Mapping Groundwater Resilience to Climate Change and Human Development in Bangkok and its Vicinity, Thailand

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Presentation Outline

I. Introduction

II. Materials and Methods

III. Results and Discussions

IV. Conclusion and Recommendation

V. Appendix

Background

Climate Change

Human Development

Increase in Water Demand

Decrease in Water Availability

Stress on Groundwater Resources

I. Introduction

Statement of problem

Rapid population growth, urbanization, fast growing economy, tourism development and industrialization are the main drivers of groundwater overexploitation in Bangkok and its vicinity (Lorphernsri et al., 2016)

Large scale groundwater degradation may lead to other environmental problems like land subsidence, groundwater contamination and continuous lowering of groundwater table (Wattayakorn et al., 2016)

Climate change might add immense pressure on groundwater by affecting the groundwater recharge rates and change the availability of groundwater.

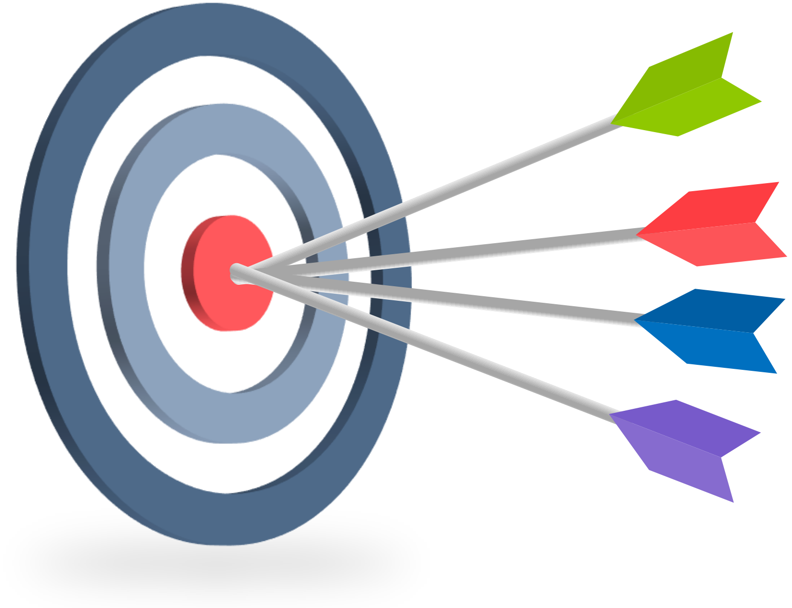
Modelling and investigating the temporal and spatial variance of different climatic parameter like rainfall, temperature and human development scenarios and their impact on groundwater recharge and groundwater level in Bangkok and its vicinity is needed for long term sustainability aspects.

I. Introduction

Objective of Study

Main Objective:

To assess the groundwater resilience to climate change and human development scenarios in Bangkok and its vicinity, Thailand.



Objective 1
To analyze the future climate and project future land use and land cover of study area.

Objective 2
To estimate the spatiotemporal distribution of groundwater recharge to climate change and human development scenarios of study area.

Objective 3
To estimate the groundwater level of the aquifers to climate change and human development scenarios of study area.

Objective 4
To develop groundwater resiliency indicator to climate change and human development and to generate groundwater resiliency map of study area.

II. Materials and Methods

Study area	Bangkok and its vicinity
Province	Bangkok, Pathum Thani, Nonthaburi, Samut Sakhon, Samut Prakan, Phra Nakhon Si Ayutthaya, Nakhon Pathom
Catchment area	10,300km^2
Country	Thailand
Population	11.3 million (2010)
Average precipitation	1146 mm/year
Average high temperature	33.12°C/year
Average low temperature	23.50°C/year
Average annual Relative Humidity	72%
Average Elevation	1.5 m amsl
Hydrogeological Unit	Bangkok, Phra Pradaeng , Nakhon Luang, Nonthaburi, Sam Kok , Phaya Thai, Thonburi and Pak Nam Aquifer
Seasons	Wet season (May to October) and Dry season (January to April and November to December)
Region	Tropical

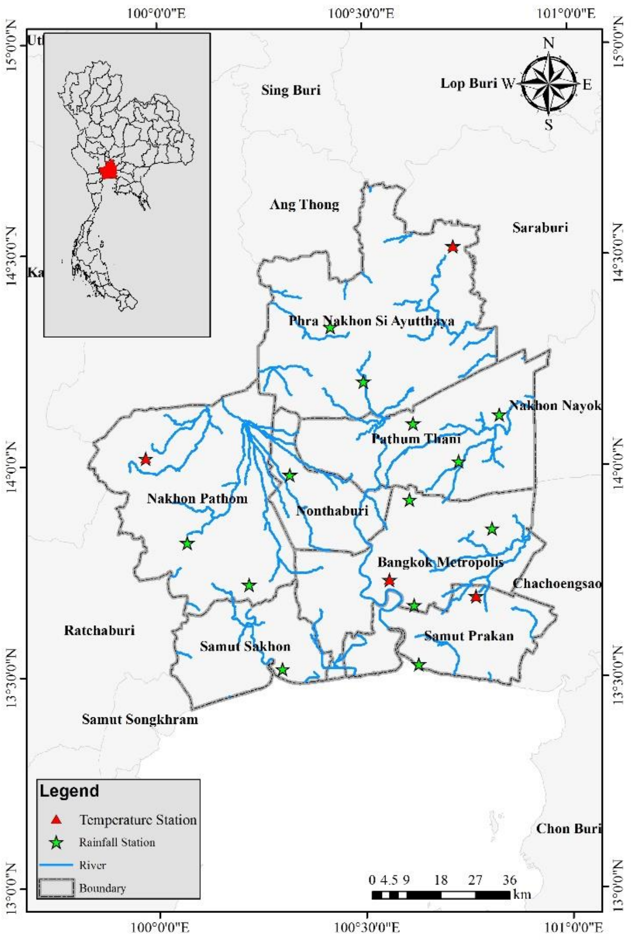


Figure: Location map of Bangkok and its vicinity with meteorological stations and river network

II. Materials and Methods

Aquifers Classification of Bangkok Aquifer System

- Unconsolidated and semi consolidated sediments interposed by clay layers
- Containing large volumes of voids for water storage, forming several confined aquifers, distinguished into 8 layers

Aquifer	Zone	Lithologs
Bangkok aquifer (BK)	50-m	Dark gray to black clay
Phra Pradaeng aquifer (PD)	100-m	Well-sorted sand and gravel
Nakhon Luang aquifer (NL)	150-m	Middle Pleistocene sediments
Nonthaburi aquifer (NB)	200-m	Middle Pleistocene sediments
Sam Khok aquifer (SK)	300-m	Pleistocene sediments
Phaya Thai aquifer (PT)	350-m	Pleistocene sediments
Thonburi aquifer (TB)	450-m	Pleistocene sediments
Pak Nam aquifer (PN)	550-m	Pleistocene sediments along with pre-tertiary basement rocks

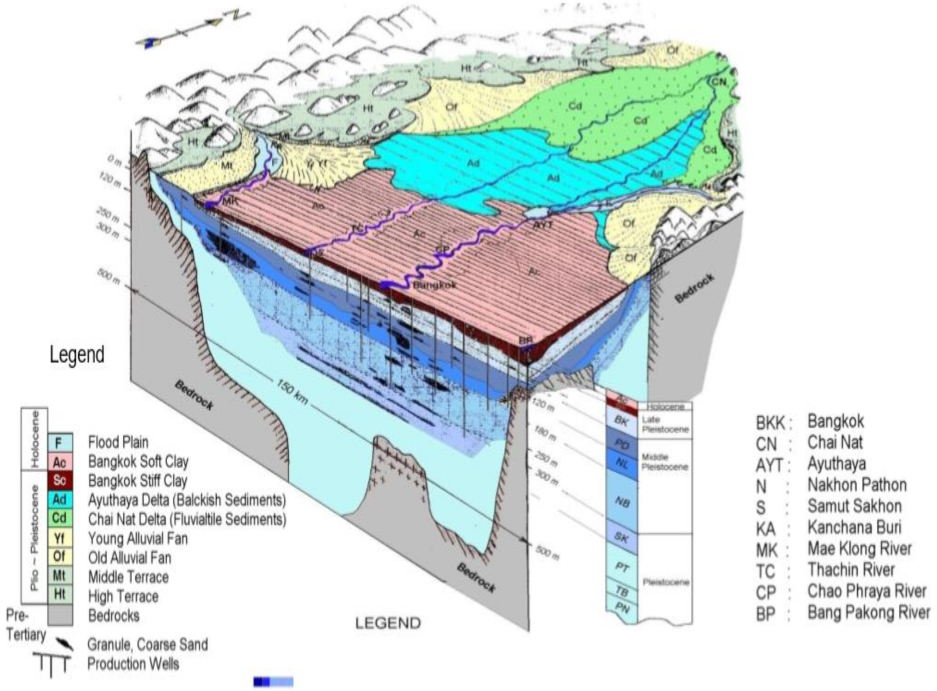


Figure: Hydrogeological setting in Lower Chao- phraya River Basin

Source: Lorphensri et al., 2016

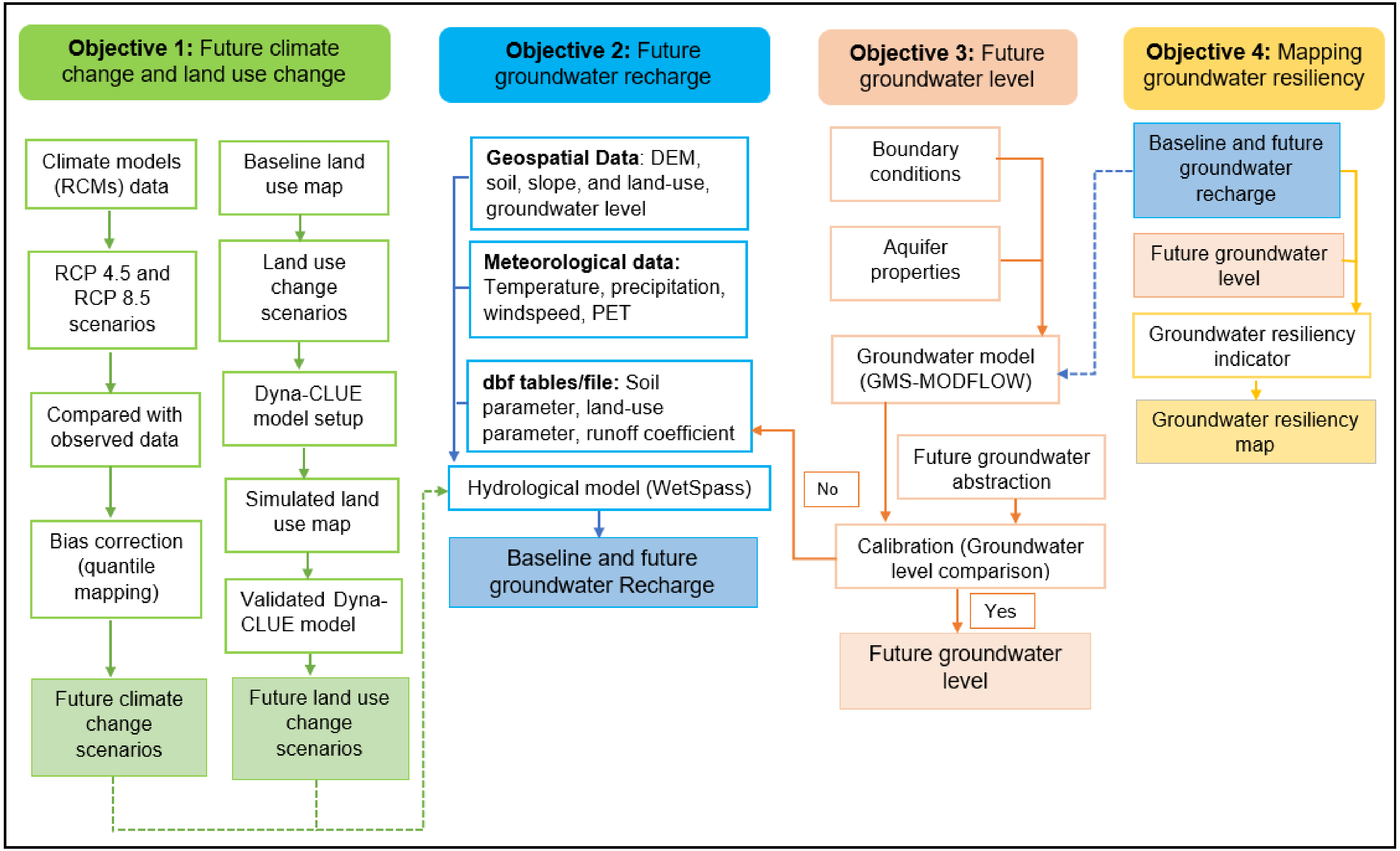
II. Materials and Methods

Data and Sources

Types of data	Frequency/Resolution	Format	Sources of data
Topography (DEM)	90m*90m	Raster	U.S. Geological Survey (USGS) website (https://earthexplorer.usgs.gov)
Land use map	300m*300m	Raster	European Space Agency (ESA) website (https://maps.elie.ucl.ac.be/cci/viewer/)
Soil Map	1:5000000	Raster	Food and Agriculture Organization of United Nations (FAO) website (http://www.fao.org/geonetwork)
Meteorological data (rainfall, temperature, evapotranspiration, wind speed)	Daily (1976-2005)	Text	Thai Meteorological Department (TMD)
Population density (per sq.km) and road network	300m*300m	Raster	Diva GIS (https://www.diva-gis.org/gdata)
Well observation data and location	Yearly (2001 and 2009)	Text	Department of Groundwater Resources, Thailand (DGR)
Well abstraction rate and location	Yearly (2001 and 2009)	Text	Department of Groundwater Resources, Thailand (DGR)
River discharge data	Daily	Text	Royal Irrigation Department, Thailand (RID)

II. Materials and Methods

Overall Methodology



II. Materials and Methods

Land use change scenarios

Land use change scenario	Remarks
High urbanization (HU) or business as usual scenario	Future land demand was assumed to follow the historical trend.
Medium urbanization (MU) scenario	The built-up areas were assumed to increase up to 25% of total land area by 2099 followed by small decrease in agricultural land, forest and grassland.
Low urbanization scenario (LU) or conservation scenario	The forest was assumed to increase up to 25% of total land area by 2099 followed by small decrease in agricultural land and grassland.

II. Materials and Methods

Future abstraction scenarios

- Scenario 1: The pumping rate was assumed to decrease by 15%,25% and 35% in 2030, 2060 and 2090 respectively (Business as usual scenario).
- Scenario 2: The pumping rate was assumed to decrease by 20%, 40% and 60% in 2030, 2060 and 2090 respectively (Safe yield pumping rate as per Department of Groundwater Resources, Thailand).
- Scenario 3: The pumping rate was assumed to increase by 20%, 40% and 60% in 2030, 2060 and 2090 respectively (Pessimistic scenario).

II. Materials and Methods

Groundwater resiliency indicator

- Resilience Based on Groundwater Level (Shrestha et al., 2020)

Here groundwater resilience is defined as percent recovery over total depletion of groundwater level at a given time

$$RI_{(n+1)} = \frac{GwR_{(n+1)}}{GwL_n - GwL_{(n+1)}} * 100$$

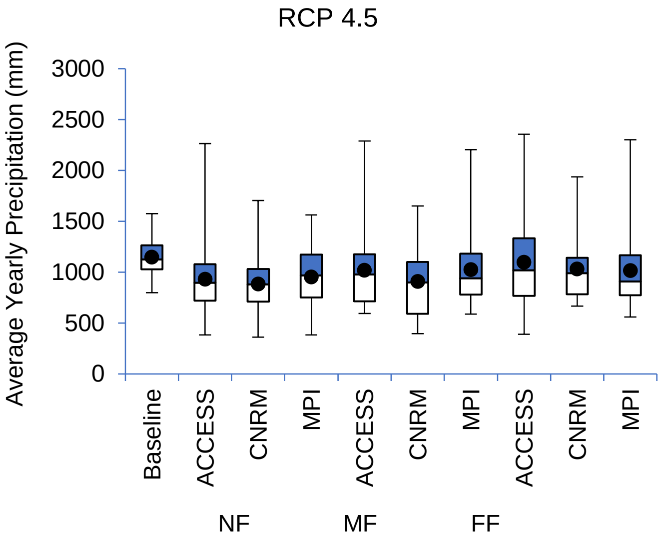
Where,
n represents the base year
RI is Resiliency Indicator
GwR is Groundwater Recharge
GwL is Groundwater Level

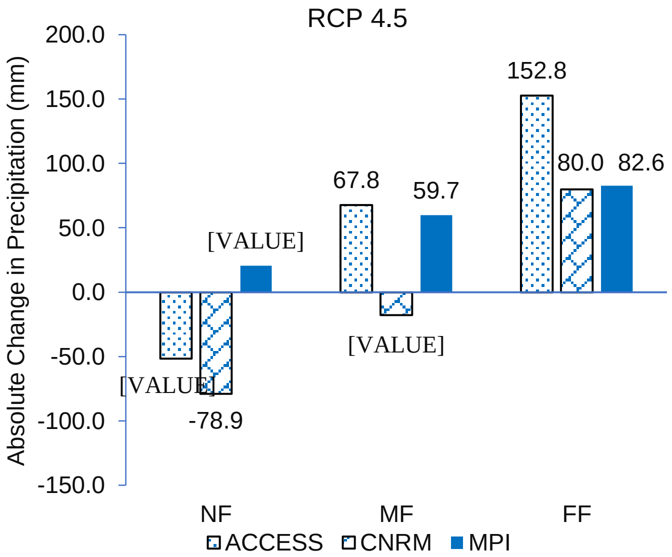
Resiliency Indicator (RI) or Percentage of Recovery (%)	Resiliency Class	Interpretation
0 to 1	Not resilient	Less groundwater recharge, higher reduction of groundwater level
1 to 3	Fairly resilient	Less groundwater recharge, fair reduction of groundwater level
3 to 5	Moderately resilient	Moderate groundwater recharge, moderate reduction of groundwater level
5 to 8	Highly resilient	Higher groundwater recharge, less reduction of groundwater level
>8	Very highly resilient	Higher groundwater recharge and very less reduction of groundwater level

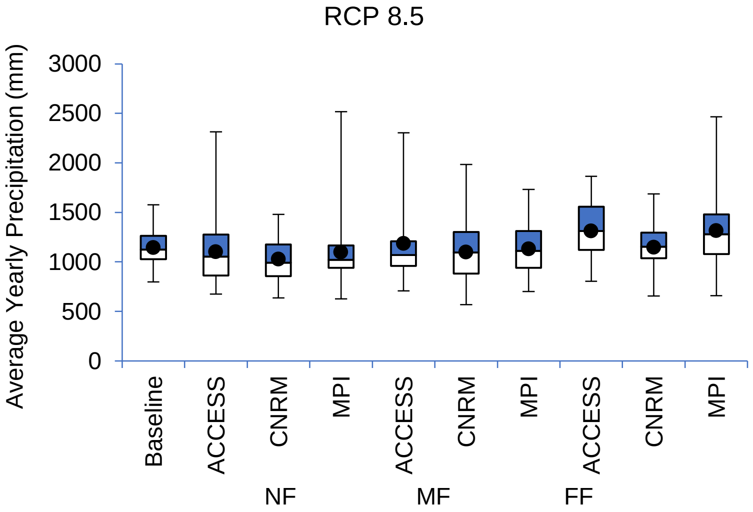
III. Results and Discussion

Projection of future climate

a. Analysis of future precipitation







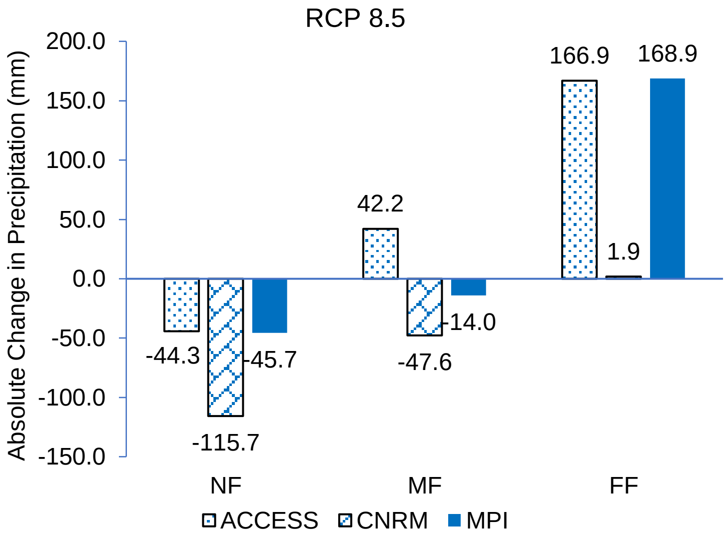


Figure: Change in basin average annual precipitation for three future period; Near Future (NF), Mid Future (MF) and Far Future (FF) relative to the baseline period under RCP 4.5 and RCP 8.5 scenarios

