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

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ABSTRACT

Groundwater is essential resource for various uses and have a great economic importance in Bangkok and its vicinity, Thailand. Groundwater resources in Bangkok and its vicinity is under immense pressure because of population growth, rapid urbanization, over exploitation and climate change. Mapping groundwater resilience under climate change and human development can be the effective tools to identify the area where the preventive measures are urgent which ultimately helps in the sustainability aspects of groundwater. We extend upon the results from Ghimire et al., 2021 on climate and land-use change impacts on spatiotemporal variations in groundwater recharge: A case study of the Bangkok Area, Thailand to include the effects of climate change and land use change on groundwater recharge. The future climate projected using the climate data of RCM's namely ACCESSCSIRO-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 RCP 4.5 and RCP 8.5 scenarios were bias corrected using quantile mapping technique. All RCMs projects that the temperature is continuously increasing in the study area, however, future precipitation is highly complex and uncertain and there was significant difference among various RCMs and both RCPs scenarios. An empirical land-use projection model (Conversion of Land-use and its Effects, Dyna-CLUE) was used. Future land-use scenarios of Low Urbanization Scenario (LU), Medium Urbanization Scenario (MU) and High Urbanization Scenario (HU) were developed in Dyna-CLUE focusing on increasing built-up area to generate land-use maps until 2099. A hydrological model WetSpass developed was used to estimate the water recharge and suggest that groundwater will be decrease in future for high and medium urbanization and the decrease in groundwater recharge ranges from 5.84mm/yr to 20.91mm/yr in RCP 4.5 scenario and 4.07mm/yr to 18.72 mm/yr in RCP 8.5 scenario. But, for low urbanization, the increase in future groundwater recharge ranges from 7.9 mm/yr to 16.66 mm/yr for RCP 4.5 scenario and 5.54 mm/yr to 20.04 mm/yr for RCP 8.5 scenario.

To estimate future groundwater level, GMS-MODFLOW model was set up using boundary conditions, recharge rates, pumping rates and hydraulic properties. The average groundwater level is projected to increase in first two 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. Based on the result of GMS-MODFLOW, groundwater resiliency indicator was used to generate the resiliency map of Bangkok and its vicinity. 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 in future.

Keywords: Climate change; Human development; GMS-MODFLOW; Groundwater resiliency

1. Introduction

In recent years, the world climate has been rapidly changing (Vijaya et al., 2011), and climate change has 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). According to the Intergovernmental Panel on Climate Change (IPCC, 2014), global temperatures have risen by 0.3-0.6°C since 1900 and will pick up to rise between 1.4 to 5.8°C by 2100.

Technological advancements have cleared the way for rapid growth and development. In most regions of the world, larger industries, jumbo infrastructures, and greater populations are quite communal. Human development, in terms of land use change and population growth, is occurring at an alarming rate, which has a direct impact on the water cycle's dynamics. According to United Nations Development Program (UNDP), Asia is the most vulnerable and scarce freshwater resources area in the world. It has been projected that freshwater resources will be more scare in the future due to climate change and augmented human demand (Wada et al., 2016; Veldkamp et al., 2017; Boretti and Rosa, 2019). Fresh water supply, both in terms of quality and quantity, will be a serious concern. Rivers, lakes, and streams, for example, may not be able to supply the ever-increasing demand of the growing population. Furthermore, the absence of infrastructure to harness freshwater resources means that groundwater will be used considerably more frequently. As a result, the reliance on groundwater is growing.

Groundwater is depicted as the world's hidden treasure, constituting 94% of its freshwater resources (Koundouri & Groom, 2010). Groundwater is the most preferable source of water supply since it is of good quality and requires less treatment than surface water (Shrestha et al., 2020). Groundwater plays a critical role in the long-term development of Asia's major cities. The importance of groundwater for the city's water supply will almost certainly increase in the future due to climate change and human development (population expansion, urbanization). As a result, for strategic planning and management of water resources in urban areas, it is critical to analyze the resiliency of groundwater under climate change and human development.

Bangkok is one of the megacities of Southeast Asia (Lorphensri et al., 2016) and it has been experiencing a noteworthy loss of groundwater since 1960s. Rapid population growth, urbanization, fast growing economy, tourism development and industrialization are the main drivers of groundwater over exploitations in Bangkok and its vicinity, Thailand (Lorphensri et al., 2016). Large scale groundwater degradation in Bangkok and its vicinity resulted in adverse environmental problems like continuous depletion of groundwater levels, land subsidence and groundwater contamination by sea water intrusion (Wattayakorn et al., 2016). The problem such as flooding, deterioration of infrastructure facilities, loss of properties, groundwater pollution and health hazards are associated with excessive groundwater extraction and land subsidence (Gupta and Babel, 2006). It is obvious that Bangkok city has experienced rapid change and development activities are still on advancement. Different human activities, imminent changing trends in climate and random extraction has a tremendous impact on groundwater resources. Therefore, there is an urgent need to implement policies to balance recharge according to withdrawal.

This study intends to assess the resiliency of groundwater system to climate change and human development in Bangkok and its vicinity, Thailand. We extend upon the results from Ghimire et al., 2021 on climate and land-use change impacts on spatiotemporal variations in groundwater recharge: A case study of the Bangkok Area, Thailand to include the effects of climate change and land use change on groundwater recharge.

2. Study area and data collection

2.1 Study area

The study area consists of Bangkok (13° 45' North, 100° 31' East) and its vicinity (Nonthaburi, Nakhon Pathom, Pathum Thani, Samut Prakan, Samut Sakhon, and Phra Nakhon Si Ayutthaya) (Figure 1). The Noi and Chao Phraya Rivers, as well as the Mae Klong, Pasak, Prachin, and Tha Chin Rivers, run through Bangkok and its surrounding provinces. The research area is located in a humid tropical climate with warm temperatures all year. Under the influence of the South Asian monsoon system, Bangkok has a tropical dry-and-wet climate with two seasons: dry (November to April) and rainy (May to October). The average annual temperature is 30 °C/year, with an average rainfall of 1500 mm. Bangkok and its environs have a total population of 11.3 million people, with a population density of 300–3,600 people per square kilometer, according to the 2010 census.

The study area covers the groundwater control areas of Bangkok and its six surrounding provinces, consisting of underlying unconsolidated sediment of the Chao Phraya-Tha Chin Basin which consist of alluvial and colluvial deposits and river terraces with a multiaquifer system. There are 8 aquifers layer in Bangkok and its vicinity; Bangkok aquifer (BK, 50m zone), Phra Pradaeng aquifer (PD, 100m zone), Nakhon Luang aquifer (NL, 150m zone), Nonthaburi aquifer (NB, 200m zone), Sam Kok aquifer (SK, 300m zone), Phaya Thai aquifer (PT, 350m zone), Thonburi aquifer (TB 450m zone), and Pak Nam aquifer (PN, 550m zone).

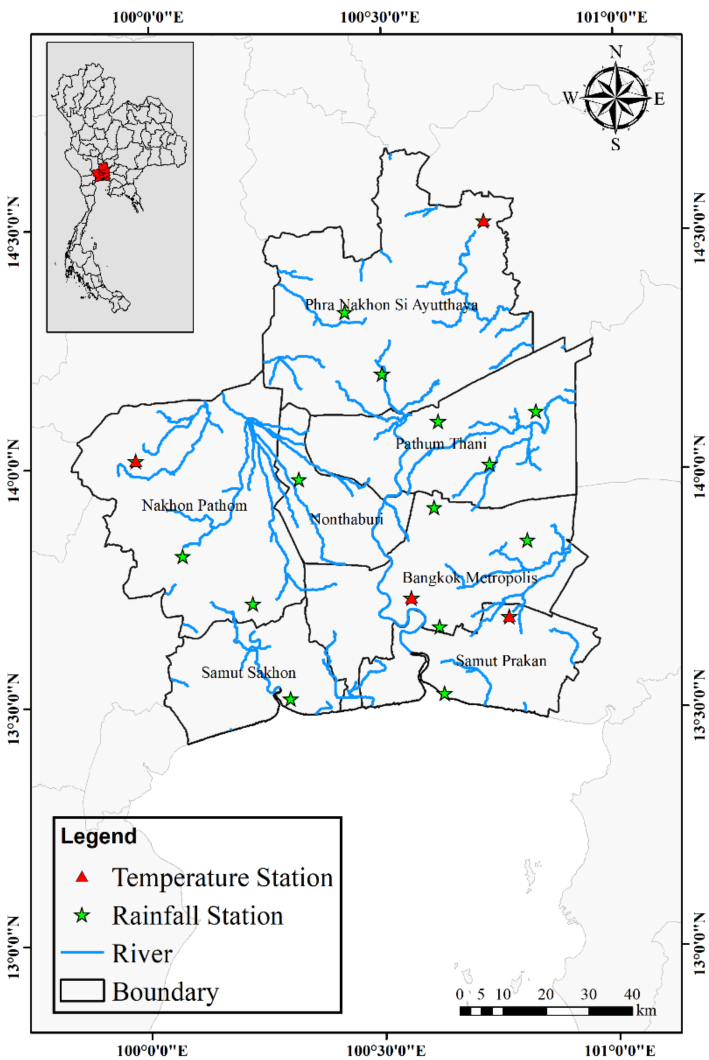


Figure 1: Location map of Bangkok and its vicinity with meteorological stations and the river network

2.2 Data Collection

Table 1: Data used in this study and corresponding sources of data

Data Type	Frequency/Time	Unit/ Format	Source
Observation/ Monitoring well data	Yearly/ 2001 and 2009	m	Department of Groundwater Resources (DGR), Thailand
Production/ Pumping well data	Yearly/ 2001 and 2009	m	
Hydrogeological properties	-	-	
River conductance and stage	-	m/sec and m	
Top and bottom elevation of each aquifers	-	masl	

3. Methodology

An overall methodology framework used in the study is stated in figure 2. The major objective of this study is to assess the resiliency of groundwater in Bangkok and its vicinity, Thailand, under climate change and human development scenarios. This process was be done through simulation using WetSpass model and Groundwater Model (GMS-MODFLOW). The climate data through baseline and future scenarios by climate models and land use change scenario created by Dyna-CLUE was fed into the WetSpass model to simulate future groundwater recharge. The effects of climate change and land use change on groundwater recharge is taken from the study by Ghimire et al., 2021 (Climate and land-use change impacts on spatiotemporal variations in groundwater recharge: A case study of the Bangkok Area, Thailand). The calibrated groundwater model MODFLOW from GMS (Groundwater Modeling System) was set up to estimate groundwater level of the study area. Finally, the groundwater resiliency indicator was developed based on the observed result which in-turn was used to develop the groundwater resilience map of the study area.

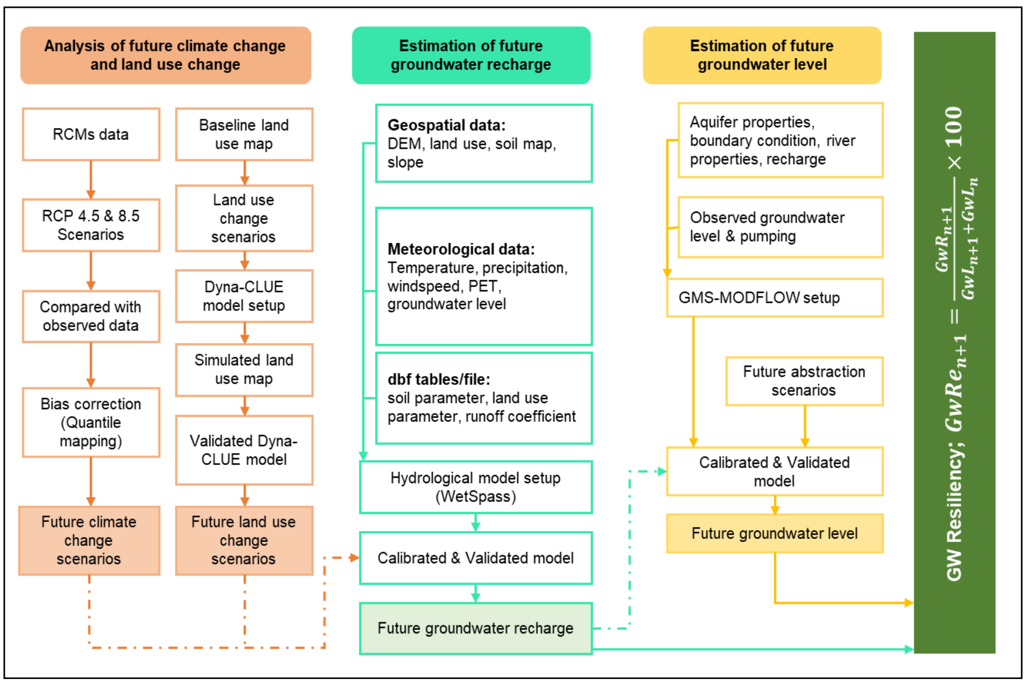


Figure 2: Groundwater resiliency mapping — Methodological Framework.

DEM is a digital elevation model; PET is potential evapotranspiration; RCM is a Regional Climate Model; GwRe is the groundwater resiliency; GwR is groundwater recharge; GwL is groundwater level; and n is the base year.

3.1 Groundwater flow model development

The groundwater level of Bangkok and its vicinity, Thailand, were simulated using the groundwater model MODFLOW from the Groundwater Modeling System (GMS). The purpose of this modeling method is to assess the temporal change in groundwater level caused by the disparity between groundwater recharge and expanding groundwater abstraction. This is one of the most extensively used groundwater models, and it may be used to investigate groundwater system dynamics and flow patterns in a variety of ways. This model can also be used as a tool for assessing recharge, discharge, and aquifer storage processes, as well as measuring long-term yields (Zhou et al., 2011). MODFLOW is also noted for its computational efficiency, accurate simulation of regional groundwater flow, and accurate representation of data. In addition, numerous academics and hydro geologists have employed the MODFLOW model to simulate groundwater flow in aquifers (Cheng et al., 2013; Lachaal et al., 2012; Yang et al., 2010; Ali et al., 2012; Maheswaran et al., 2016).

The three-dimensional groundwater flow through the porous medium is governed by the following equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial x}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial z}-W \tag{1}$$

Where, K_x, K_y, K_z are the values of hydraulic conductivity along x, y and z axes [LT-1], h is the hydraulic head [L], W is flux per unit volume, representing sink and/or sources of water [T-1], S_s is the specific storage of the aquifer [L-1].

Equation 1 describes the transient flow when combined with both the initial and boundary conditions and steady state, while the term in the right-side of the equation is assumed to be zero. Flow area in the MODFLOW is represented by grids and layers. Each grid and layer is expected to have consistent properties and Equation 1 is used to calculate the head of the layer. For confined layers, the head can rise above the top elevation while the simulated head remains below the surface of the unconfined layer.

The GMS-MODFLOW model was setup by discretizing a groundwater basin of 10,199 km^2 into 138 rows and 123 columns with a cell size of 1000m×1000m enclosed in modified UTM coordinates of 590000 m east to 148500 m north. The inside grid of the groundwater border was set as an active area and the outside grid an indolent or inactive area. Vertically, the grids are alienated into 16 layers out of which 8 were aquifers (2,4,6,8,10,12,14 and 16) and remaining were aquitards (1,3,5,7,9,11,13 and 15). Model inputs include the elevation of each layer, hydrogeological properties, boundary conditions, initial groundwater levels, recharge and discharge. The groundwater level data for 139 observation wells and pumping data for 7,791 pumping wells were used in the model. Groundwater level data for 139 observation wells in 2001 was used for model calibration with 2009 used for model validation. The model simulation was conducted in the steady state condition to obtain future groundwater levels. The hydraulic properties, observation well and pumping well of the Bangkok aquifer system are summarized in Table 2.

Table 2: Hydraulic properties, observation well and pumping well details of the Bangkok aquifer system

Parameters /Aquifers	Bangkok	Phra Pradang	Nakhon Luang	Nontha Buri	Sam Khok	Phaya Thai	Thonburi	Pak Nam
K_x (m/day)	70	100	59	30	16.1	10.8	3.7	17.5
K_y (m/day)	70	100	59	30	16.1	10.8	3.7	17.5
K_z (m/day)	7	10	5.9	3	1.61	1.08	0.37	1.75
S_s (1/m)	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005
Number of pumping well	67	2091	3110	1774	415	236	68	30
Pumping rate (m^3/day)	1741.5	212586.1	610157.0	687788.8	249920.4	39455.8	21069.6	11190.2
Number of observation well	3	40	41	50	2	1	2	-

3.2 Groundwater resiliency mapping

The term resilience refers to an ecosystem's ability to withstand long-term damage as well as the time it takes to recover after a disturbance (Gunderson, 2000). In the context of climate change, resilience is defined as a system's ability to absorb disruptions while maintaining its core structure and ways of operating, as well as its ability to adapt to stress and change (IPCC, 2007). In an interconnected system, groundwater resiliency is defined as the aquifer's ability to withstand varied pumping stress while maintaining the same basic functionality in the context of variable surface water supply and recharge. According to Peters et al. (2004), resilience refers to "how rapidly a system is likely to recover from a failure, whereas vulnerability refers to the severity of the failure." Groundwater resilience, according to Sharma & Sharma (2006), is the "system's ability to retain groundwater reserves despite large perturbations."

In this study groundwater resiliency is defined as the percentage recovery from total depletion at a given time (Shrestha et al., 2020).

$$GwRe_{n+1} = \frac{GwR_{(n+1)}}{GwL_{(n+1)} - GwL_n} \times 100 \qquad (2)$$

Where, n represents the base year, GwRe is groundwater resiliency, GwR is groundwater recharge (m/yr) and GwL is groundwater level (m/yr).

Groundwater resiliency (GwRe) was further divided into five different classes to develop a groundwater resiliency map of Bangkok and its vicinity (Table 3).

Table 3: Groundwater resiliency classification

Groundwater Resiliency (GwRe) 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

3.3 Future abstraction scenarios

To analyze the impact of climate change and human development in groundwater level three pumping scenarios were assumed.

I. Pumping Scenario 1 (S1):

In this scenario, pumping rate was assumed to follow existing trend. After analyzing the pumping rate for 2001 and 2004, the pumping rate was decreased by 0.50% per year. Therefore, the pumping rate was assumed to decrease by 15% in 2030, by 25% in 2060 and by 35% in 2090. In this scenario, the pumping rate was assumed to be decreased by same rate as the baseline period. Thus, this scenario is the business as usual scenario.

II. Pumping scenario 2 (S2):

In this scenario, the pumping rate was assumed to be same as the study results of safe yield pumping model in the ground water critical area conducted by Department of Groundwater Resources, Thailand. The evaluation result on the potential groundwater consumption of 8 confined aquifers was found that the safe yield pumping rate of the whole area was 733,564 m3/day i.e. decrease of pumping rate than that of baseline pumping rate. This scenario is the optimistic scenario where the groundwater abstraction further decreases in future. Pumping rate was assumed to decrease by 20% in 2030, by 40% in 2060 and by 60% in 2090.

III. Pumping scenario 3 (S3):

In this scenario, the pumping rate was assumed to increase by same rate as of decrease rate in scenario 2. This scenario is the pessimistic scenario where the groundwater abstraction further increases in future. Pumping rate was assumed to increase by 20% in 2030, by 40% in 2060 and by 60% in far future 2090.

4. Results and discussion

4.1 Calibration and validation of groundwater model

A steady state groundwater model was developed for 2001. To achieve good agreement between the simulated and observed hydraulic heads, the values of hydraulic conductivities in each layer were adjusted within the acceptable limits. Model calibration was conducted by the trial and error method, and after several runs, the values of hydraulic conductivities in different layers were adjusted until a good match was achieved between observed and simulated heads. In addition, adjustments were also made to the river conductance and depth for model calibration. The model was validated for 2009, keeping the same calibration parameter and only changing the input data such as groundwater recharge, groundwater abstraction and observed groundwater levels. The model performance was evaluated using R^2 as a statistical measure. The R^2 value for the calibration period was found to be 0.80 and 0.75 for the validation period. This suggests that the overall performance of the model is fairly good. The relationship between observed and simulated heads for both calibration and validation periods are shown in Figure 3.

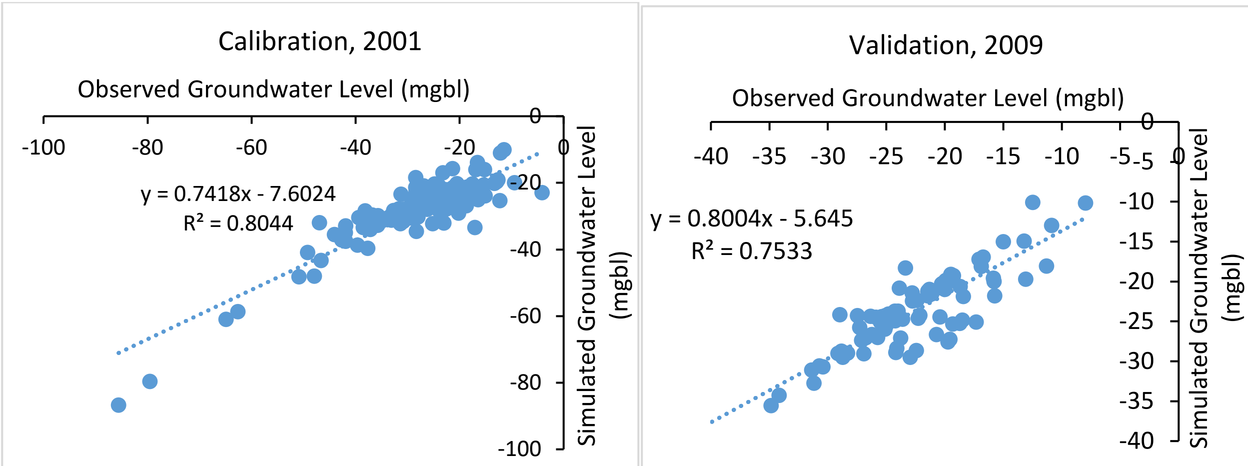


Figure 3: Relationship between observed head (mgbl) and simulated head (mgbl) in the steady state condition for calibration period (2001) and validation period (2009).

4.2 Impact of climate change and land use change in groundwater level

The impact of climate change and land use change on groundwater level was projected for three future periods: 2030, 2060 and 2090 under two RCPs scenario (RCP 4.5 and RCP 8.5) and three land use change scenarios (high, medium and low urbanization) after comparison with baseline (2001). Three pumping scenarios (S1, S2 and S3) were also analyzed to calculate future groundwater abstraction and subsequently used to calculate future groundwater level in all the aquifer layers. The results of three aquifer layers: Phra Pradaeng aquifer (PD, 100m zone), Nakhon Luang aquifer (NL, 150m zone), Nonthaburi aquifer (NB, 200m zone) is presented here as these layers are the most productive aquifer layers with good groundwater quality.

The result reveals that under all RCPs scenario and land use change scenario, groundwater level is projected to increase for pumping scenario S1 and S2. Whereas, for pumping scenario S3 it is projected to decrease in future. The maximum increase in average groundwater level is seen in low urbanization scenario and pumping scenario S2. The average increase in groundwater level ranges from 2.2m to 7.9m, 4m to 10.3m and 3.8m to 7.9m for PD, NL and NB aquifer and RCP 4.5 scenario respectively and 1.6m to 8.8m, 3.4m to 11.2m and 3.7m to 11.9m for PD, NL and NB aquifer and RCP 8.5 scenario respectively. The maximum decrease in average groundwater level is seen in high urbanization scenario and pumping scenario S3. The average decrease in groundwater level ranges from 2.9m to 5.6m, 2.8m to 6.7m and 3.2m to 7.6m for PD, NL and NB aquifer and RCP 4.5 scenario respectively and 3.3m to 4.9m, 3.2m to 5.9m and 3.7m to 7m for PD, NL and NB aquifer and RCP 8.5 scenario respectively (Figure 4).

The rate of change in groundwater level throughout the Bangkok city is not uniform. The central part of the city experience the decrease in groundwater level under all RCPs, land use and pumping scenarios. The maximum decrease in groundwater level was seen in NB aquifer by 28.4m and 27.7m for RCP 4.5 and RCP 8.5 scenario respectively under high urbanization and pumping scenario S3. The western and Eastern part of Bangkok city experience increase in groundwater level under all RCPs, land use and pumping scenarios and maximum increase in groundwater level was seen in NB aquifer by 27.6m and 26.7m for RCP 4.5 and RCP 8.5 scenario respectively under low urbanization and pumping scenario S2. The 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 three land use scenario (low, medium and high urbanization scenario) and RCP 4.5 and 8.5 scenario for pumping scenario S3 is stated in figure 5. Whereas, for pumping scenario S1 and S2 it is presented in supplementary figure 1 and 2 respectively.

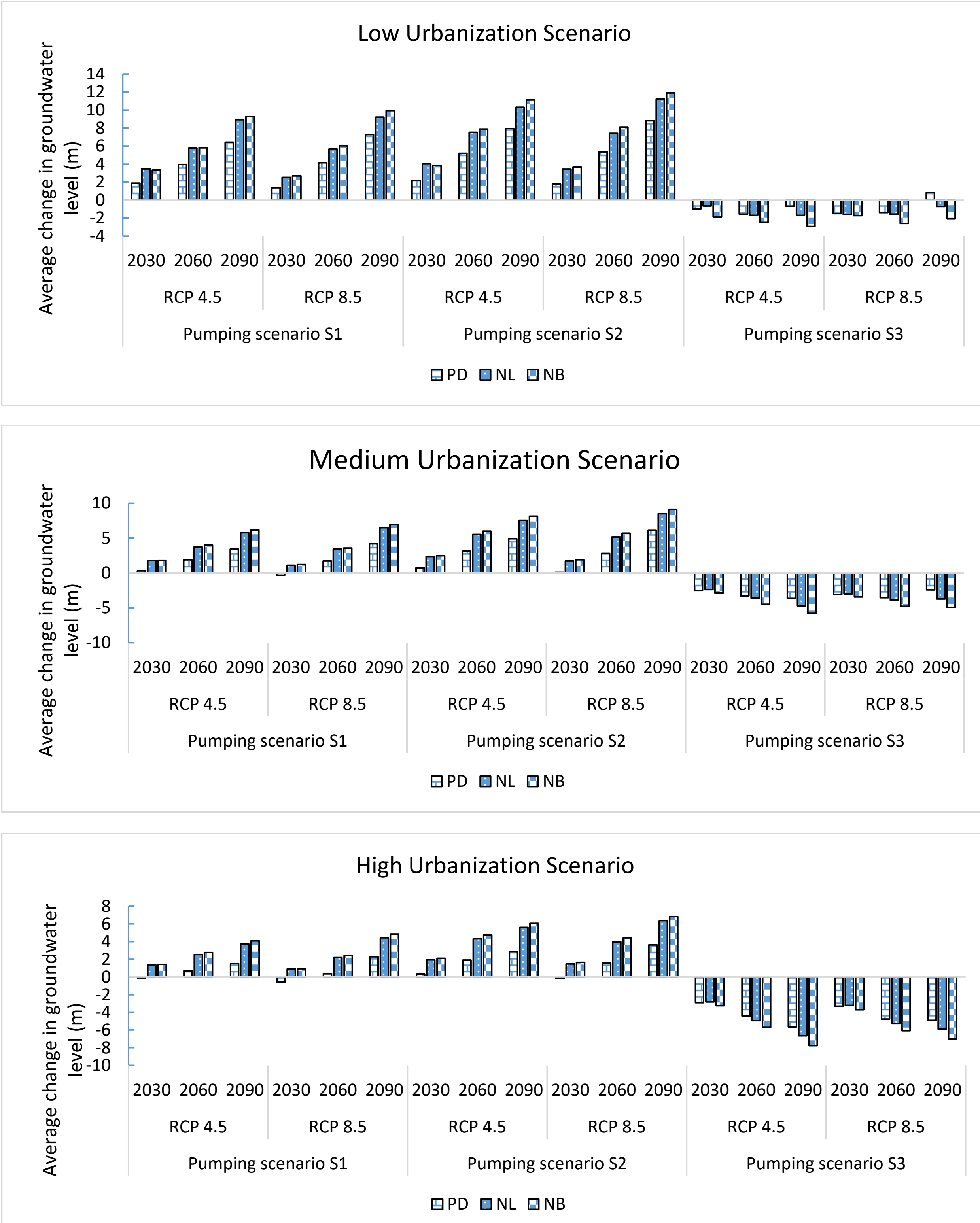
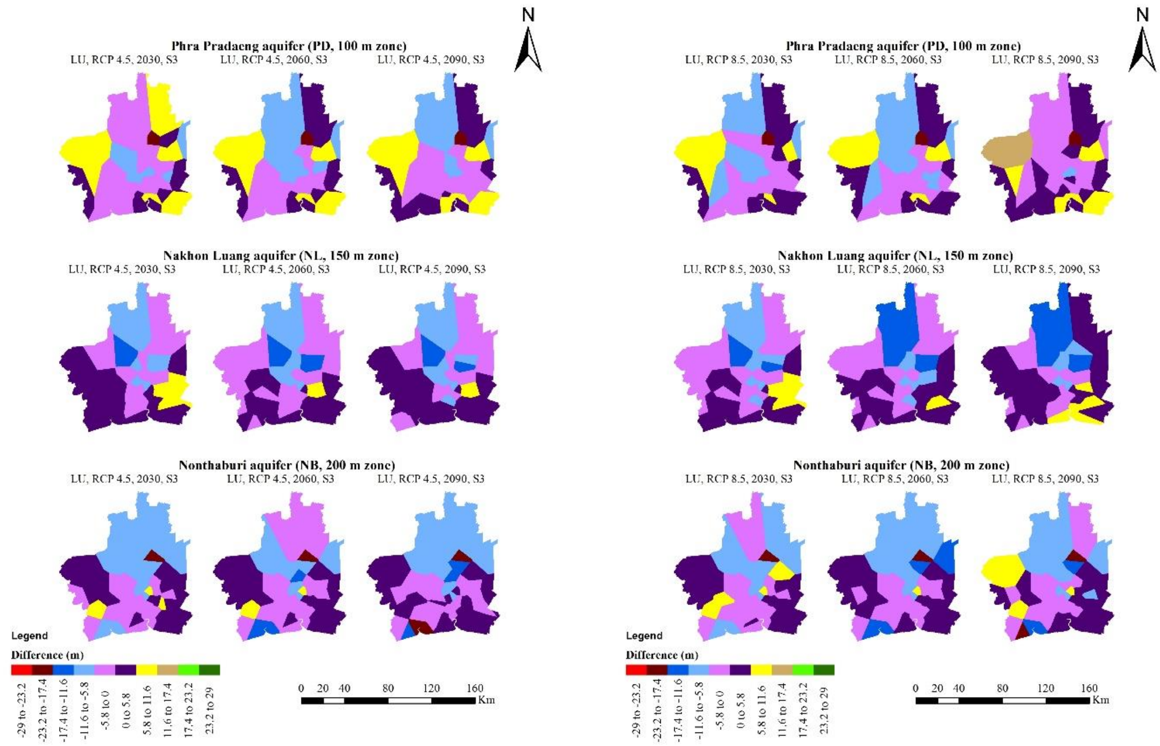


Figure 4: Average change in groundwater level for both RCP scenarios (RCP 4.5, RCP 8.5), three land use change scenario (low, medium and high urbanization) and three pumping scenarios (S1, S2 and S3) for three future periods: 2030, 2060 and 2090 relative to the baseline (2001).


N
Phra Pradaeng aquifer (PD, 100 m zone)
LU, RCP 4.5, 2030, S3
LU, RCP 4.5, 2060, S3
LU, RCP 4.5, 2090, S3
Nakhon Luang aquifer (NL, 150 m zone)
LU, RCP 4.5, 2030, S3
LU, RCP 4.5, 2060, S3
LU, RCP 4.5, 2090, S3
Nonthaburi aquifer (NB, 200 m zone)
LU, RCP 4.5, 2030, S3
LU, RCP 4.5, 2060, S3
LU, RCP 4.5, 2090, S3
Legend
Difference (m)
-29 to -23.2
-23.2 to -17.4
-17.4 to -11.6
-11.6 to -5.8
-5.8 to 0
0 to 5.8
5.8 to 11.6
11.6 to 17.4
17.4 to 23.2
23.2 to 29
0 20 40 80 120 160
Km
N
Phra Pradaeng aquifer (PD, 100 m zone)
LU, RCP 8.5, 2030, S3
LU, RCP 8.5, 2060, S3
LU, RCP 8.5, 2090, S3
Nakhon Luang aquifer (NL, 150 m zone)
LU, RCP 8.5, 2030, S3
LU, RCP 8.5, 2060, S3
LU, RCP 8.5, 2090, S3
Nonthaburi aquifer (NB, 200 m zone)
LU, RCP 8.5, 2030, S3
LU, RCP 8.5, 2060, S3
LU, RCP 8.5, 2090, S3
Legend
Difference (m)
-29 to -23.2
-23.2 to -17.4
-17.4 to -11.6
-11.6 to -5.8
-5.8 to 0
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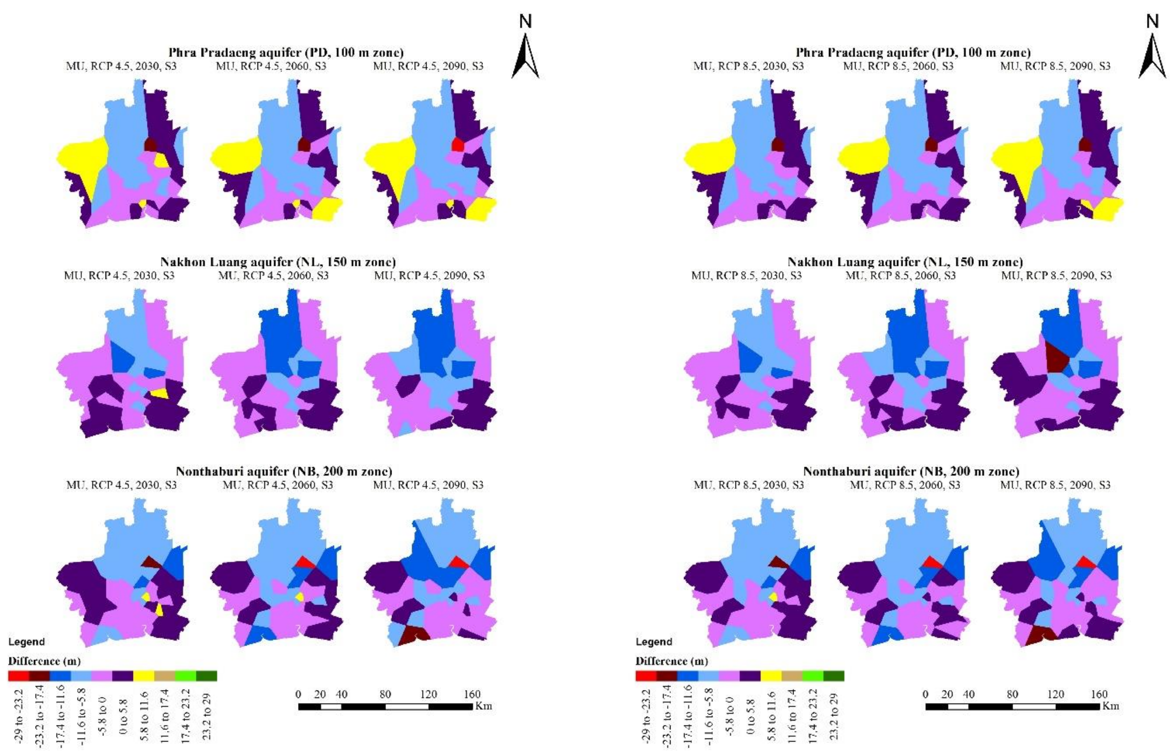
N
Phra Pradaeng aquifer (PD, 100 m zone)
MU, RCP 4.5, 2030, S3
MU, RCP 4.5, 2060, S3
MU, RCP 4.5, 2090, S3
Nakhon Luang aquifer (NL, 150 m zone)
MU, RCP 4.5, 2030, S3
MU, RCP 4.5, 2060, S3
MU, RCP 4.5, 2090, S3
Nonthaburi aquifer (NB, 200 m zone)
MU, RCP 4.5, 2030, S3
MU, RCP 4.5, 2060, S3
MU, RCP 4.5, 2090, S3
Legend
Difference (m)
-29 to -23.2
-23.2 to -17.4
-17.4 to -11.6
-11.6 to -5.8
-5.8 to 0
0 to 5.8
5.8 to 11.6
11.6 to 17.4
17.4 to 23.2
23.2 to 29
0 20 40 80 120 160
Km
N
Phra Pradaeng aquifer (PD, 100 m zone)
MU, RCP 8.5, 2030, S3
MU, RCP 8.5, 2060, S3
MU, RCP 8.5, 2090, S3
Nakhon Luang aquifer (NL, 150 m zone)
MU, RCP 8.5, 2030, S3
MU, RCP 8.5, 2060, S3
MU, RCP 8.5, 2090, S3
Nonthaburi aquifer (NB, 200 m zone)
MU, RCP 8.5, 2030, S3
MU, RCP 8.5, 2060, S3
MU, RCP 8.5, 2090, S3
Legend
Difference (m)
-29 to -23.2
-23.2 to -17.4
-17.4 to -11.6
-11.6 to -5.8
-5.8 to 0
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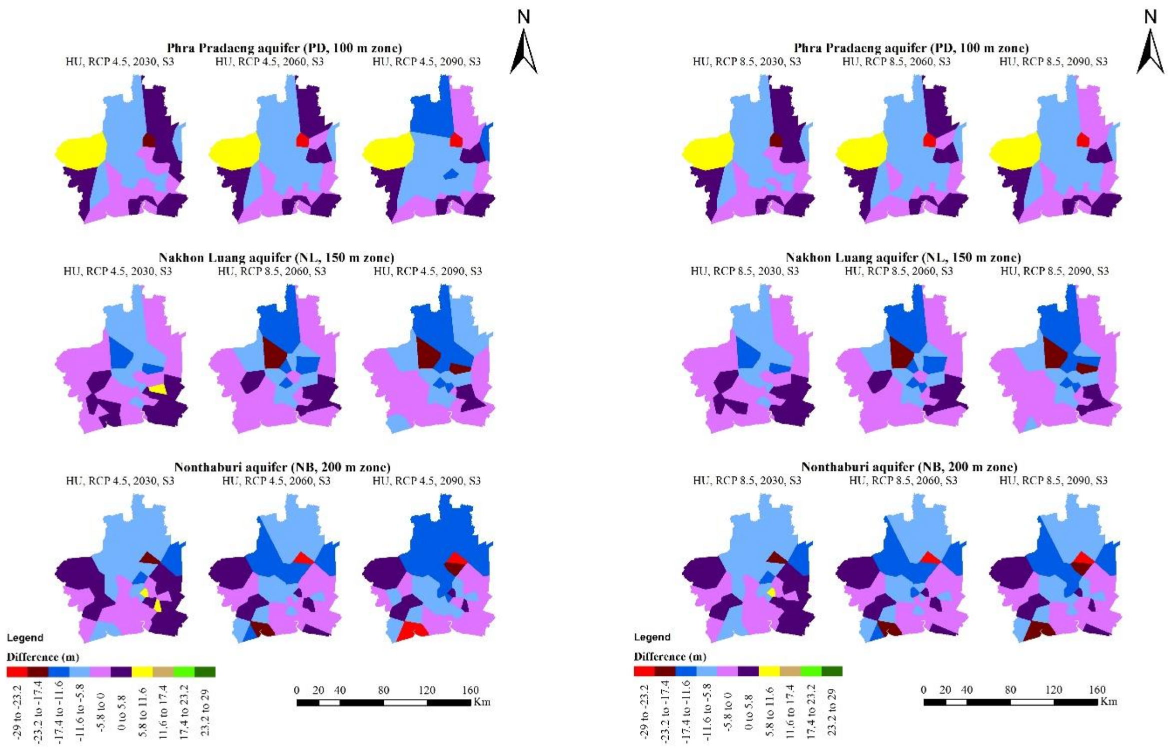
b



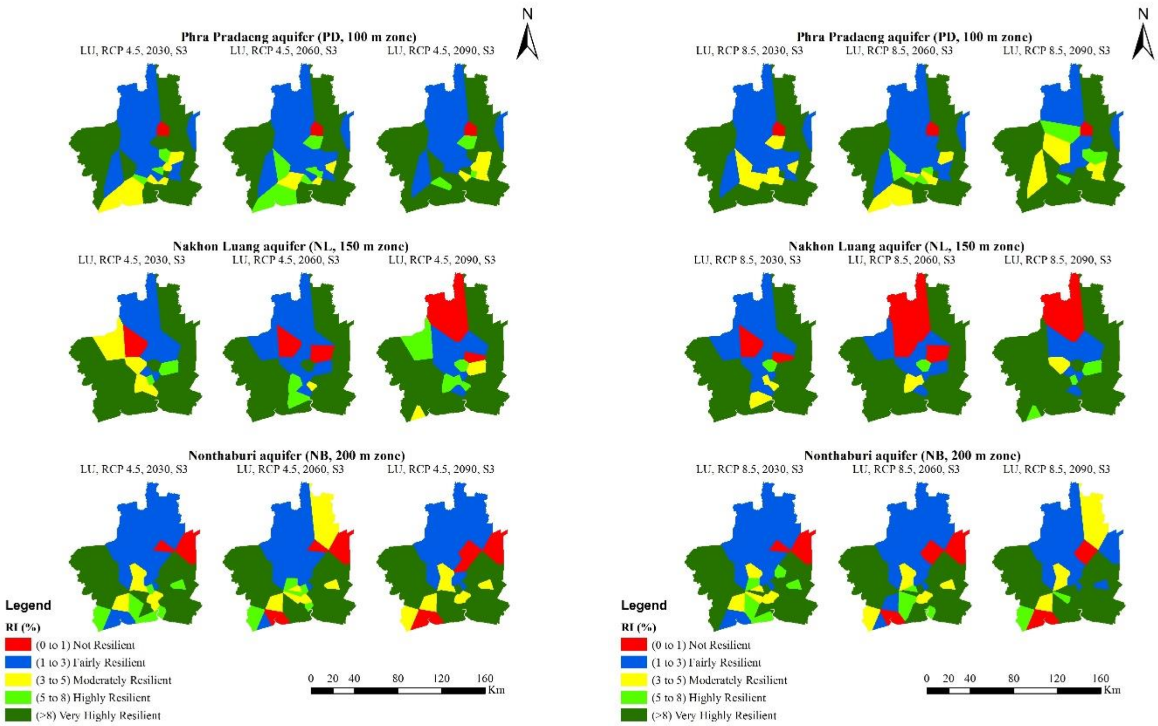
C

Figure 5: 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) (fig. 5a), medium urbanization scenario (MU) (fig. 5b) and high urbanization scenario (HU) (fig. 5c) and RCP 4.5 and 8.5 scenario for pumping scenario S3

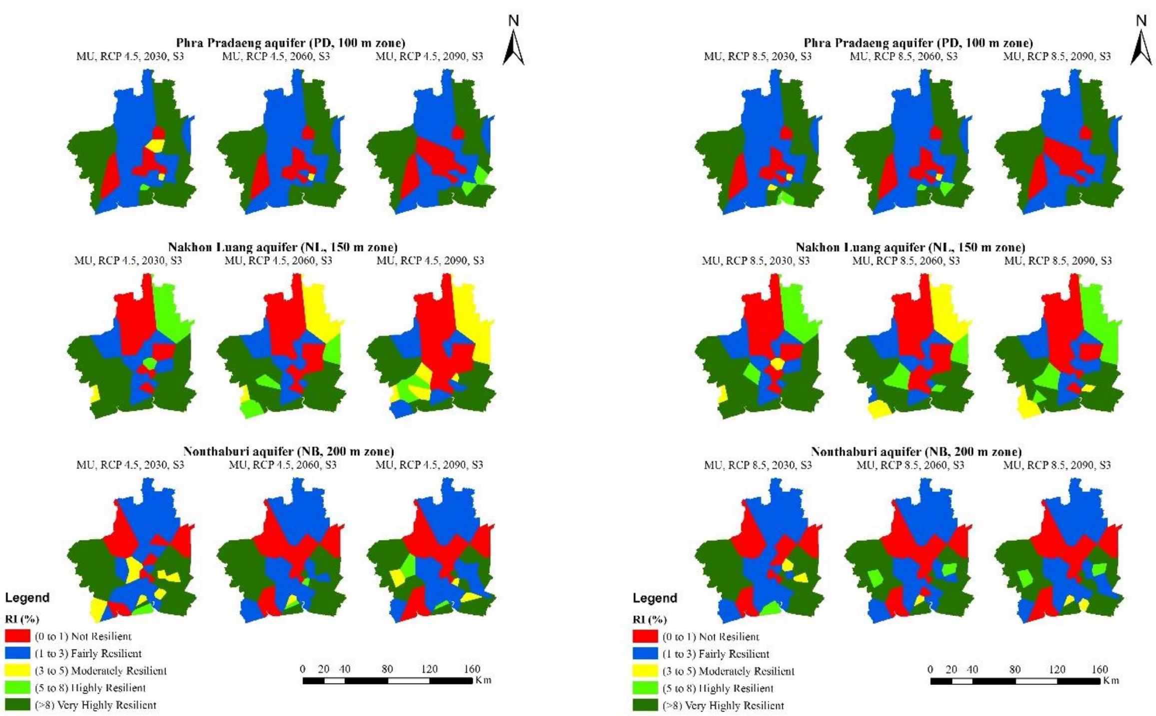
4.3 Spatial distribution of groundwater resiliency

The groundwater resiliency map of the Bangkok and its vicinity was developed based on the indicators described in Section 3.2 for all three pumping scenarios (S1, S2, S3) and three time periods (2031, 2061, 2091) under RCP 4.5 and RCP 8.5 scenario and three land use scenario (low, medium and high urbanization scenario). The results shows projected increase in percentage of area under very highly resilient class, whereas, the area under not resilient class is very low or some time even zero for pumping scenario S1 and S2, and for pumping scenario S3, there is projected decrease in percentage of area under very highly resilience class while the area under not resilient class is increasing and this is valid for all land use scenario, climate change scenario and all three aquifer layer.

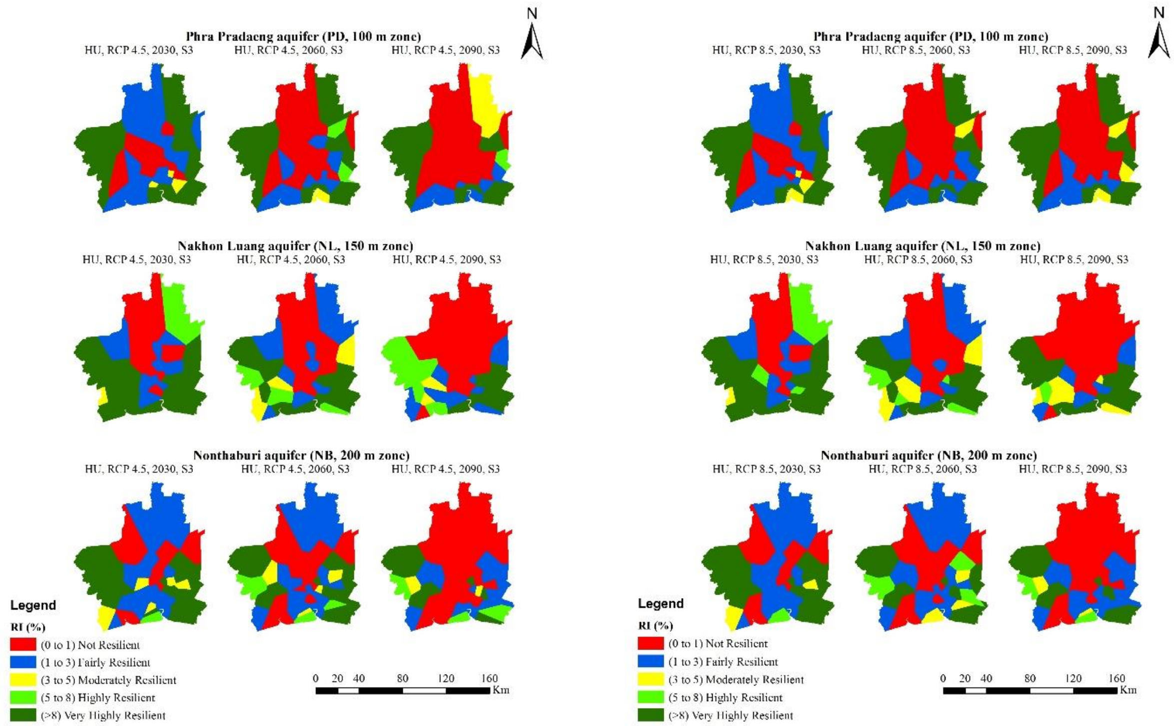
For high urbanization scenario and pumping scenario S3, by 2090 48.8%, 54.2% and 57.9% of area in PD, NL and NB aquifers respectively is under not-resilient class under RCP 4.5 scenario. Whereas, for RCP 8.5 scenario, 43.7%, 53.7% and 53.3& of area in PD, NL and NB aquifers respectively is under not-resilient class. For low urbanization scenario and pumping scenario S2, by 2090 almost 100% of the area is under very highly resilient class and this is valid for all climate scenario and three aquifer layer. The result reveals that the majority of the study area in central part is projected to fall under the not resilient and fairly resilient classes whereas the area in the eastern and western parts of the study area are resilient for all three land use scenarios, pumping scenario and RCP scenarios. Groundwater resilience map of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S3) under low, medium and high urbanization and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB is shown in figure 6. Whereas the groundwater resiliency map of pumping scenario S1 and S2 is stated in Supplementary figure 3-4 respectively.



a



b



c

Figure 6: Groundwater resiliency map of Bangkok and its vicinity, Thailand for three different time period 2030, 2060 and 2090 for Pumping scenario (S3) under low, medium and high urbanization (fig 6a, 6b, 6c) and RCP 4.5 and RCP 8.5 scenario of aquifers PD, NL and NB

5. Conclusion

The groundwater resiliency map of Bangkok and its vicinity was developed using the results from the hydrological model, groundwater model under RCP scenarios (RCP 4.5 and RCP 8.5), three land use change scenarios (low, medium and high urbanization scenario) and three pumping scenarios (S1, S2 and S3). We expand on Ghimire et al., 2021's findings on climate and land-use change influences on spatiotemporal variability in groundwater recharge: A case study of the Bangkok Area, Thailand to include climate change and land-use change effects on groundwater recharge.

The impact of climate change and land use change on groundwater level was also analyzed. The results show that for pumping scenarios S1 and S2, groundwater levels are expected to rise under all RCP scenarios and land use change scenarios. In the case of pumping scenario S3, it is expected to decline in the future. The maximum increase in average groundwater level by 12m is seen in low urbanization scenario and pumping scenario S2 whereas, the maximum decrease in average groundwater level up to 7m is seen in high urbanization scenario and pumping scenario S3. However, the decrease in groundwater level is uneven across the Bangkok city. The central part of the city faces a higher decrease in groundwater level than the eastern and eastern areas. The results shows projected increase in percentage of area under very highly resilient class, whereas, the area under not resilient class is very low or some time even zero for pumping scenario S1 and S2, and for pumping scenario S3, there is projected decrease in percentage of area under very highly resilience class while the area under not resilient class is increasing and this is valid for all land use scenario, climate change scenario and all three aquifer layer.

Based on the findings and climate change and land use change variability, it can be concluded that Bangkok's groundwater resources are under severe threat from climate change and land use change. As a result, proper groundwater monitoring and the development of a credible strategy to safeguard it from human-induced causes and climate change are critical for the long-term management of groundwater resources in Bangkok and its vicinity, Thailand.

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