Science of the Total Environment 792 (2021) 148370

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Climate and land-use change impacts on spatiotemporal variations in groundwater recharge: A case study of the Bangkok Area, Thailand

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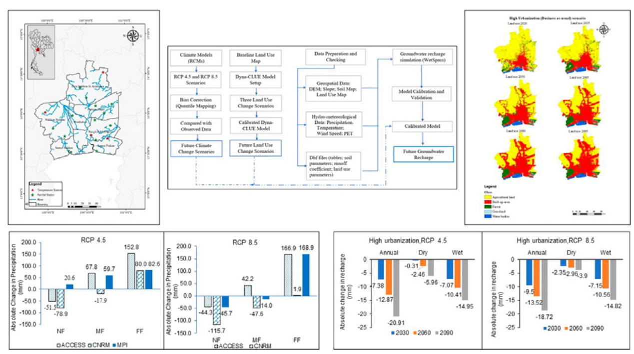
HIGHLIGHTS

- Climate change and land-use change impact on groundwater recharge were assessed.
- Future temperature is projected to increase in accordance with the global trend.
- Precipitation is not uniform and varying throughout the future.
- Three land-use change scenarios; high, medium, and low urbanisation were analysed.
- Combined climate and land-use change increased groundwater recharge for low urbanisation scenario.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 30 March 2021
Received in revised form 4 June 2021
Accepted 7 June 2021
Available online 17 June 2021

Guest Editor: Elena Paoletti

Keywords:
Climate change
Quantile mapping
Urbanisation
Dyna-CLUE
WetSpass
Bangkok

ABSTRACT

Groundwater contributes to the socioeconomic development of the Thai capital Bangkok and its vicinity. However, groundwater resources are under immense pressure due to population growth, rapid urbanisation, overexploitation, and climate change. Therefore, evaluating the combined impact of climate change and land-use change on groundwater recharge can be useful for developing sound groundwater management systems. In this research, the future climate is projected using three Regional Climate Models (RCMs), namely ACCESS-CSIRO-CCAM, CNRM-CM5-CSIRO-CCAM, and MPI-ESM-LR-CSIRO-CCAM for three future periods: near future (2010–2039), mid future (2040–2069), and far future (2070–2099) under two Representative Concentration Pathway (RCP) scenarios 4.5 and 8.5 as suggested in the IPCC's Fifth Assessment Report. All RCMs project the temperature to rise incessantly, although future precipitation is predicted to fluctuate (increase and decrease) among the various RCMs and RCP scenarios. A Dyna-CLUE model is employed to analyse the future land-use change scenarios (low, medium, and high urbanisation), with the aim of expanding the built-up area and creating land-use maps covering the period to 2099. A hydrological model, WetSpass, is used to estimate groundwater recharge under future climate and land-use change. The findings reveal that groundwater recharge is expected to decrease in high and medium urbanisation areas, ranging from 5.84 to 20.91 mm/yr for the RCP 4.5 scenario and 4.07 to 18.72 mm/yr for RCP 8.5. In contrast, for the low urbanisation scenario, the model projects an increase in groundwater recharge ranging from 7.9 to 16.66 mm/yr for the RCP 4.5 scenario and 5.54 to 20.04 mm/yr for RCP 8.5.

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https://doi.org/10.1016/j.scitotenv.2021.148370
0048-9697/

1. Introduction

Rapid urbanisation, population growth, industrialisation, overexploitation of surface and groundwater resources, tourism, and economic development have created huge pressure on groundwater resources, which will eventually lead to decline in the water table and groundwater recharge rates (Gautam and Prajapati, 2014). Climate change has also become a serious threat to water resources by affecting major long-term climate variables such as air temperature, precipitation, and evapotranspiration (Treidel et al., 2012). The risks induced by intense climate change events are observed to be huge, even with a 1 °C increase in maximum temperature. In several tropical and sub-tropical regions, water availability is projected to alter (IPCC, 2014). Under such circumstances, the hydrological cycle experiences erratic changes in precipitation and evaporation. As this trend continues, it will seriously impact on surface and groundwater resources.

There is a complex linkage between climate change and land-use change. Land-use change is an important driver of climate change since a changing climate can lead to alterations in land use and land cover. Like all resources, freshwater resources are greatly impacted because all human activities are reliant upon them. Climate change and land-use change directly influence both surface water and groundwater resources, but evaluating the level of impact on groundwater resources presents a significant challenge. Since groundwater resources are vital for both humans and the ecosystem, groundwater recharge should be considered in an analytical and sustainable way to achieve effective water resources management under varying environmental conditions (Pan et al., 2011). Good insight into the hydrological process supports the accurate estimation of regional groundwater recharge which could be greatly altered by human activities and worldwide climate change. Land-use change impacts the availability of water resources by changing the water balance in the area (Kundu et al., 2017). Therefore, the impacts of climate and land-use variation on groundwater recharge should be thoroughly explored, especially in areas experiencing rapid human expansion and inadequate shallow water.

The need for fresh water continues to rise globally, led by the growth of irrigated agriculture, an increase in the overall population, and commercial growth (Siebert et al., 2010; Wada et al., 2010). This growing demand is mainly met by groundwater, especially in areas where surface water pressure generally persists (Wada et al., 2010). The considerable effect on groundwater recharge has recently been analysed in Ho Chi Minh (HCMC) due to variations in the impermeable urbanised area (Adhikari et al., 2020). Therefore, assessing the impact of land-use change on groundwater recharge depends on the accurate forecasting of changes in major land use, population size, and evaluation of groundwater recharge. According to Pholkern et al., 2018, in Central Huai Luang Basin, Northeast Thailand, climate change has impacted on groundwater recharge, soil salinity distribution, and waterlogging, while the analysis by Shrestha et al. (2020) concluded that groundwater resources in Kathmandu Valley are at risk due to climate change. Similarly, a study by Ali et al. (2012) focused on South-Western Australia, revealing that a decrease in rainfall in addition to groundwater overextraction is the main reasons for declining groundwater levels and dependent ecosystems. Furthermore, these researchers found that all water balance components such as evapotranspiration, surface runoff, and percolation are affected by climate change, further impacting on the extractable water from both confined and unconfined aquifers. The outcomes from the study by Tam and Nga (2018) indicated that the decline in groundwater level was due to massive groundwater abstraction, while a rise in impermeable areas due to rapid development only triggered a small groundwater recharge decrease in the case of Hanoi, Vietnam.