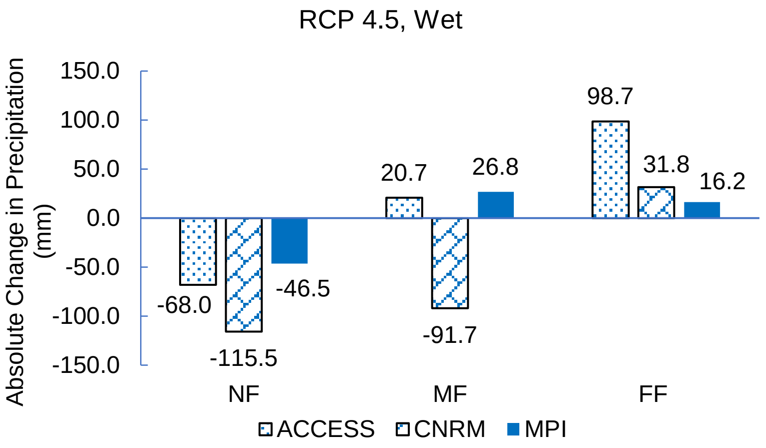
Baseline: 1976-2005; NF: 2010-2039; MF: 2040-2069; FF: 2070-2099

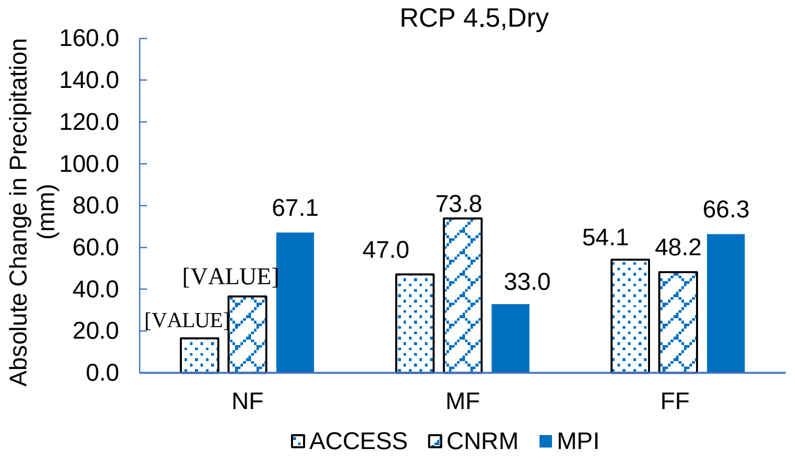
III. Results and Discussion

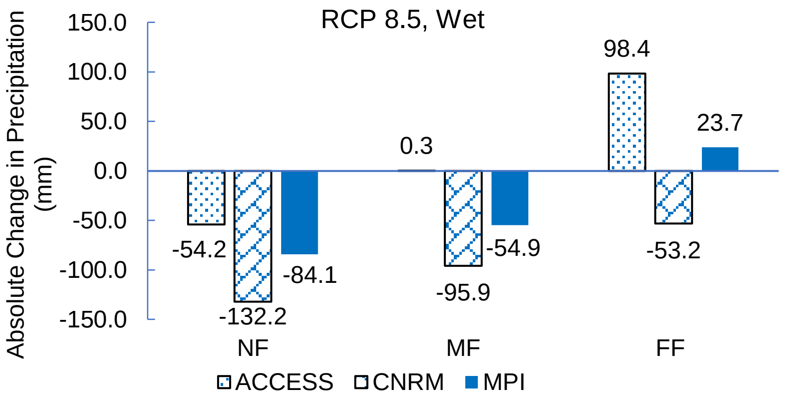
Projection of future climate

Wet season (May-Oct) and Dry season (Jan-Apr and Nov-Dec)

b. Seasonal analysis of future precipitation







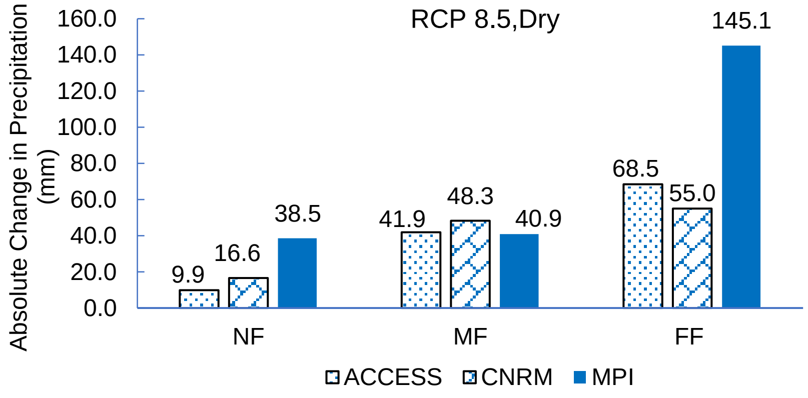


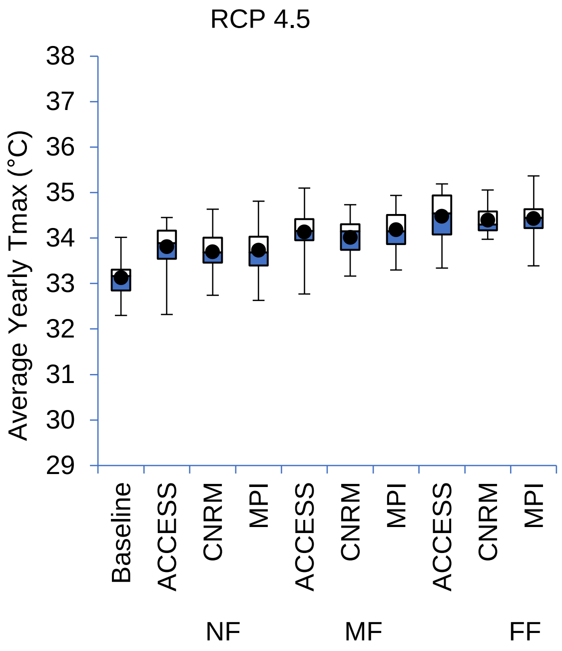
Figure: Change in average wet and dry season precipitation in three future periods; Near Future (NF), Mid Future (MF), Far Future (FF) relative to baseline period for RCP 4.5 and RCP 8.5 Scenario

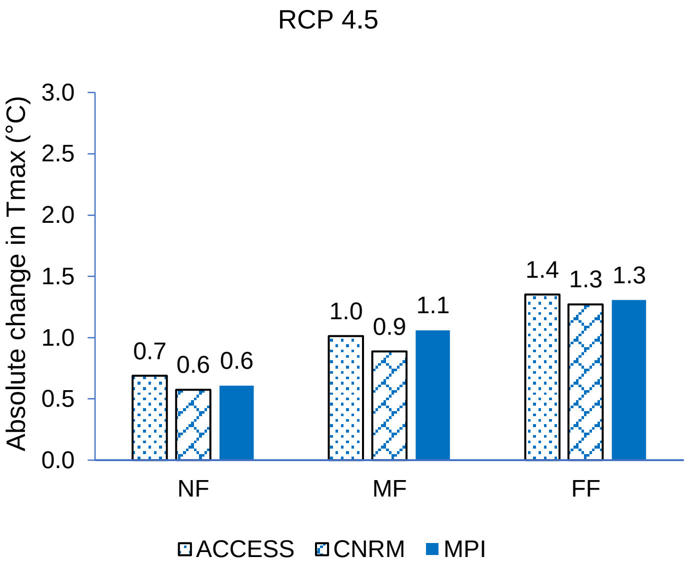
Baseline: 1976-2005; NF: 2010-2039; MF: 2040-2069; FF: 2070-2099

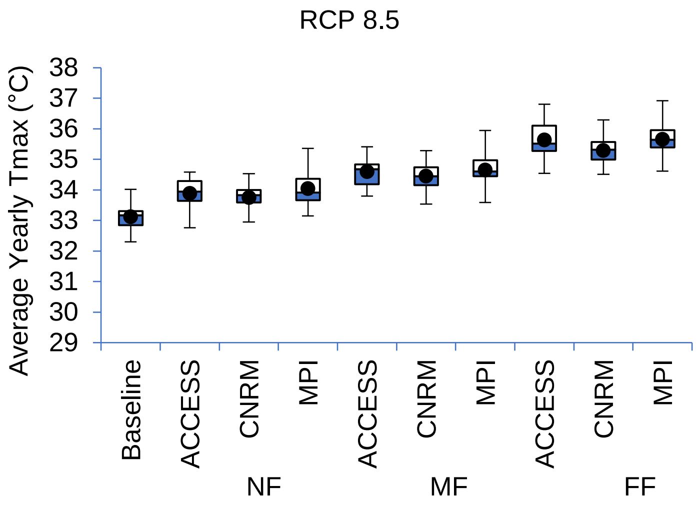
III. Results and Discussion

Projection of future climate

c. Analysis of future maximum temperature, T_{max}







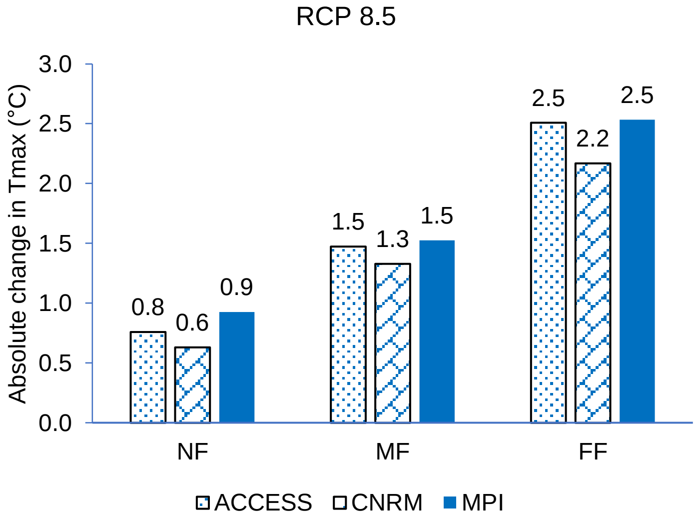


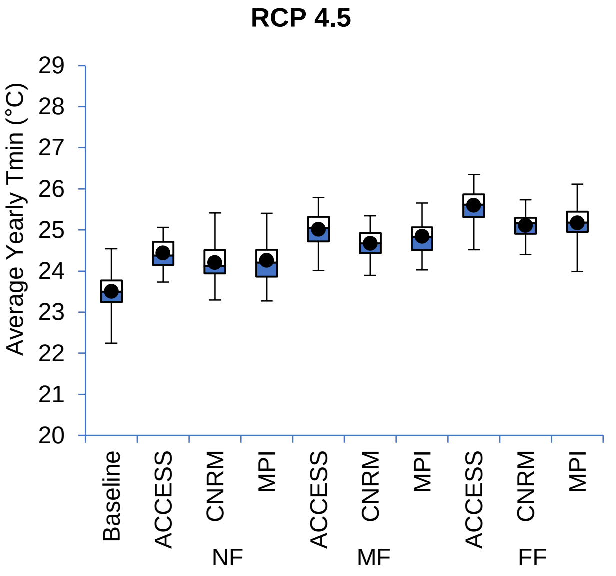
Figure: Variation of annual T_{max} under RCP 4.5 and RCP 8.5 scenarios in three future periods; Near Future (NF), Mid Future (MF) and Far Future (FF) relative to baseline period

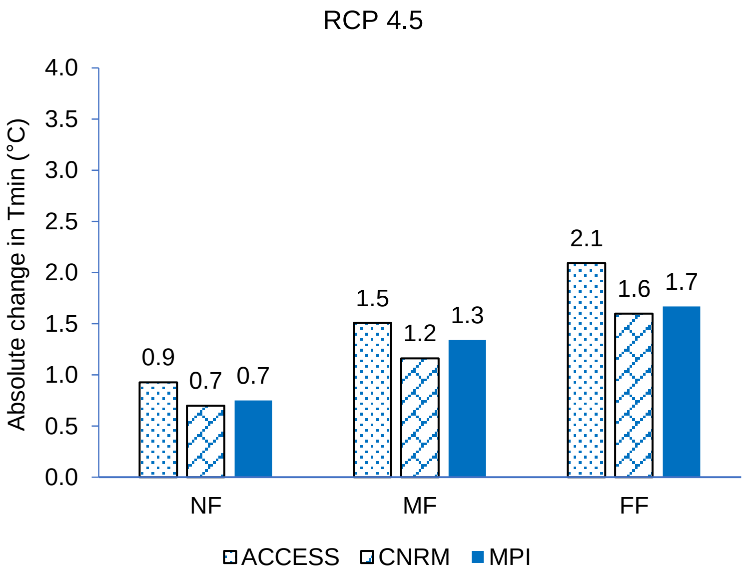
Baseline: 1976-2005; NF: 2010-2039; MF: 2040-2069; FF: 2070-2099

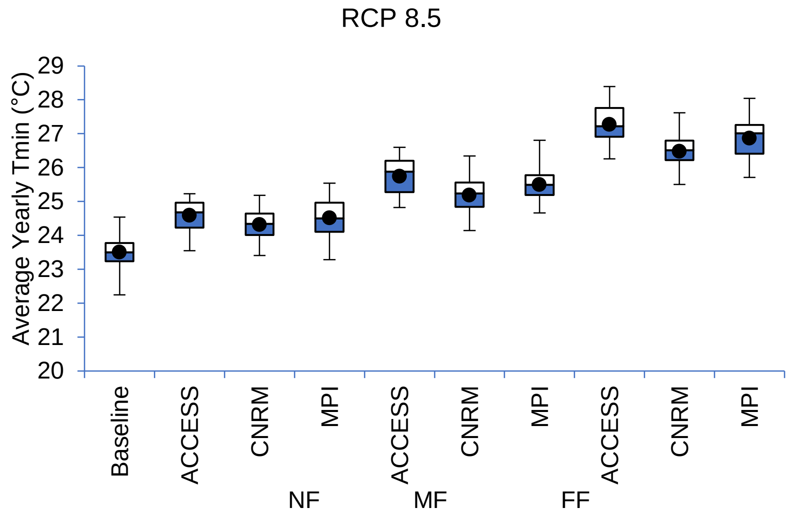
III. Results and Discussion

Projection of future climate

d. Analysis of future minimum temperature, T_{min}







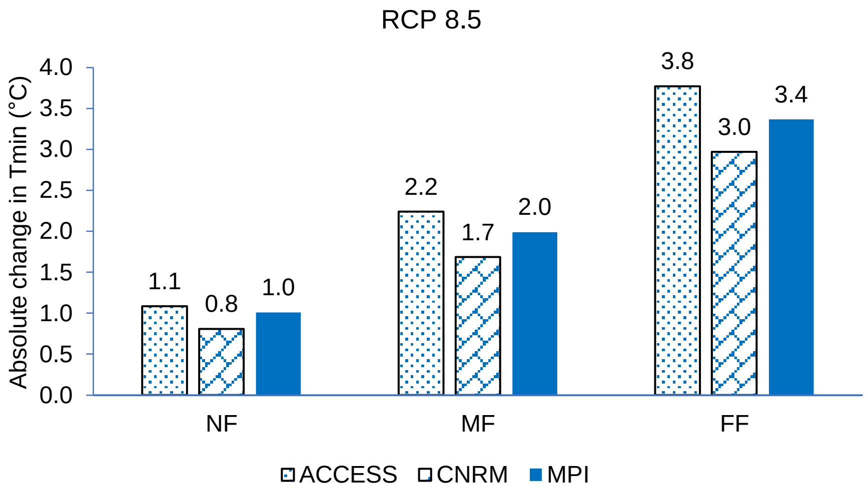


Figure: Variation of annual T_{min} under RCP 4.5 and RCP 8.5 scenarios in three future periods; Near Future (NF), Mid Future (MF) and Far Future (FF) relative to baseline period

Baseline: 1976-2005; NF: 2010-2039; MF: 2040-2069; FF: 2070-2099

Projection of future climate

e. Performance of bias corrected precipitation and temperature

- R^2 for precipitation ranges from **0.104 to 0.422**
- R^2 for maximum temperature ranges from **0.124 to 0.682**
- R^2 for minimum temperature ranges from **0.611 to 0.792**
- R^2 for bias corrected RCM data is always higher than raw RCM data
- RMSE for bias corrected RCM data is always less than raw RCM data

Projection of future land use change

a. Past land use analysis

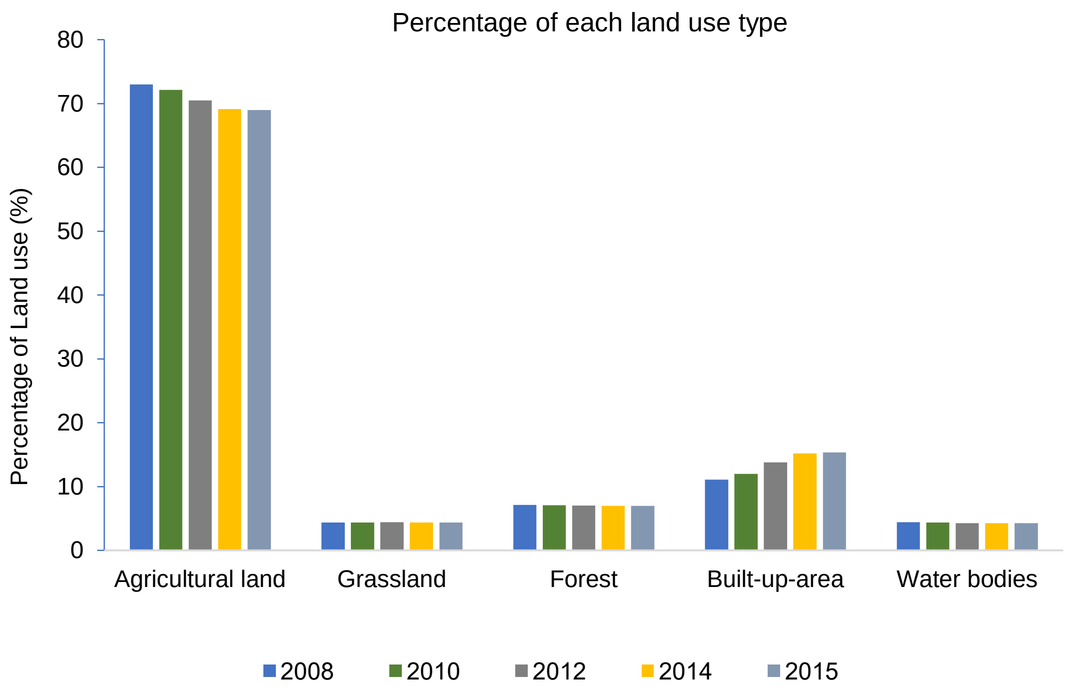


Figure: Percentage of different land use classes in 2008, 2010, 2012, 2014 and 2015 in Bangkok and its vicinity, Thailand (Source: ESA)

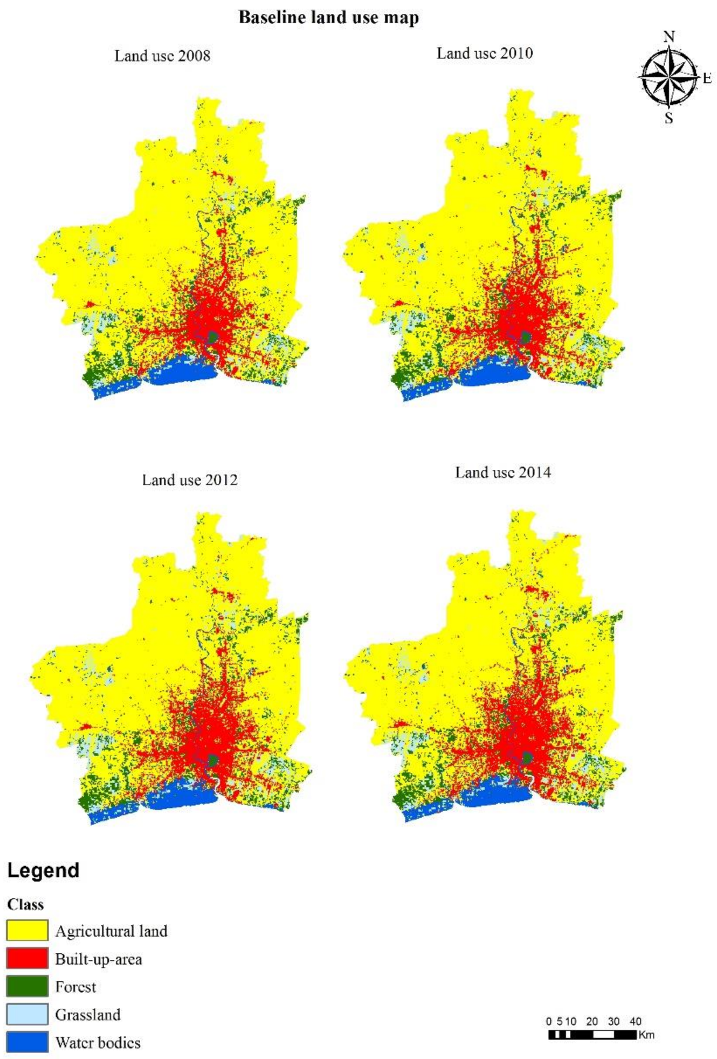


Figure: Observed land use map in 2008, 2010, 2012 and 2014 in Bangkok and its vicinity, Thailand (Source – ESA)

