Tmax (ºC)		21.1	19.5	21	22.8		17	15.5	17	18.8		29.1	27.6	29	30.9
	Change (ºC)		+2.2	+0.6	+2.1	+3.9		+2	+0.5	+2	+3.8		+2.5	+1	+2.4	+4.3

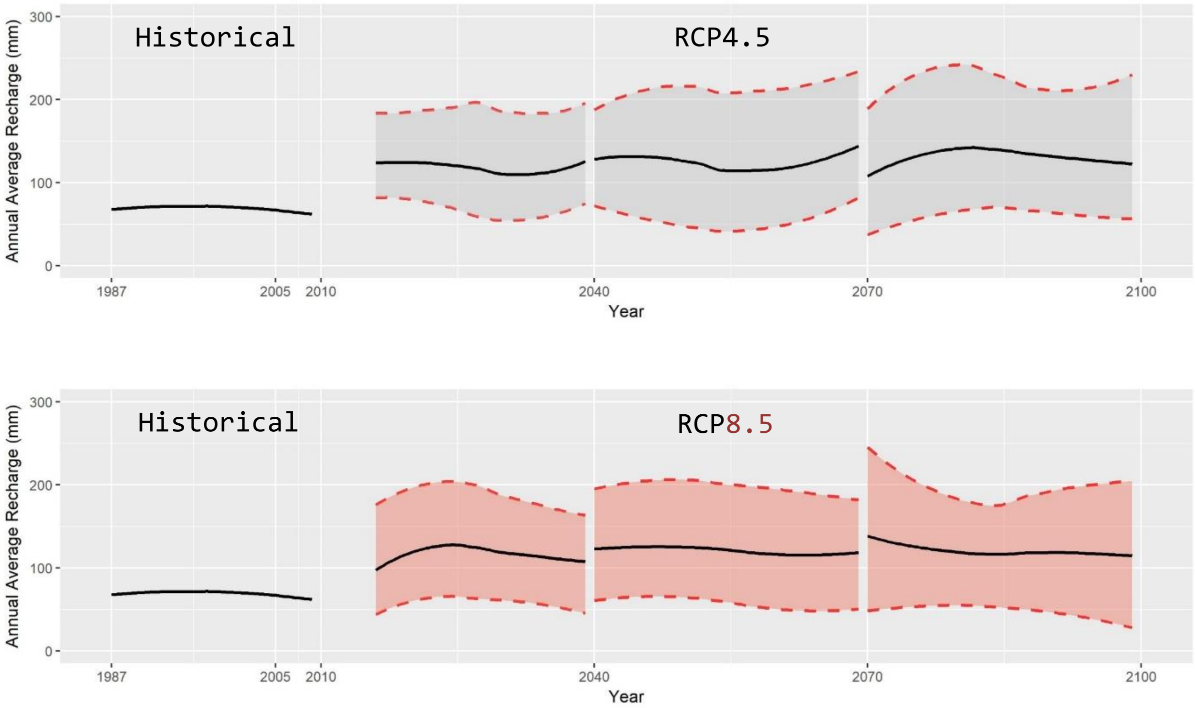
3.2.2. Groundwater Recharge Projections

Model Performance

Soil and Water Assessment Tool (SWAT), Model was used for recharge estimation. With climate input at 1 rainfall station and 1 temperature station, calibration of the SWAT model for Lahroe was carried out for the years 2000 to 2005. The comparison of discharge at outlet station at Shahdra showed a match of 0.44 Nash Sutcliffe Efficiency (NSE) and a volume bias of -38.7%. Validation of the model (2006 – 2009) showed NSE of 0.50 and volume bias of -36.7%. The hydrograph match between the observed discharge at Shahdra and the SWAT simulated discharge is shown in the following figure.



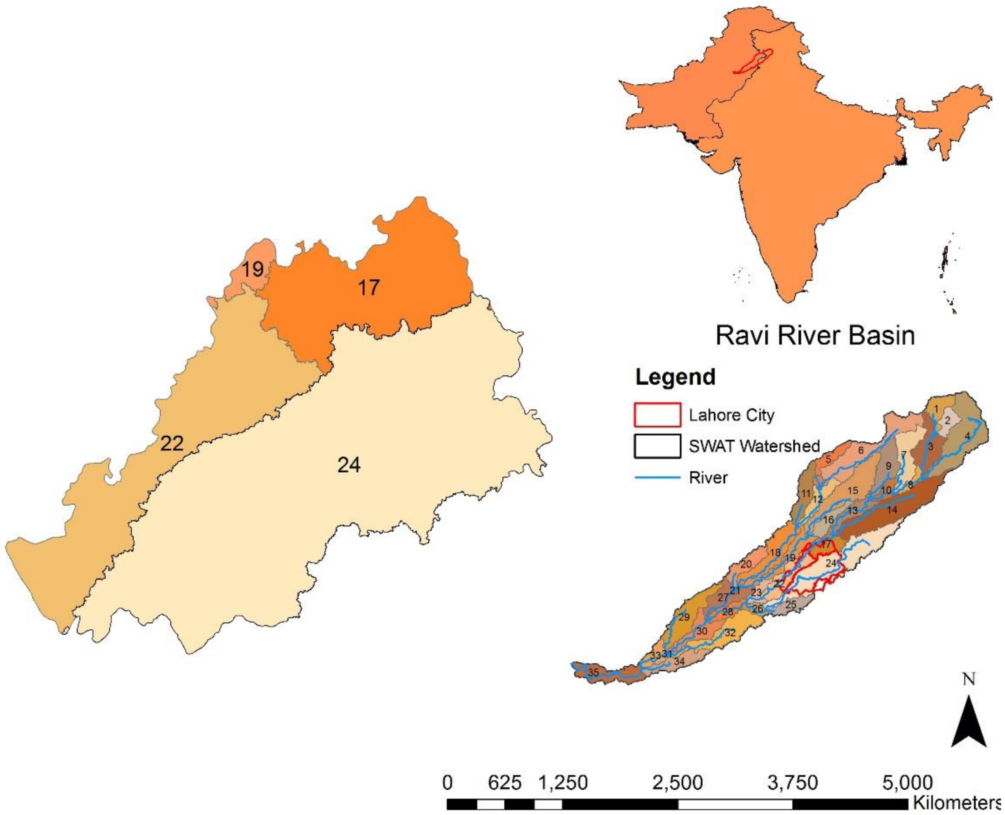
Annual Trend of Groundwater Recharge

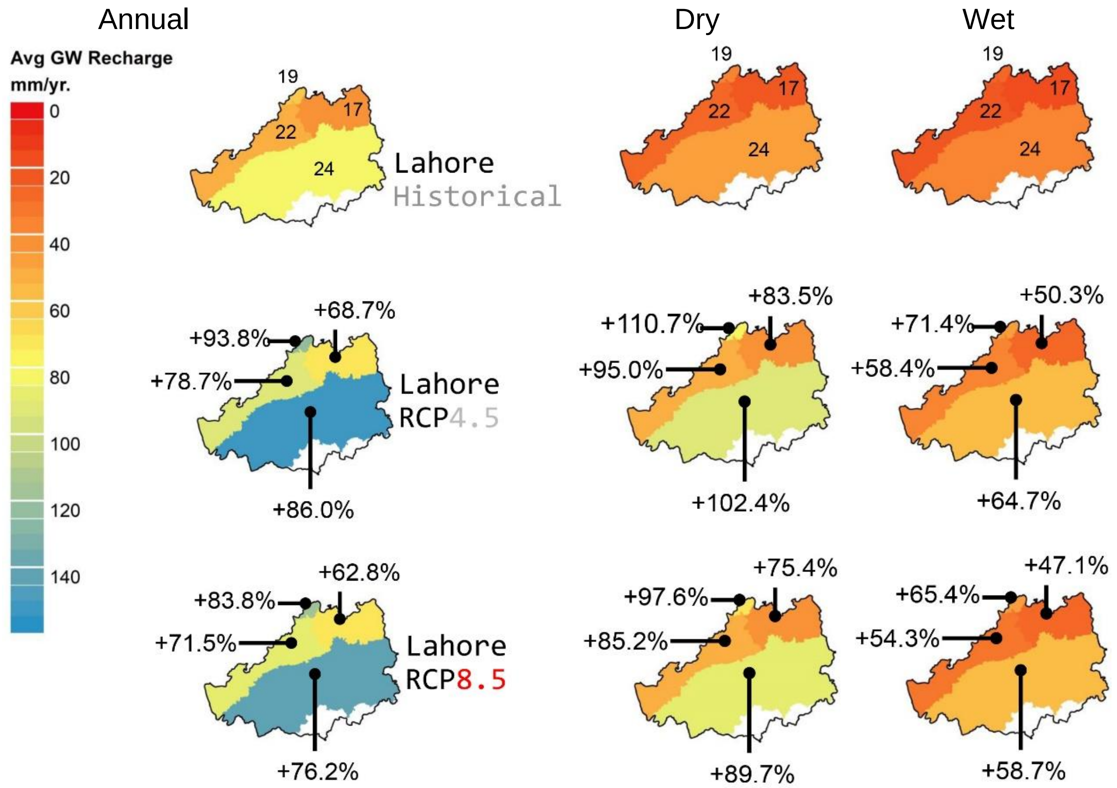


In the recent years, Lahore's groundwater recharge (GWR) is seen to have a decreasing trend in recent years. Under RCP 4.5 GWR is projected to increase with likely fluctuations observed though out the 21st century. For RCP8.5 an overall increase is projected with smooth patterns compared to RCP4.5.

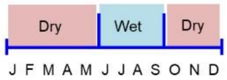
Spatial Variation and Seasonality of Groundwater Recharge

The SWAT model domain of Lahore alongside the sub-basins of the city for spatial variation analyses is as depicted in the figure below. The sub-basins are based on the hydrological sub-division of the watershed. There were 35 sub basins delineated in the SWAT model for Ravi River Basin, out of which the city encompasses sub-basins 17, 19, 22 and 24.





On both annual and seasonal scales, compared to historic recharge in the city, all sub-basins will observe substantial increase in GWR in 21st century. For RCP4.5 Sub-basin 19 will observe largest increase in GWR while sub-basin 17 the least. For RCP8.5 increase in GWR will likely to have same pattern as under RCP4.5. On annual scale there will be larger increase in GWR in Lahore by an amount of 5.9% to 10% under RCP4.5 than RCP8.5. In wet and dry seasons increase in recharge will be 3% to 6% and 8.1% to 13.1% under RCP4.5 than RCP8.5 respectively.



Lahore, Pakistan		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	30s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	30s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	30s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average GWR (mm/yr.)	68.6					38.6					30				
RCP 4.5	Average GWR (mm/yr.)		125.5	117.6	126.5	130.8		76.8	70.8	77.4	81.1		48.7	46.9	49.1	49.7
	Change (mm)		56.9 **+82.9%**	49 **+71.4%**	57.9 **+84.4%**	62.2 **+90.7%**		38.2 **+99%**	32.2 **+83.4%**	38.8 **+101%**	42.5 **+110%**		18.7 **+62.3%**	16.9 **+56.3%**	19.1 **+63.7%**	19.7 **+65.7%**
RCP 8.5	Average GWR (mm/yr.)		119.4	117	120.4	120.3		72.3	69.9	73	73.5		47.1	47	47.3	46.9
	Change (mm)		50.8 **+74.1%**	48.4 **+70.6%**	51.8 **+75.5%**	51.7 **+75.4%**		33.7 **+87.3%**	31.3 **+81.1%**	34.4 **+89.1%**	34.9 **+90.4%**		17.1 **+57%**	17 **+56.7%**	17.3 **+57.7%**	16.9 **+56.3%**

Summary of Groundwater Recharge

In summary, the GWR in Lahore is projected to increase by 82.9% and 74.1% based on RCP 4.5 and 8.5 respectively. The larger proportion of the increase is seen in the dry season with 99% and 87.3% increase comparison to 62.3% and 57% increase in wet season for RCP 4.5 and 8.5 respectively.