Bangkok has been experiencing a significant reduction in groundwater since the 1960s. Several reports have indicated that rapid development and climate change are the most likely causes of groundwater loss due to a decrease in the recharge of shallow aquifers. However, groundwater has also been affected by non-climatic factors such as industrial growth, population increase, a reduction in surface water resources, and land-use change practices. The high level of groundwater consumption in Bangkok and its vicinity has created adverse economic and environmental challenges like the continuous decline in the potentiometric surface of pumped aquifers, and water quality degradation by saltwater intrusion (Buapeng and Wattayakorn, 2008). In addition, the overutilisation of groundwater has induced significant land subsidence in the area (Lorphensri et al., 2016). Excessive groundwater abstraction and land subsidence lead to numerous challenges such as groundwater pollution, health hazards, loss of properties, flooding, and the devastation of infrastructure facilities (Gupta and Babel, 2006). Even though groundwater plays a significant role, only a few studies have been conducted in this area compared to surface water resources in the context of land-use change and climate change scenarios. Therefore, this study relating to the impact of land-use change and climate change on groundwater recharge is imperative for bridging the research gap.

This study intends to examine the impact of climate change and land-use change on groundwater recharge in Bangkok and its vicinity. The specific objectives of this study comprise: i) an analysis of the future climate change using the quantile mapping technique; ii) investigation of past, present, and future land-use patterns employing the Dyna-CLUE model; and iii) the estimation of spatial and temporal groundwater recharge distribution in Bangkok and its vicinity using the hydrological model WetSpass. The hypothesis of this study is: the combined impact of climate change and land use change on groundwater recharge of Bangkok and its vicinity is significant and may lead to increase or decrease of groundwater recharge.

2. Study area and data collection

2.1. Study area

The study area is Thailand's capital Bangkok (13° 45′ North and 100° 31′ East) and its vicinity (Nonthaburi, Nakhon Pathom, Pathum Thani, Samut Prakan, Samut Sakhon, and Phra Nakhon Si Ayutthaya) (Fig. 1). Bangkok and its nearby provinces are located along the banks of the Noi and Chao Phraya Rivers, while the other major rivers are Mae Klong, Pasak, Prachin, and Tha Chin. The study area is situated in a humid tropical region with warm temperatures throughout the year. Bangkok has a tropical dry-and-wet climate, with two seasons: dry (November to April) and wet (May to October), under the influence of the South Asian monsoon system. The average temperature is 30 °C/year with an average rainfall of 1500 mm/yr. According to the 2010 census, Bangkok and its vicinity have a total population of 11.3 million and a population density of 300–3600 persons/km^2. The use of groundwater began in the mid-1950s and continued to rise until 1997. The main groundwater-associated problems are land subsidence (rate = 1.0 cm/y from 2006 to 2012), reduction and resurgence in groundwater concentrations, and groundwater quality degradation. Agricultural land is the main land-use category in the study area but exhibits a continuous decrease while the built-up area continues to grow.

2.2. Data collection

2.2.1. Historical and future climate scenarios

Baseline precipitation and temperature data from 1976 to 2005, obtained from the Thai Meteorological Department (TMD), Thailand, is used in this study to analyse the future climate data for Bangkok and its vicinity, along with three Regional Climate Models (RCMs): ACCESS-CSIRO-CCAM, MPI-ESM-LR-CSIRO-CCAM, and CNRM-CM5-CSIRO-CCAM under RCP 4.5 (medium) and RCP 8.5 (high) emission scenarios, downloaded from the CORDEX (South Asia) data portal (http://cccr.tropmet.res.in/home/index.jsp). Climate data (precipitation and temperature) is initially obtained from each RCM (Table 1). The quantile mapping technique is employed to correct bias in the future climate

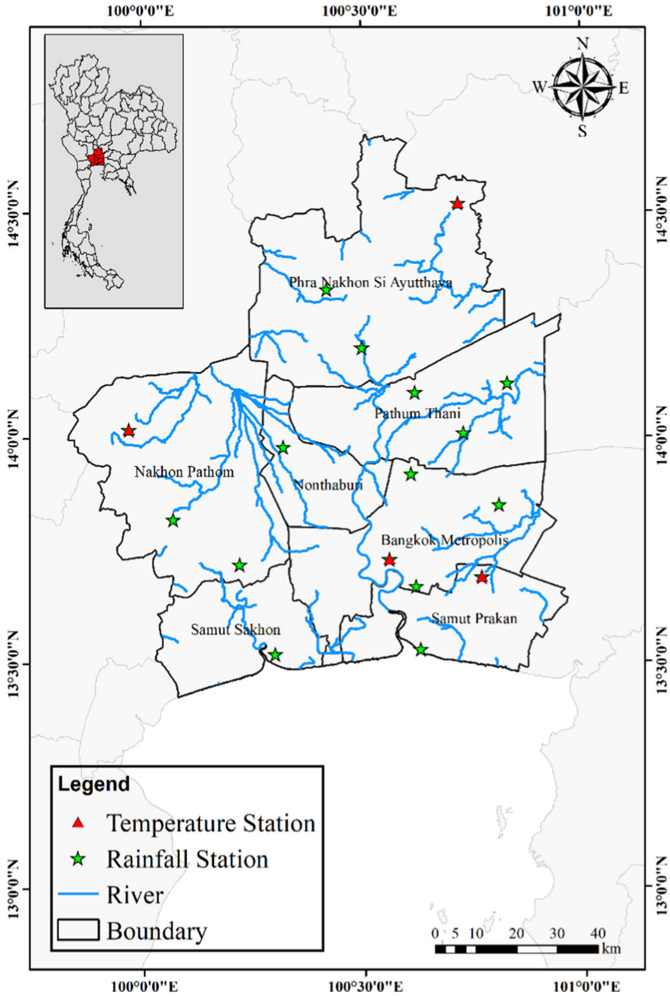

Fig. 1. Location map of Bangkok and its vicinity with meteorological stations and the river network.

data for the area. From the time perspective, the RCP scenarios differ in radiative forcing and greenhouse gas intensity. The main objective of the RCP scenarios is to identify future uncertainties without forecasting them, with different socioeconomic hypotheses used in their development (Moss et al., 2010; Rogelj et al., 2012). In this study, two scenarios are used: RCP 4.5 and RCP 8.5.

Table 2
Land-use area in Bangkok and its vicinity for 2008, 2010, 2012, 2014, and 2015.