Projection of future land use change

b. Validation of Dyna-CLUE model

Table: Area of land use class for observed period (2015) and simulated period (2015)

Area (Km^2)			
Code	Land use type	Observed 2015	Simulated 2015
0	Agricultural land	6868.62	6853.5
1	Grassland	435.33	410.2
2	Forest	695.7	687.3
3	Built-up areas	1529.82	1562.99
4	Water bodies	424.08	439.2

$$k = \frac{(P_0 - P_e)}{(1 - P_e)}$$,Kappa (k) =81.84%

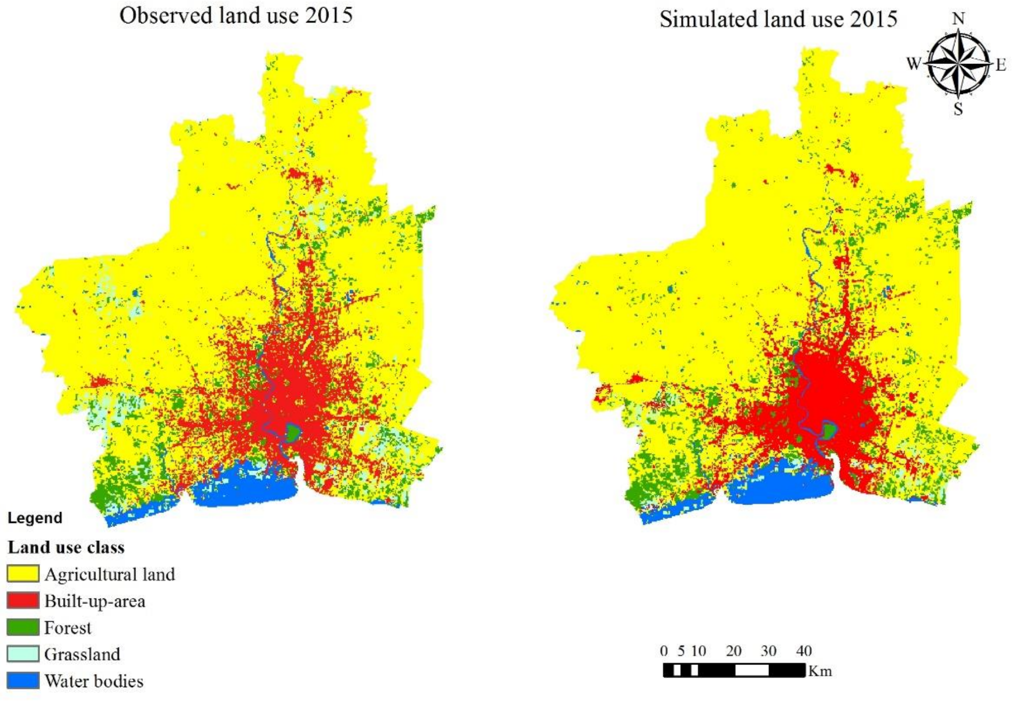


Figure: Comparison of the observed land use map of 2015 with simulated land use map of 2015 by Dyna-CLUE

III. Results and Discussion

Projection of future land use change

c. High urbanization scenario

Table: Area and percentage of land use classes in 2015, 2020, 2035, 2050, 2065, 2080 and 2095 in Bangkok and its vicinity, Thailand for high urbanization scenario

Land use class	Area (Km^2/%)						
	2015	2020	2035	2050	2065	2080	2095
Agricultural land	6868.62 (69%)	6630.8 (66.61%)	5962.7 (59.90%)	5294.6 (53.19%)	4626.5 (46.48%)	3958.4 (39.76%)	3290.3 (33.05%)
Grassland	435.33 (4.37%)	434.03 (4.36%)	430.13 (4.32%)	426.23 (4.28%)	422.33 (4.24%)	418.43 (4.20%)	414.53 (4.16%)
Forest	695.7 (6.98%)	690.5 (6.93%)	674.9 (6.78%)	659.3 (6.62%)	643.7 (6.46%)	628.1 (6.31%0	612.5 (6.15%)
Built-up-area	1529.82 (15.36%)	1759.02 (17.67%)	2446.62 (24.58%)	3134.22 (31.48%)	3821.82 (38.39%)	4509.42 (45.30%)	5197.02 (52.2%)
Water bodies	424.08 (4.26%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)

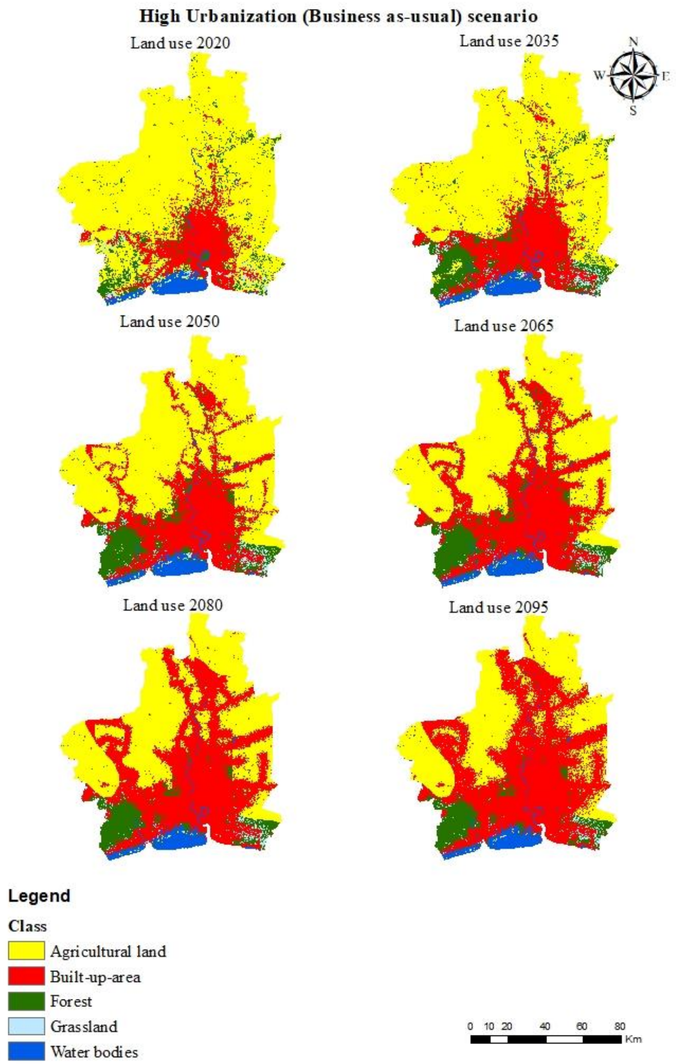


Figure: Future land use maps of high urbanization scenario for year 2020, 2035, 2050, 2065, 2080 and 2095

III. Results and Discussion

Projection of future land use change

d. Medium urbanization scenario

Table: Area and percentage of land use classes in 2015, 2020, 2035, 2050, 2065, 2080 and 2095 in Bangkok and its vicinity, Thailand for medium urbanization scenario

Land use class	Area (Km^2/%)						
	2015	2020	2035	2050	2065	2080	2095
Agricultural land	6868.62 (69%)	6813.5 (68.45%)	6693.5 (67.24%)	6573.5 (66.04%)	6453.5 (64.83%)	6333.5 (63.63%)	6213.5 (62.42%)
Grassland	435.33 (4.37%)	430.33 (4.32%)	415.33 (4.12%)	400.33 (4.02%)	385.33 (3.87%)	370.33 (3.72%)	355.33 (3.56%)
Forest	695.7 (6.98%)	683.95 (6.87%)	648.7 (6.51%)	613.45 (6.16%)	578.2 (5.80%)	542.95 (5.45%)	507.7 (5.10%)
Built-up-area	1529.82 (15.36%)	1586.57 (15.93%)	1756.82 (17.65%)	1927.07 (19.36%)	2097.32 (21.07%)	2267.57 (22.78%)	2437.82 (24.49%)
Water bodies	424.08 (4.26%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)

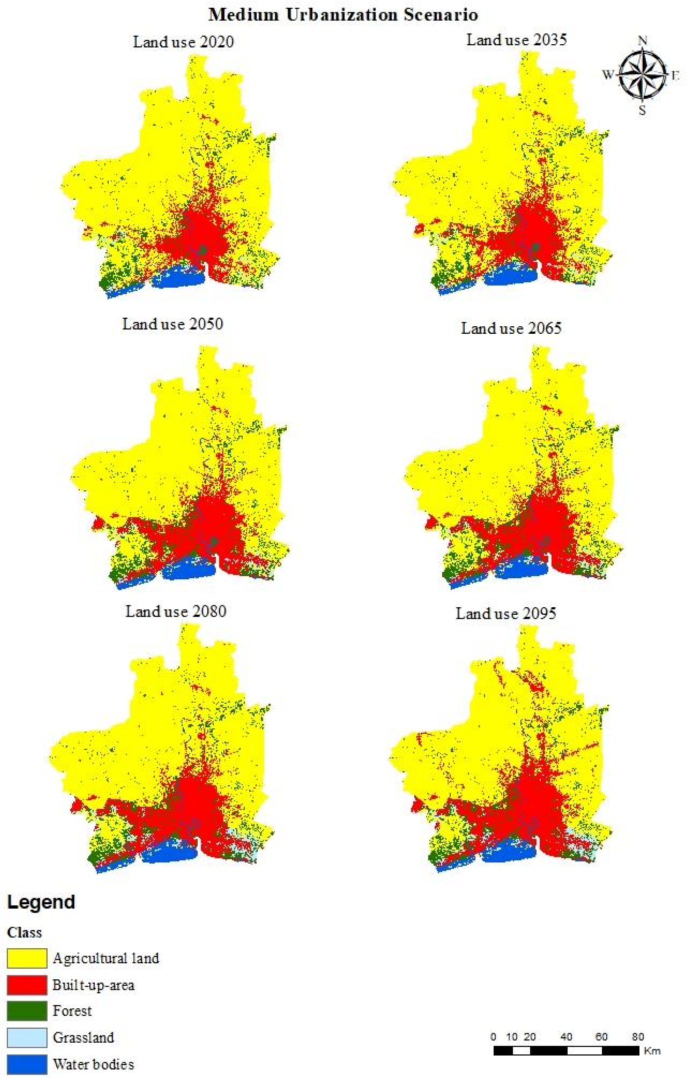


Figure: Future land use maps of medium urbanization scenario for year 2020, 2035, 2050, 2065, 2080 and 2095

Projection of future land use change

e. Low urbanization scenario

Table: Area and percentage of land use classes in 2015, 2020, 2035, 2050, 2065, 2080 and 2095 in Bangkok and its vicinity, Thailand for low urbanization scenario

Land use class	Area (Km²/%)						
	2015	2020	2035	2050	2065	2080	2095
Agricultural land	6868.62 (69%)	6753.5 (67.85%)	6453.5 (64.83%)	6153.5 (61.82%)	5853.5 (58.80%)	5553.5 (55.79%)	5253.5 (52.78%)
Grassland	435.33 (4.37%)	423.83 (4.25%)	389.33 (3.91%)	354.83 (3.56%)	320.33 (3.21%)	285.83 (2.87%)	251.33 (2.52%)
Forest	695.7 (6.98%)	802.2 (8.05%)	1121.7 (11.26%)	1441.2 (14.47%)	1760.7 (17.68%)	2080.2 (20.89%)	2399.7 (24.10%)
Built-up-area	1529.82 (15.36%)	1534.82 (15.41%)	1549.82 (15.57%)	1564.82 (15.72%)	1579.82 (15.87%)	1594.82 (16.02%)	1609.82 (16.17%)
Water bodies	424.08 (4.26%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)	439.2 (4.41%)

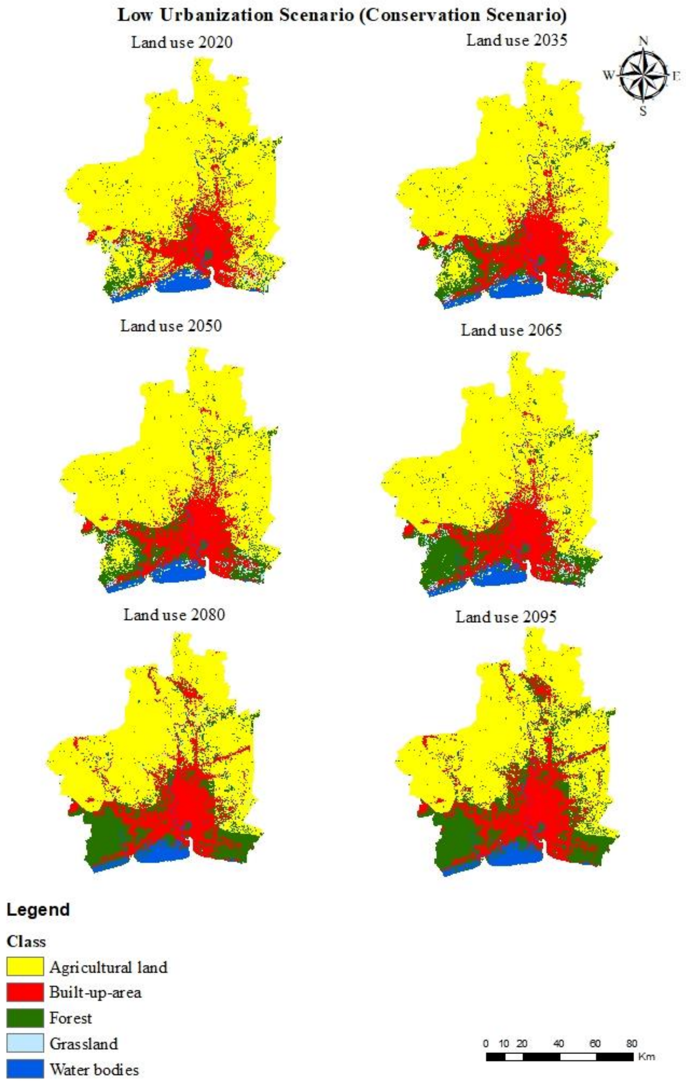


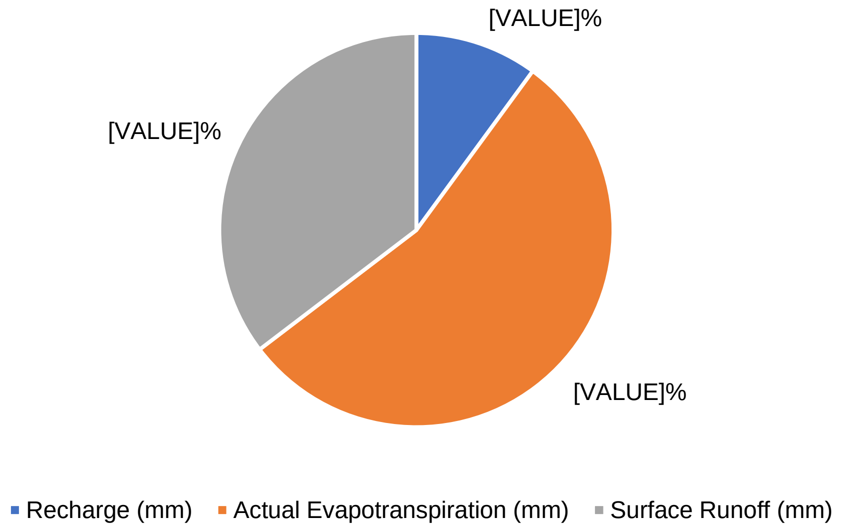
Figure: Future land use maps of low urbanization scenario for year 2020, 2035, 2050, 2065, 2080 and 2095

Hydrological modelling

a. Water balance of WetSpass model

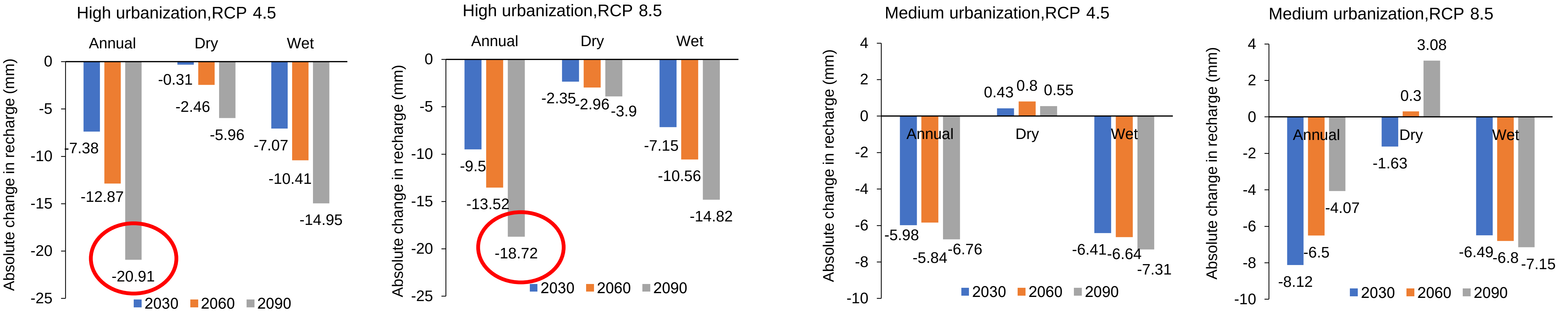
Table: Water balance of Bangkok and its vicinity obtained from WetSpass model

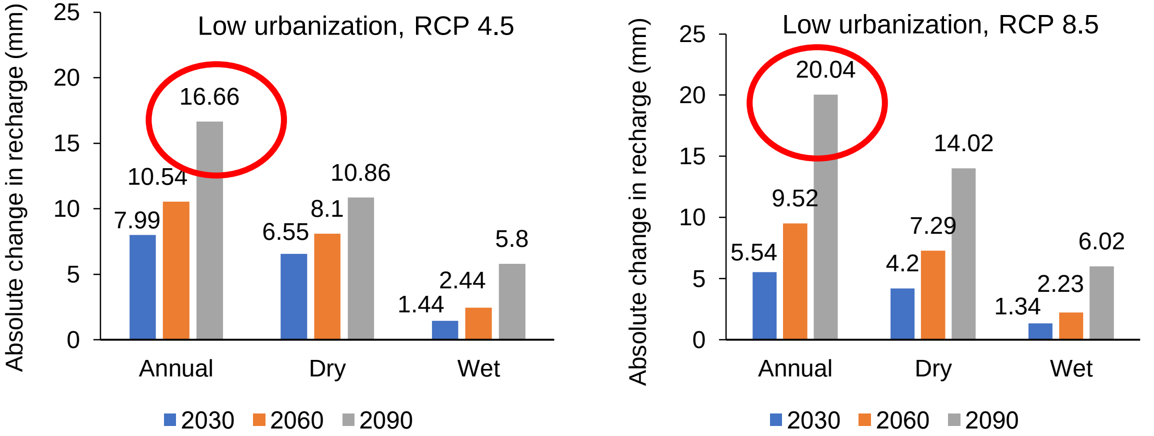
Annual Water Balance			
Precipitation (mm)	Recharge (mm)	Actual Evapotranspiration (mm)	Surface Runoff (mm)
1146.5	115.3	625.8	405.4
Wet Season Water Balance			
997.19	63.6	557.99	375.6
Dry Season Water Balance			
149.31	51.7	67.81	29.8



Hydrological modelling

b. Estimation of groundwater recharge under all urbanization scenarios and climate change scenarios





- *Wet season (May-Oct) and Dry season (Jan-Apr and Nov-Dec)*

Figure: Combined impacts of climate change under RCP 4.5 and RCP 8.5 scenarios and land use change under all urbanization scenarios on groundwater recharge during three future period; 2030, 2060 and 2090 relative to the baseline period (2001)