3.2.3. Adaptation Options

Projected recharge in Lahore aquifer is expected to increase in near and far futures. However, soil is predominantly loam and therefore, strategies for enhancing recharge at a larger scale may be less useful. In this context, Lahore needs strategies to regulate groundwater abstraction. Following adaptation options, in decreasing order of priority, are identified;

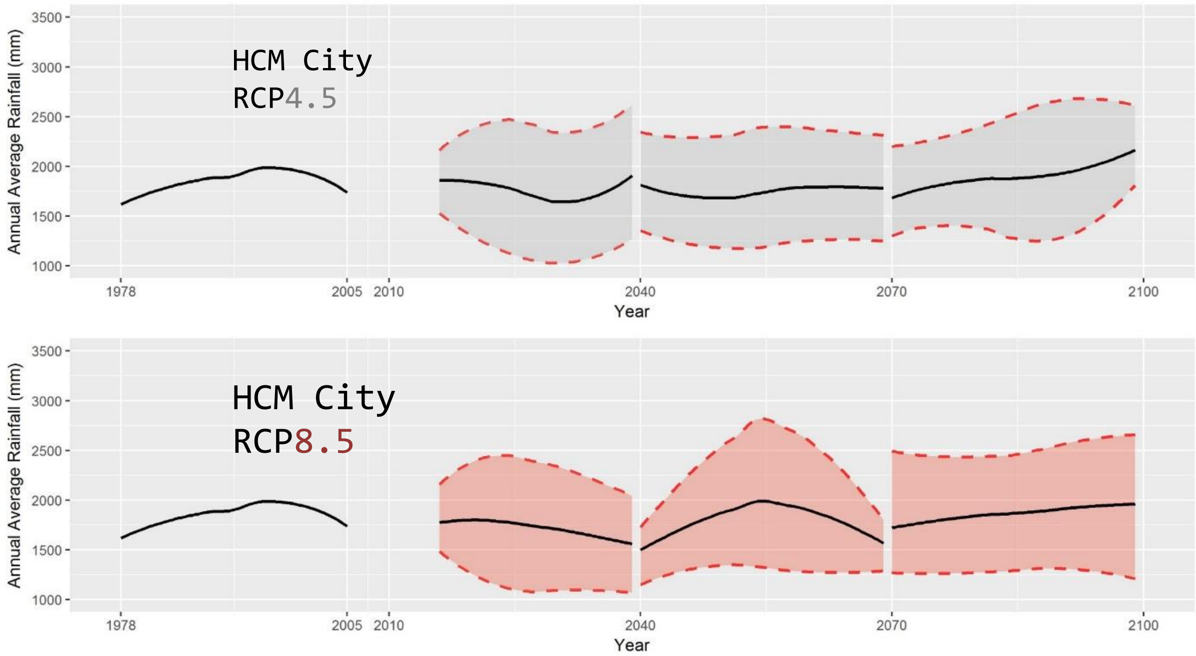
- Direct recharge using recharge wells (same as the abstraction well) fed by rainwater harvesting
- Augmenting river flow by contracting check-dams across the rivers.
- Enhancing agriculture return flow by increasing intensity of irrigation (water allocation)
- Regulating groundwater abstraction from groundwater depression zones combining with rainwater harvesting techniques and/or conjunctive water use or re-use of used water
- Identifying groundwater recharge potential zones and formulating regulations for their protection.

- Establishing monitoring mechanism, both network and institutions, for groundwater levels
- Mainstreaming groundwater issues in resilient cities or other similar city-wide adaptation initiatives

3.3. Ho Chi Minh City, Vietnam

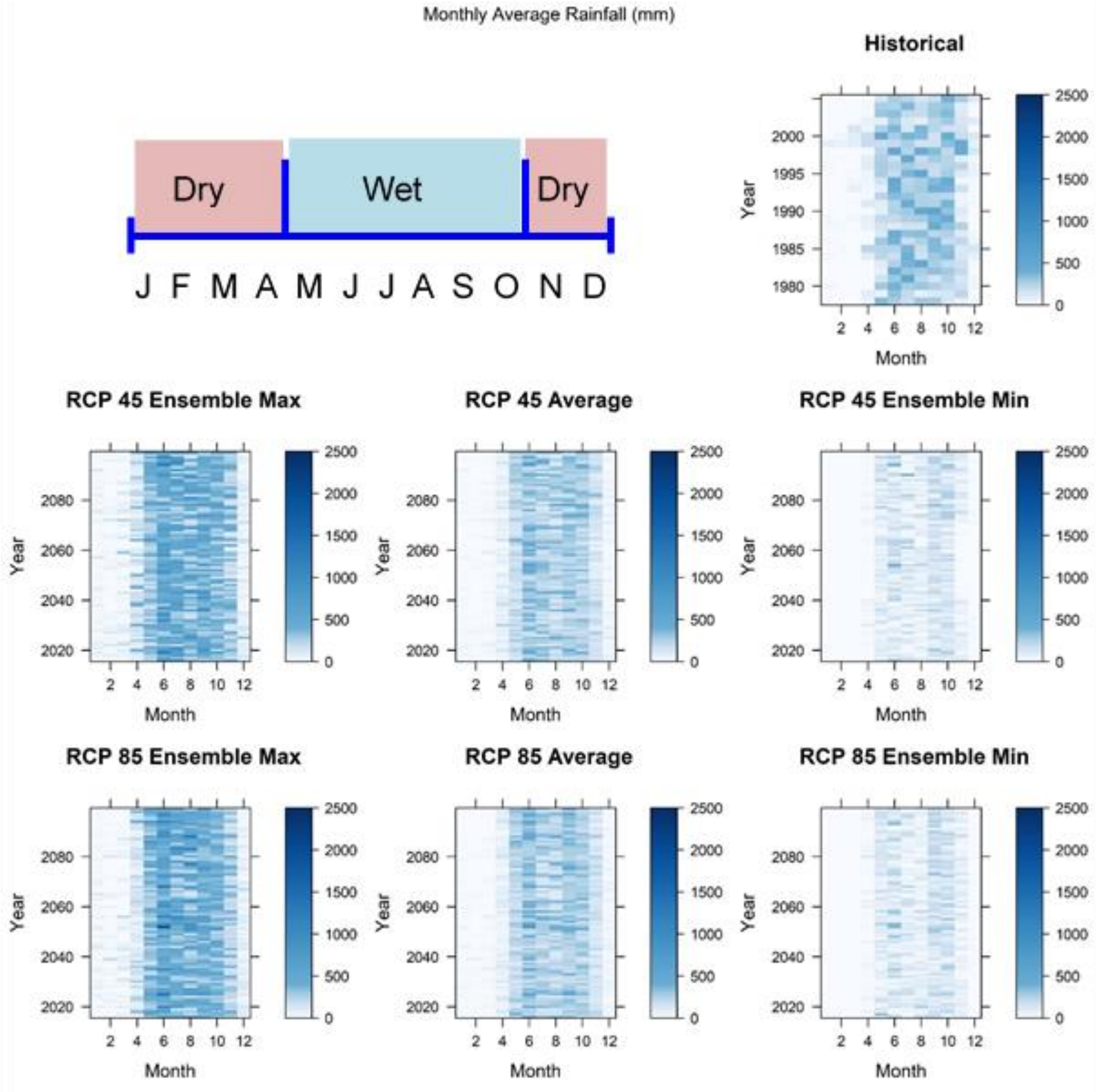
3.3.1. Climate Change Projections

Annual Trend of Rainfall



The annual rainfall in the past period of Ho Chi Minh City (1978-2005) significantly decreased in a short period from 2000-2005 after reaching the peak at 2000. It is predicted that the near future by 2040, the rainfall might continuously go down. Under RCP 4.5 scenario, the future rainfall showed slightly downward trend in overall with some increment from 2080s, while the prediction rainfall under RCP 8.5 varied more considerably. From now to 2070, Ho Chi Minh City might possibly face drier years, then by 2080s, the rainfall start raising again.

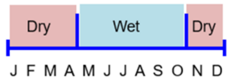
Seasonal Rainfall



As Bandung, Ho Chi Minh City Vietnam has typical tropical monsoon climate. The wet season is normally from May to November, and the dry season is from December to April next year. The monthly average rainfall plots showed the change in amount of rainfall and seasonal patterns. It can be seen that the wet season is getting more rainfall in the future, in contrast dry season is facing shortage of rainfall amount. The seasonal patterns also showed a slightly movement, the wet season likely shifted by one-month lag, from June to December.

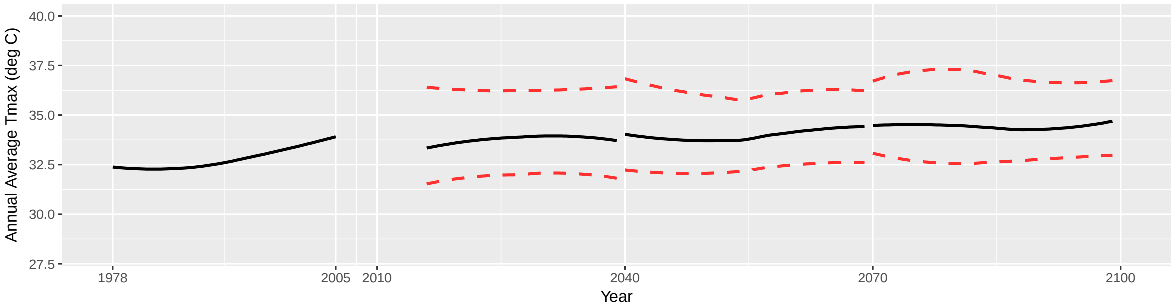
Rainfall Summary

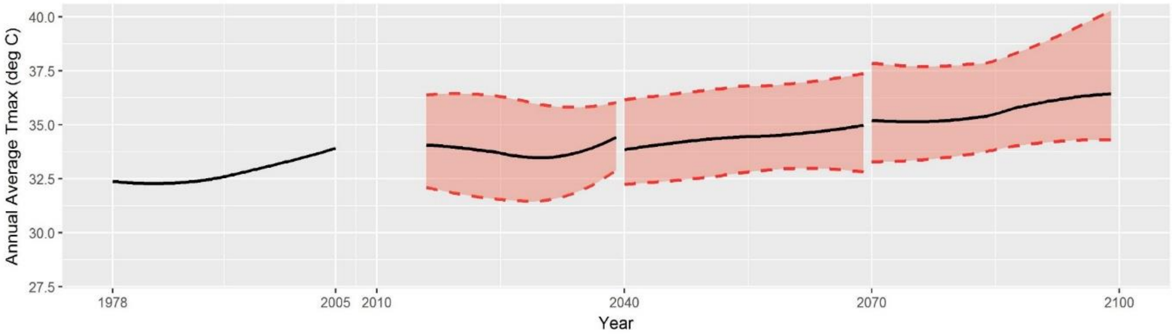
In short, future rainfall of Ho Chi Minh City might follow the downward trend. It is found that, the amount of rainfall is going to decrease in both dry season and wet season, with different the degree of reduction under RCP 8.5 (-4.2%), and RCP 4.5 (-3.3%). The table below showed the amount of changing in future rainfall of Ho Chi Minh City in details.



Ho Chi Minh City, Vietnam		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Rainfall (mm/yr.)	1869					277					1592				
RCP 4.5	Average Rainfall (mm/yr.)		1807	1766	1745	1902		269	311	210	295		1538	1456	1535	1606
	Change (mm)		-62 **-3.3%**	-103 **-5.5%**	-124 **-6.6%**	33 **+1.8%**		-8 **-2.9%**	34 **+12.3%**	-67 **-24.2%**	18 **+6.5%**		-54 **-3.4%**	-136 **-8.5%**	-57 **-3.6%**	14 **+0.9%**
RCP 8.5	Average Rainfall (mm/yr.)		1791	1719	1777	1863		250	263	248	242		1541	1456	1529	1621
	Change (mm)		-78 **-4.2%**	-150 **-8%**	-92 **-4.9%**	-6 **-0.3%**		-27 **-9.7%**	-14 **-5.1%**	-29 **-10.5%**	-35 **-12.6%**		-51 **-3.2%**	-136 **-8.5%**	-63 **-4%**	29 **+1.8%**