Code	Aggregated class	Baseline year					Percentage change/year
		2008	2010	2012	2014	2015	
0	Agricultural land	73.0%	72.2%	70.5%	69.2%	69.0%	−0.570
1	Grassland	4.4%	4.4%	4.4%	4.4%	4.4%	−0.003
2	Forest	7.1%	7.1%	7.0%	7.0%	7.0%	−0.017
3	Built-up areas	11.1%	12.0%	13.8%	15.2%	15.4%	0.611
4	Water bodies	4.4%	4.4%	4.3%	4.3%	4.3%	−0.022

2.2.2. Historical land use in Bangkok and its vicinity

In this study, land-use maps of 2008, 2010, 2012, 2014, and 2015 were obtained from the European Space Agency (ESA) data portal (https://maps.elie.ucl.ac.be/cci/viewer/). After analysing the land-use patterns from 2008 to 2015, five major land-use classes were identified: agricultural land, grassland, forest, built-up areas, and water bodies. The percentage area under each land use for 2008, 2010, 2012, 2014, and 2015 is shown in Table 2. In 2008, a total area of 9954 km^2, about 72.9% (7266 km^2), was used for agricultural activities, decreasing to about 69% (6869 km^2) in 2015. The built-up area has experienced continuous growth since 2008, covering about 11.09% (1104 km^2) of the area. In 2015, the built-up area represented 15.36% (1530 km^2) of the total land use. However, only a slight change occurred in grassland, forest, and water bodies from 2008 to 2015.

3. Research methodology

The overall methodology used in this research is shown in Fig. 2. The climate data for the baseline and future scenarios obtained from the climate models and land-use change scenarios, developed using the Dyna-CLUE model, are input into the WetSpass model to simulate future groundwater recharge. The simulation is based on observed daily climate data (i.e., 30 years) and baseline land-use change scenarios.

3.1. Future climate projection

The future climate is projected using climate data from three RCM and two RCP scenarios. Logical error is present in the model, causing

Table 1
Data used in this study and its sources.

SN	Data	Source/developer	Spatial/temporal resolution	Time period
Physical characteristics of the catchment area				
1	Elevation	United States Geological Survey (USGS) (2019) website (https://earthexplorer.usgs.gov)	90 m/—	–
2	Soil	Food and Agriculture Organization (FAO) (2019) website (http://www.fao.org/geonetwork)	1:5000000	–
3	Land Use	European Space Agency (ESA) (2019) website (https://maps.elie.ucl.ac.be/cci/viewer/)	300 m/—	5 maps 2008, 2010, 2012, 2014, and 2015
Time series data				
1	Meteorology	Thai Meteorological Department (TMD)	Point/daily	17 rain and 4 temperature stations (1976–2005), 7 windspeed stations and evapotranspiration
2	Hydrology	Royal Irrigation Department, Thailand (RID)	Point/daily	2001
3	Groundwater Level	Department of Groundwater Resources, Thailand (DGR)	Point/yearly	2001
RCM data for future climate projection				
1	ACCESS-CSIRO-CCAM	In association with Australia Weather and Climate Research, Australian Government	0.5°/daily	RCP 4.5 and RCP 8.5: 1975–2099
2	MPI-ESM-LR-CSIRO-CCAM	National Center for Meteorological Research		
3	CNRM-CM5-CSIRO-CCAM	European Network for Earth System Modeling		

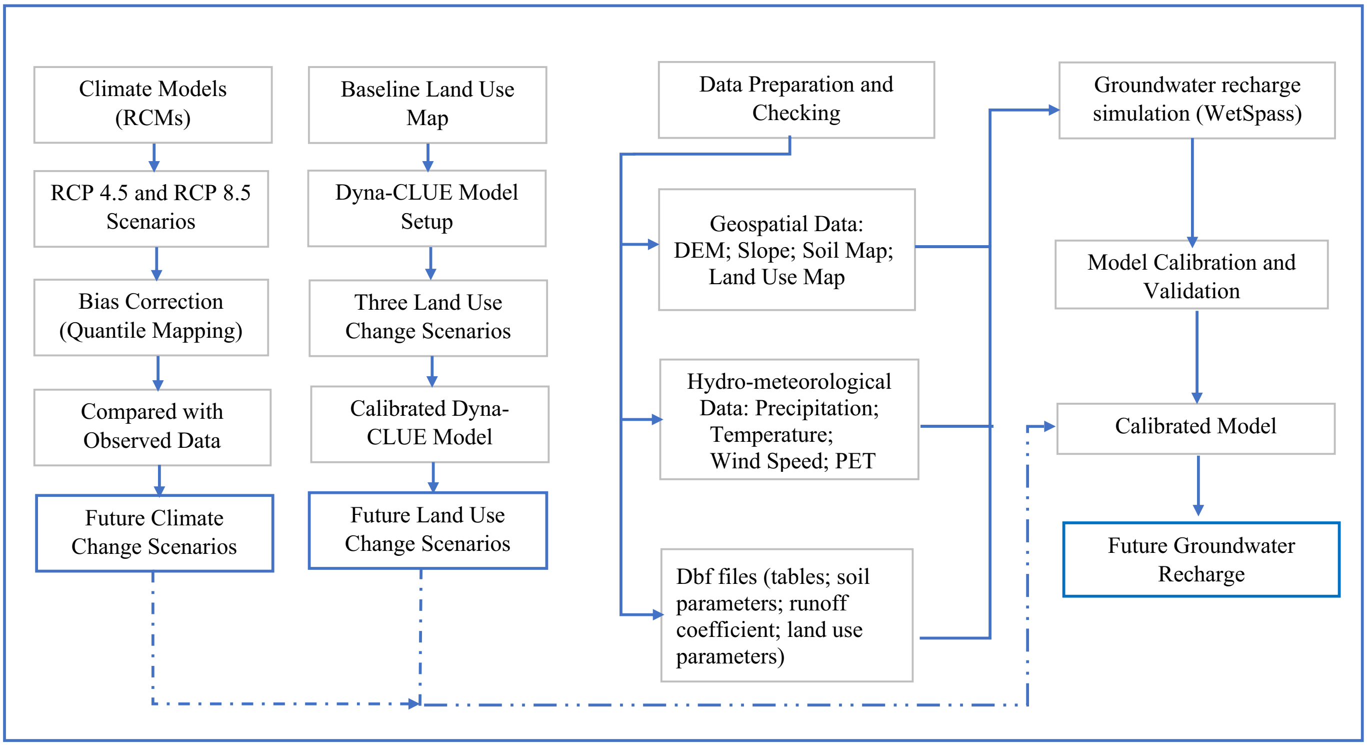

Fig. 2. Overall methodology used to assess the impact of climate change and land-use change on the spatiotemporal variation of groundwater recharge in Bangkok and its vicinity.