Groundwater modelling

a. Calibration and Validation of Groundwater model

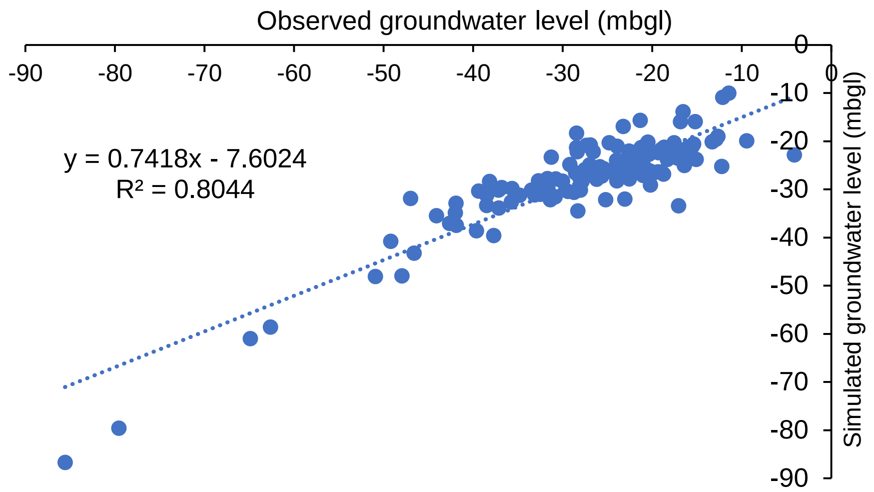


Figure: Relationship between observed head (mbgl) and simulated head (mbgl) for steady state condition for calibration period 2001

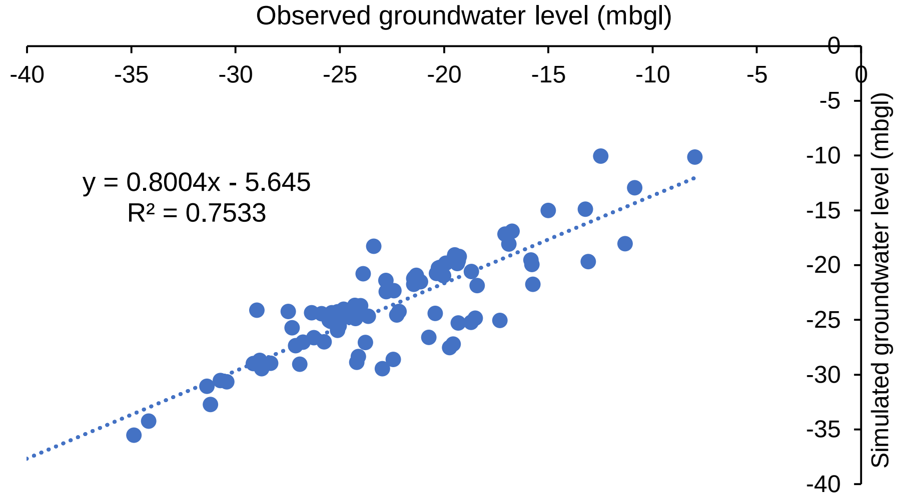


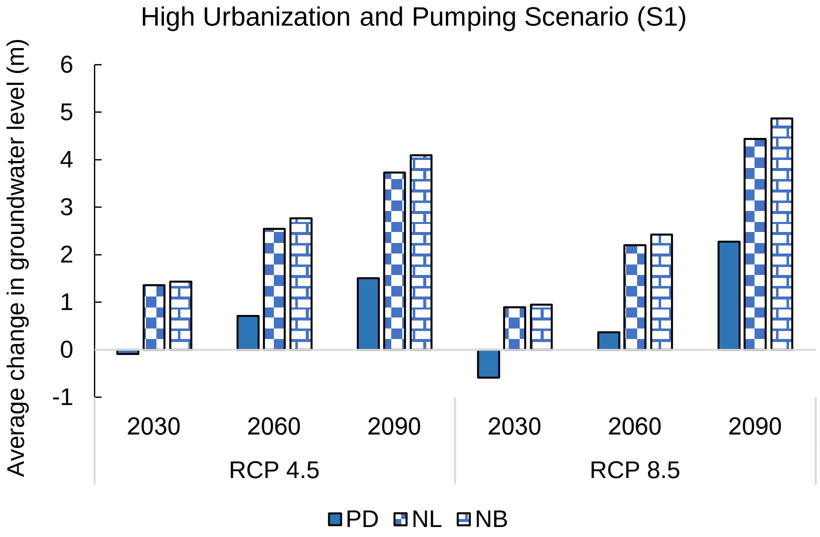
Figure: Relationship between observed head (mbgl) and simulated head (mbgl) for steady state condition for validation period 2009

Table: Final value of hydrogeologic parameter obtained after calibration

SN	Aquifers	K_x (m/day)	K_y (m/day)	K_z (m/day)	Specific Storage (1/m)
1	Bangkok (BK)	70	70	7	0.0005
2	Phra Pradang (PD)	100	100	10	0.0005
3	Nakhon Luang (NL)	59	59	5.9	0.0005
4	Nonthaburi (NB)	30	30	3	0.0005
5	Sam Khok (SK)	16.1	16.1	1.61	0.0005
6	Phaya Thai (PT)	10.8	10.8	1.08	0.0005
7	Thonburi (TB)	3.7	3.7	0.37	0.0005
8	Paknam (PK)	17.5	17.5	1.75	0.0005

Groundwater modelling

b. Estimation of future groundwater level for high urbanization and pumping scenario 1



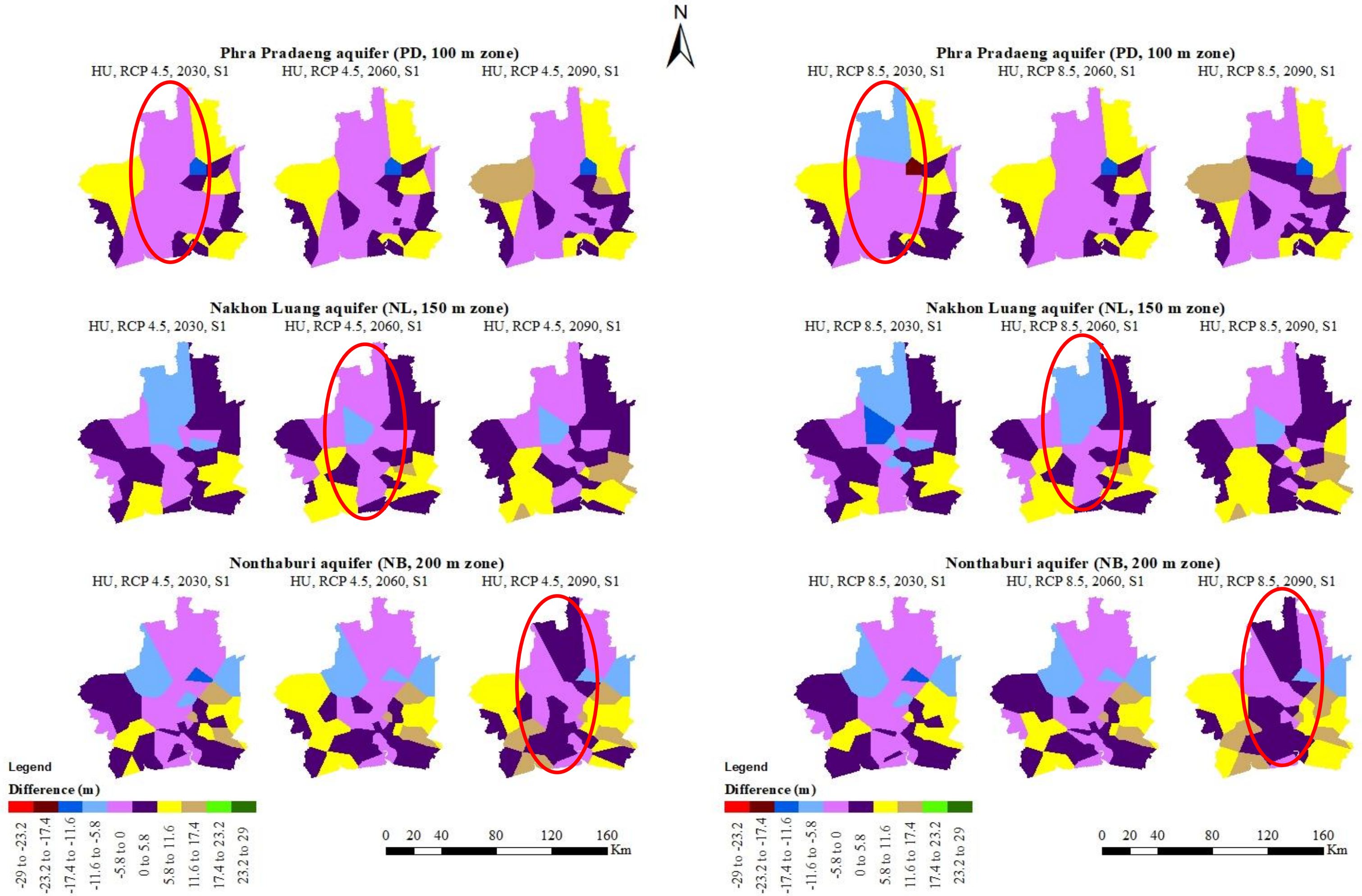
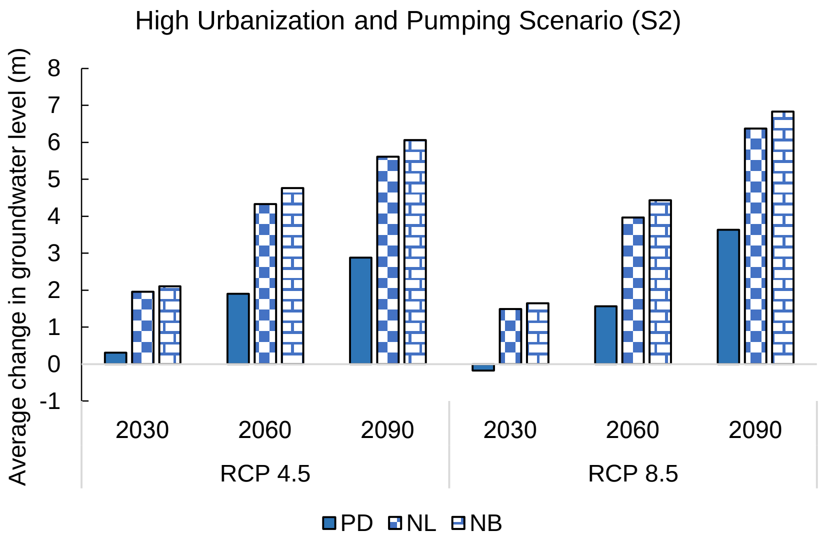


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under High Urbanization scenario (HU) and RCP 4.5 and 8.5 scenario for pumping scenario 1

III. Results and Discussion

Groundwater modelling

c. Estimation of future groundwater level for high urbanization and pumping scenario 2



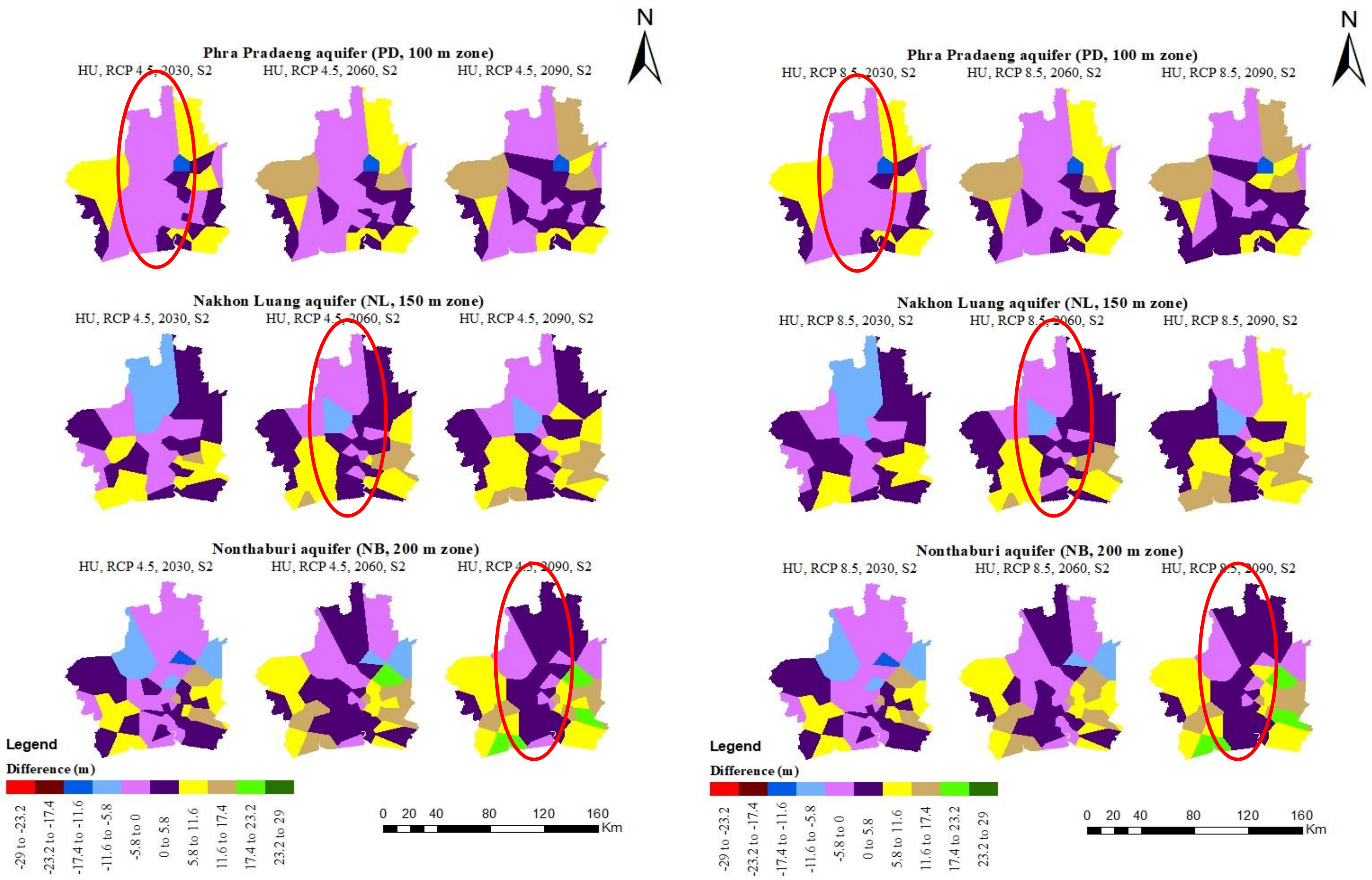
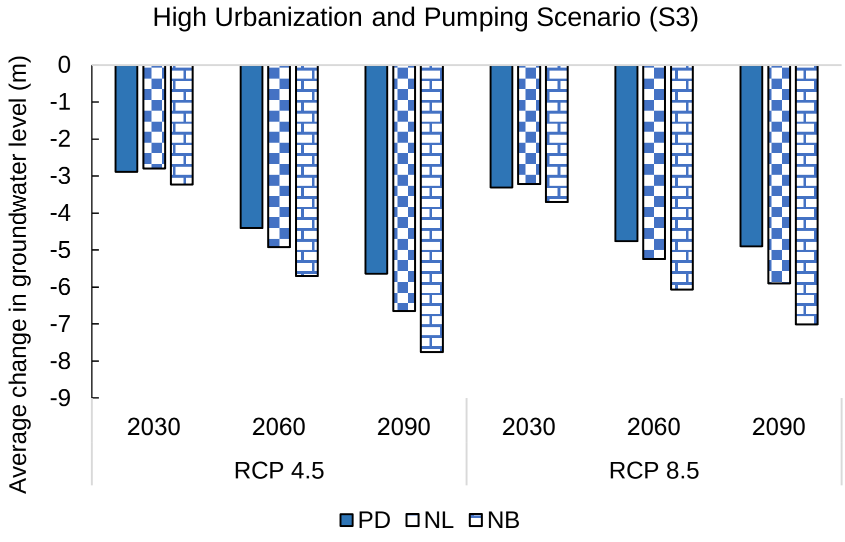


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under High Urbanization scenario (HU) and RCP 4.5 and 8.5 scenario for pumping scenario 2

Groundwater modelling

d. Estimation of future groundwater level for high urbanization and pumping scenario 3



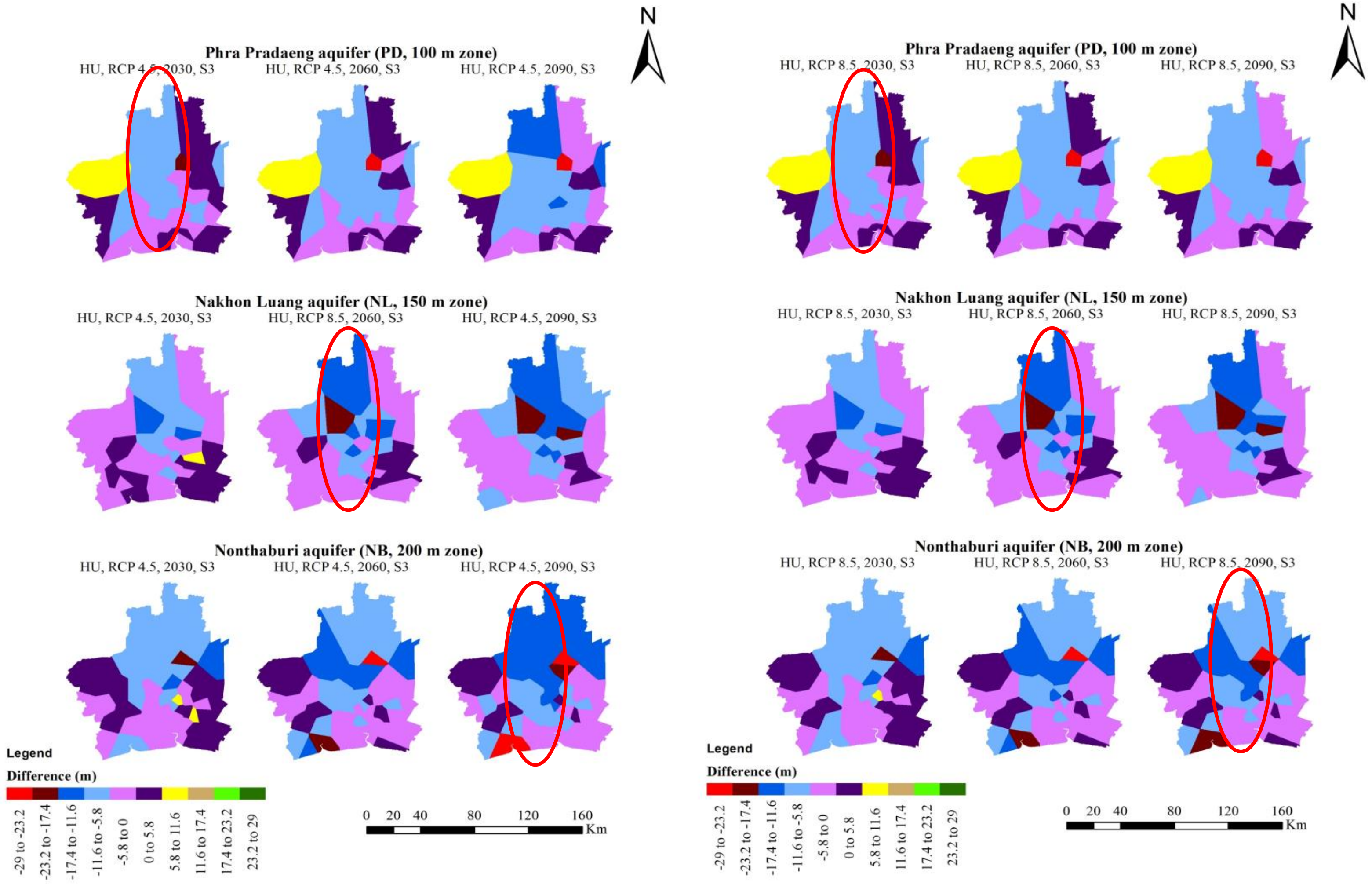


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under High Urbanization scenario (HU) and RCP 4.5 and 8.5 scenario for pumping scenario 3

III. Results and Discussion

Mapping groundwater resiliency

a. Groundwater resiliency mapping for high urbanization and pumping scenario 1

Resiliency Class	Percentage of area under high urbanization scenario and pumping scenario (S1)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	1.2	1.2	2.1	1.2	1.2
Fairly Resilient	39.9	33.3	29.6	40.1	44.5	28.1
Moderately Resilient	6.3	12.4	10.3	8.3	1.7	1.9
Highly Resilient	4.3	0.4	0.7	2.3	0.0	3.4
Very Highly Resilient	48.3	52.6	58.2	47.2	52.6	65.4
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	4.9	4.2	4.2	5.4	4.2	4.2
Fairly Resilient	21.7	18.8	18.8	24.8	20.3	17.4
Moderately Resilient	10.3	3.6	6.2	6.7	8.3	1.4
Highly Resilient	1.1	8.2	0.0	1.1	5.2	0.0
Very Highly Resilient	62.0	65.2	70.8	62.0	62.0	77.1
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	2.2	1.2	1.2	2.8	1.2	1.2
Fairly Resilient	16.5	17.5	15.0	17.3	17.5	14.7
Moderately Resilient	27.5	9.3	11.1	26.1	10.4	0.3
Highly Resilient	0.0	15.5	0.0	5.3	16.7	11.1
Very Highly Resilient	53.8	56.4	72.6	48.5	54.2	72.6