Annual Trend of Maximum Temperature

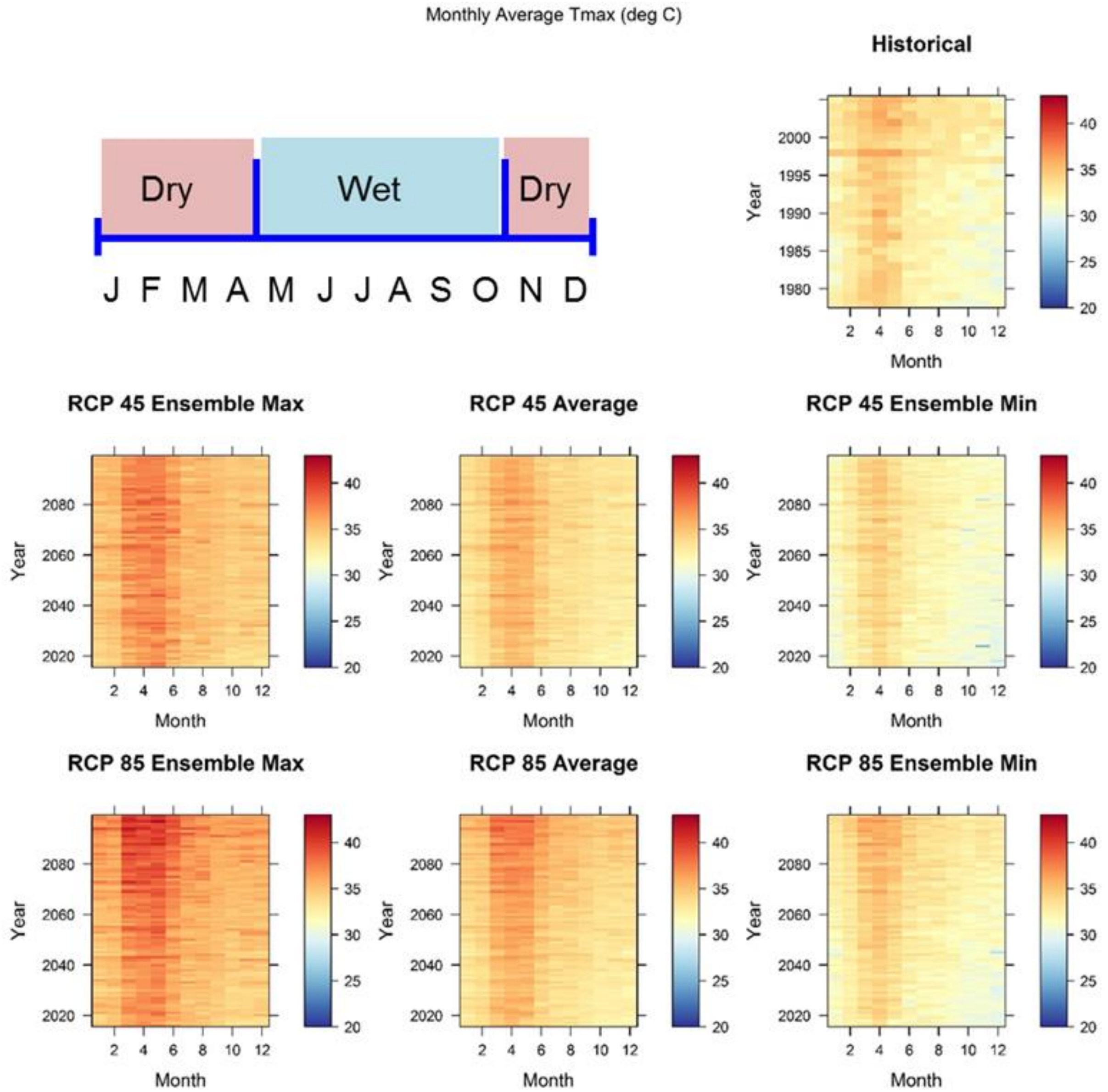




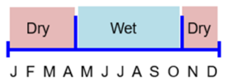
In Ho Chi Minh City, the upward trend of the maximum temperature is found under both RCP4.5 and RCP 8.5 comparing to historical period (1978- 2005). The RCP 4.5 predicted that the maximum temperature will rise by 1ºC by the end of the century, and it will increase by almost 2.5ºC under RCP 8.5, with continuously increasing trends over 20s, 50s, and 80s.

Seasonal of Maximum Temperature

In Ho Chi Minh City, the maximum temperature (Tmax) used to exceed 30ºC in the end of dry season and early of wet season (from February to June). The future maximum temperature showed the expending of hot month under both RCP 4.5 and RCP 8.5 comparing to the historical period, and the wet season is getting hotter also.

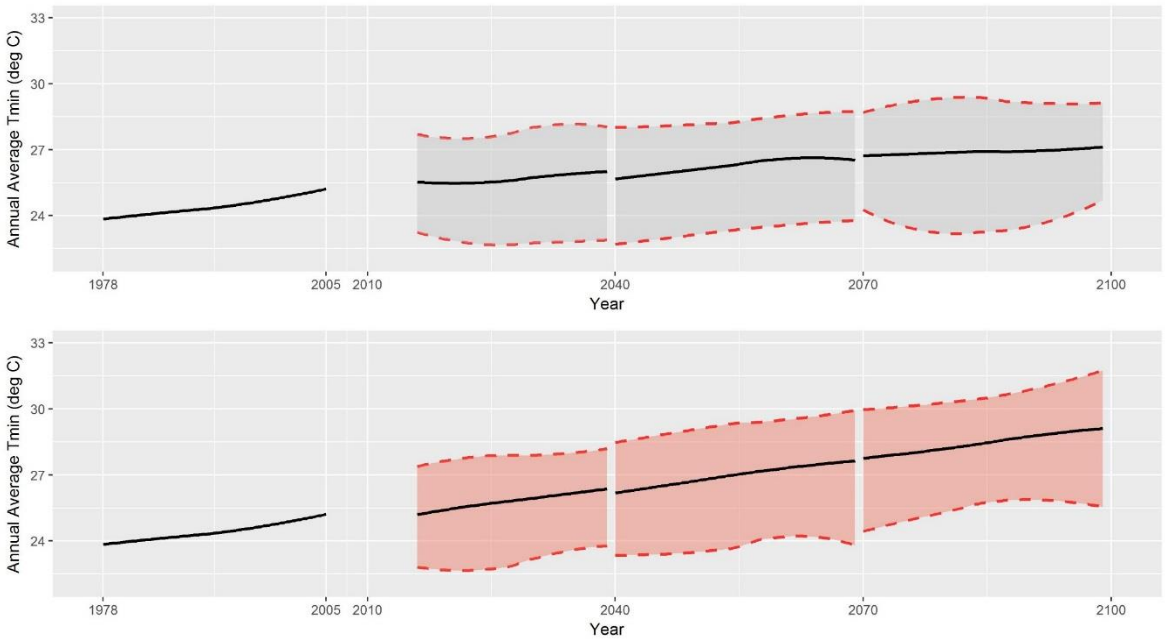


Summary of Maximum Temperature

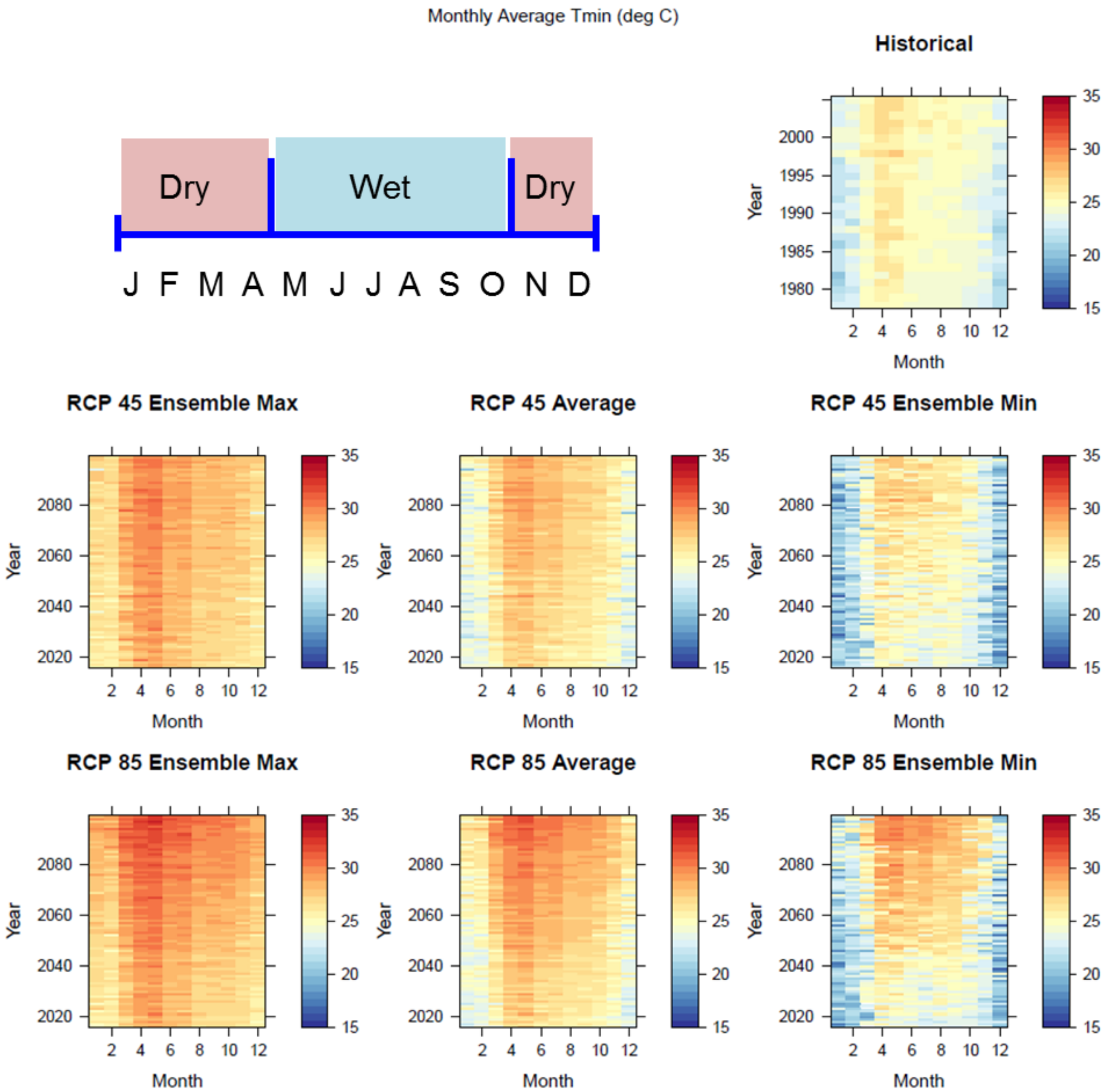


Ho Chi Minh City, Vietnam		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmax (ºC)	32.8					33					32.7				
RCP 4.5	Average Tmax (ºC)		34	33.6	34	34.2		34	33.5	34	34.4		33.9	33.6	33.9	34.2
	Change (ºC)		+1.2	+0.8	+1.2	+1.4		+1	+0.5	+1	+1.4		+1.2	+0.9	+1.2	+1.5
RCP 8.5	Average Tmax (ºC)		34.5	33.7	34.4	35.6		34.6	33.8	34.4	35.6		34.5	33.7	34.4	35.5
	Change (ºC)		+1.7	+0.9	+1.6	+2.8		+1.6	+0.8	+1.4	+2.6		+1.8	+1	+1.7	+2.8

Annual Trend of Minimum Temperature



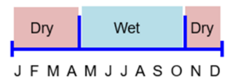
In Ho Chi Minh City, the past trend showed the increase in daily minimum temperature (Tmin) as per the observed data by +1.5⁰C from 1978 to 2005 (almost 3 decades). Overall, it is predicted that Tmin increase by more than 1.5ºC by the end of century comparing to the baseline period (1978-2005) under RCP4.5. Regarding the RCP8.5, the minimum temperature is projected to increase more than 3.5ºC at the end of the century with steep trends over 20s. 50s, and 80s (comparison to 2005 value)



The plots showed the average monthly (Tmin) seldom crossed 25^{0}C except for the hottest months of April and May in Ho Chi Minh City. In recent years March, June, July, August are seen to become hotter. In the future, under RCP 4.5, significant change in seasonal Tmin as most of the months (except Jan, Feb and Dec) regularly cross 25^{0}C. This increase in Tmin is greater in the second half of the century. Similar projections as shown by RCP4.5. The main difference being the higher Tmin values in the 80s where it exceeds 25^{0}C + (monthly average) year round under RCP 8.5

Summary of Minimum Temperature

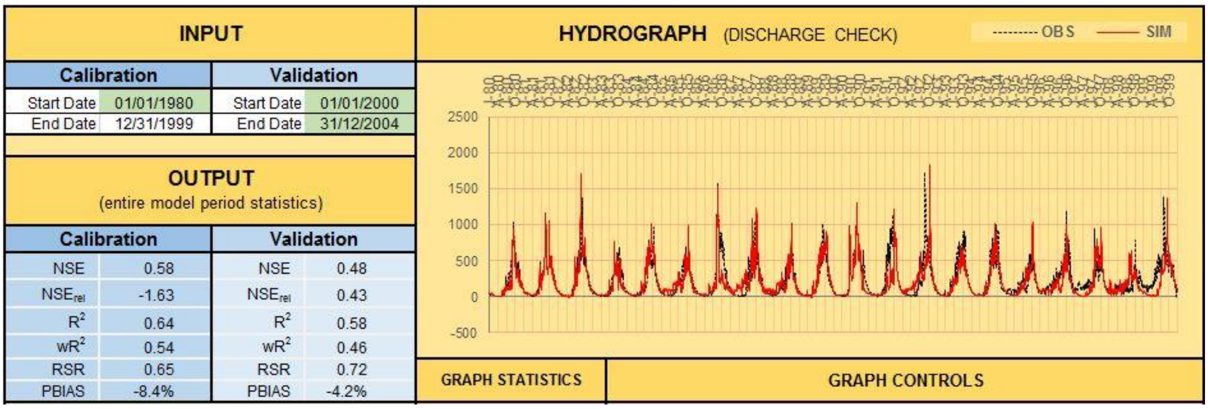
In summary, the minimum temperatures in Ho Chi Minh over the 21st century is predicted to follow the upward trend, even with a faster rate of increasing than maximum temperatures. By the end of this century, it is projected that Tmin increase 1.9^{o}C and 2.6^{o}C under the RCP 4.5 and RCP 8.5 respectively.