many faulty concepts and resulting in discretisation and dimensional averaging within the grid cell. The need for bias correction expressively creates doubt in the modeling of climate change effects. In this study, the quantile mapping method (QM) is chosen to correct the bias in climate data of selected RCMs since it decreases bias in daily temperature and precipitation by roughly one order of magnitude (Themebl et al., 2012), and is better than other methods for correcting peak values, especially the 90th percentile (M'Po et al., 2016). In this research, empirical QM is applied with the 99-percentile table created and linear interpolation between them. This method employs the R language (Venables and Smith, 2012) using the "qmap" package (Gudmundsson, 2014). The following equations are applied for quantile mapping:

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

$$P_{sim}(d)* = F^{-1}_{obs,m}\lfloor F_{sim,m}(P_{sim,m})\rfloor \quad (2)$$

$$T_{his}(d)* = F^{-1}_{obs,m}\lfloor F_{his,m}(T_{his,m})\rfloor \quad (3)$$

$$T_{sim}(d)* = F^{-1}_{obs,m}\lfloor F_{sim,m}(T_{sim,m})\rfloor \quad (4)$$

where, P = precipitation, T = temperature, d = daily, m = monthly * = bias corrected, his = Raw RCM data, obs = observed data, sim = Raw RCM future data, F = Cumulative Distribution Function (CDF), F^{-1} = inverse of CDF.

The future time series data obtained after bias correction is analysed and compared with the baseline climate data in terms of variation across different future periods, seasonal change, long-term average, and RCP scenario changes.

3.2. Land-use projection using Dyna-CLUE model

Future land-use change is projected using the Dyna-CLUE model, with the national level demands being spatially allocated to each grid cell concerning the demanded area with the area accessible for the respective land-use type and simulation of land use being done using iterative procedure. It can be applied to evaluate the influence of land-cover change on cropland quality to obtain more precise outcomes (Wang et al., 2019). Similarly, this model has the capability to better simulate land-cover change under well-defined scenarios along with the related spatial policies and restrictions, driving forces, and suitability with respect to planned scenarios. The step-by-step logistic regression technique is applied to assess the suitability of the neighborhood and location for the individual land-use category, with logistic regression determined as shown in Eq. (5) (Verburg and Overmars, 2009).

$$\mathrm{Log}\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \beta_n X_{n,i} \quad (5)$$

where,Pi = the probability that the respected land-use feature may appear in a particular grid cell.Xs = the driving factors.β (coefficient) estimated using logit regression.

For Bangkok and its vicinity, the Dyna-CLUE model was adjusted by utilising the 2008 land-use map to simulate that of 2015, under the following three scenarios:

1. High urbanisation scenario (business as usual)
   In this scenario, huge changes are expected in the land-use pattern, while future land demand is assumed to follow the historical trend.
2. Medium urbanisation scenario (MU)

High economic growth is assumed, resulting in low demand for grassland and forest areas. Built-up areas are assumed to increase to about 25% of the total land area by 2099, followed by a small decrease in agriculture and grassland.

3. Low urbanisation scenario (conservation)

This scenario assumes that the conservation of forest and ecology is prioritised, meaning no rapid change is likely to occur in the built-up area. The forest is assumed to increase to 25% of the total land area by 2099, followed by a small decrease in agriculture and grassland.

These scenarios are based on those proposed in a similar study conducted by Shrestha et al. (2018a, 2018b) in the Songkhram River Basin, Thailand.

The Kappa analysis method was adopted in this study to compare the observed and simulated land use for 2015. The verification inaccuracy is quantified by applying Kappa statistical analysis (K), as shown in Eq. (6). The value of K ranges from 0 to 1, with nearer to 1 signifying better arrangement between the observed and simulated maps (Cohen, 1960).

$$K = \frac{\Pr(a) - \Pr(e)}{1 - Pr(e)} \tag{6}$$

where,Pr(a) = the measured agreement among all rasters.Pr(e) = the hypothetical probability of agreement.

3.3. Hydrological model development

Hydrological models are mostly employed as a standard tool for studying hydrological courses, several of which have varying applications, ranging from small watersheds to worldwide models. Each model has unique applications, features, characteristics, and demerits. In this study, the WetSpass (Water and Energy Transfer between Soil, Plants and Atmosphere under Steady State conditions) model is used to calculate the water balance of a grid cell (considering the fractions of bare soil, vegetation, impervious area, and open water). This model offers significant advantages when evaluating long-term average spatial patterns of groundwater recharge (Batelaan and De Smedt, 2007). In the case of Bangkok only, the WetSpass model is used to cover a hydrological catchment within the city (Shrestha et al., 2018a, 2018b). The WetSpass model has the ability to effectively estimate groundwater recharge (Aish et al., 2009; Tesfamichael, 2009; Saleem et al., 2010; Graf and Kajewski, 2013). It has also been used to calculate the approximate impact of climate change and urbanisation on the water balance component (Zhang et al., 2017). In this study, the WetSpass model is integrated into the GIS ArcView as a raster model, coded in Avenue. The overall water balance of a raster cell can be stated scientifically as given in the following Eqs. 7–9:

$$ET_{raster} = a_v ET_v + a_s E_s + a_0 E_0 + a_i E_i \tag{7}$$

$$S_{raster} = a_v S_v + a_s S_s + a_0 S_0 + a_i S_i \tag{8}$$

$$R_{raster} = a_v R_v + a_s R_s + a_0 R_0 + a_i R_i \tag{9}$$

where, ET_{raster}, R_{raster}, S_{raster} represent the total evapotranspiration, groundwater recharge, and surface runoff of a single grid cell, respectively and a_v, a_s, a_0, and a_i are the vegetated, bare soil, open water, and impervious area components, respectively.