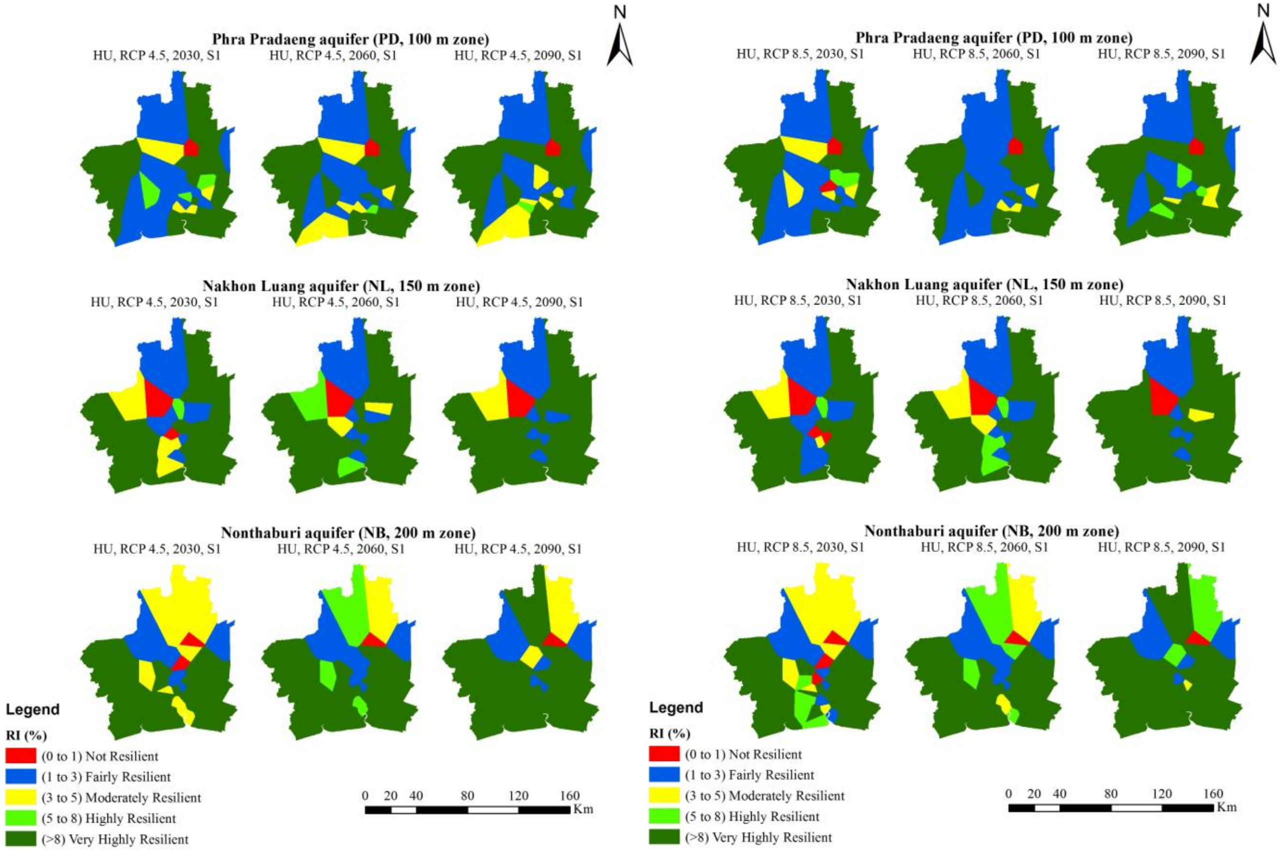


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S1) under High Urbanization (HU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

III. Results and Discussion

Mapping groundwater resiliency

b. Groundwater resiliency mapping for high urbanization and pumping scenario 2

Resiliency Class	Percentage of area under high urbanization scenario and pumping scenario (S2)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	1.2	1.2	1.2	1.2	1.2
Fairly Resilient	39.9	12.3	20.2	40.3	12.3	0.0
Moderately Resilient	6.3	19.9	5.7	6.4	27.0	5.8
Highly Resilient	0.0	7.8	3.0	3.8	1.4	19.3
Very Highly Resilient	52.6	58.8	69.9	48.3	58.2	73.7
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	4.2	4.2	4.2	4.9	4.2	4.2
Fairly Resilient	18.8	17.4	15.4	21.7	17.4	0.0
Moderately Resilient	9.8	0.0	1.5	10.3	1.4	0.0
Highly Resilient	4.1	1.4	0.5	0.0	0.0	16.1
Very Highly Resilient	63.1	77.1	78.4	63.1	77.1	79.7
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	2.2	0.0	0.0	2.2	1.2	0.0
Fairly Resilient	16.5	15.9	14.3	17.2	14.7	5.5
Moderately Resilient	9.9	0.3	0.6	24.9	2.2	8.8
Highly Resilient	17.5	1.9	1.0	1.2	9.3	0.0
Very Highly Resilient	53.8	81.9	84.1	54.5	72.6	85.7

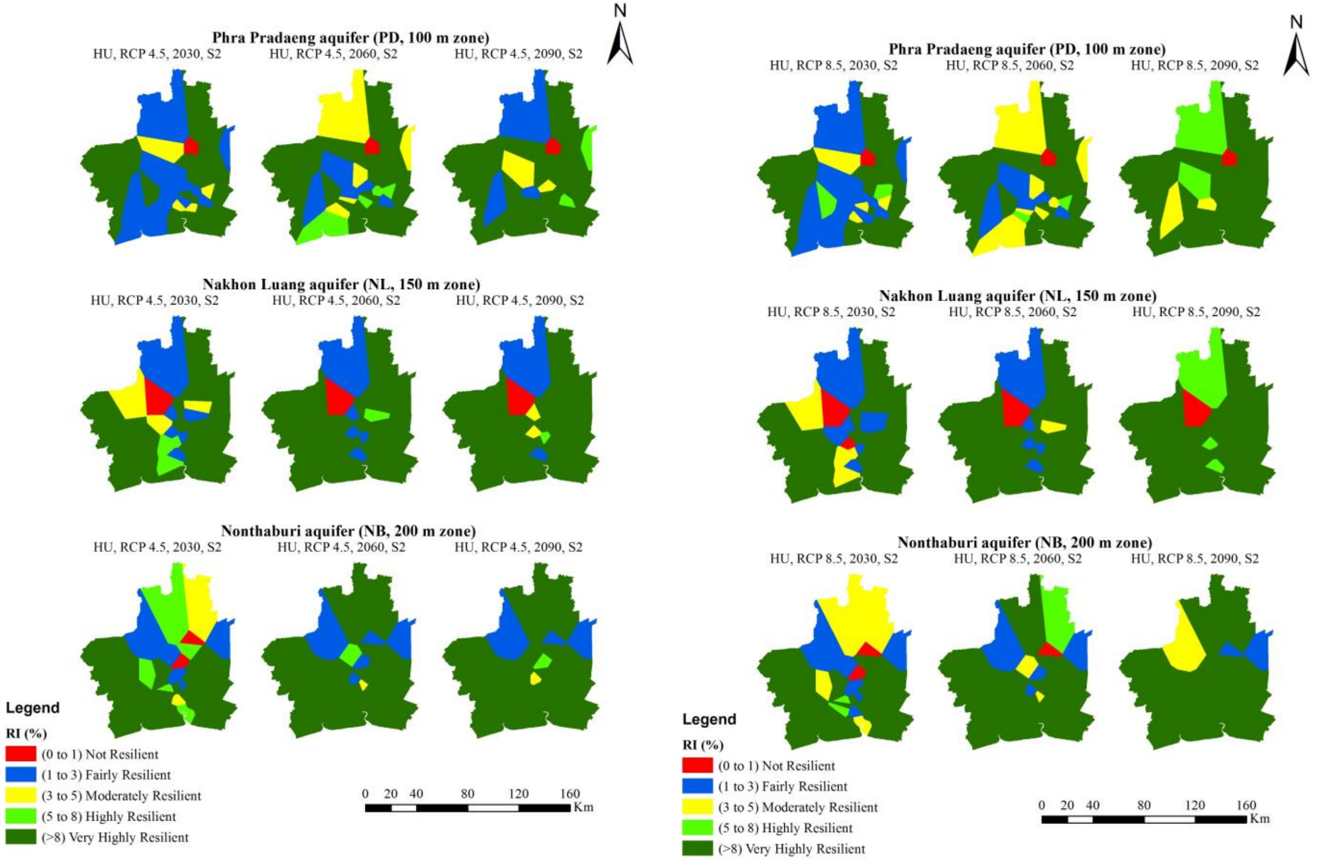


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S2) under High Urbanization (HU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

Mapping groundwater resiliency

c. Groundwater resiliency mapping for high urbanization and pumping scenario 3

Resiliency Class	Percentage of area under high urbanization scenario and pumping scenario (S3)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	16.1	41.3	48.8	16.7	42.9	43.7
Fairly Resilient	38.3	14.9	10.3	38.1	16.2	12.5
Moderately Resilient	1.8	1.3	11.4	2.7	1.9	4.8
Highly Resilient	0.0	3.5	1.8	0.0	0.0	0.0
Very Highly Resilient	43.8	39.0	27.8	42.5	39.0	39.0
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	26.6	32.5	54.2	27.0	33.6	53.7
Fairly Resilient	16.8	26.3	14.3	16.3	25.2	10.2
Moderately Resilient	0.9	7.8	2.6	0.9	9.7	7.2
Highly Resilient	11.9	7.4	16.7	14.4	5.9	5.1
Very Highly Resilient	43.8	26.0	12.2	41.3	25.7	23.8
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	20.5	27.9	57.9	22.4	29.0	53.3
Fairly Resilient	38.4	36.5	19.0	38.5	37.9	23.2
Moderately Resilient	5.5	4.2	2.1	3.4	4.1	2.0
Highly Resilient	1.3	6.3	6.2	1.7	8.4	3.7
Very Highly Resilient	34.3	25.1	14.8	33.9	20.6	17.9

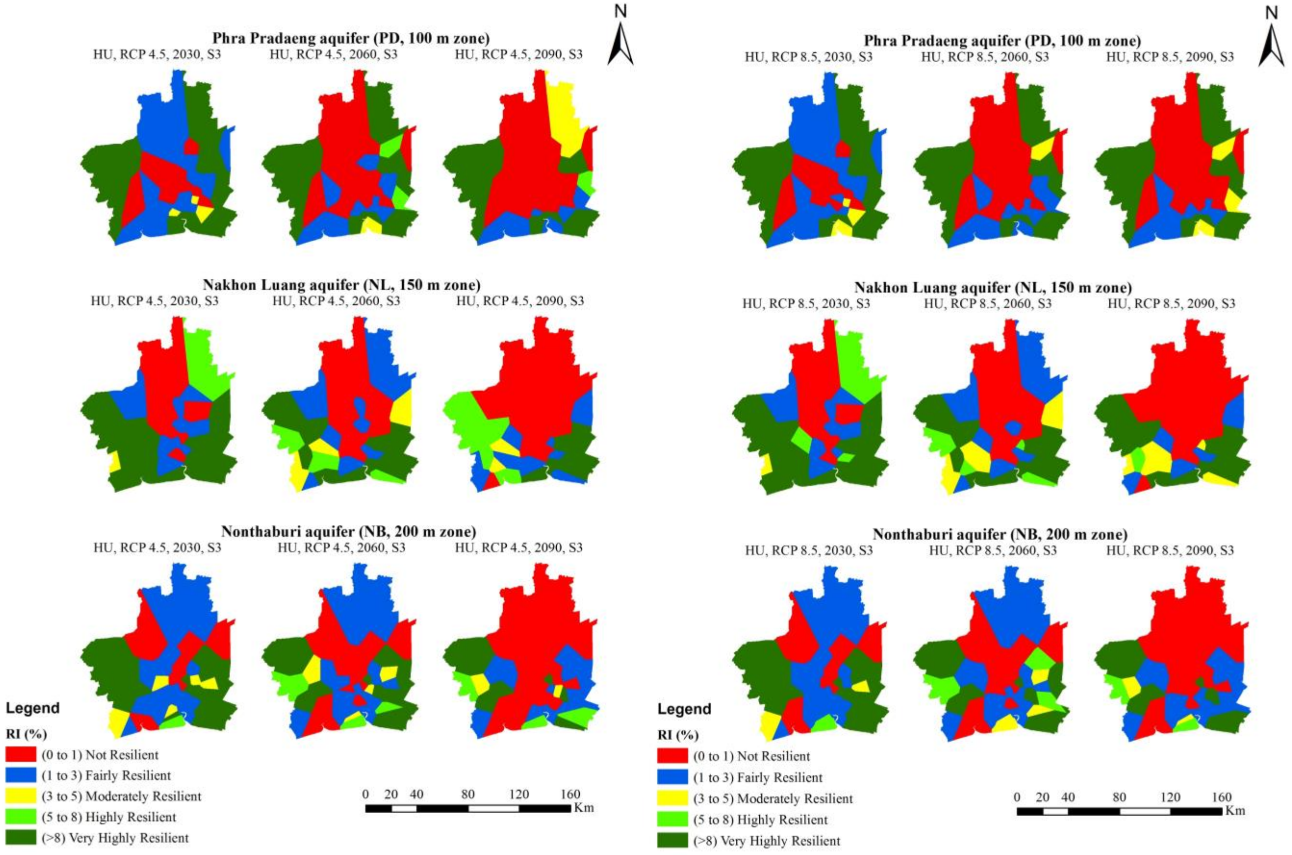


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S3) under High Urbanization (HU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

IV. Conclusion and Recommendation

Conclusions

Following conclusions are drawn from the study:

- Future precipitation is not uniform and varying throughout the future. The annual average future precipitation in dry season is projected to increase under both RCPs scenarios. Whereas the annual average precipitation in wet season is projected to decrease in near and mid future and increase in far future for both RCPs scenarios.
- Temperature is projected to increase in Bangkok and its vicinity, Thailand during all future time period in both RCPs scenarios. The increase in minimum temperature is higher than increase in maximum temperature.
- Three land use scenarios were developed in order to analyze its impact on groundwater, and they are high urbanization, medium urbanization and low urbanization scenarios.
- Future groundwater recharge is projected to increase in low urbanization scenario and both RCPs scenarios. The groundwater recharge is projected to decrease in future for high and medium urbanization scenarios and both RCPs scenarios. The decrease in future groundwater recharge is significant in wet season.

IV. Conclusion and Recommendation

Conclusions

- The average groundwater level is projected to increase in pumping scenarios S1 and S2, all land use scenarios and both RCPs scenarios. Whereas the average groundwater level is projected to decrease in pumping scenarios S3, all land use scenarios and both RCPs scenarios. Spatially, the decrease in groundwater level is higher in central part as compared to eastern and western part of the study area due to less recharge and more abstraction.

- The area classified as “very highly resilient” is projected to increase for pumping scenarios S1 and S2 in future. Whereas, for pumping scenario S3, the area under “very high resilient class” decreases and area under “not resilient” class increases as we moved to future. Most of the area in central and north-eastern part of the study area falls under “not resilient class” and the area in western part is likely to be “resilient” for pumping scenario S3. However, for pumping scenario S1 and S2 majority of the area are “resilient”.

IV. Conclusion and Recommendation

Recommendations

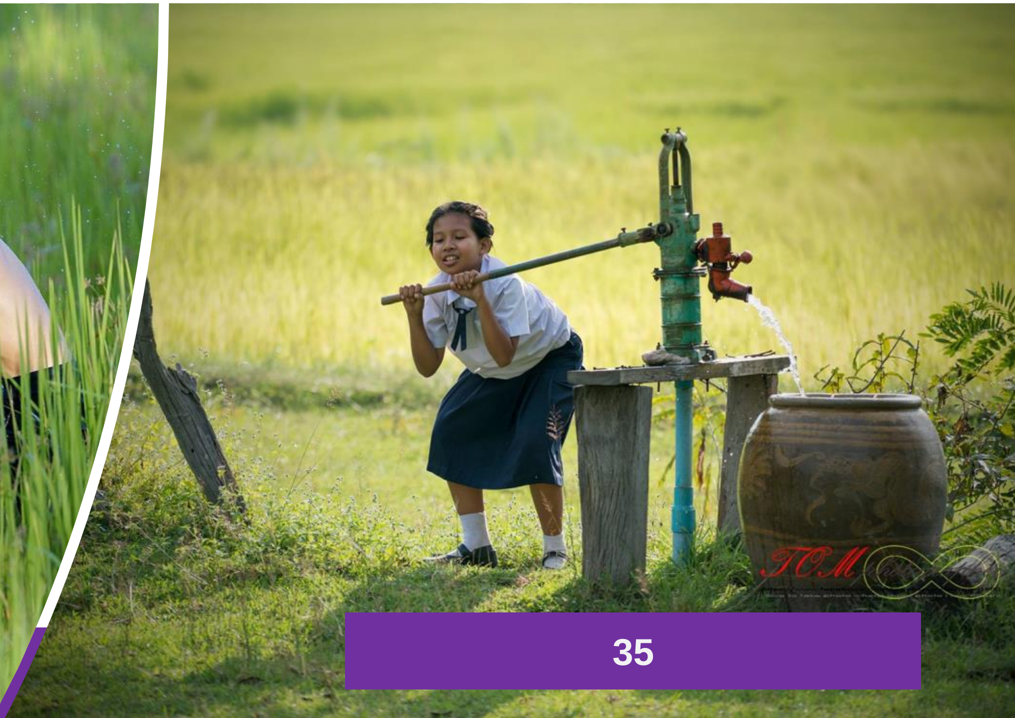
Based on the results of the study conducted, the following are the recommendations:

- The precipitation pattern is expected to fluctuate seasonally causing seasonal imbalance in water. Therefore, different structural and nonstructural measures should be implemented for efficient management of water resources.
- Land use change by increasing built-up area has caused vast impact on the groundwater recharge. So, urban planning must be done properly in order to manage the haphazard increase in built -up area in Bangkok and its vicinity.
- Reduction in recharge rates generate large runoffs and results in urban floods which can be devastating for Bangkok and its vicinity.

Recommendations for further research are given below:

- The groundwater model GMS-MODFLOW for this study was developed and analyzed in steady state condition, further work can be done in transient state to simulate the groundwater flow.
- Studying the impact of climate change and human development on the groundwater quality in Bangkok and its vicinity can be important research topic.