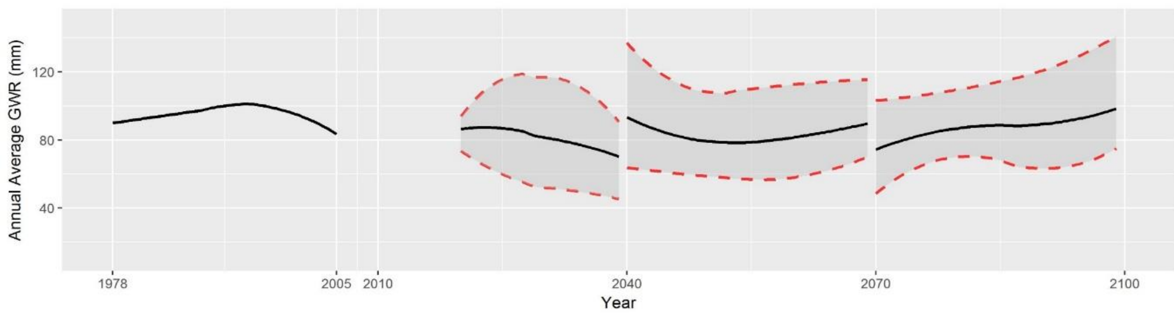
Ho Chi Minh City, Vietnam		ANNUAL					DRY					WET				
		Past (1980–2005)	21st century	20s (2010–2039)	50s (2040–2069)	80s (2070–2099)	Past (1980–2005)	21st century	20s (2010–2039)	50s (2040–2069)	80s (2070–2099)	Past (1980–2005)	21st century	20s (2010–2039)	50s (2040–2069)	80s (2070–2099)
Base-line	Average Tmax (ºC)	24.4					23.6					25.3				
RCP 4.5	Average Tmax (ºC)		26.3	25.7	26.3	26.9		25.1	24.6	25.2	25.6		27.4	26.8	27.4	28.1
	Change (ºC)		+1.9	+1.3	+1.9	+2.5		+1.5	+1	+1.6	+2		+2.1	+1.5	+2.1	+2.8
RCP 8.5	Average Tmax (ºC)		27	25.8	27	28.5		26	24.8	25.7	27.2		28.2	26.8	28.2	29.6
	Change (ºC)		+2.6	+1.4	+2.6	+4.1		+2.4	+1.2	+2.1	+3.6		+2.9	+1.5	+2.9	+4.3

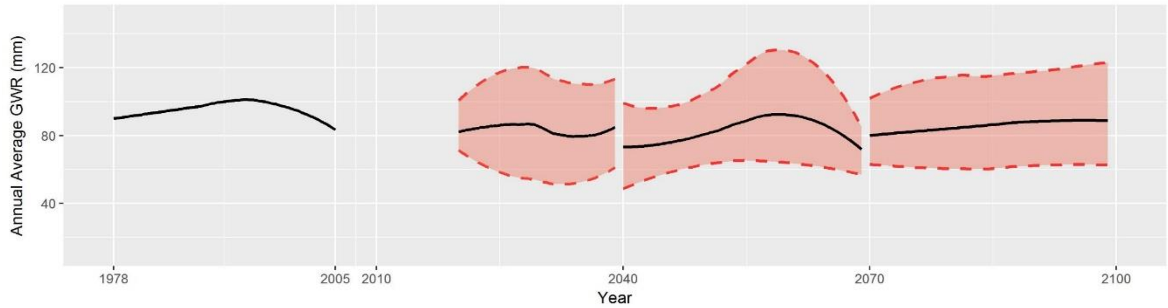
3.3.2. Groundwater Recharge Projections

Model Performance



Annual trend of Groundwater Recharge

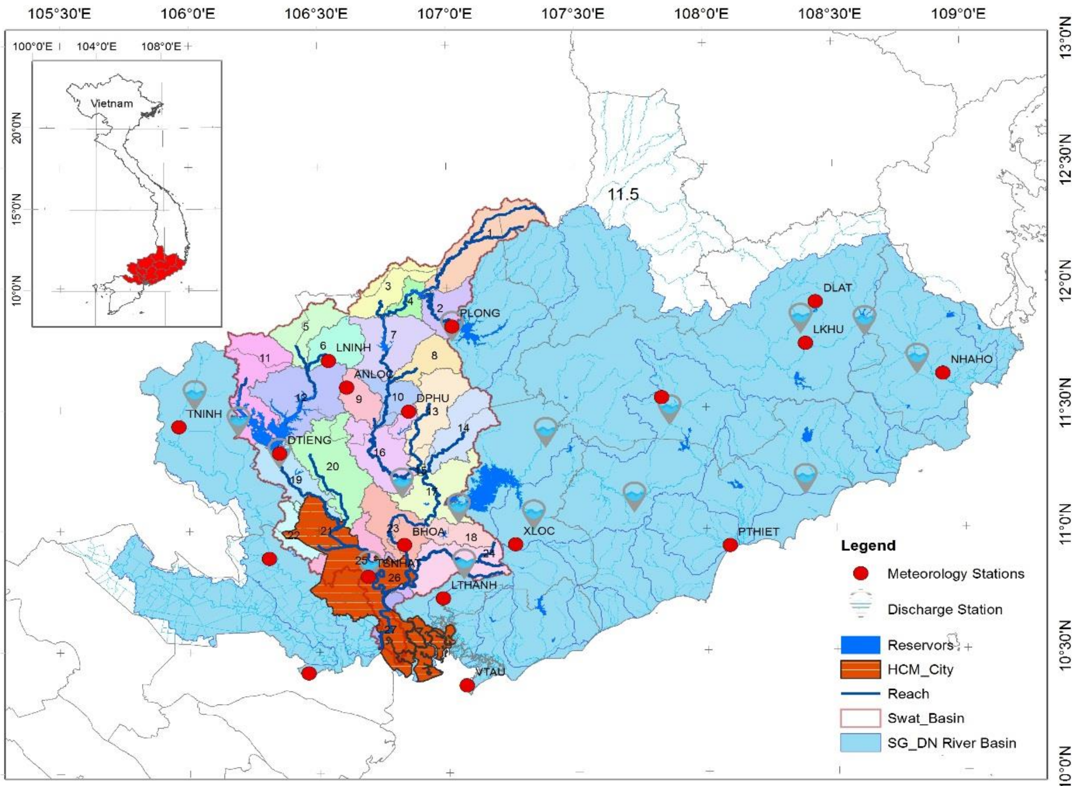




The groundwater recharge experience a downward trend in recent years. In the future the groundwater recharge is getting more stable under both RCP 4.5 and RCP 8.5, however, the overall trend is decreasing compare to baseline period.

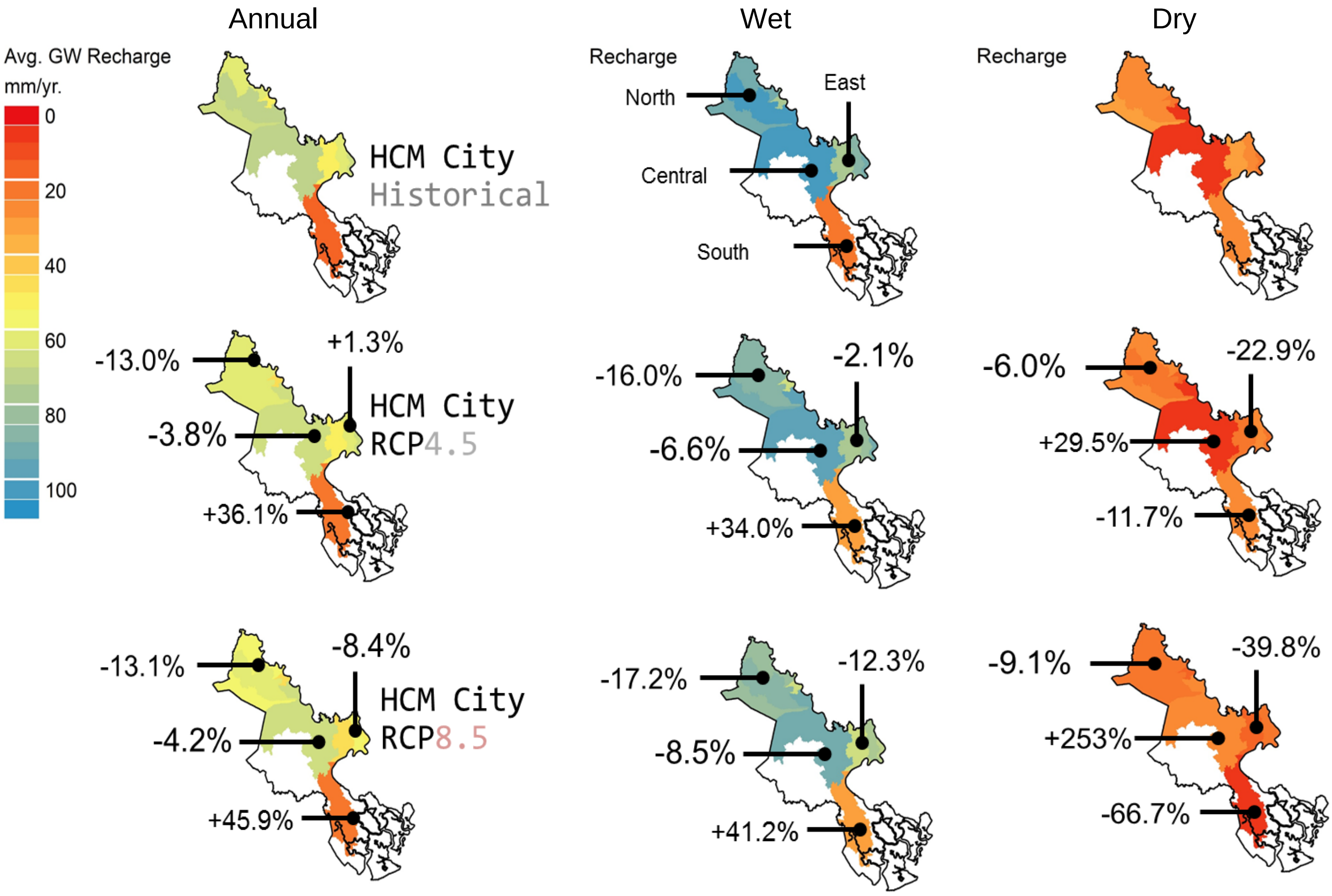
Spatial Variation and Seasonality of Groundwater Recharge

The SWAT model domain of Ho Chi Minh City is cover an area of 13000km^2 of Sai Gon – Dong Nai River basin which included 70% of Ho Chi Minh area. There were 10 meteorological stations were used to develop and calibrate the historical model and Phuoc Long and Phuoc Hoa discharge stations. There were 23 sub basins in total, and 9 sub basins fall in the boundary of Ho Chi Minh City which is 19-27.



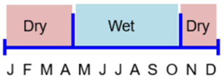
From the spatial distribution of groundwater recharge plots, it can be seen that central zone is the most recharged and safest area in terms of climate change impact on GWR. Although there is large positive recharge trend in the Southern zone, the magnitude of recharge is still low. The Northern and Eastern zones also have moderate annual GW recharge.

In dry season, the Southern zone is seen to suffer most in terms of GWR decline due to climate change. The projections show improvement in GWR for the central zone. The Eastern zone is also seen to have lower GWR in dry season. In wet season, except for the Southern zone, all other zones are seen to be only slightly affected by climate change impact on GWR. Whereas for the South zone, in spite of large percentage increase in GWR, the magnitude of GWR is still very low.



Summary of Groundwater Recharge

In summary, the GWR in Ho Chi Minh City is projected to decrease by -13.8% and -14.4% based on RCP 4.5 and 8.5 respectively. The larger proportion of the decrease is seen in the dry season with -33.2% and -38.5 % decrease in the dry season in comparison to -4% and ---2% fluctuations in wet season for RCP 4.5 and 8.5 respectively.