WetSpass model requires seasonal parameters, and therefore the six months from May to October are counted as summer (wet season), and the other six months as winter (dry season) in the study area. Climate data such as daily average temperature, precipitation, wind speed, and potential evapotranspiration are used as the observed data. Similarly, the grid maps for land use, slope, soil texture, topography, and groundwater levels are prepared in GIS. The input files required as parameter tables for summer and winter land use, runoff coefficient, and soil texture are in a database file format (dbf). The parameter values are selected from those reviewed in the existing literature. The present and future climate data is managed in GIS to create spatial maps and then input into the WetSpass model. The model is then calibrated to evaluate the effect of climate change and land-use change in groundwater recharge. Since the groundwater level is input into the WetSpass simulation, the GMS-MODFLOW (Groundwater Modeling System-MODFLOW) and WetSpass models must be performed one after another by exchanging recharge and groundwater depth. This will lead to a stable solution for the discharge areas and groundwater level after a few iterations. After calibration of the WetSpass model, future groundwater recharge under both RCPs scenarios and all land-use change scenarios is then projected. The model estimates the spatial distribution of recharge from the water balance concept. In this research, an ensemble (average) between the RCMs represents the projection for each RCP 4.5 and RCP 8.5 scenario.

4. Results and discussion

4.1. Projected future climate of Bangkok and its vicinity

The future climate of Bangkok and its vicinity is projected using the RCM (CSIRO-CCAM) but driven by three different GCMs: ACCESS-CSIRO-CCAM, MPI-ESM-LR-CSIRO-CCAM, and CNRM-CM5-CSIRO-CCAM under two emission scenarios (RCP 4.5 and RCP 8.5) for the near future (2010–2039), mid future (2040–2069), and far future (2070–2099). The process involves comparing the observed (1960–2005) and bias-corrected climate dataset, and computing the standard deviation, RMSE, and R^2 among these two datasets.

The yearly average baseline precipitation, and maximum and minimum temperatures for Bangkok and its vicinity are 1146 mm, 33.12 °C, and 23.50 °C, respectively. All RCMs and both RCP scenarios agree that the future maximum and minimum temperatures will increase annually and seasonally throughout all time periods. By the end of the twenty-first century, the average yearly maximum temperature is expected to increase by 0.6 to 1.4 °C in RCP 4.5 and 0.6 to 2.5 °C in the RCP 8.5 scenario. Similarly, the average yearly minimum temperature is forecast to increase by 0.7 to 2.1 °C in RCP 4.5 and 0.8 to 3.8 °C in RCP 8.5. The ACCESS-CSIRO-CCAM projected the highest increase in both future maximum and minimum temperature throughout the future period and both RCP scenarios. The increase in future minimum temperature is projected to be significantly higher than that of the future maximum temperature (Vose et al., 2005; Kharin et al., 2013; Shrestha et al., 2018a, 2018b, 2020).

The precipitation is not uniform and varies throughout the future in Bangkok and its vicinity. The annual average future precipitation in the dry season is projected to increase by 16.6 to 73.8 mm under the RCP 4.5 scenario and 9.9 to 145.1 mm for RCP 8.5. Whereas the annual average precipitation in the wet season is expected to decrease in the near and mid future and increase in the far future under both RCPs scenarios. The rate of decrease in precipitation for RCP 8.5 is higher compared to RCP 4.5, with CNRM-CM5-CSIRO-CCAM indicating a greater reduction in precipitation of 115.7 mm under the RCP 8.5 scenario for the near future. The ACCESS-CSIRO-CCAM indicates a decline in precipitation of 51.5 mm for the near future and an increase of 67.8 and 152.8 mm in the mid and far future, respectively under the RCP 4.5 scenario. However, for the RCP 8.5 scenario, ACCESS-CSIRO-CCAM projects precipitation to decrease by 44.3 mm in the near future, while increasing in the mid and far future by 42.2 and 166.9 mm, respectively. The MPI-ESM-LR-CSIRO-CCAM projects that precipitation will increase in the near future, mid future, and far future under the RCP 4.5 scenario. Likewise, precipitation will decrease in the near and mid future and increase by 168.9 mm in the far future in the case of MPI-ESM-LR-CSIRO-CCAM for the RCP 8.5 scenario. The variation in annual precipitation, and maximum and minimum temperatures relative to the baseline period are detailed in Fig. 3. The results indicate that the projected precipitation varies according to the RCMs selected and there is no clear pattern in the increasing or decreasing trend of future precipitation. This illustrates the uncertainty that may arise due to these inputs in terms of hydrological simulation for future conditions. Therefore, more than one RCM is used in this study to assess the impact of climate change on the hydrological process in the future (Shrestha et al., 2016, 2020).

4.2. Future land-use projection of Bangkok and its vicinity

The observed and simulated land use for 2015 are compared using the Kappa analysis method. The verification error is computed using