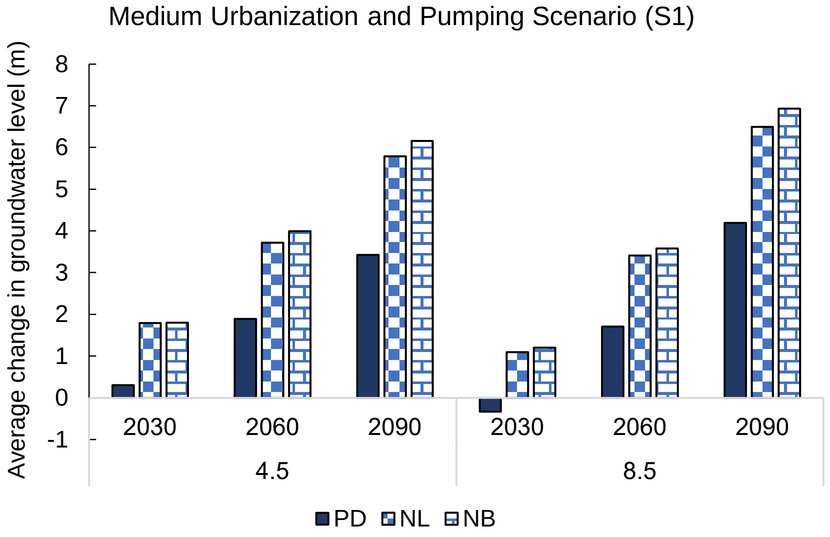
Thank You



APPENDIX

Groundwater modelling

a. Estimation of future groundwater level for medium urbanization and pumping scenario 1



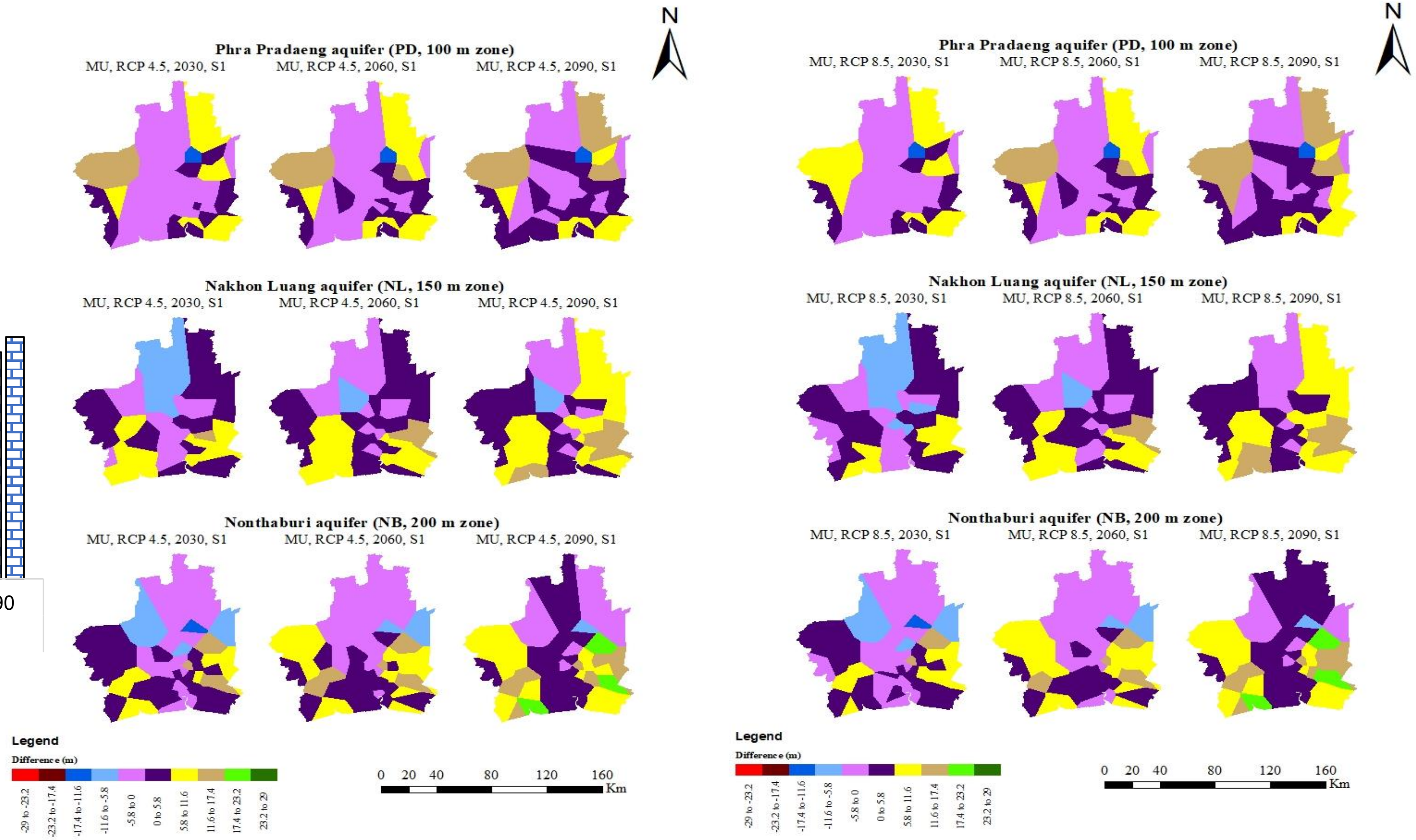
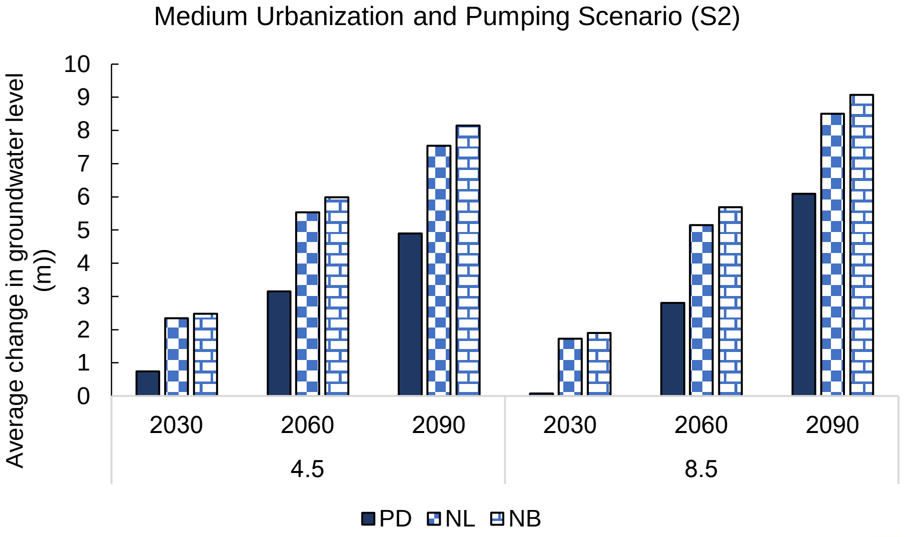


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under Medium Urbanization scenario (MU) and RCP 4.5 and 8.5 scenario for pumping scenario 1

Groundwater modelling

b. Estimation of future groundwater level for medium urbanization and pumping scenario 2



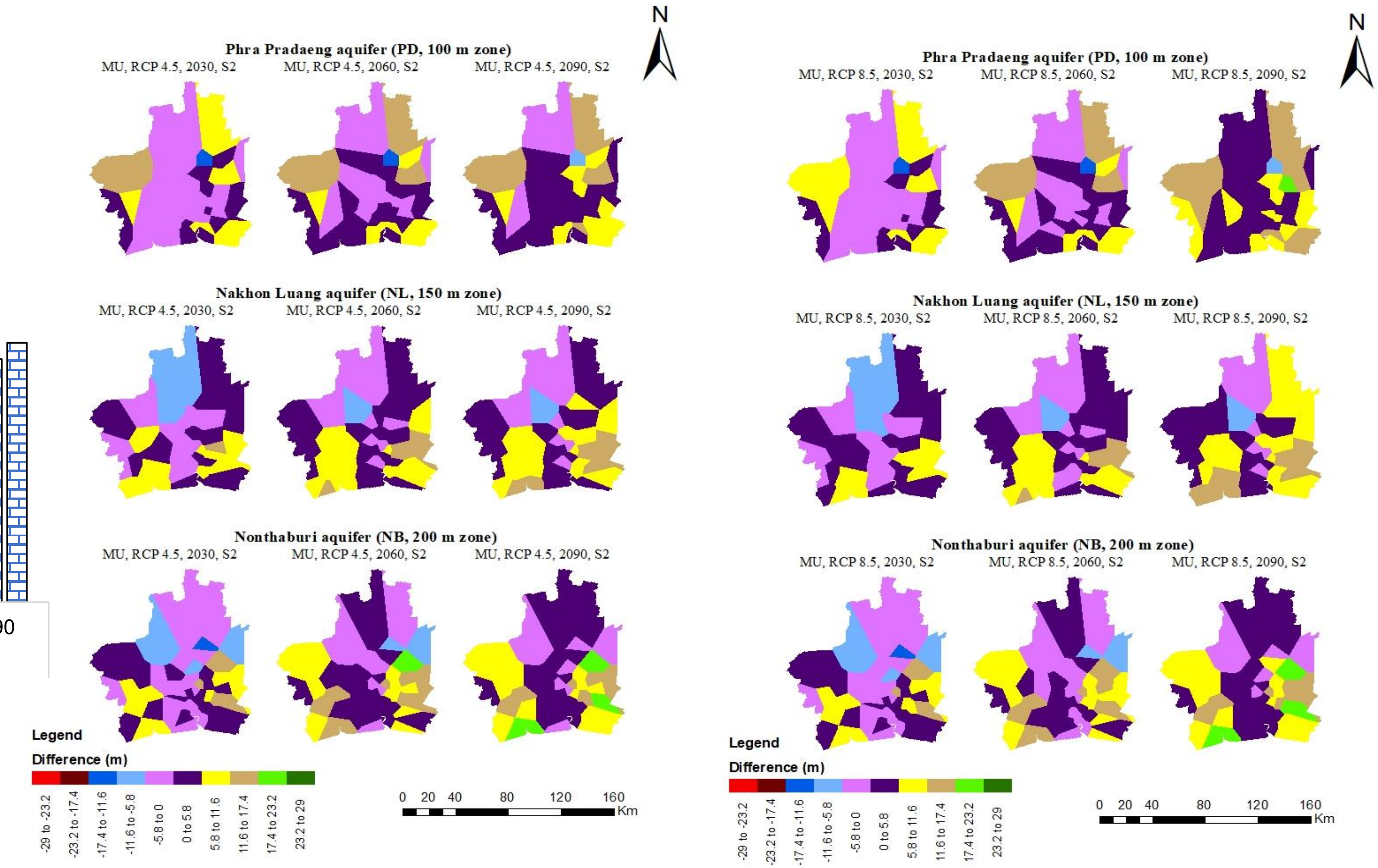
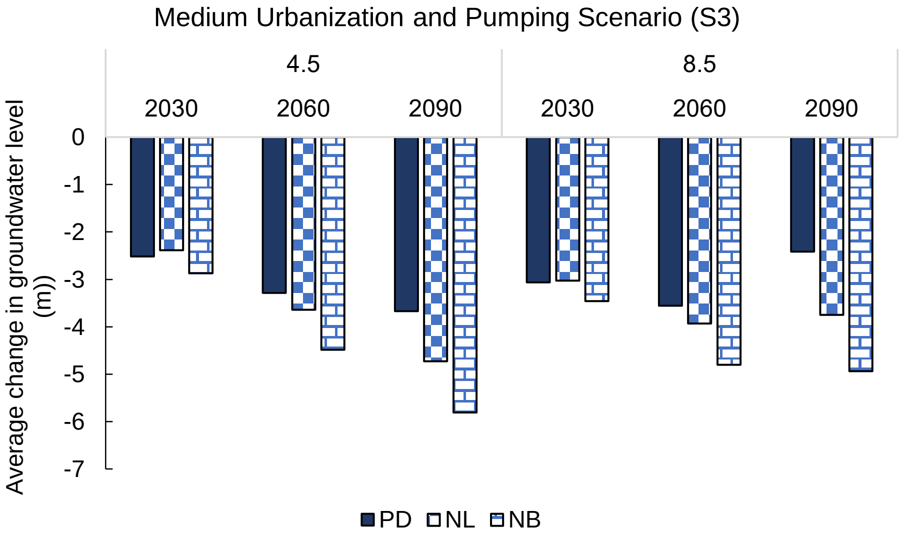


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under Medium Urbanization scenario (MU) and RCP 4.5 and 8.5 scenario for pumping scenario 2

Groundwater modelling

c. Estimation of future groundwater level for medium urbanization and pumping scenario 3



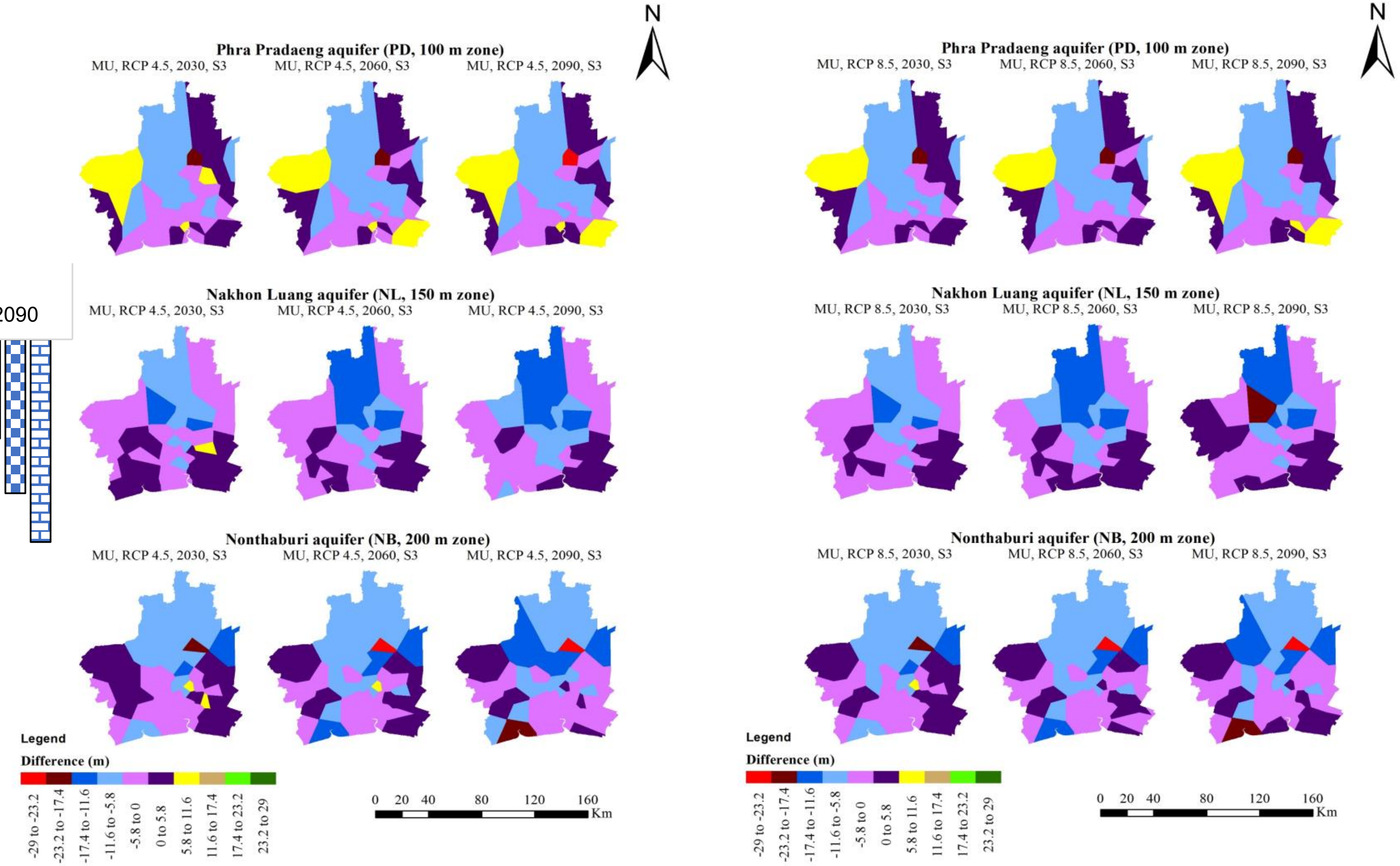
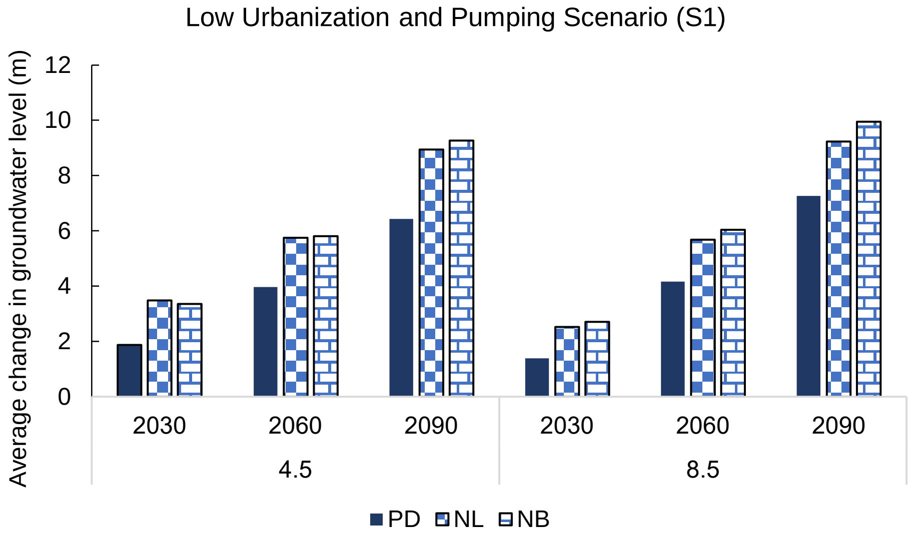


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under Medium Urbanization scenario (MU) and RCP 4.5 and 8.5 scenario for pumping scenario 3

V. Appendix

Groundwater modelling

d. Estimation of future groundwater level for low urbanization and pumping scenario 1



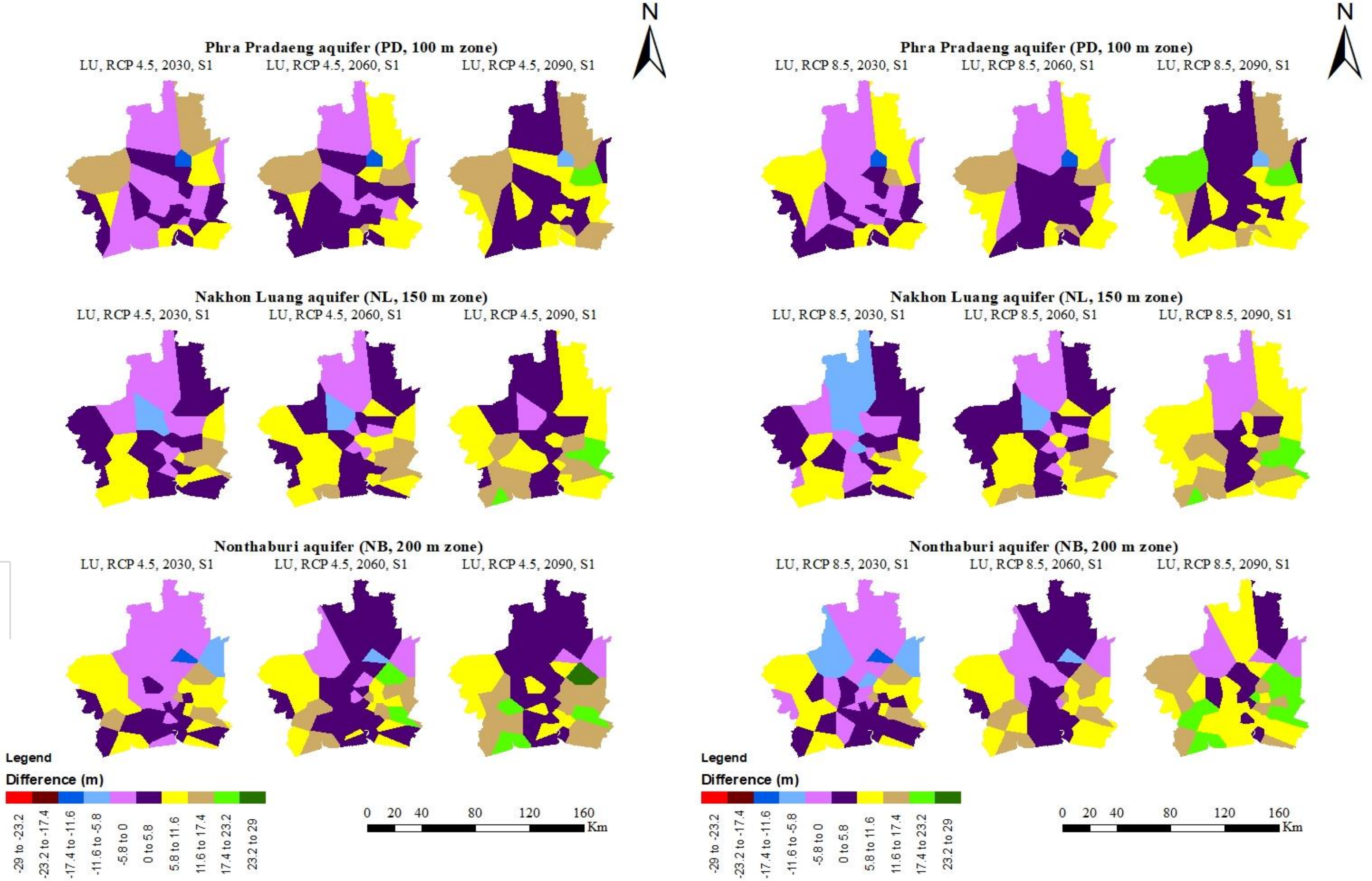
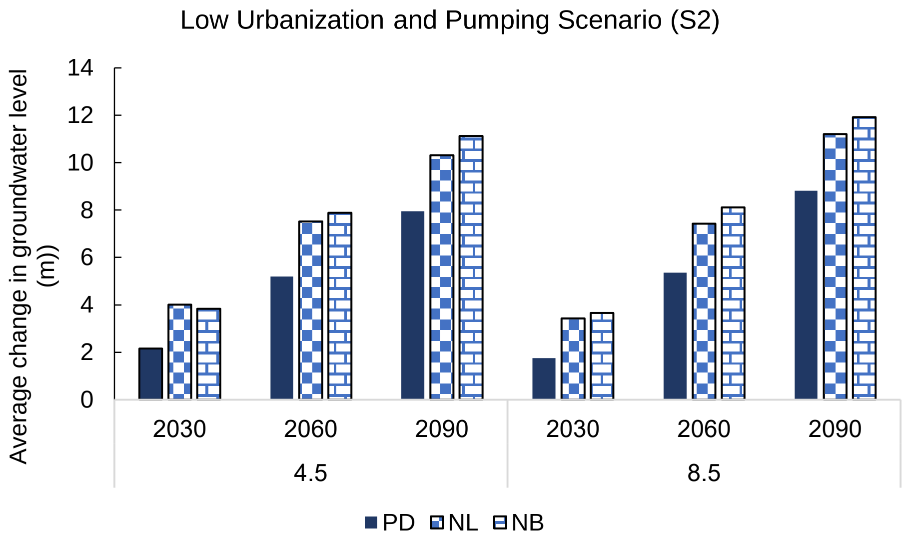