Ho Chi Minh City, Vietnam		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average GWR (mm/yr.)	95.56					32.14					63.42				
RCP 4.5	Average GWR (mm/yr.)		82.36	78.46	82.22	86.41		21.48	16.34	20.8	24.82		60.88	62.12	58.67	55.27
	Change (mm)		-13.2 **-13.8%**	-17.1 **-17.9%**	-13.34 **-14%**	-9.15 **-9.6%**		-10.66 **-33.2%**	-15.8 **-49.2%**	-11.34 **-35.3%**	-7.32 **-7.32%**		-2.54 **-4%**	-1.3 **-2%**	-4.75 **-7.5%**	-7.15 **-12.9%**
RCP 8.5	Average GWR (mm/yr.)		81.83	76.91	83.41	85.17		19.78	15.49	19.99	21.75		62.05	62.42	59.14	52.73
	Change (mm)		-13.73 **-14.4%**	-18.65 **-19.5%**	-12.15 **-12.7%**	-10.39 **-10.9%**		-12.36 **-38.5%**	-16.65 **-51.8%**	-12.15 **-37.8%**	-10.39 **-32.3%**		-1.37 **-2.2%**	-1.0 **-1.6%**	-4.28 **-6.7%**	-10.39 **-16.9%**

3.3.3. Adaptation Options

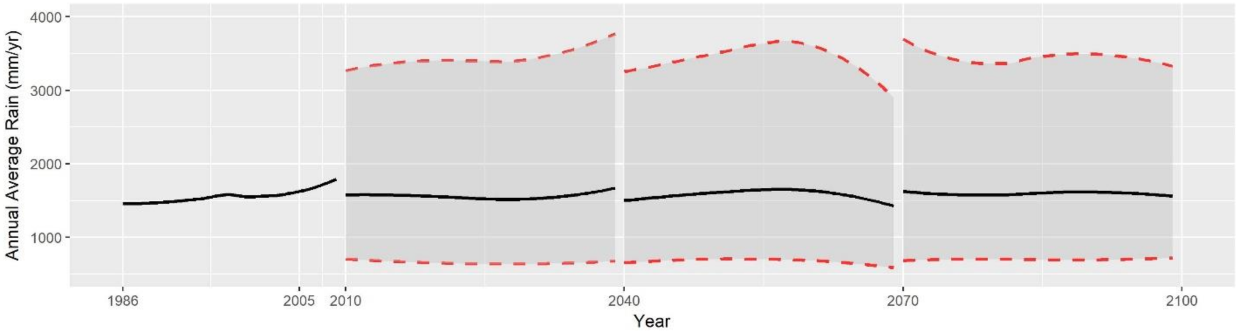
Following three problems related to groundwater in Ho Chi Minh city were identified during the second regional workshop: i) quantity of groundwater is depleting due to various reasons and different locations may experience varying degree of depletion in future; ii) saline water intrusion; and iii) land subsidence. Following adaptation options are identified and listed in order of decreasing priority for the purpose of addressing the issue of groundwater depletion;

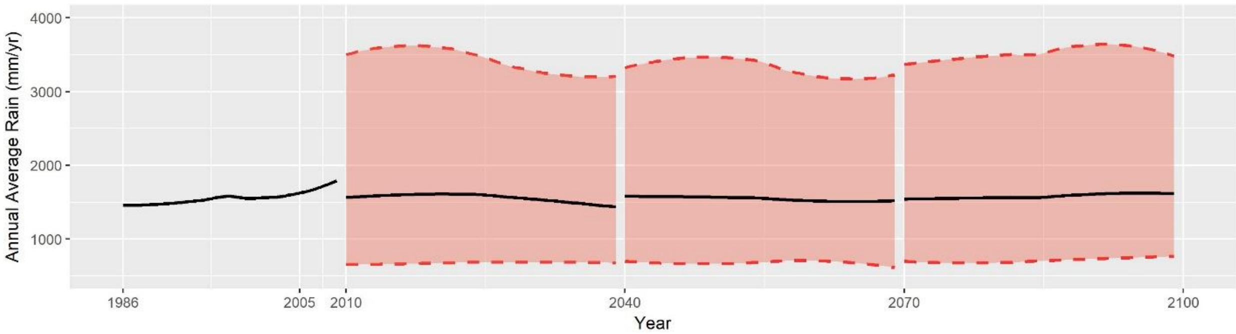
- Calculating safe yield complying with existing regulations for current and future time periods
- Identifying areas with higher level of groundwater depletion for current and future conditions
- Integrating recharge agenda with flood control agenda and vice-versa
- Bank infiltration structures at suitable locations
- Moving well-field towards northern part of the city

3.4. **Bangkok, Thailand**

3.4.1. Climate Change Projections

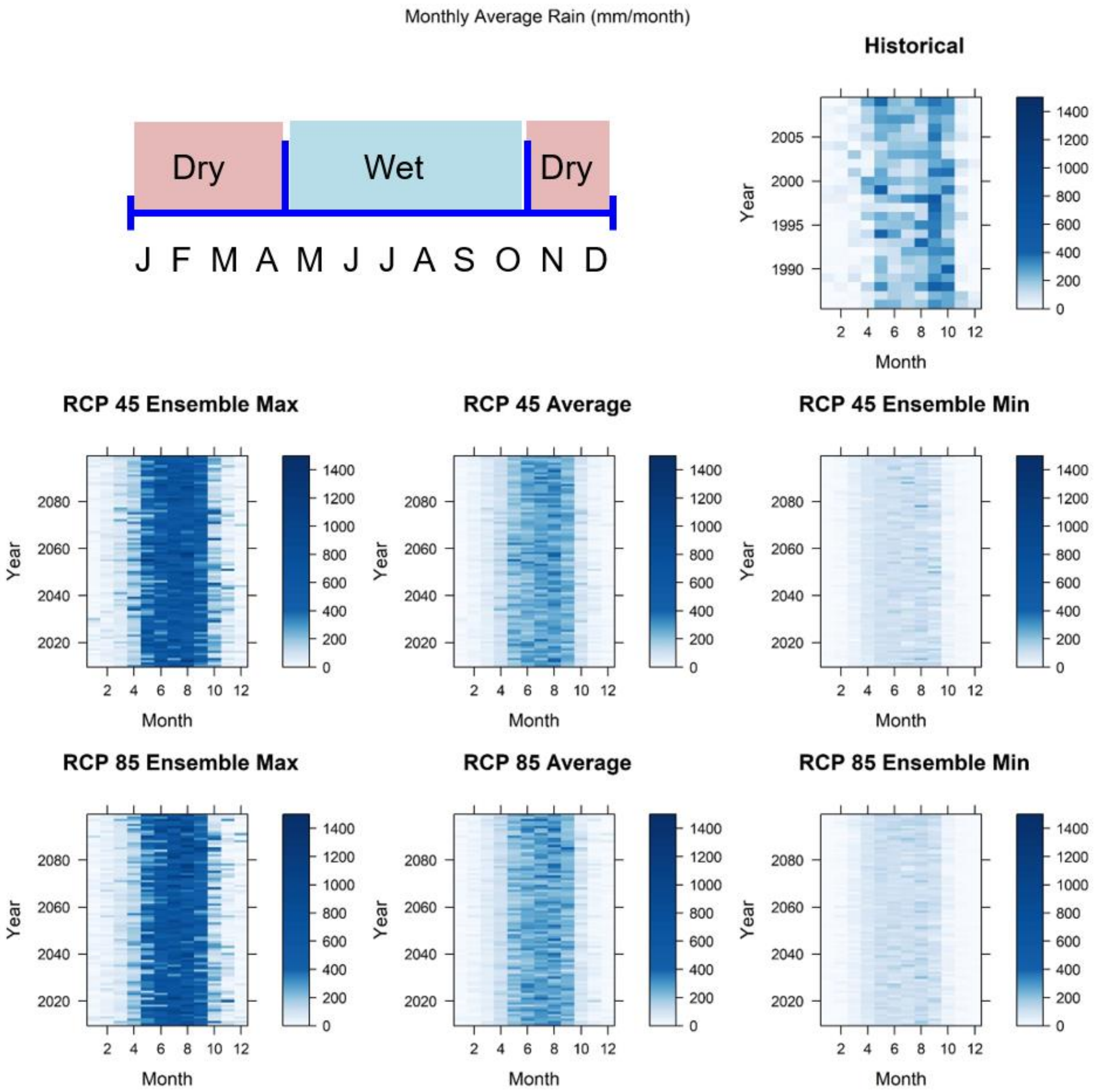
Annual Trend of Rainfall





In Bangkok, during the historical period (1980 – 2005) the average annual rainfall was 1545 mm, and the rainfall had slightly increasing trend with 12 mm/year during past. The past trend shows increase in rainfall is in higher amount in recent years. Compared the historical rainfall with projected rainfall under RCP 4.5 ensemble (average) projects an overall slight increase with higher increase during far future (2070 - 2099) by 4%. The projected increase in rainfall during near future (2010 – 2039) is 1.2% and during mid-future (2040- 2069) is 2.2%. Therefore, the ensemble of four RCMs under RCP 4.5 projects rainfall during all future period will be increase. While with RCP8.5, there is overall increase in annual rainfall during 20s and 80s period by 9mm and 40mm respectively. Meanwhile, there is overall decrease in rainfall during 50s period with plunging below 1542 mm per year.

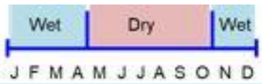
Seasonality of Rainfall



The weather in the Bangkok is dominated by a tropical monsoon climate with distinct two seasons i.e. dry and wet. The above level plots shows that in the past the maximum rainfall has occurred in the month of May, September and October. The month September contributes 20% of average annual rainfall in the past. Level plots shows very less rainfall occurred in January and December. Here, we can see vast deviation in rainfall of dry and wet season, more than 86% of average annual rainfall occurred in wet season. In both RCP4.5 and RCP8.5, however, the wettest month shifted to August. Some dry months (Jan, Feb, and Mar) are seen to become wetter and some months (Nov, Dec) turn drier than observed in the past.

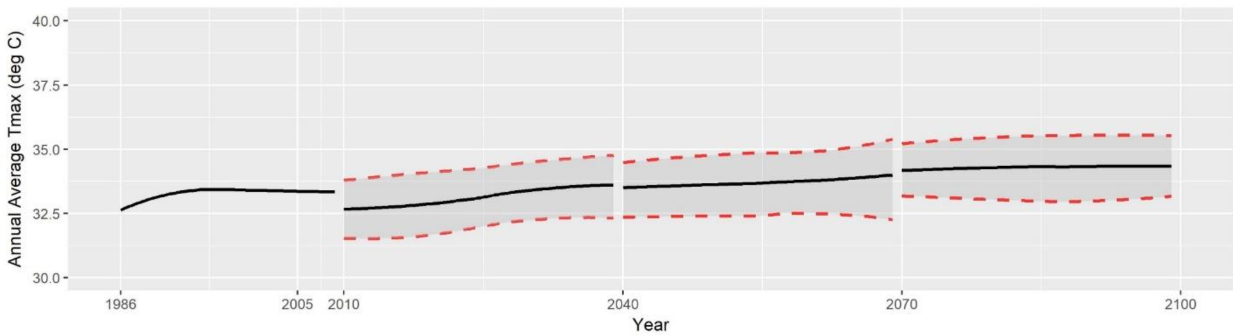
Rainfall Summary

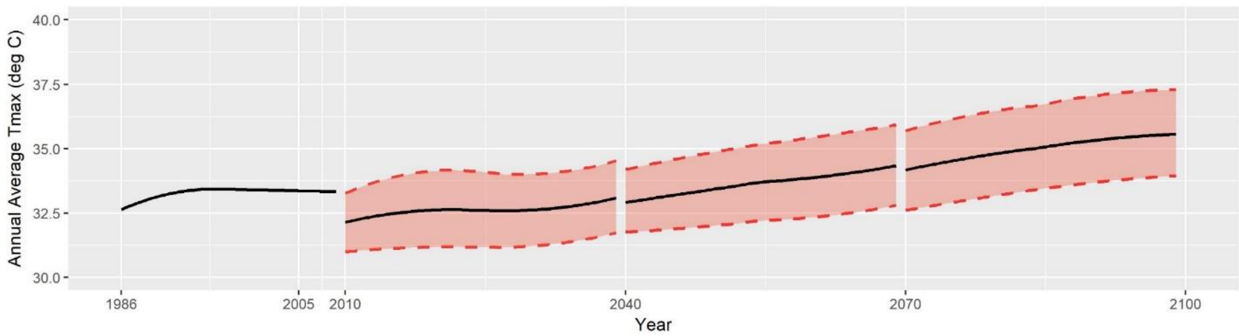
In summary, Bangkok future climate projections tell us that the average annual rainfall is going to increase except in 2050s period under RCP8.5. The projected rainfall during dry season under both RCPs scenarios is going to increase; however, the rainfall during wet season is going to increase under RCP4.5 and is going to decrease under RCP8.5.