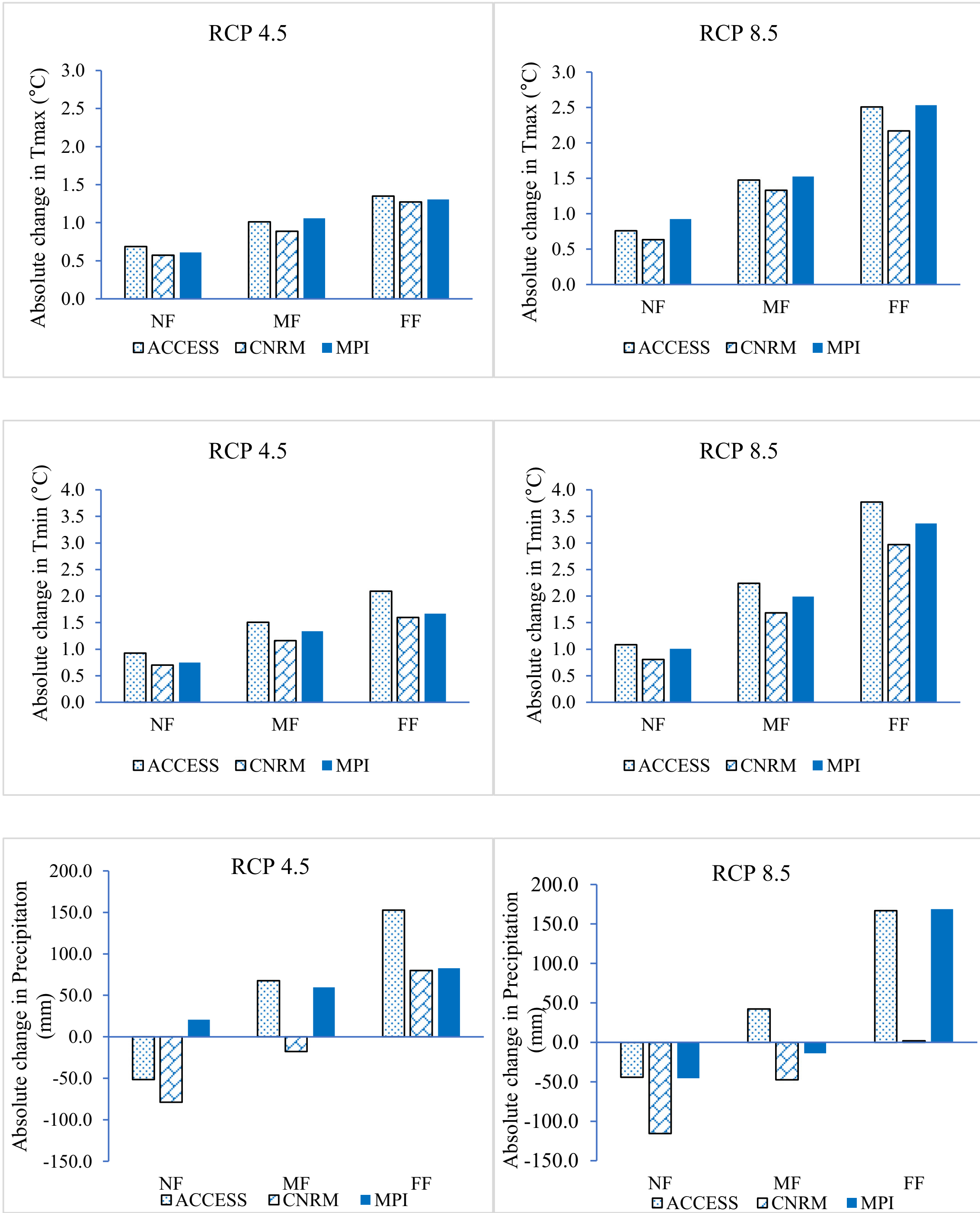

Fig. 3. Absolute change relative to the baseline period (1976–2005) in maximum temperature, minimum temperature, and precipitation (top, middle, bottom, respectively).

Kappa statistical analysis (K). The value of K was found to be 0.82, signifying better agreement between the observed and simulated maps (Shrestha et al., 2018a, 2018b).

4.2.1. High urbanisation scenario (business as usual)

In this scenario, the increment or decrement rate of different land-use classes follows historical trends. The built-up area is projected to increase by 0.61% per annum, and at this rate of increase, it will cover 66.2% of the total land area in 2099 as opposed to 15.36% in 2015. Agricultural land is projected to decrease from 69% in 2015 to 20.6% in 2099. Forest areas will decrease from 6.98% in the baseline period to 5.09% in 2099. The amount of area covered by water bodies is projected to remain the same (4.41%) throughout the future, while grassland will also decrease from 4.25% in 2015 to 3.5% in 2099. The diminution in agriculture, grassland, and forest areas is due to the high escalation of the built-up area. Future land use in the study area during the years 2020, 2035, 2050, 2065, 2080, and 2095 is shown in Fig. 4.

4.2.2. Medium urbanisation scenario (MU)

In this scenario, the total built-up area is assumed to be 25% of the total land area by 2099, i.e., a medium increase in the built-up area with a slight decrease in agricultural land, forest, and

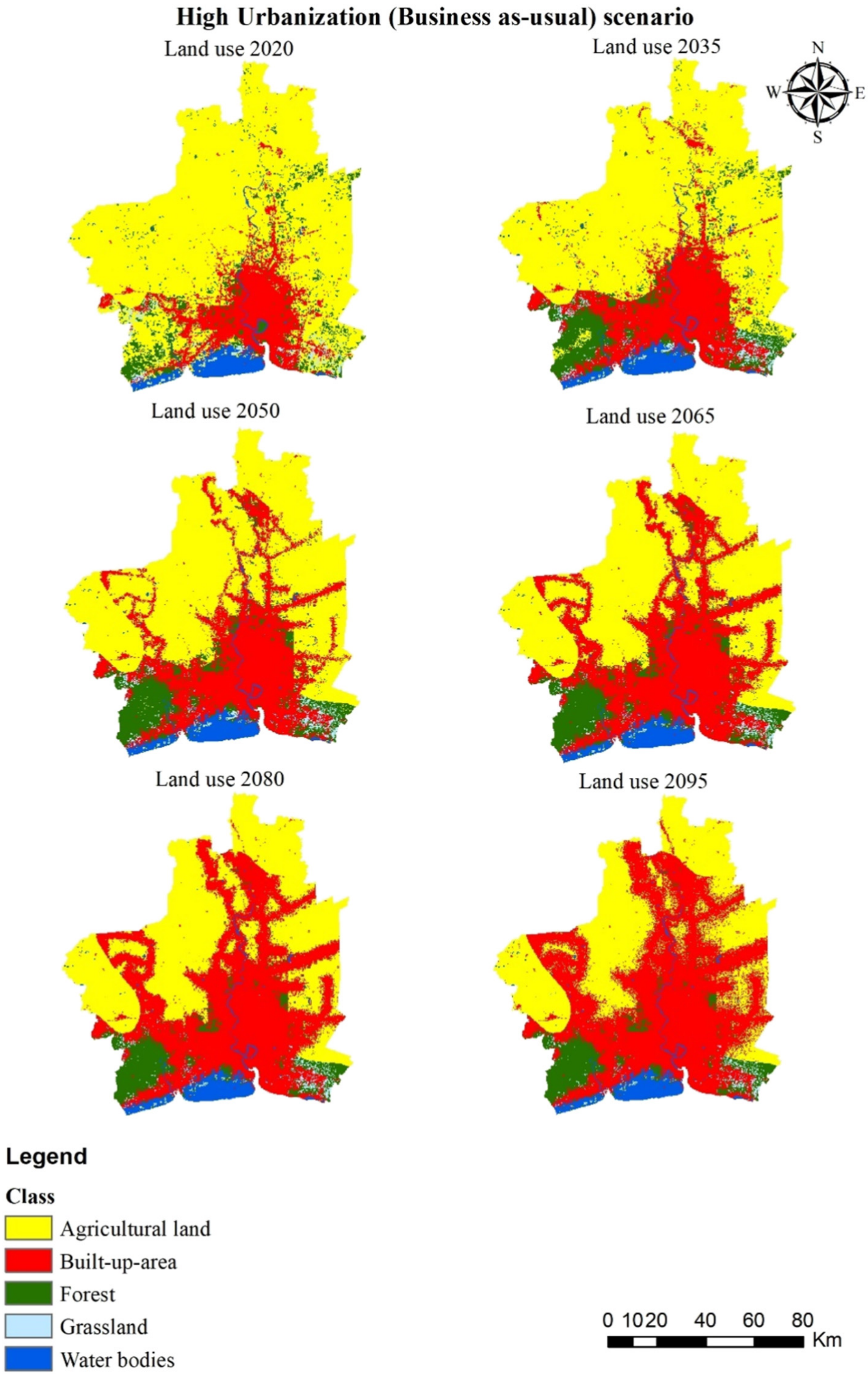

Fig. 4. Future land-use maps for 2020, 2035, 2050, 2065, 2080, and 2095 under the high urbanisation scenario.

grassland. The percentage of built-up areas is assumed to increase from 15.36% in 2015 to increase to 25% in 2099. Likewise, the area covered by agriculture is projected to decrease from 69% in 2015 to about 62.10% in 2099. The area covered by water bodies remains constant (4.41%) throughout the projection, i.e., from 2016 to 2099. The grassland area is projected to decrease from 4.25% in 2015 to 3.53% in 2099, while the forest area will decrease from 6.98% in 2015 to 5% in 2099. Future land use in the study area during the years 2020, 2035, 2050, 2065, 2080, and 2095 is shown in Supplementary Fig. 1.

4.2.3. Low urbanisation scenario (conservation)

In this scenario, no rapid change in the built-up area is projected. The forest is presumed to increase to 25% of the total land area by 2099 as opposed to covering 6.98% of the total study area in 2015, followed by a small decrease in agricultural land and grassland. Conversion of the agricultural area into forest is unlikely, but the scenario is developed to study the effect on recharge when the built-up area remains unchanged (Adhikari et al., 2020). Moreover, the built-up area remains almost constant from 2016 to 2099, while covering 15.36% of the total area in 2008. The area occupied by water bodies is projected to remain constant throughout the time periods under study, i.e., 4.41% of the total area. Agricultural land is projected to decrease from 69% of the total land area in 2015 to 51.9% in 2099. Similarly, grassland is assumed to decrease from 4.25% in 2015 to 2.43% in 2099. Future land use in the study area during the years 2020, 2035, 2050, 2065, 2080, and 2095 is shown in Supplementary Fig. 2.

4.3. Water balance in Bangkok and its vicinity

The annual water balance (Fig. 5) for the baseline period (2001) in Bangkok and its vicinity regarding inflow in the form of precipitation equates to 1146.5 mm, while outflow in the form of recharge, actual evapotranspiration (AET), and surface runoff equates to 115.3, 625.8, and 405.4 mm, respectively. During the wet season, the water balance inflow in the form of precipitation equates to 997.19 mm, while outflow in the form of recharge, AET, and surface runoff equates to 63.6, 557.99, and 375.6 mm, respectively. During the dry season, the water balance inflow in the form of precipitation equates to 149.31 mm, while outflow in the form of recharge, AET, and surface runoff equates to 51.7, 67.8, and 29.8 mm, respectively. The final estimated land-use and soil parameters in the WetSpass model through the calibration process are shown in Supplementary Table 1.

4.4. Impact of climate change and land-use change on groundwater recharge

In this study, the groundwater recharge for the baseline period 2001 and three future time periods: 2030, 2060, and 2090 are estimated annually as well as seasonally (wet season from May to October and dry season from November to April). Future groundwater recharge is expected to decline in the high and medium urbanisation scenarios but increase in the low urbanisation scenario and both RCP scenarios. The expected increase in future groundwater recharge ranges from 7.9 to 16.66 mm/yr for RCP 4.5 scenario and 5.54 to 20.04 mm/yr for RCP 8.5. The increase in future groundwater recharge is expected to be higher in the dry season. The groundwater recharge is forecast to decline in the future for the high and medium urbanisation scenarios and both RCP scenarios. The decline in future groundwater recharge is expected to vary from 5.84 to 20.91 mm/yr for RCP 4.5 and 4.07 to 18.72 mm/yr for the RCP 8.5 scenario. The decline in future groundwater recharge is expected to be significant in the wet season (Fig. 6). The results indicate a gradual increase in groundwater recharge in the low urbanisation scenarios from the near future towards the far future, with the lowest recharge observed in both high and medium urbanisation scenarios. This is due to a greater increase in the built-up area (impervious surface) caused by high and medium urbanisation (Adhikari et al., 2020). It can also be concluded that land-use pattern changes significantly contribute to the increase or decrease in groundwater recharge in comparison to changes in climate.

5. Conclusion

This study assesses the impact of climate change and land-use change on groundwater recharge in the Thai capital Bangkok and its vicinity using a hydrological model, land-use change model, and three RCMs under two RCP scenarios. The results show that precipitation is projected to fluctuate throughout the future. The average annual precipitation in the future for the dry season is forecast to rise under both RCP scenarios. Whereas the average annual precipitation in the wet season is expected to decline in the near and mid future but increase in the far future for both RCPs scenarios. Temperature is projected to increase in Bangkok and its vicinity during all future time periods in both RCP scenarios, with the rise in minimum temperature being greater than that of the maximum temperature.

The Dyna-CLUE model is employed to analyse the land-use shift, with the development of three land-use scenarios to explore its effect on groundwater. Firstly, in the high urbanisation scenario, the built-up area is predicted to expand at the same rate as in the past. Secondly, in the medium urbanisation scenario, the built-up area is assumed to increase to 25% of the total land area by 2099, followed by small decreases in agricultural land, forest, and grassland. Thirdly, in the low urbanisation scenario, forest is predicted to increase to 25% of the total land area by 2099, followed by small decreases in agricultural land and grassland.

In this study, the WetSpass model is used to assess the future groundwater recharge, based on changes in both land use and climate. Future groundwater recharge is projected to rise in the low urbanisation scenario and both RCP scenarios. The groundwater recharge is projected to decline in the future for high and medium urbanisation scenarios and both RCP scenarios. The decrease in future groundwater recharge is significant during the wet season.

Annual Water Balance			
Precipitation (mm)	Recharge (mm)	Annual Evapotranspiration (mm)	Surface Runoff (mm)
1146.5	115.3	625.8	405.4
Wet Season Water Balance			
997.19	63.6	557.99	375.6
Dry Season Water Balance			
149.31	51.7	67.81	29.8

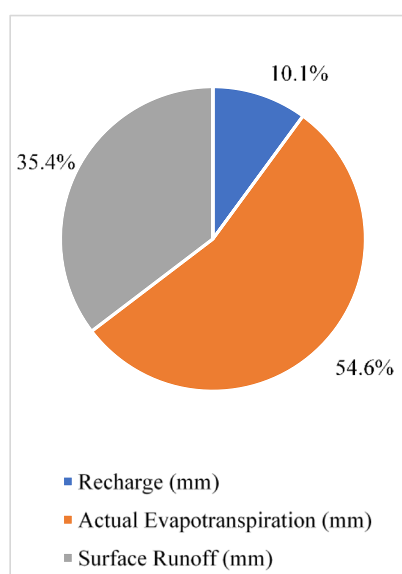

Fig. 5. Water balance of Bangkok and its vicinity obtained from the WetSpass model for the baseline period (2001).

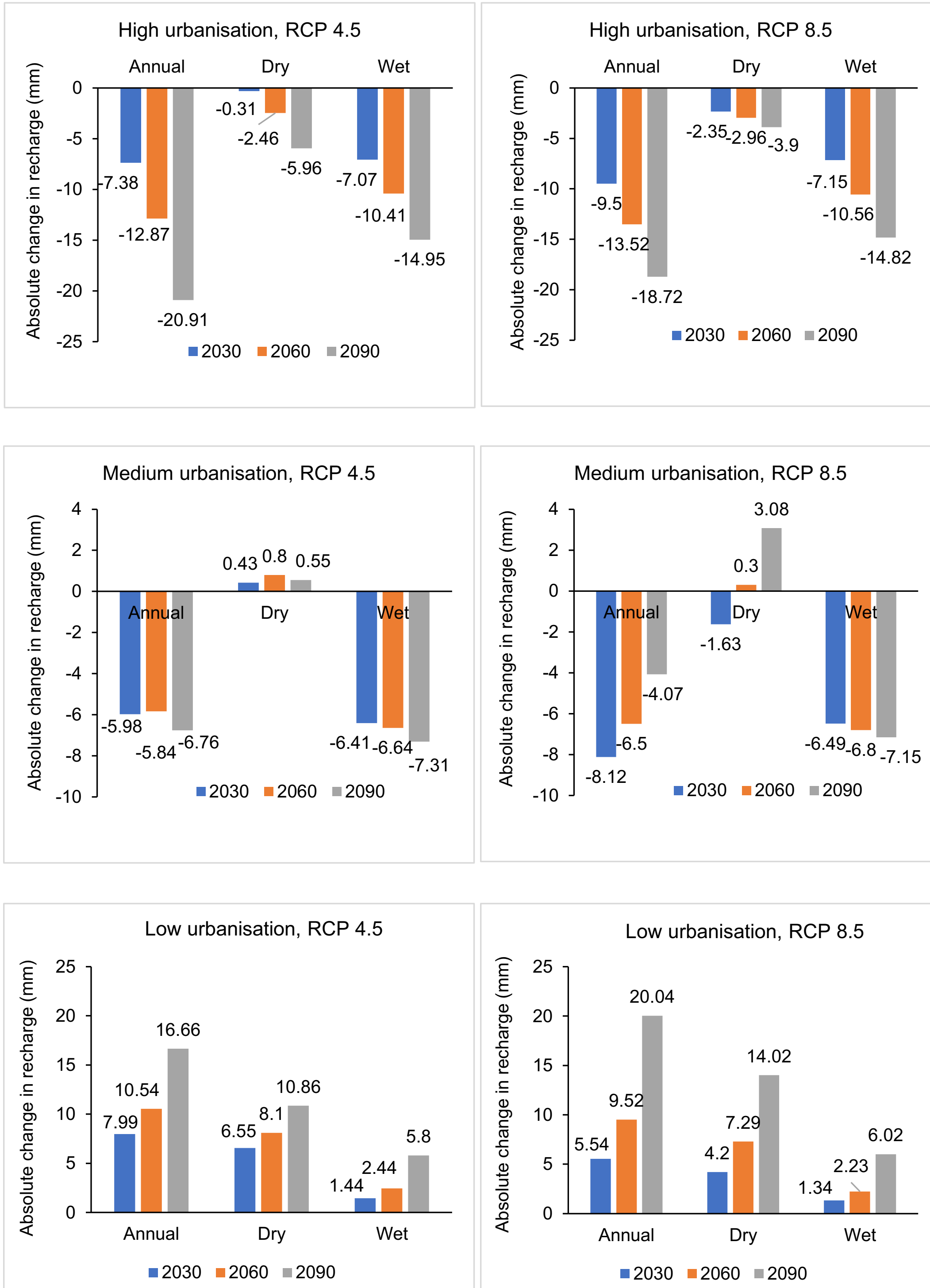

Fig. 6. Combined impacts of climate change under RCP 4.5 and RCP 8.5 scenarios and land use change under high, medium, and low urbanisation scenario (top, middle, bottom respectively) on groundwater recharge during three future period; 2030, 2060 and 2090 relative to the baseline period (2001).

Based on the results, it can be concluded that climate change and land-use change impact significantly on groundwater recharge in Bangkok and its vicinity. The predicted decline in recharge rates will generate large runoffs, resulting in urban floods which can be devastating for a city like Bangkok and its surrounding provinces. Since expansion of the built-up area and corresponding land-use change will have an immense impact on groundwater recharge, rigid regulations and effective urban planning policies must be implemented to manage the haphazard increase in the built-up area of Bangkok and its vicinity.

In the future, a more in-depth analysis could be carried out using additional climate models, climate scenarios, and land-use change scenarios. The groundwater level could also be analysed to provide a more detailed impact assessment and greater understanding of the groundwater phenomenon.

CRediT authorship contribution statement

The first author collected data, conducted modeling experiments. The second author conceptualized the research. All other authors contributed in terms of comments and suggestions to improve the research.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was conducted under the project “Mapping groundwater resilience to climate change and human development in Asian cities” (CRRP 2018-01MY-Shrestha) funded by the Asia-Pacific Network for Global Change Research (APN).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148370.

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