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under Low Urbanization scenario (LU) and RCP 4.5 and 8.5 scenario for pumping scenario 1

Groundwater modelling

e. Estimation of future groundwater level for low urbanization and pumping scenario 2



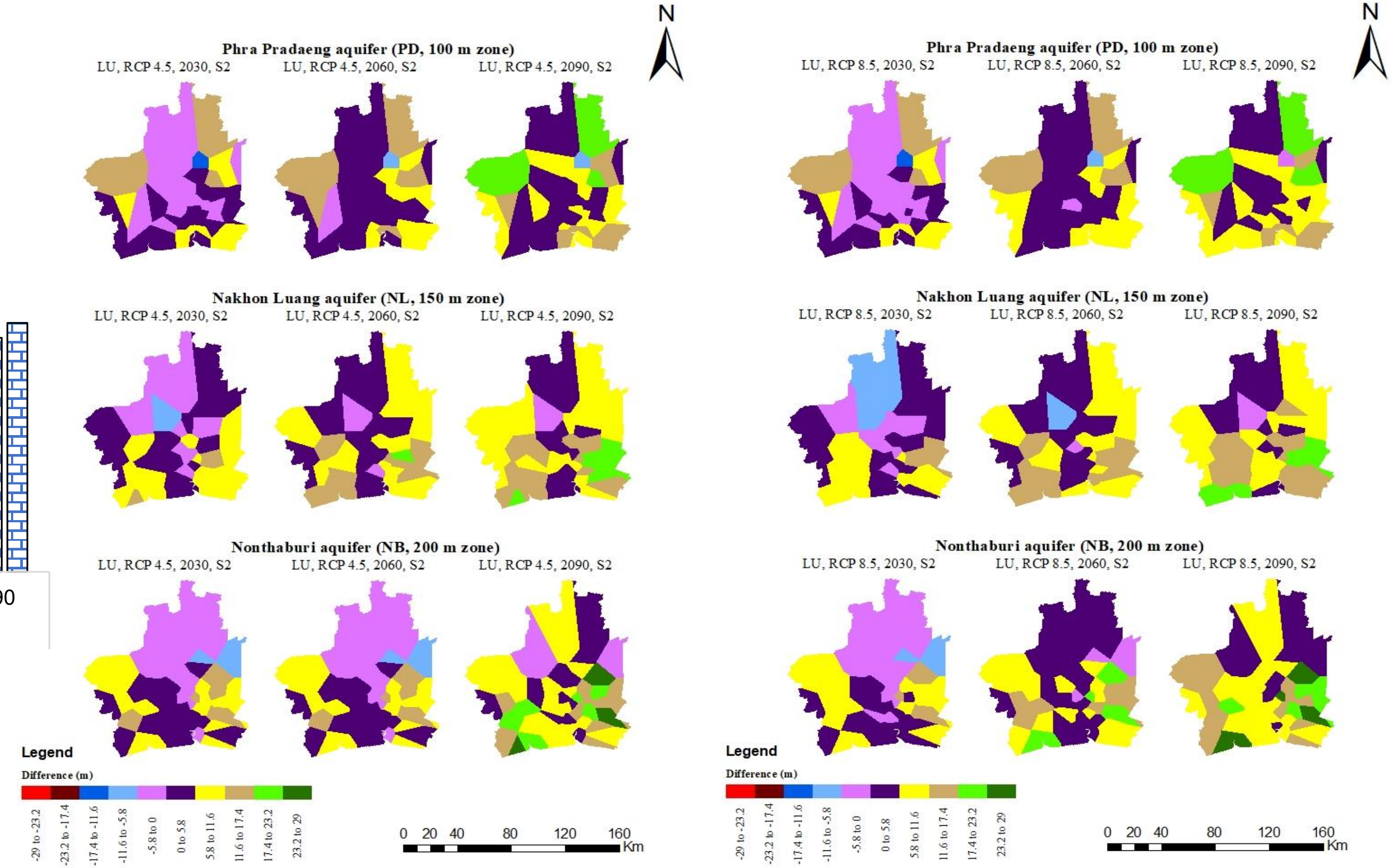
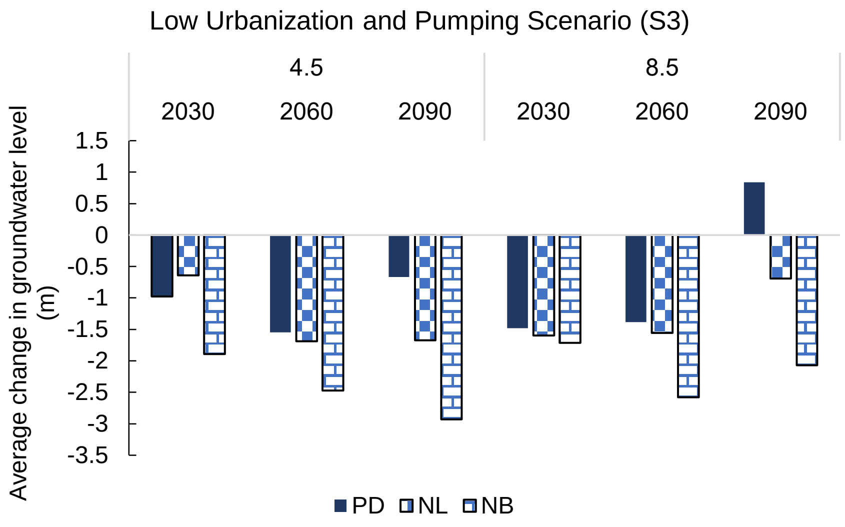


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under Low Urbanization scenario (LU) and RCP 4.5 and 8.5 scenario for pumping scenario 2

Groundwater modelling

f. Estimation of future groundwater level for low urbanization and pumping scenario 3



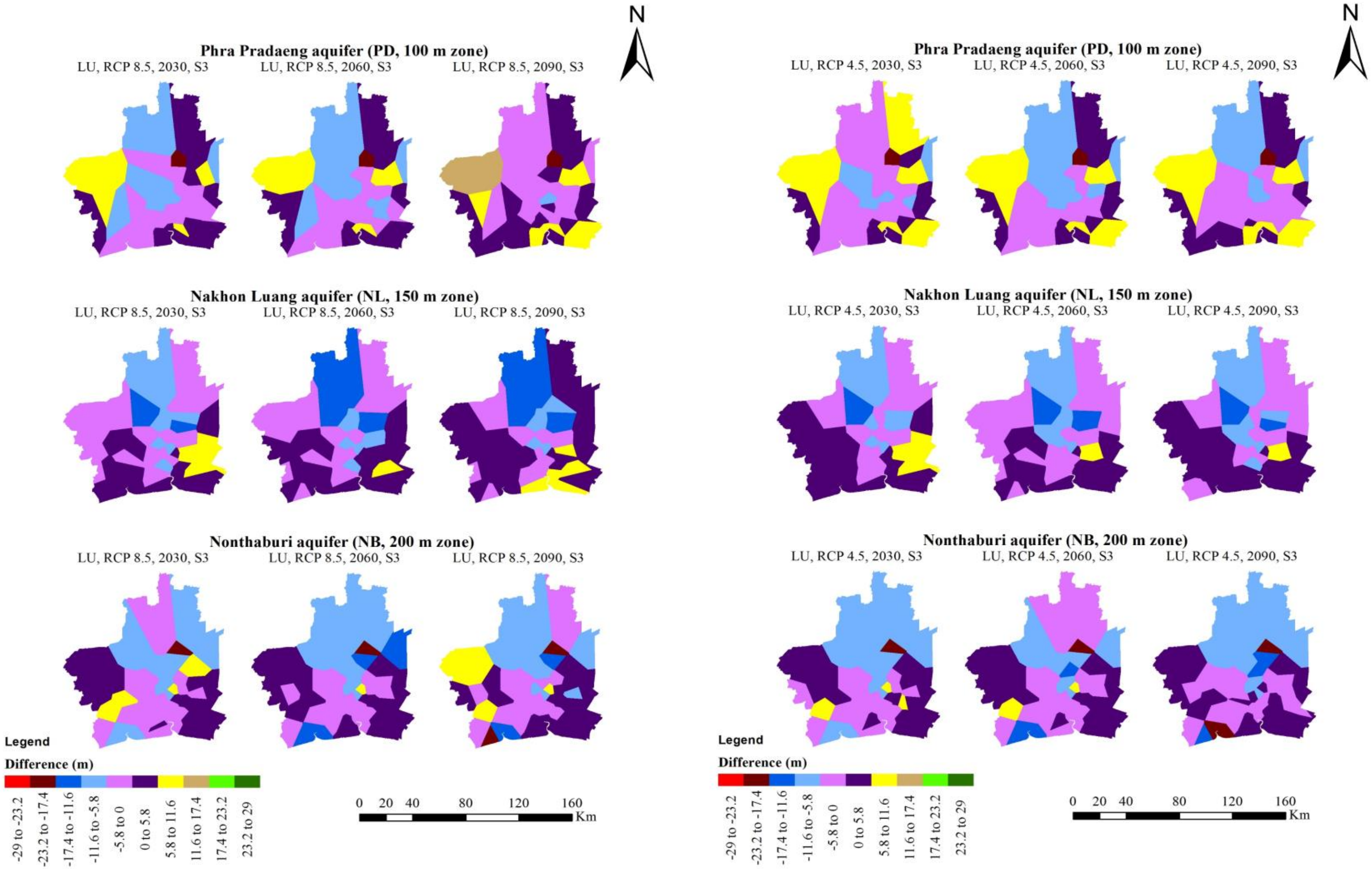


Figure: Absolute change in future groundwater level with respect to observed groundwater level (2001) in 2030, 2060 and 2090 for PD, NL and NB aquifer layers under Low Urbanization scenario (LU) and RCP 4.5 and 8.5 scenario for pumping scenario 3

Mapping groundwater resiliency

a. Groundwater resiliency mapping for medium urbanization and pumping scenario 1

Resiliency Class	Percentage of area under medium urbanization scenario and pumping scenario (S1)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	1.2	1.2	1.2	1.2	1.2
Fairly Resilient	39.2	22.7	6.0	40.4	8.7	0.0
Moderately Resilient	7.0	9.1	19.9	6.2	23.5	6.0
Highly Resilient	0.5	0.7	2.2	3.8	7.1	15.3
Very Highly Resilient	52.1	66.3	70.7	48.3	59.5	77.5
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	4.2	0.0	0.0	5.4	0.0	0.0
Fairly Resilient	20.3	21.6	4.2	19.1	21.6	4.2
Moderately Resilient	8.2	1.4	16.1	12.4	1.4	14.5
Highly Resilient	4.2	0.0	0.0	1.1	0.0	0.0
Very Highly Resilient	63.1	77.1	79.7	62.0	77.1	81.3
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	1.2	0.0	0.0	1.8	0.0	0.0
Fairly Resilient	16.9	16.2	6.5	17.0	16.2	5.5
Moderately Resilient	26.5	0.0	8.8	27.5	1.9	8.8
Highly Resilient	1.2	1.9	0.6	0.8	9.9	1.0
Very Highly Resilient	54.2	81.9	84.1	53.0	72.0	84.7

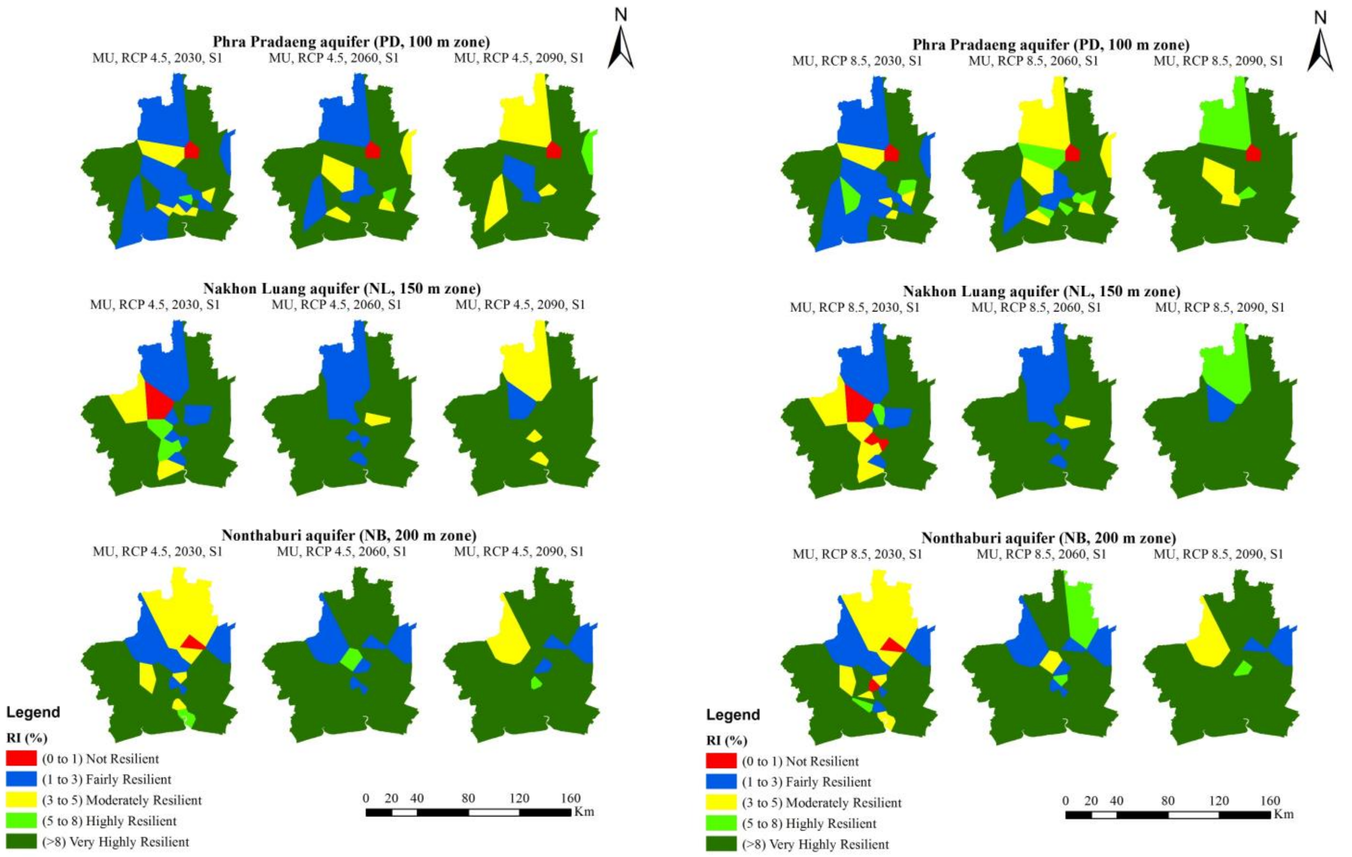


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S1) under Medium Urbanization (MU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

Mapping groundwater resiliency

b. Groundwater resiliency mapping for medium urbanization and pumping scenario 2

Resiliency Class	Percentage of area under medium urbanization scenario and pumping scenario (S2)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	1.2	1.2	1.2	1.2	0.0
Fairly Resilient	32.5	10.3	0.0	39.9	1.2	1.2
Moderately Resilient	7.4	1.2	0.0	6.8	23.9	0.0
Highly Resilient	6.3	0.0	0.0	3.8	3.7	0.0
Very Highly Resilient	52.6	87.3	98.8	48.3	70.0	98.8
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	4.2	0.0	0.0	4.2	0.0	0.0
Fairly Resilient	18.8	4.9	4.2	20.3	5.8	0.0
Moderately Resilient	1.6	15.4	0.0	8.7	14.9	0.0
Highly Resilient	3.7	0.8	0.0	3.7	0.8	0.0
Very Highly Resilient	71.8	78.9	95.8	63.1	78.4	100.0
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	1.2	0.0	0.0	1.2	0.0	0.0
Fairly Resilient	15.0	14.3	0.0	17.5	6.5	0.0
Moderately Resilient	11.8	0.0	5.5	26.3	9.4	4.3
Highly Resilient	5.1	1.6	8.8	2.0	0.0	0.0
Very Highly Resilient	66.8	84.1	85.7	53.0	84.1	95.7

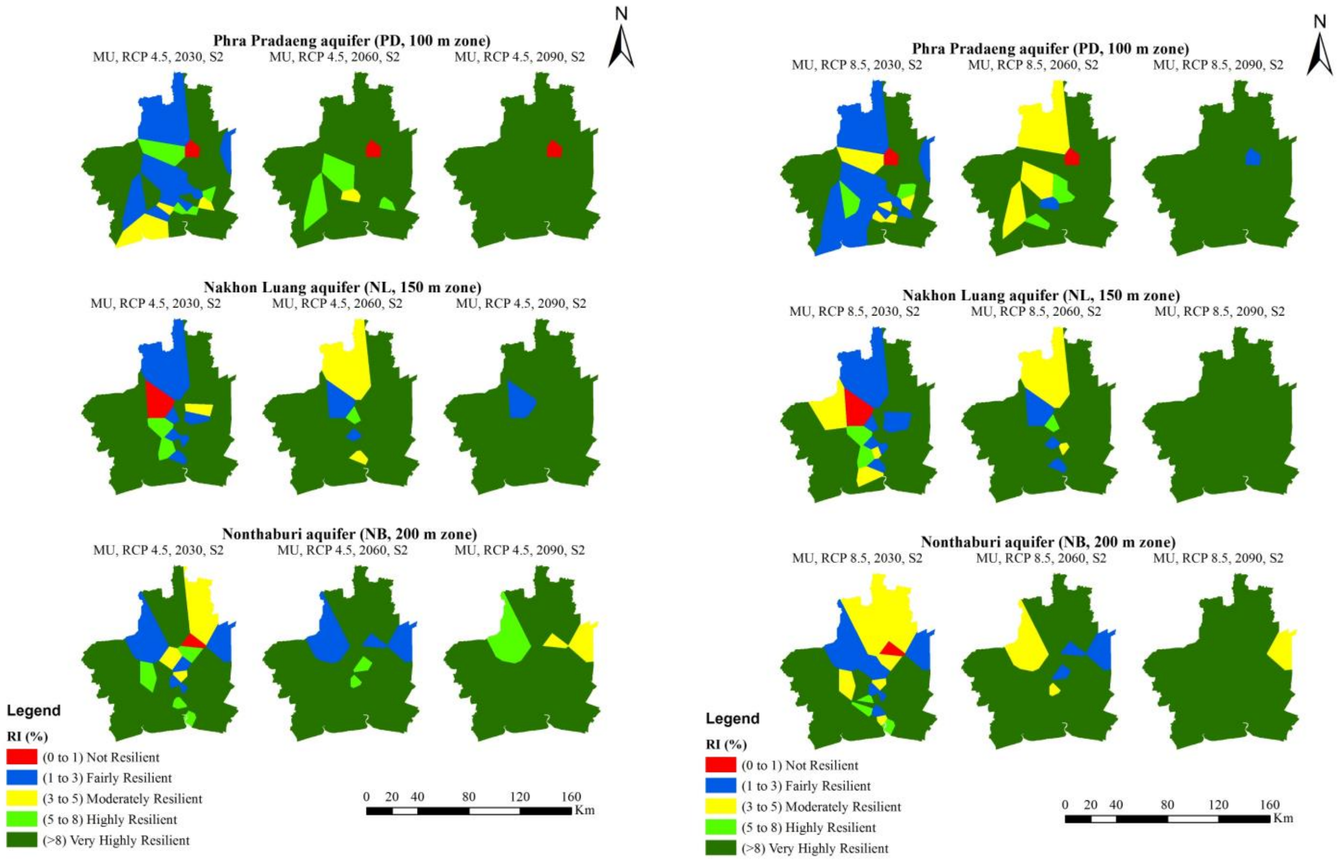


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S2) under Medium Urbanization (MU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