Bangkok, Thailand		ANNUAL Past (1980 – 2005)	ANNUAL 21st century	ANNUAL 20s (2010 – 2039)	ANNUAL 50s (2040 – 2069)	ANNUAL 80s (2070 – 2099)	DRY Past (1980 – 2005)	DRY 21st century	DRY 20s (2010 – 2039)	DRY 50s (2040 – 2069)	DRY 80s (2070 – 2099)	WET Past (1980 – 2005)	WET 21st century	WET 20s (2010 – 2039)	WET 50s (2040 – 2069)	WET 80s (2070 – 2099)
Base-line	Average Rainfall (mm/yr.)	1545					215 (14%)					1330 (86%)				
RCP 4.5	Average Rainfall (mm/yr.)		1578	1563	1579	1592		240	229	246	249		1338	1334	1333	1343
	Change (mm)		33 2.2%	18 1.2%	34 2.2%	47 3.4%		25 11.6%	14 6.5%	31 14.5%	34 16%		8 0.6%	4 0.3%	3 0.22%	13 0.98%
RCP 8.5	Average Rainfall (mm/yr.)		1560	1554	1542	1585		232	230	225	242		1328	1324	1317	1343
	Change (mm)		15 0.97%	9 0.58%	-3 -0.2%	40 2.6%		17 8%	15 7%	10 5%	27 13%		-2 -0.15%	-6 -0.45%	-13 -0.98%	13 0.98%

Annual Trend of Maximum Temperature

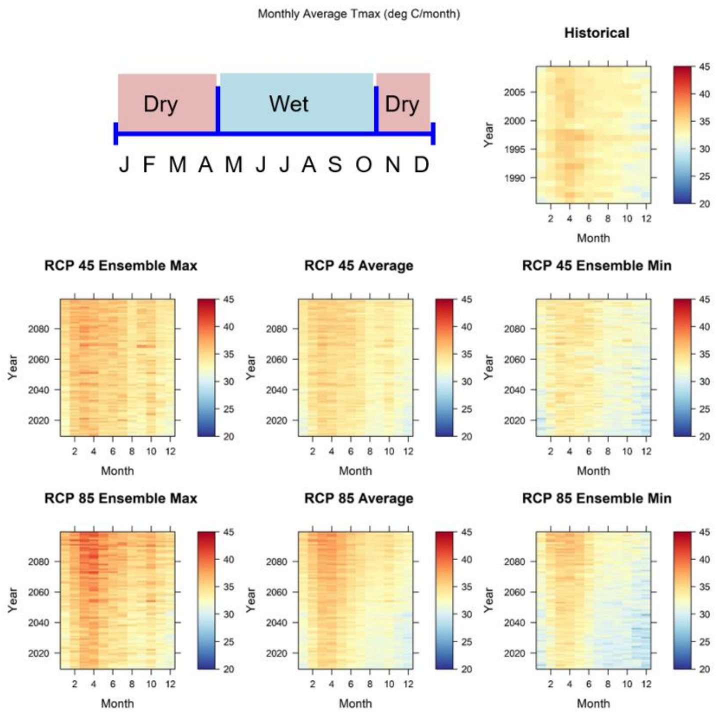




The Past trend of maximum temperature in Bangkok gives us an increasing trend in the recent years with 0.02°C/yr. According to RCP4.5, there will be an increase by 0.42ºC and 1.01ºC during 50s and 80s period and will be an overall decrease by 0.14ºC during 20s period [comparison to baseline value 33.28°C].Whereas, for RCP8.5 the overall increase will be 0.34ºC, 0.37ºC and 1.77ºC during 20s, 50s and 80s respectively. So, here we can see the constant increasing trend in maximum temperature over 20s, 50s, and 80s.

Seasonality of Maximum Temperature

In Bangkok, the maximum average temperature (Tmax) used to exceed 34ºC in the months of February, March, April, and May (first two months are ending of dry season and last two month are starting of wet season). But in RCP4.5, Tmax (ensemble average) is seen to regularly crosses the baseline temperature. On the 20s period of dry season maximum temperature might have negative changes, but during 50s and 80s period, temperature will be increase with significant value under both RCPs scenario. RCP8.5 shows similar contrasts with year round increase in temperature. This can be especially significant on the second half of the century where the hottest months will observe Tmax nearing to 37ºC and the values will stay above 32ºC year round. Almost similar result can be seen during the wet season under both RCPs scenario. As comparison with baseline temperature, temperature during wet season can project to decrease during 20s period and project to increase during 50s and 80s period.



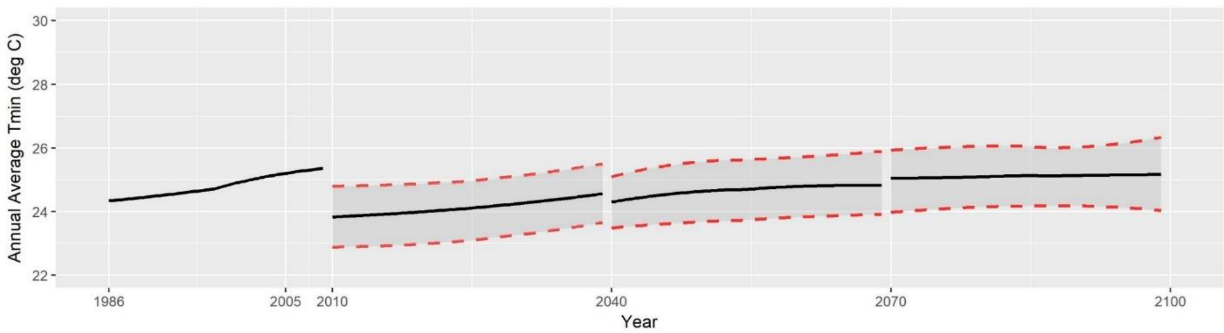
Summary of Maximum Temperature

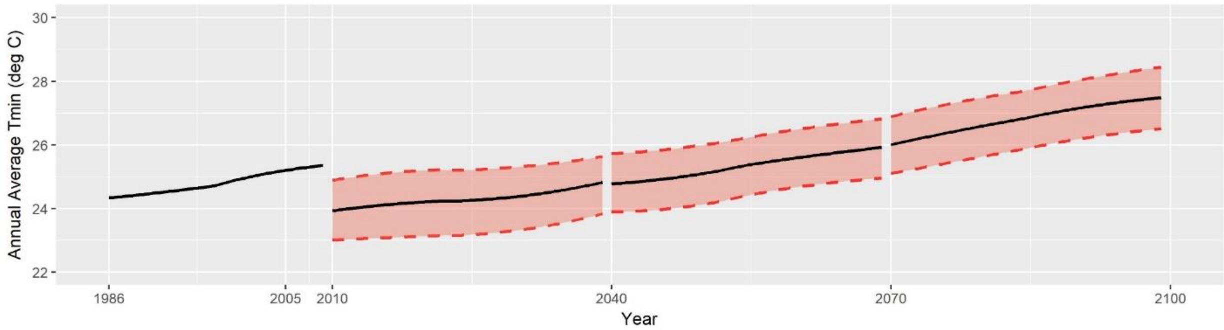
In short, the maximum temperature for Bangkok will increase in future under both the RCP scenarios except 20s period. The increase in the 21st century (ensemble average) is projected to be 0.43ºC for RCP 4.5 and 0.47ºC for RCP 8.5. The inter seasonal comparison of the changes were showed almost comparable increase between the wet and dry months.

Wet | Dry | Wet
J F M A M J J A S O N D

Bangkok, Thailand		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmax (°C)	33.28					33.31					33.25				
RCP 4.5	Average Tmax (°C)		33.71	33.14	33.70	34.29		33.68	33.05	33.66	34.3		33.75	33.2	33.75	34.28
	Change (°C)		+0.43	-0.14	+0.42	+1.01		0.37	-0.26	0.35	0.99		+0.5	-0.05	+0.5	+1.03
RCP 8.5	Average Tmax (°C)		33.75	33.62	33.65	35.05		33.95	32.8	33.83	35.25		33.54	32.45	33.47	34.8
	Change (°C)		+0.47	+0.34	+0.37	+1.77		0.64	-0.51	0.52	1.94		+0.30	-0.8	+0.22	+1.55

Annual Trend of Minimum Temperature

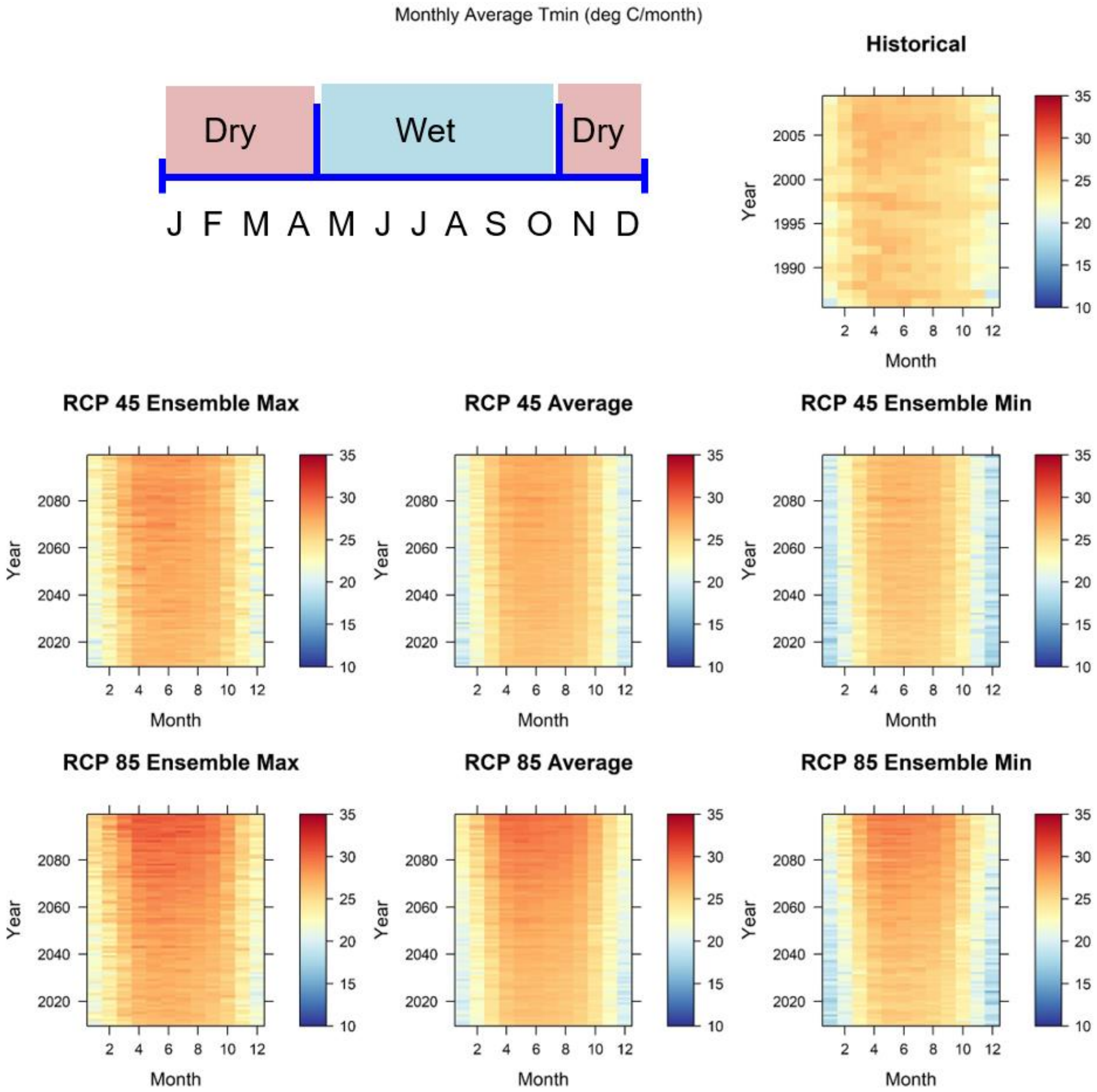




The minimum temperature (Tmin) in the past shows an increasing trend in recent years in the rate of 0.05 ºC/year. In future, RCP4.5 based projection shows an overall increase by 0.3ºC at the end of the century. Meanwhile, RCP4.5 based projection shows minimum temperature will be decrease during 20s and 50s period by 0.67ºC and 0.13ºC respectively. Whereas by RCP8.5, the overall increase would spike up to around 2.02ºC at the end of the century, with constantly increasing trends over 20s, 50s and 80s.

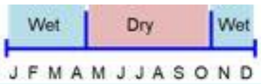
Seasonality of Minimum Temperature

The average monthly minimum temperature of the Bangkok in the past is higher in rainy months and the values seldom-crossing over 25ºC. Since then the wet months usually are seen to have Tmin around >25ºC. But the monthly Tmin never fall below 19ºC .In contrast, RCP4.5 ensemble average projection shows Tmin regularly crossing 21ºC threshold throughout the year. RCP8.5 illustrates similar effect with a much larger amplification. In this scenario, Tmin increases drastically in most of the 50s and 80s with year round average monthly Tmin of > 22ºC with values shooting 28ºC+ in months of May and June.



Summary of Minimum Temperature

In summary, the minimum temperatures in Bangkok over the 21st century is projected to increase under RCP8.5 by 0.7ºC and projected to decrease under RCP4.5 by 0.16ºC. By the end of the century, its projected that Tmin increases by 0.3ºC and 2.02ºC under RCP 4.5 and 8.5 respectively. However, seasonal values reveals wet months to be affected more in terms of increase in Tmin and dry months to be affected more in terms of decrease in Tmin.

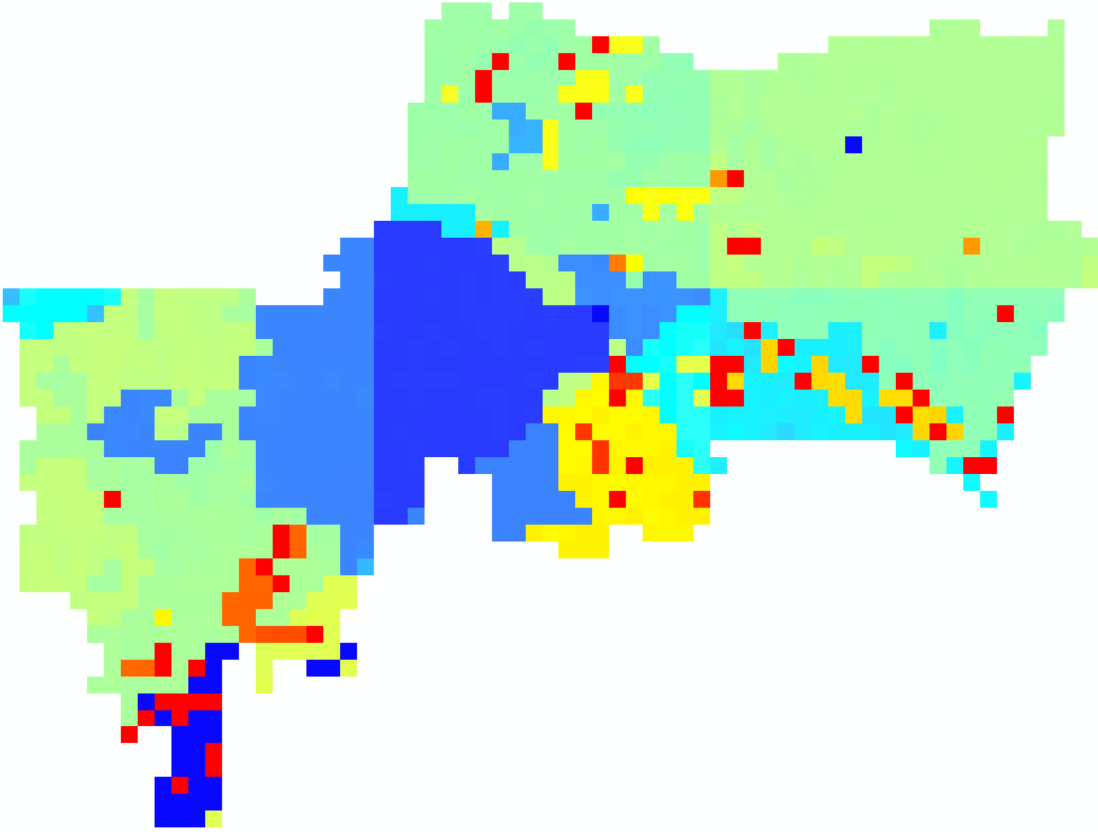


Bangkok, Thailand		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average Tmin (°C)	24.8					24.1					25.45				
RCP 4.5	Average Tmin (°C)		24.64	24.13	24.67	25.10		22.93	22.37	22.95	23.46		26.35	25.9	26.04	26.75
	Change (°C)		-0.16	-0.67	-0.13	+0.3		-1.17	-1.73	-1.15	-0.64		+0.9	+0.45	+0.59	+1.3
RCP 8.5	Average Tmin (°C)		25.5	24.23	25.32	26.82		23.83	22.63	23.64	25.22		27.15	26	27	28.45
	Change (°C)		+0.7	-0.57	+0.52	+2.02		-0.27	-1.47	0.46	+1.12		+1.7	+0.55	+1.55	+3

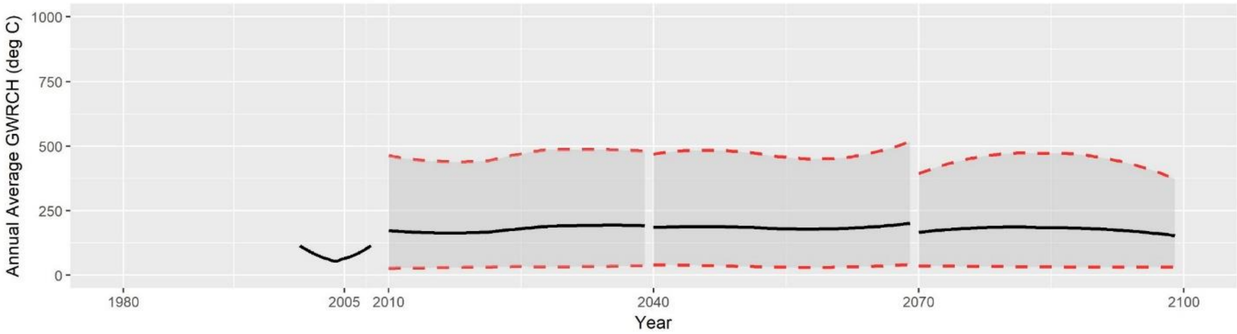
3.4.2. Groundwater Recharge Projections

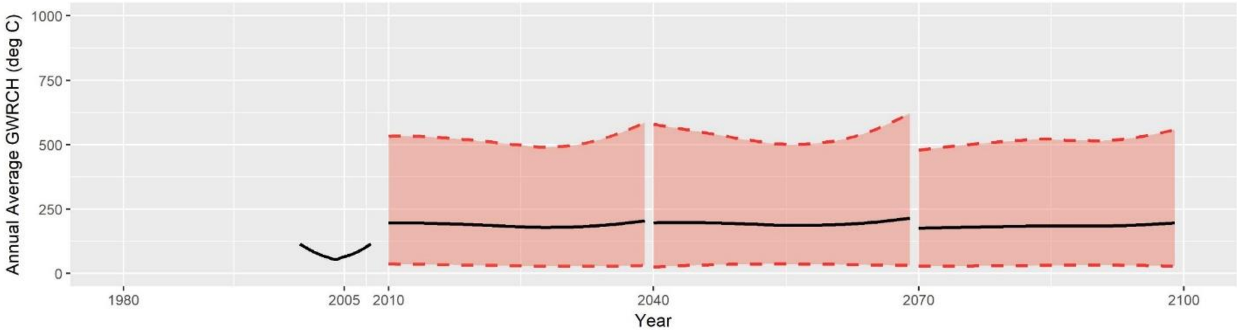
Model Performance

WetSpass was used to simulate the Groundwater Recharge of the city with climate input at three rainfall and temperature stations, other required data to run the model was extracted from global data sources. Most of the methods used to estimate groundwater recharge are point estimate. However, groundwater quantification needs a method which is not only flexible but also reliable in order to accurately quantify its spatial and temporal variability. That's why we decided to use spatially distributed model i.e. WetSpass. To calibrate and validate the model is quite complex as comparison with other modeling technique. This model cannot be calibrated and validated independently, however, GMS could be the best link to calibrate and validate the recharge. Here, we developed the 1555 cells of 1km^2 size, so that recharge is available from 1555 points. As we are not going to use GMS for the project, calibration and validation of the model is assumed correct at first iteration. The spatial variation of groundwater recharge at Bangkok city is shown in the following figure.



Annual Trend of Groundwater Recharge

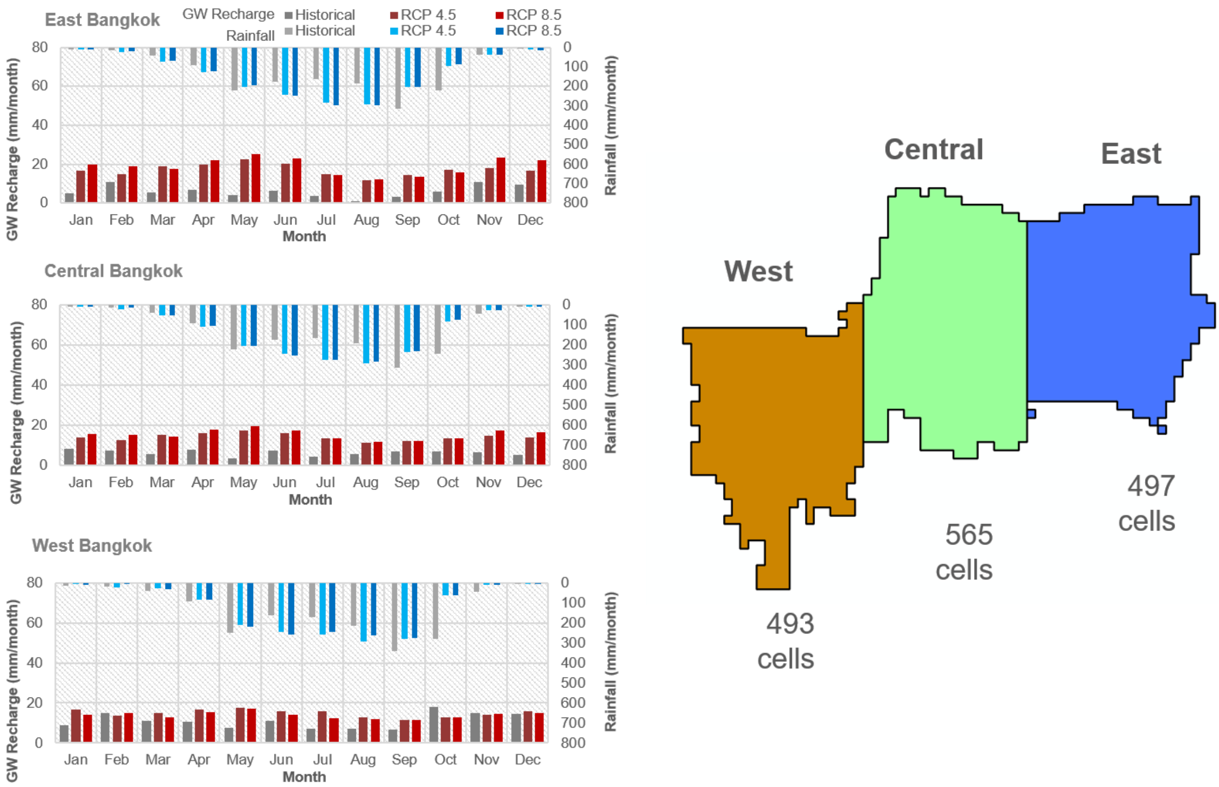




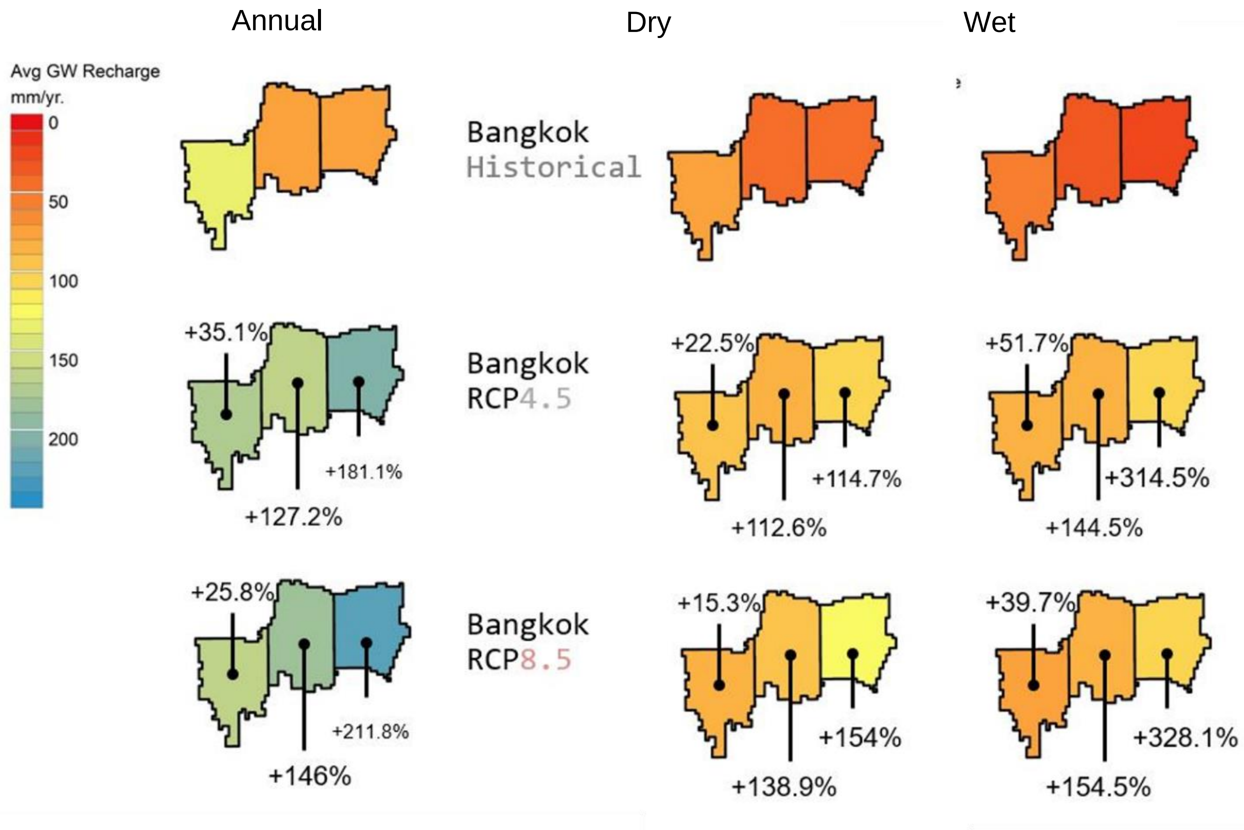
In the recent years, Bangkok's groundwater recharge (GWR) is seen to have a decreasing trend by 0.15mm/year. The average annual (ensemble) recharge under RCP4.5 shows increasing trend by 108%, 116% and 107% during 20s, 50s and 80s periods. In case of RCP8.5 the increase is even larger compared to RCP4.5.

Spatial Variation and Seasonality of Groundwater Recharge

The WetSpass model domain of Bangkok alongside the zonation of the city for spatial variation alalysis is as depicted in the figure below i.e. West, Central, and East.The zonation is based on the area covered by the three zones (almost equally devided), so that we can have the recharge of each zone with respect to constant area. There were 1555 cells of 1km^2 size, we can get different recharge value from each cell but we are not requiresd that much minute analysis so we moved ahead by considering three zones, each zones comprises 493 (west), 565 (central), and 497 (east) cells of 1km^2.

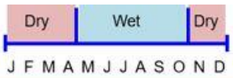


Looking at the groundwater results, all the zones are safer in terms of climate change impact (CCI) on GWR. The average annual recharge value of the city is higher in western part and is slightly decline towards eastern part. During the historical time, the average annual value of recharge was 85.9mm in decreasing trend of 0.15mm/year. As replicated in below figure, the projected recharge is in increasing order under both RCPs scenarios but in terms of percentage change, higher increase can be seen under RCP8.5. The recharge will be increase in dramatic amount in eastern part under both RCPs scenario and as compare to other two part the increasing amount is slightly low in western part of the city. So, climate change will not have negative impact in recharge in Bangkok city, for all three zones (well recharged). Figure shows increase recharge during both dry and wet seasons with higher positive change during wet seasons under both climate scenarios.



Summary of Groundwater Recharge

In summary, the groundwater recharge of the Bangkok is projected to increase by 111% and 120% based on RCP4.5 and RCP8.5 respectively. The larger proportion of the increase is seen in the wet seasons with 154% and 162% under RCP4.5 and RCP8.5 respectively. Recharge during dry season also have positive change but as comparison with wet season the change is less.



Bangkok, Thailand		ANNUAL					DRY					WET				
		Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)	Past (1980 – 2005)	21st century	20s (2010 – 2039)	50s (2040 – 2069)	80s (2070 – 2099)
Base-line	Average GWR (mm/yr.)	85.9					49.9					36				
RCP 4.5	Average GWR (mm/yr.)		180.9	179.1	185.9	177.6		92.1	90.4	94.5	91.4		88.8	88.7	91.4	86.2
	Change (mm)		95 +111%	93.2 +108%	100 +116%	91.7 +107%		42.2 +84.6%	40.5 +81.2%	44.6 +89.4%	41.5 +83.2%		52.8 +147%	52.7 +146%	55.4 +154%	50.2 +139%
RCP 8.5	Average GWR (mm/yr.)		189.2	189.4	194.9	183.2		100.3	101.6	100.6	98.7		88.8	87.7	94.3	84.5
	Change (mm)		103 +120%	104 +120%	109 +127%	97.3 +113%		50.4 +101%	51.7 +104%	50.7 +102%	48.8 +97.8%		52.8 +147%	51.7 +144%	58.3 +162%	48.5 +135%

3.4.3. Adaptation Options

Groundwater management in Bangkok is already in advance stage compared to other cities. Groundwater Act is already in place for a long time with provisions for economic instruments. Critical zones for groundwater abstraction is already identified. A project for artificial recharge along the Chao Phraya river is also in place. Therefore, adaptation strategies are a bit different than other cities. The adaptation options identified during the second regional workshop are listed hereunder in decreasing order of priority;

- Regulatory mechanisms to increase groundwater abstraction in the areas of rising groundwater levels to keep the groundwater level within safer depth
- Awareness raising of stakeholders on groundwater rising on post-regulation stage
- Evaluate/update safe yield at regular intervals to maintain groundwater level at a certain depth
- Mainstreaming groundwater issues in resilient cities or other similar city-wide adaptation initiatives

4. Conclusions

4.1. Climate Change Projections summary

In summary, the range of change in climate projected varies between the four project cities. In terms of rainfall, Ho Chi Minh city is going to see a decrease in rainfall by around 3 – 4 % than in the past. Bandung is also projected to receive lesser rainfall, especially from the RCP 8.5 scenario basis. Whereas Bangkok and even more so Lahore are expected to get a boost in annual precipitation, with the former having a +10 to +14.5 % increase and the latter getting up to +2.2 % increase in rain.

Climate Change Projections in the 21st century		Project Cities			
		Bandung	**Lahore**	**Ho Chi Minh**	**Bangkok**
Rainfall **% against baseline**	RCP 4.5	-1.0 %	+14.5 %	-3.3 %	+2.2 %
	RCP 8.5	-3.5 %	+10.7 %	-4.2 %	+0.97 %
Maximum Temperature **Degree C**	RCP 4.5	+1.1	+1.2	+1.2	+0.43
	RCP 8.5	+1.7	+2.6	+1.7	+0.47
Minimum Temperature **Degree C**	RCP 4.5	+1.9	+1.1	+1.9	-0.16
	RCP 8.5	+3.1	+2.2	+2.6	+0.7

In case of temperature, Bangkok is seen to receive least fluctuations from the baseline in the upcoming century. Whereas, all the other three cities are seen to get an increase in temperature in the range of +1.1 to + 3.1 ^{0}C. However, it was seen that minimum temperature is more affected by climate change compared to the maximum daily temperatures.

4.2. **Groundwater Recharge Projections summary**

Climate model input based modelling of groundwater recharge projections show contrasting results for the four project cities. At one end, there is Bandung and Ho Chi Minh city who have a declining groundwater recharge projected in the upcoming decades. While on the other hand, Bangkok and Lahore are expected to get huge increase in groundwater recharge. This is in line with the projected changes in rainfall for the four cities. However, in case of Bangkok the minimal changes in temperature seems to have played a big role in simulating large groundwater recharge increase in the future compared to the baseline.

GW Recharge Projections in the 21st century % against baseline		Project Cities			
		Bandung	Lahore	Ho Chi Minh	Bangkok
Annual	RCP 4.5	-2.9 %	+82.9 %	-13.8 %	+111 %
	RCP 8.5	-10 %	+74.1 %	-14.4 %	+120 %
Dry Season	RCP 4.5	-8.2 %	+99.0 %	-33.2 %	+84.6 %
	RCP 8.5	-14.7 %	+87.3 %	-38.5 %	+101 %
Wet Season	RCP 4.5	+2.0 %	+62.3 %	-4.0 %	+147 %
	RCP 8.5	-5.6 %	+57.0 %	-2.2 %	+147 %

In case of Bandung and Ho Chi Minh city, the decrease in groundwater recharge is more severe in the dry season with Ho Chi Minh city projected to suffer up to -38.5% decrease in recharge rates. In case of the recharge increase in Lahore and Bangkok, the rate is higher in the dry season for Lahore while its lower in dry season for Bangkok.

5. Future Directions

We believe that a practice of detailed groundwater vulnerability such as this study provides the opportunity to explore further in the following avenues –

1. To carry out detailed capacity building including hands-on training on the methods utilized in this project.
2. Numerical evaluation of the discussed adaptation options.
3. Evaluation of climate change impact on groundwater via numerical modelling using groundwater models.

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Appendix

Conferences/Symposia/Workshops

Attached in Appendix

List of Young Scientists

Include brief detail (full name, involvement in the project activity) and contact detail (name of institution/country and email address) of your scientists involved in the project. Also include short message from the young scientists about his/her involvement in the project and how it helps develop/build his capacity and the knowledge he gained.

"This was a big learning experience for me, simply because of the multi dimension scope of work ranging between organizing events, correspondence with project partners, coordinating a team of numerical modellers and doing model analysis. It was a uniquely designed project that led to substantial growth of the young researchers in the team including me. "

Pallav Kumar Shrestha – Project coordination and leading modelling component
Asian Institute of Technology, Thailand, pallav@ait.asia

"This project has been a great learning experience for a young researcher like me. From working on hydroclimatic modelling to managing the project and interacting with the collaborators and expertise through emails, webinars and workshop has helped me grow as researcher."

Ranju Chapagain – Hydroclimatic modeller (till 1st Workshop)
Asian Institute of Technology, Thailand, ranju@ait.asia

"Working on regional groundwater modelling has always been a difficult and time-consuming exercise, and that if adequate data are not available assumptions have to be made regarding processes and parameters. In an effort to link the climate parameters to groundwater modelling through the hydrological model (recharge model), we provide the impact analysis of climate change on groundwater resource. Working with multiple models ranging from climate model to hydrological model (SWAT) and groundwater model has fully developed my comprehensive understanding on hydrology cycles and enhanced my modelling skills. In addition, involved into regional workshops and co-operation with other partners was a great opportunity for me to understand the current situation at four selected cities as well as expended the networking”

Hoàng Thị Ngọc Anh – Hydroclimatic and Groundwater modeller
Asian Institute of Technology, Thailand, anhhtn96@wru.vn

“I try not to think about anyone’s expectations but rather focus on always doing my personal best. Hydrological and Groundwater Modelling was never a thought in my mind growing up, but my supervisor felt it was important for me to be open business opportunities and expand my horizons. This project was a big platform for me to be developed myself as a hydrological and groundwater modeller at a same time. As we were having data deficit problems during the modelling time, I have got imperturbable idea to work with dearth data. Projects boost up my confident to work in-group, to develop the technical report, to proceed the modelling work with insufficient data, and analysis of results from different angle of eye. So, working with this team in APN project by considering the scattered cities of ASIA was milestone turning of my modelling career.”

Binod Bhatta – Hydroclimatic and Groundwater modeller
Asian Institute of Technology, Thailand, binodbhatta40@gmail.com

Rana Ammar Aslam – PhD student
Asian Institute of Technology, Thailand, engr.ammar.ok@gmail.com

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Glossary

APN	-	Asia Pacific Network
CCA	-	Climate change analysis
CCI	-	Climate change impact

DEM	-	Digital Elevation Model
GDP	-	Gross Development Product
GIS	-	Geographic Information System
GWR	-	Ground water recharge
HRU	-	Hydrological response unit
IPCC	-	International panel on climate change
HCMC	-	Ho Chi Minh City
LS	-	Linear Scaling
QM	-	Quantile mapping
RCM	-	Regional climate model
RCP	-	Regional concentration pathways
SWAT	-	Soil and Water Assessment Tool
WETSPASS	-	Water and Energy Transfer between Soil, Plants and Atmosphere under Steady State condition

In the Appendix section, the report may also include:

- *Actual data or access to data used in the study*
- *Abstracts, Power Point Slides of conference/symposia/workshop presentations*
- *Conference/symposium/workshop*