Mapping groundwater resiliency

c. Groundwater resiliency mapping for medium urbanization and pumping scenario 3

Resiliency Class	Percentage of area under medium urbanization scenario and pumping scenario (S3)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	10.0	11.0	15.4	11.0	11.0	15.4
Fairly Resilient	42.8	43.4	39.6	43.4	43.4	39.3
Moderately Resilient	2.0	0.3	0.0	0.7	0.3	0.0
Highly Resilient	0.4	0.0	2.7	1.3	1.5	0.0
Very Highly Resilient	44.9	45.3	42.2	43.6	43.8	45.3
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	23.7	26.9	31.7	25.0	28.5	26.6
Fairly Resilient	18.6	16.5	15.0	17.3	15.8	16.8
Moderately Resilient	0.9	12.8	20.4	2.0	14.5	4.2
Highly Resilient	13.0	7.8	4.1	13.8	7.7	19.8
Very Highly Resilient	43.8	36.0	28.8	41.9	33.5	32.6
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	18.3	24.3	25.3	21.8	25.0	25.3
Fairly Resilient	37.3	39.5	42.2	40.7	38.9	39.7
Moderately Resilient	7.8	0.5	3.0	1.8	0.5	1.3
Highly Resilient	1.3	0.8	2.6	1.7	2.8	2.8
Very Highly Resilient	35.3	34.9	26.9	33.9	32.8	30.9

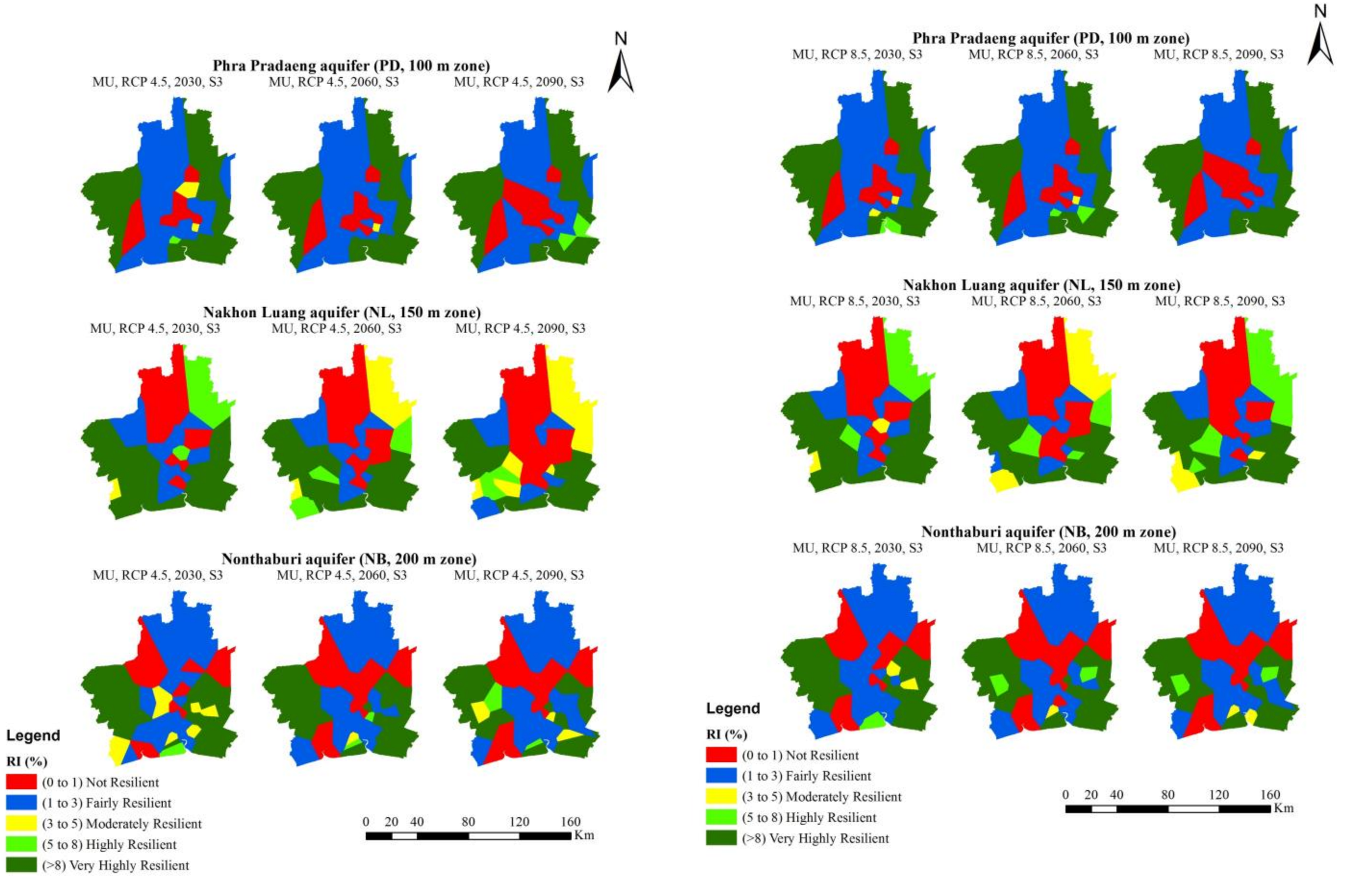


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S3) under Medium Urbanization (MU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

Mapping groundwater resiliency

d. Groundwater resiliency mapping for low urbanization and pumping scenario 1

Resiliency Class	Percentage of area under low urbanization scenario and pumping scenario (S1)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	1.2	0.0	1.2	1.2	0.0
Fairly Resilient	0.8	0.0	1.2	18.3	0.0	1.2
Moderately Resilient	24.0	0.0	0.0	10.2	0.0	0.0
Highly Resilient	7.4	20.5	0.0	2.7	2.2	0.0
Very Highly Resilient	66.6	78.3	98.8	67.6	96.6	98.8
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	0.0	0.0	0.0	4.2	0.0	0.0
Fairly Resilient	19.5	4.2	0.0	5.8	18.7	0.0
Moderately Resilient	9.7	0.8	0.0	6.2	0.0	4.2
Highly Resilient	1.6	15.8	4.2	0.0	0.7	0.0
Very Highly Resilient	69.3	79.2	95.8	83.7	80.6	95.8
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	1.2	0.0	0.0	1.2	0.0	0.0
Fairly Resilient	14.1	5.5	1.2	15.0	14.3	1.2
Moderately Resilient	0.6	1.0	0.0	14.0	0.0	0.0
Highly Resilient	12.6	8.8	0.0	10.8	0.0	8.8
Very Highly Resilient	71.5	84.7	98.8	59.0	85.7	89.9

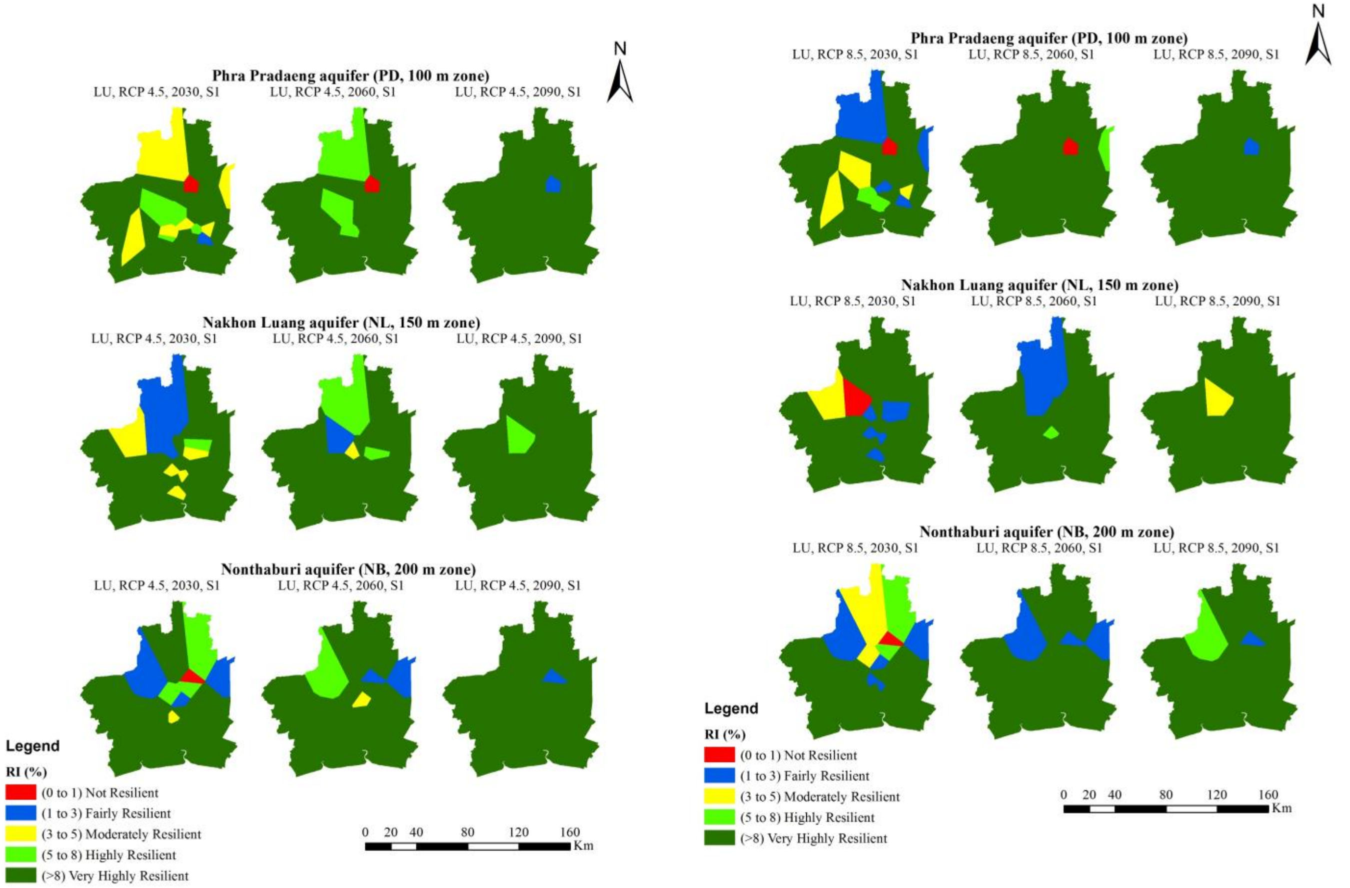


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S1) under Low Urbanization (LU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

Mapping groundwater resiliency

e. Groundwater resiliency mapping for low urbanization and pumping scenario 2

Resiliency Class	Percentage of area under low urbanization scenario and pumping scenario (S2)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	0.0	0.0	1.2	0.0	0.0
Fairly Resilient	16.6	1.2	0.0	14.4	1.2	1.2
Moderately Resilient	13.0	0.0	0.0	7.8	0.0	0.0
Highly Resilient	5.4	0.0	0.0	10.4	1.2	0.0
Very Highly Resilient	63.7	98.8	100.0	66.1	97.6	98.8
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	0.0	0.0	0.0	0.0	0.0	0.0
Fairly Resilient	4.9	4.2	0.0	20.0	0.0	0.0
Moderately Resilient	16.7	0.0	0.0	2.9	0.0	0.0
Highly Resilient	2.9	0.0	0.0	7.8	0.0	0.0
Very Highly Resilient	75.5	95.8	100.0	69.3	100.0	100.0
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	0.0	0.0	0.0	0.0	0.0	0.0
Fairly Resilient	14.3	1.2	0.0	14.3	1.2	0.0
Moderately Resilient	3.8	0.0	0.0	1.9	4.3	0.0
Highly Resilient	9.9	8.8	0.0	13.7	0.0	0.0
Very Highly Resilient	72.0	89.9	100.0	70.1	94.5	100.0

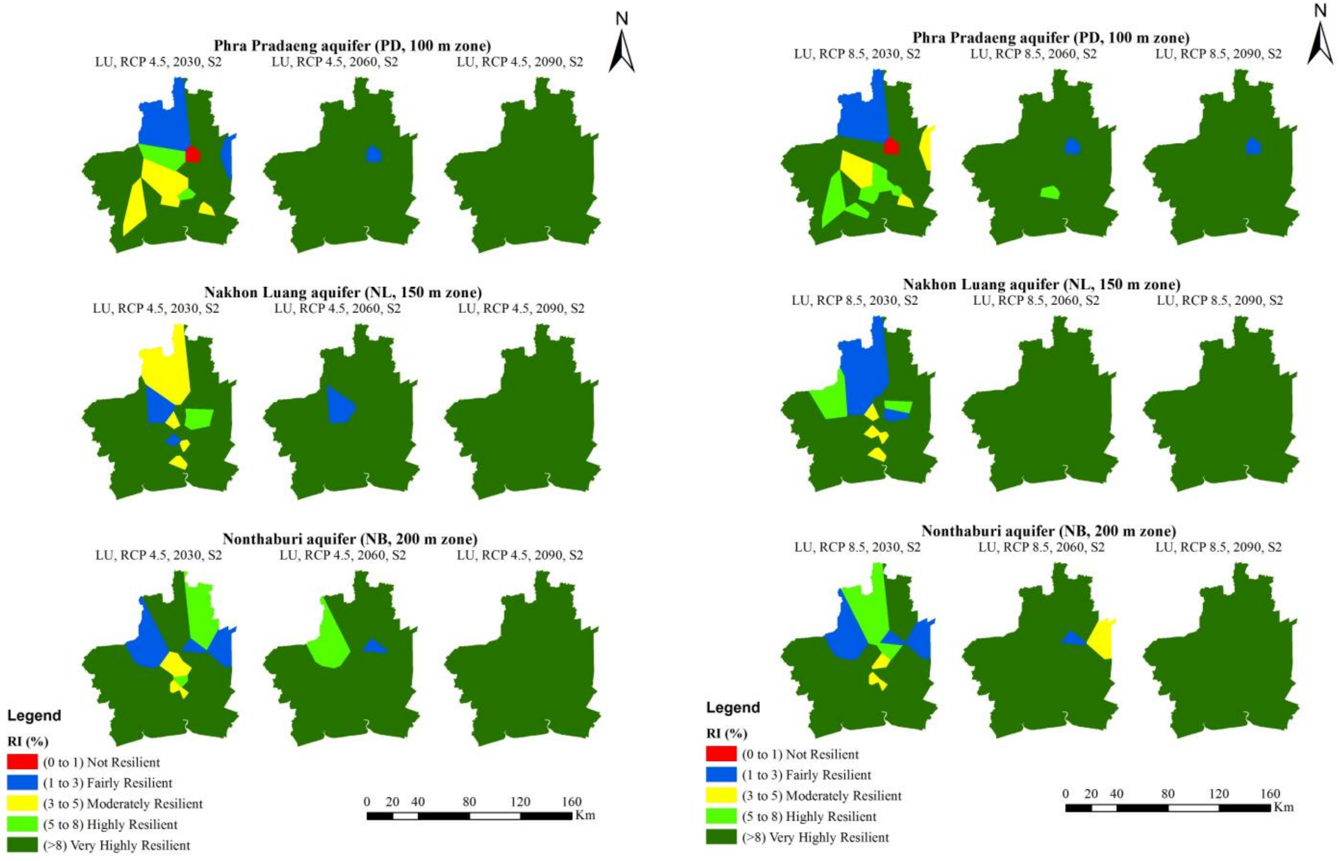


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S2) under Low Urbanization (LU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

V. Appendix

Mapping groundwater resiliency

f. Groundwater resiliency mapping for low urbanization and pumping scenario 3

Resiliency Class	Percentage of area under low urbanization scenario and pumping scenario (S3)					
	Phra Pradaeng Aquifer (PD, 100m Zone)					
	RCP 4.5			RCP 8.5		
	2030	2060	2090	2030	2060	2090
Not Resilient	1.2	1.2	1.2	1.2	1.2	1.2
Fairly Resilient	36.8	38.5	39.5	37.9	39.0	34.9
Moderately Resilient	10.0	3.5	9.2	9.3	8.7	11.5
Highly Resilient	2.2	11.5	8.5	0.0	4.2	7.6
Very Highly Resilient	49.8	45.3	41.5	51.5	46.8	44.8
	Nakhon Luang Aquifer (NL, 150m Zone)					
Not Resilient	4.2	7.1	15.8	5.6	21.6	24.2
Fairly Resilient	22.4	31.0	13.7	31.8	16.1	12.7
Moderately Resilient	10.8	0.5	2.9	3.0	2.1	2.1
Highly Resilient	2.4	3.7	9.9	1.1	1.1	3.4
Very Highly Resilient	60.2	57.7	57.7	58.6	59.1	57.7
	Nonthaburi Aquifer (NB, 200m Zone)					
Not Resilient	5.5	7.6	11.1	5.5	9.0	11.1
Fairly Resilient	41.6	31.7	36.0	41.6	40.0	32.9
Moderately Resilient	6.6	14.0	9.5	5.8	7.1	13.8
Highly Resilient	7.9	4.9	0.0	6.3	4.0	3.3
Very Highly Resilient	38.4	41.8	43.4	40.8	39.8	39.0

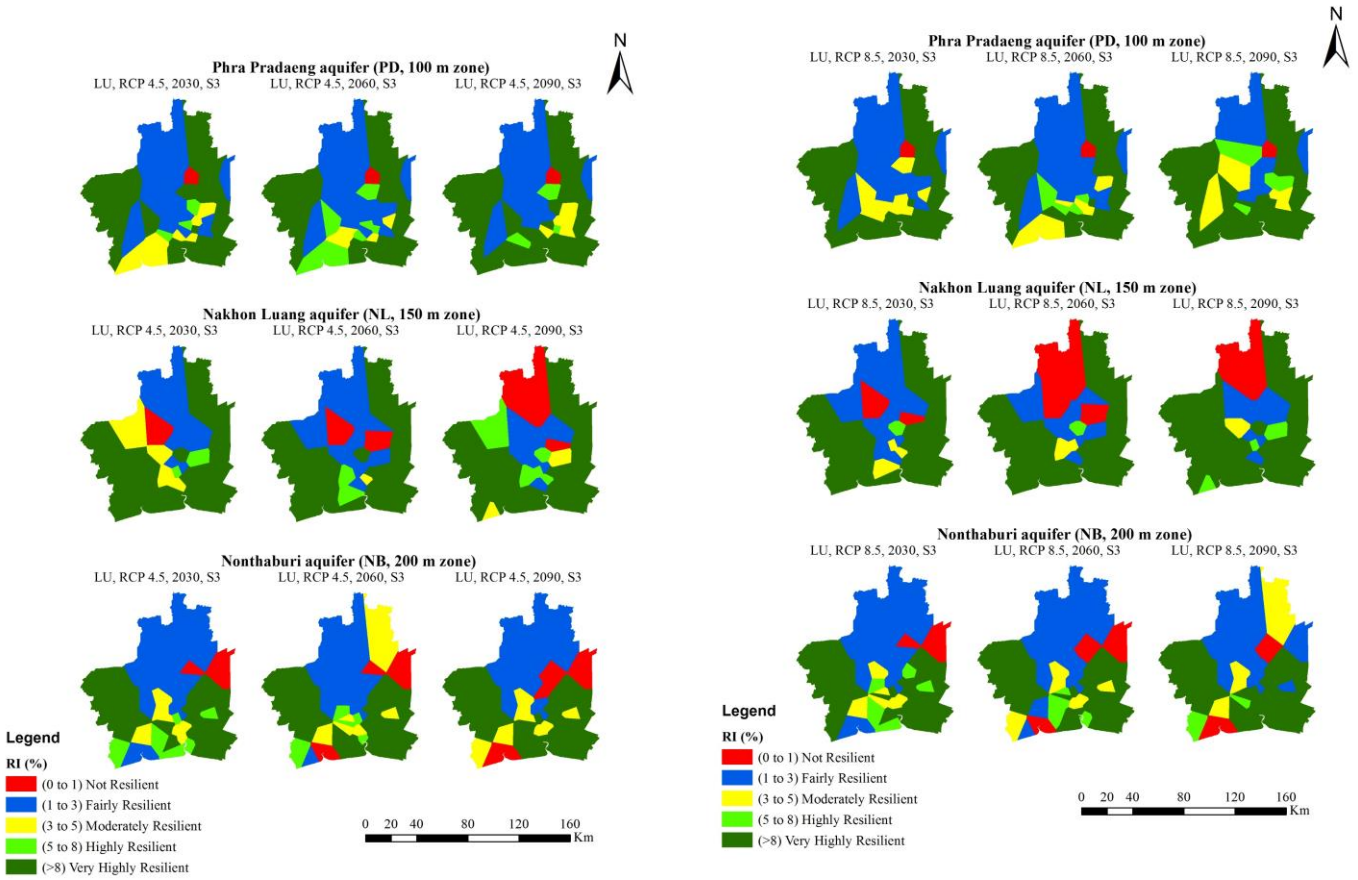


Figure: Groundwater resilience mapping of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S3) under Low Urbanization (LU) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB