IMPROVING GROUNDWATER GOVERNANCE IN RAPIDLY URBANIZING AREAS UNDER MULTIPLE STRESSES: A CASE OF KHON KAEN, THAILAND

by

XXXXXXX

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AUTHOR'S DECLARATION

I, xxxxxx, declare that the research work carried out for this dissertation was in accordance with the regulations of the Asian Institute of Technology. The work presented in it is my own and has been generated by me as the result of my original research, and if external sources were used, such sources have been cited. It is original and has not been submitted to any other institution to obtain another degree or qualification. This is a true copy of the dissertation, including final revisions.

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ABSTRACT

Groundwater plays a vital role in water security, poverty reduction, and sustainable development of the Lower Mekong Region (LMR). The common-pool resource has a considerable share of domestic, agricultural, and industrial water supply. However, the resource’s effective and efficient management is challenging in the context of increased climatic and non-climatic stresses. Therefore, this study evaluates the current state of groundwater governance in a rapidly urbanizing city, Khon Kaen, Thailand, and recommends strategies to improve governance on an evidence-based understanding of groundwater availability under future stresses. Initially, a new pragmatic framework was developed, which provides Groundwater Governance Index (GGI) ranging from 0-3 (non-existence to optimum). The expert survey results indicated that groundwater governance in Khon Kaen, Thailand is at an acceptable state (GGI = 1.18) from a dimensional perspective with fair provisions of technical resources and regulatory and legal outlines. Then after, the study projected the future changes in four stresses (climate, land use, population, and water demand) to analyze their impact on groundwater level under Shared Socio-economic Pathways (SSPs). The results show that the rainfall, temperature, urban land use, urban population, and sectoral groundwater abstraction in Khon Kaen will likely increase in the future, resulting in a decrease in groundwater recharge and groundwater level. The results of the Soil and Water Assessment Tool (SWAT) showed that the groundwater recharge is expected to decrease by 5-10% and 9-15%, and the Multiple Linear Regression (MLR) model showed that the consequent average decrease in groundwater level is likely to be 0.8-3 m and 1.7-6.3 m under SSP2-4.5 and SSP5-8.5 scenarios respectively. Finally, the study provided strategies to enhance the current provisions and future needs (stakeholder engagement, gender sensitization, cooperation, technical resources, progressive policies, capacity, etc.) based on the prevailing state and likely impact under multiple stresses. The results from the study shall assist policymakers, regulators, groundwater experts, and stakeholders in benchmarking and visualizing the current strengths, gaps, and areas for improvement in the state of groundwater governance and develop suitable strategies for its improvement under multiple future stresses in Khon Kaen, Thailand.

Keywords: Groundwater governance framework, Climate change, Urbanization, Groundwater governance index, Aquifer management

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
AR5	Assessment Report Five
CDF	Cumulative Distribution Function
CI	Consistency Index
CMIP	Coupled Model Intercomparison Project
CN	Curve Number
CORDEX	Coordinated Regional Climate Downscaling Experiment
CR	Consistency Ratio
DGR	Department of Groundwater Resources
DIW	Department of Industrial Works
ESGF	Earth System Grid Federation
FAO	Food and Agriculture Organization
GCM	General Circulation Models or Global Climate Model
GDP	Gross Domestic Product
GGI	Groundwater Governance Index
GGRETA	Governance of Groundwater Resources in Transboundary Aquifers
GMS	Groundwater Modeling System
GW-MATE	Groundwater Management Advisory Team
HII	Hydro Informatics Institute
IAM	Integrated Assessment Model
IPCC	Intergovernmental Panel on Climate Change
IUWM	Integrated Urban Water Management
IWRM	Integrated Water Resources Management
LMB	Lower Mekong Basin

LMR	Lower Mekong Region
LULCC	Land Use and Land Cover Change
MLR	Multiple Linear Regression
NCAR	National Center for Atmospheric Research
OECD	Organisation for Economic Co-operation and Development
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RID	Royal Irrigation Department
SRES	Special Report Emissions Scenario
SSPs	Shared Socioeconomic Pathways
SWAT	Soil and Water Assessment Tool
TMD	Thai Meteorological Department
UHI	Urban Heat Island
UN	United Nations
UNDP	United Nations Development Programme
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific
UNESCO	United Nations Educational, Scientific and Cultural Organization
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WWAP	World Water Assessment Programme

CHAPTER 1

INTRODUCTION

1.1 Background of the Study

Globally, the movement of rural settlement to urban areas is estimated to increase, elevating the world's urban population to 68% by 2050, with the majorly in the developing nations of Asia and Africa (United Nations, 2018). The interconnection of the trio, i.e., urbanization, industrialization, and globalization in economic development, has a crucial role in the transformation of society, thus, motivating both established as well as freshly industrialized nations to the dynamic process of urbanization thru specialization and exchange of labor and services (Chen et al., 2014). The term "urbanization" is a demographic movement to an urban area and is a complex socio-economic process that shifts the spatial distribution of a population, included with the transformation of the built environment (Malik et al., 2017; United Nations, 2018). Currently, the rate of urbanization in freshly developing nations is dramatically high than in technologically and socio-economically advanced nations. This unprecedented rate is mainly by the increased urban population with economic growth (Angel et al., 2011; Bian et al., 2018). Studies have shown the consensus that despite the importance of urbanization in economic and other aspects of development, the entire process is excessively destroying the environment (Hua et al., 2020). Furthermore, urbanization is an essential driver for alteration in the normal functioning of the hydrological, biogeochemical, and carbon cycles at the local and global scale (Hua et al., 2020). While urban transformation is evolving, natural-driven or urban-growth-driven climate change is expected to affect the urban hydrological cycle (McDonald et al., 2011).

Climate change is the alteration in the statistical distribution of climatic variables for a comparatively more extended period and is currently the most highlighted global interest. The Intergovernmental Panel on Climate Change (IPCC) stated the influence of humans and their activities on the climate system and projected a global temperature increase between 1.4℃ -5.8℃ by 2100 as compared to the temperature during 1900 AD. The unprecedented rate of urbanization further stresses its impact, especially in the context of a warming climate (naturally and human-induced), altering spatial and temporal rainfall patterns and intensity (Paul et al., 2018). The urban land cover is crucial in defining the city's thermal characteristics as the increased tendency of using fuels emitting greenhouse gas by the huge number of populations, expansion in rough impervious surfaces, and rise in the number of multifaceted elevated urban structures but a massive reduction in carbon sinking vegetative sources adds more instability in warmer air at the local level creating urban heat islands (Paul et al., 2018; Pramanik & Punia, 2019). Huong & Pathirana, (2013) mentioned the generation of extremely intense rainfall events in urban areas because of changes in local climatic features (local temperature, evaporation, and evapotranspiration rate, absorption in solar radiations, etc.) as an effect of urban heat islands.

The urbanization process has greatly affected the environment and climate as multiple human activities alter water, energy, food, and land consumption patterns, polluting the urban environment. But in contrast to this, urbanization is inextricably associated with economic development quantified as population, income, and output. This demonstrates the significance of urban centers or cities in domestic economics and their requirement to supply the highest quality public and private services. So, rapidly urbanizing areas are extremely stressed in terms of public service deliveries like traffic, education, employment, health, waste management, etc. (Bloom et al., 2008), and one of the significant urban public services is the "water supply and sanitation" (H. Jones et al., 2014).

Water, the basic requirement for human well-being is finite and only renewable when properly managed. It has a critical role in sustainable development, but the propagation of its scarcity has crossed borders of the areas experiencing constant water shortages and thus, making it as the major global challenges today (Jacobson et al., 2013; Ojeda Olivares et al., 2020). Studies have revealed the scarcity of freshwater resources is likely to amplify in the future mainly due to human-induced climate change impacts and increased demand for freshwater resources (Boretti & Rosa, 2019; Veldkamp et al., 2017). Out of 2.5% freshwater available in the Earth, much of the portion is sealed in glaciers and ice leaving groundwater as the major source of freshwater resources.

Globally, groundwater is the source of one-third of all freshwater withdrawals, supplying an estimated 36, 42, and 27% of water used for domestic, agricultural, and industrial purposes, respectively (Döll et al., 2012). It is a moving natural resource below the earth's surface and shows the double character as a "mineral resource" and as a "water resources". Thus, the groundwater's safe yield depends on the hydrogeologic environment of the area and physical-geographical factors as it is directly interlinked with the surface water and atmosphere (Zektser & Everett, 2004). Furthermore, the human-induced dynamics also play a vital role in its safe yield, used for multiple human activities. Besides being one of the most readily available freshwater resources, its superior quality, uniform regional spread, level of safety from the possible pollutants, very lesser tendency to periodic fluctuation, and reduced investment and operational cost has comparatively reinforced its advantages over surface water as a source of water supply. In addition to this, with the increasing demand for urban infrastructures, the cities impervious surfaces expand exponentially (Han & Burian, 2009; Sankalp & Sahoo, 2018) impacting freshwater availability, quality, and delivery. The reduction in the infiltration capacity of the urban centers on one side decreases the probability of the groundwater resources being recharged and on the other side, the increased abstraction to fulfill the demand of increased populations lowers the level of groundwater thus, making it more scare and vulnerable to availability and contaminants. According to FAO, (2016), the volume of groundwater extraction has raised by fourfold over the past 50 years and the tendency is likely to persist in the future due to increased demand for agriculture, industry, and domestic water supply included with ecosystems services. Furthermore, the silent side of this escalating trend is due to the improvement in extraction technology, increased exploration in hydro-geological understanding, and ease of energy availability. This over-extraction tendency, on one hand, has exploited the limited freshwater resources and on the other hand, has worsened both the quality and quantity of available water each year resulting in water table drawdown and increasing salt intrusion in coastal areas (Mohamed & Elmahdy, 2015).

The 1-3% annual increase in abstraction of groundwater (Wada et al., 2014) included with its extensive challenge of continuous contamination has increased its adverse effects in groundwater-dependent ecosystems (de Chaisemartin et al., 2017). In addition to this, climate change and climate variability have further impacted both recharge and demand of groundwater (Taylor et al., 2013) and the landcover changes have further exaggerated the process. The decreasing level of aquifer, increasing demand, and pollution in one hand and on the other hand, unfair access to the resource it's poor management has created challenges worldwide (Closas & Villholth, 2020). So, one of the gentle approaches of managing and addressing the water crisis challenges is realizing and understanding the importance of groundwater governance (Closas & Villholth, 2020; de Chaisemartin et al., 2017; Mukherji & Shah, 2005). The process of groundwater governance ensures the protection and control of this common-pool resource with its sustainability by supporting the promotion of responsible collective action (Closas & Villholth, 2020). Further, this is aided by the legal regulatory frameworks, policies and plans, effective institutional arrangement, shared information and knowledge, finances, and motivative structure that is aligned to the goal of the society (FAO, 2016). Thus, groundwater governance has emerged as an appropriate recipe for the management of groundwater resources sustainably with the attention of all the related stakeholders. Responsible use of groundwater with equity, efficiency, and sustainability can only result in effective groundwater management policies that are identified and applied based on the principles of governance (Varady et al., 2013). Therefore, largely, managing groundwater resources equitably and sustainably among nations, regions, and sectors means making informed decisions and influencing the behavior of multiple actors and individuals. Therefore, it is very essential to assess the current state of groundwater governance in rapidly urbanizing areas to recommend the possible improvements for the sustainable use and management of the resources under multiple future stresses.

1.2 Problem Statement

Groundwater is a common-pool resource of global importance. This, real hidden treasure is vulnerable to unrestricted exploration and exploitation by humans without considering the interests of the wider community (Foster & Garduño, 2013; Megdal et al., 2015). At least half of the global population use groundwater as drinking water supply and in the context of agriculture, about 43% of all water used for irrigation is groundwater (Connor, 2015) making it a crucial component for supply for domestic, agricultural, industrial sectors, ecosystem services, etc. and also a challenging component for effective and efficient management on the context of increased stress and demand.

One of the key stresses for this escalating dependence is urbanization leading to rapid demographic growth, increased freshwater demand, and change in local climatic conditions (naturally and/or human-induced) impacting both demand and supply (Megdal, 2018). As the evolution of urbanization involves spatial and vertical transformation of unmoved soil and natural land cover with the modern service infrastructures and impervious surfaces (Paul et al., 2018). These impervious surfaces are anthropogenically altered surfaces impact hydrologic response and increases the surface water runoff, rate of sediment deposits within any catchment, and averts sub-surface infiltration (Sankalp & Sahoo, 2018). One of the significant effects is on the carbon and the water cycle due to the exaggeration between the natural environment and the humans. The consequences of rapid urbanization are reduction in green vegetation, escalation in urban population density, excessive use of fossil fuels which creates a discrepancy between production and consumption of greenhouse gases like carbon dioxide affecting the carbon cycle (Churkina, 2016). On the other side, this alteration in natural cover also reduces percolating capacity, escalates the surface runoff, and rate of sediment deposition shifting the natural urban watercourse, and thus, impacting the entire water cycle (Viger et al., 2011). Furthermore, the prolongation of this trend is likely to alter climatic characteristics, globally and locally with extreme effects on the hydrologic cycle mainly due to rainfall and temperature with evapotranspiration and soil water content (Kumar, 2012). The process of urbanization further amplifies the process by increasing the heat stress because of urban rough surfaces and rising temperature creating Urban Heat Island (UHI) effect. The effect alters the urban climate, thus intensifying the unequally distributed rainfall and increasing the rate of evaporation exposing the urban residents to more heat stress (Chapman et al., 2017). This has a significant impact on ample freshwater availability as well as management for the regular anthropogenic activities and ecosystem services.

Globally, the population residing in the urban centers is likely to rise to 68% by 2050 and the major contribution is projected from the middle and low-income nations from Asia and Africa (United Nations, 2018). In the Asian context, the rate of urbanization is escalating very rapidly to about 30%, 48%, 55%, 40% in South Asia, South East Asia, East Asia, and Central and West Asia respectively in 2015 which was about 25% in South Asia and about 30% for other Asian regions during 1995 (Arfanuzzaman & Dahiya, 2019). This increased urban economic centers in the Asian regions have not only upsurge the urban population and changes in land-use but also has increased the rate of resource exploitation and degradation of the environment because of the increasing demand for resource accessibility. This in Asia has been further amplified by the changes in climate naturally and most importantly changes driven by human activities and has become an essential topic for the urban water system (Collin & Melloul, 2003). One of the primary concerns of all the pressures and impacts of urbanization is on the groundwater (Hua et al., 2020; Yao et al., 2019).

Groundwater is an very essential freshwater resources for the social and economic development in all countries of Lower Mekong Region (LMR) in South East Asia where the stress in land and freshwater resources has considerably increased with the accompanying economic growth (Lyon et al., 2017). Many studies have revealed the consequences of urbanization in the quantity, quality, and interaction between surface and groundwater hydrology in the region (Adhikari et al., 2020; Homdee et al., 2011; Ly et al., 2020). Thus, the understanding of groundwater management which is repeatedly ignored and underrated in the rapidly urbanizing areas of LMR under multiple stresses and increased demand is very crucial and challenging. Additionally, realizing the importance of the groundwater resource governance is a crucial soft approach towards its management which is more about guiding the actions of the multiple actors/stakeholders and its successes and failure are often the result of the adequacy of its governance arrangements (Foster & Garduño, 2013). So, it is very important to understand the provisions of groundwater governance at the local level rather than the top-level as it is a widely distributed local resource. All the aspects of socio-economic development should be combined with the integrated groundwater management such that it addresses multi-disciplinary sectors and actors for effectively managing the hidden resources (de Chaisemartin et al., 2017). The governing and managing groundwater resources, which exploitation is distributed in space (especially among private sectors) is a process of changing the attitude and manipulating the decisions of multiple actors. Rapidly urbanizing areas of are already stressed for delivering freshwater resources and future stresses pressurize it more. Therefore, these areas essentially require assessing the current state of groundwater development, governance, and management to explore its strengths, gaps, and areas for improvement. Furthermore, the assessment also enables shall be a benchmark for planning and developing strategies in improving the governance gaps for the sustainable and equitable use and management of the groundwater resources under multiple stresses in rapidly urbanizing areas.

1.3 Research Questions

This study provides an answer to the following research questions:

1. What is the current state of groundwater governance and management in the study area? Does the current groundwater governance address the social equality, conflicts & gender dimensions?
2. How will the multiple stresses like population, land-use, climate, and water demand change in the study area?
3. How will the multiple stresses in the study area impact the future groundwater availability?
4. What are the strategies for improving groundwater governance under multiple stresses?

1.4 Rationale

Groundwater is one of the most vital resources and is heavily threatened due to rapid urbanization, external climate stressors and increased demand impacting its sustainability. In addition, urbanizing areas face socio-economic problems relating to distribution and equity, the efficiency of use and inter-sectoral allocation. The growing socio-economic importance of groundwater resources and the rising risks to its sustainability indicates that sound governance is a pressing priority. Yet, groundwater governance is a serious challenge, and despite many studies focusing on groundwater assessments, its governance has been largely neglected. This study develops a groundwater diagnostic framework to analyze the current state of groundwater governance in a setting and discuss the prevailing status of groundwater governance in rapidly urbanizing areas. Further, it provides recommendations for possible improvements for the weaker components of groundwater governance under multiple future stresses for its sustainable use and management.

The finding from this research will assist in stocktaking of the governance situation (actors, legal framework, policies and plans, available knowledge) together with an assessment of strengths, gaps, opportunities and areas of improvement. The detailed diagnosis will facilitate (local) government, planners, managers and related actors in inclusive decision-making and initiate an urgent call for action toward sustainable groundwater management.

1.5 Objectives of the Study

The main objective of the study is to evaluate the current state of groundwater governance and recommend ways for improved groundwater governance in rapidly urbanizing areas under multiple stresses. The specific objectives are:

1. To develop a groundwater governance framework and assess the current state of groundwater governance in the rapidly urbanizing area (Khon Kaen, Thailand)
2. To project future change in multiple stresses (climate, land use, population, sectoral abstraction) under various scenarios.
3. To analyze the impact of multiple stresses on groundwater availability.
4. To recommend strategies for improved groundwater governance under multiple stresses.

1.6 Scope and Limitations of the Study

The research covers the following scope:

1. Develop groundwater governance framework for rapidly urbanizing areas.
2. Analyze the current state of groundwater governance in the study area.
3. Project the future climate of the study area under multiple climate change scenarios.
4. Project future population and land use change using the Dyna-CLUE model.
5. Project future sectoral (domestic, industrial, and agricultural) groundwater abstraction of the study area.
6. Estimate the impact of stresses on future groundwater availability using the SWAT hydrological model (groundwater recharge) and multiple regression (groundwater level).
7. Identify the current state of different components of groundwater governance and provide strategies (with case studies) for improved groundwater governance.

1.7 Organization of the Study

The dissertation is arranged into nine chapters:

- Chapter 1 covers the introduction to the study with background, problem statement, research questions, rationale, objectives, scope, and limitations.
- Chapter 2 reviews related literature on stresses and impacts on groundwater resources, climate change, climate scenarios, population projection, land use projection, sectoral demand projection, groundwater governance assessment methodologies, and hydrological modelling.
- Chapter 3 shows the study area, the data necessary for the study, and their sources.
- Chapter 4 explains the approaches employed to attain the study objectives.
- Chapter 5 elaborates on the results and discusses the development and application of the current state of the groundwater governance framework.
- Chapter 6 elaborates on the results and discussion on the projection of multiple future stresses (climate, land use, population, groundwater demand) under shared socio-economic pathways.
- Chapter 7 elaborates on the results and discussion of multiple stresses' impact on groundwater availability (groundwater recharge and level).
- Chapter 8 elaborates on the results and discussion on the state of different components of groundwater governance in Khon Kaen and provides several strategies for improving groundwater governance under multiple stresses.
- Chapter 9 contains the study's summary and conclusions and provides recommendations for policymakers and future research.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews and summarizes various information regarding multiple stresses in groundwater, individual and combined impact due to the stresses in groundwater resources, different types of climate models, climate scenarios, bias correction methods, land use, population, and sectoral water demand projection techniques. Furthermore, the chapter also summarizes different ways for evaluating groundwater governance and hydrological modelling based on the critical review of related literature.

2.1 Multiple Stresses in Groundwater Resources

Groundwater resources are the huge subsurface reservoirs that are accessible or provide buffer storage during surface water shortages (Lapworth et al., 2013) and are less vulnerable to drought and quality degradation than surface water resources (Schwartz & Ibaraki, 2011). Globally, this complex hydrological system provides 33% of total water withdrawal, satisfying about 85% rural and about 50% urban water needs (Aslam et al., 2018). It is evident that dependence of groundwater in semiarid regions is more, especially in Asia where irrigation dominates the withdrawal of the freshwater resources followed by the domestic and industrial use in rapidly growing cities.

Furthermore, multiple studies reveal that the freshwater resources are threatened more by the rapid growth in the world's population leading to urbanization, global and local climate change, agricultural commercialization, and industrial development (Hutchins et al., 2018; Vörösmarty et al., 2010; Wen et al., 2017). Regardless of the importance of fresh (ground)water resources for sustainable development, its mismanagement and additional stress for multiple drivers have depleted and degraded in terms of quantity and quality respectively making it more vulnerable in the future. These multiple stressors can be both climatic and non-climatic factors waring the quality and quantity of the groundwater resources.

Studies have enlisted climate change, urbanization (increased population density, higher living standards, increased water-energy-food demand, change in land-use and land cover, etc.), development of industrial and commercial zones, tourism development as major stressors for groundwater resources, especially in the urbanizing areas (Hutchins et al., 2018; J. M. Lee et al., 2019; Olivares et al., 2019; L. Qiu et al., 2018; Shrestha et al., 2016). These stressors can be natural and human-induced that impacts the sustainability of groundwater resources (Lee et al., 2019). Olivares et al., (2019), adopted climate, land use/land cover, and demographic change as drivers for the depletion of groundwater resources in Mexico which generated stress to encourage its unsustainable use. The study in five different provinces and cities in the coastal areas by Qiu et al., (2018), showed economic growth as a stressor that alters the groundwater consumption thus substantially exploiting it (both in terms of water level and salt intrusion) because of socioeconomic development. Furthermore, studies on the groundwater environment of 14 different Asian cities considered population growth, urbanization, tourism, industrialization, agricultural intensification, and climate change (precipitation and temperature) as the main driver for current and future groundwater degradation (Shrestha et al., 2016). Thus, these complexes, interlinked, and intra-linked multiple stresses impact on the flow, storage, and chemistry of groundwater bodies should be identified and analyzed for sustainable use and management of the limitedly available groundwater resources.

2.2 Impact of Urbanization on Groundwater Resources

Urbanization is a complicated socio-economic transformation that shifts the spatial distribution of the population and the environment (Malik et al., 2017). It is the process in which the quantity of people gets concentrated in smaller areas forming cities. The United Nations projects that the people living in the urban areas by 2050 shall reach to 68% and this transformation will be majorly in freshly developing nations in Asia and Africa (United Nations, 2018). Studies reveal the exploitation of the environment, imbalance in biogeochemical, water, and carbon cycle, urban growth-driven climate change because of the rapid urbanization despite its contribution and importance in economic and social development (Hua et al., 2020; McDonald et al., 2011). The extraction of groundwater has increased four times in the last 50 years and this is expected to remain increasing in the future due to an increase in sectoral demand, ecosystem services (FAO, 2016) included with modernization and improvement of pumping technology, energy availability, and understanding of hydrogeological settings.

One of the major transformation due to the process of urbanization is the land use with the replacement of the natural landcover with the impervious one (Batisani & Yarnal, 2009; Hassan & Nazem, 2016; Mohan et al., 2011). These surfaces increase the volume of the surface runoff, rate of sediment deposits, and reduces the urban population increases the rate and quantity of abstraction to meet the quantity of rainfall infiltrating into the ground (Sajikumar & Remya, 2015; Sankalp & Sahoo, 2018). In addition to this, the rough and reflecting urban surfaces and increased local temperature creates the UHI effect which modifies the urban micro-climatic parameters exposing the urban population to increased heat stresses (Chapman et al., 2017). This has a significant impact on ample groundwater availability due to an increased rate of evaporation (UHI effect) and decreased rate of infiltration (imperviousness). On the other hand, the increasing sectoral (domestic, agricultural, and industrial) demand of the rapidly growing demand resulting in depletion and unequal accessibility of the groundwater resources in the cities (Foster et al., 1994; Sajikumar & Remya, 2015). Thus, the groundwater recharge rate and level are the two crucial variables that are impacted by the process of urbanization. Studies show a decrease in the groundwater recharge and an increase in surface runoff compared to natural conditions due to the urban surface sealing (Grischek et al., 1996; Hardison et al., 2009; Rose & Peters, 2001). The study by Rose & Peters (2001), in the vicinity of Atlanta in the United States showed a significant fall in water level in wells in urban areas as compared to non-urban wells. In contrast to the theory that the impermeabilization due to urbanization decreases the urban groundwater recharge, several case-studies in cities worldwide indicate an increase in urban recharge contributing through sources such as excessive water supply and wastewater leakages, reduction in evapotranspiration, use of green urban infrastructures, etc. (Barron et al., 2013; Garcia-Fresca, 2007; Lerner, 2002; Wakode et al., 2018). Overall, it is difficult to calculate the actual total effect of urbanization on urban groundwater recharge and thus water level as each case is different in setting and climatic conditions. Furthermore, the water level is also dependent on other factors of urbanization which is the population growth leading to increased demand and water abstraction. Not only in quantity, but the impact of urbanization is also impacting in its quality as multiple anthropogenic contaminants are likely to transport by the recharging water generated through urban runoff, urban industrial discharge, and wastewater leakages (Carlson et al., 2011; Lohse et al., 2010; Minnig et al., 2018; Wakode et al., 2018). Thus, the process of urbanization and multiple anthropogenic activities impacts both the climate and groundwater environment stressing the urbanizing areas in urban public service delivery.

2.3 Impact of Climate Change on Groundwater Resources

The earth (including oceans and atmosphere) absorbs 70% of the solar energy which is transmitted by heat fluxes or infrared radiation. But some layer of gases in the troposphere and stratosphere blocks or absorbs it from going back to space thereby increasing the temperature of the lower atmosphere. These gases are called greenhouse gases (IPCC, 2007) and its effect on earth being warmer is referred to as the greenhouse effect. Though the greenhouse gases are very important for the life of the earth but its increased concentration because of several human activities is the major concern that changes the thermal characteristics of the lower atmosphere altering the usual climatic patterns. Thus, the (IPCC, 2007), defines climate change as "any change in climate over time, whether due to natural variability or as a result of human activity". This change in climate (long term) or climate variability (short term) has a great influence in the groundwater environment majorly in terms of its recharge and use which is furthermore modified by the human activities and level of infrastructural and socio-economic development (Taylor et al., 2013).

Several studies around the world revealed that the change in rainfall patterns and increase in the temperature as a result of climate change shall pose a high risk to groundwater resource predicted affecting its accessibility and recharge (Eslamian & Eslamian, 2017; Meixner et al., 2016; Salem et al., 2018). The study to assess the impact of climate change on groundwater resources done by Shrestha, et al., (2016), in the Mekong Delta aquifer, revealed a decline in groundwater recharge and thus, drop in level and storage resulting due to seasonal change in rainfall and increase in average annual temperature. Several studies have assessed the impact of changes in the climatic conditions on the level of the groundwater resources (Ranjan et al., 2006b; Treidel et al., 2011). However, studies also revealed an increase in the recharge because of climate change (Gurdak & Roe, 2010; Jyrkama & Sykes, 2007). The recharge of groundwater not only depends on the overall climatic parameters but also on the temporal climate variability, land-use scenario, and the type of soil and vegetation in the selected area. Included with the amount of rainfall and other factors, evapotranspiration and surface water changes also impact subsurface hydrology. The change in storage of groundwater also results from the enhancement of evapotranspiration, snowmelt, and increased pumping driven by climate change (Wu et al., 2020). Also, flood and droughts because of increased rainfall variability and increased extreme events (both rainfall and temperature) caused by climate change immediately affects the groundwater resources availability and dependency (Delpla et al., 2009). The longer duration and occurrence of droughts in areas with shallow aquifer increases the higher risk in quicker depletion and rapid urbanization increases the demand for groundwater resources. In addition to this, climate change also impacts the groundwater quality particularly in the unconfined aquifer with higher hydraulic conductivities (Aladejana et al., 2020). Studies on the Eastern Dahomey basin showed a threat to water quality in shallow aquifers due to seasonal flooding caused because of climate change (Ayolabi et al., 2015; S. & B., 2017). Furthermore, sea-level rise resulting due to the change in the climate change (Aladejana et al., 2020), leads to the intrusion of saltwater in coastal aquifers contaminating the entire freshwater system. The extent of the intrusion depends on multiple factors such as landscape, recharge, and abstraction of groundwater in the area (Taylor et al., 2013). This effect is more likely to be exaggerated in the urban areas and its vicinity where the abstraction is more. Studies have revealed the effect of saltwater incursion majorly due to intensively groundwater pumping in the vicinity of highly dense cities such as Gaza, Bangkok, Jakarta (Taniguchi, 2011; Yakirevich et al., 1998). Thus, groundwater for surcharging global demand and food security is likely to intensify due to frequent climate extremes, variability, and urbanization. So, assessing the availability of groundwater resources under natural and human-induced changes in climatic conditions is critically important and required.

2.4 Combined Impact of Urbanization and Climate Change on Groundwater Resources

Freshwater resources are being threatened more due to multiple stresses like urbanization, industrialization, and climate change (Wen et al., 2017) impacting the flow, storage, and chemical properties. Furthermore, the change in the water cycle, surface energy budget, and yield is the result of a significant impact on the water resources due to rapid urban development and climate change affecting availability and demand (Mirchi et al., 2013; Wada et al., 2011). Groundwater is a common-pool resource of global importance and urbanization implicating rapid population growth, change in land use and land cover, increased living standard and demand for freshwater, and changes in microclimatic conditions impact both demand and supply (Megdal, 2018). The urban land cover also impacts the thermal characteristics of the area as a result of increased greenhouse gases, expansion of imperviousness, and reduction in carbon sinking sources adding more instability in warmer air creating the urban heat island effect (Paul et al., 2018; Pramanik & Punia, 2019). A study by Huong & Pathirana, (2013), revealed about the changes in the microclimatic events as an effect of urban heat islands in cities. Thus, urbanization driven changes in land use alter the groundwater recharge (Ranjan et al., 2006a) and distribution of the temperature (Majorowicz et al., 2006), evaluated the dual impact of urbanization and climate change in Sendai plain, Japan with a major focus on aquifer temperature and found about 75% change in ground surface temperature resulting due to urbanization. Furthermore, the study also predicted a likely decrease in groundwater recharge despite of increase in rainfall because due to increased evapotranspiration because of increased surface air temperature. Studies have predicted changing rainfall and temperature patterns and other climatic variables due to climate change impacting groundwater recharge, level, and accessibility (Eslamian & Eslamian, 2017; Meixner et al., 2016; Salem et al., 2018). The change in groundwater storages is a complex process and it not only depends on the amount of the precipitation or recharge but also depends on other factors like the rate of recharge, evapotranspiration, and rate and quantity of abstraction driven by urbanization as well as climate change (Wu et al., 2020). In addition to this, rapid urbanization, increased demand, and changes in climatic conditions collective puts coastal cities under immense pressure to water availability including risk to contamination. Saltwater intrusion in coastal freshwater resources is the major threat (Chang et al., 2016; Green et al., 2011; Praveena et al., 2010). Chang et al., (2016), evaluated the impact of the vulnerability of coastal aquifer to climate change and urbanization in Dauphin Island between the Mississippi Sound and the Gulf of Mexico. The result of the study showed a decreased level of the water table, moderate to severe intrusion of seawater under the dual impact of urbanization and climate change concluding the unsustainability of the shallow unconfined aquifer for any substantial future urbanization and adverse climatic setting. Thus, understand the coupled impact of climate change and urbanization with change in human dependent activities to understand the sustainability of the groundwater resources is very crucial for integrated planning, governance, and management.

2.5 Climate Models

The investigation or prediction or projection of the climate-related variables and assessment of its impact in the future (seasonal to decadal) usually rely on climate models. These are based on the laws of physics, chemistry, and fluid motion constituting a system of differential equations. This mathematical form replicates the interconnection and interaction of the complex climate system. Thus, to understand the phenomena of climate science the climate models are the essential tools (Knüsel & Baumberger, 2020). These models predict the current and future climatic variables in grids which illustrate the depth-wise associated physical and chemical reactions. The projection of change in the climatic variables is mainly based on the greenhouse gas concentration or emission, concentration of the aerosols, or multiple radiative forcing settings which presents the uncertainties associated with the climate model and its projection (Anandhi et al., 2008). There is a necessity to investigate the impact of climate change in the water sector and IPCC's Assessment Report Five (AR5) has already stated the associated risks of climate change on freshwater resources is likely to increase more resulting due to the increased anthropogenic activities which have increased the concentration of greenhouse gas in the atmosphere (Field, 2014). Thus, the study of the impact on freshwater resources depends on many factors and some of them are the geographical coverage, level of necessity, and accessibility of observed data. And, based on these factors different climate models are used to investigate the impact.

The General Circulation Models or Global Climate Models (GCMs) are the finest, powerful, and suitable tools in anticipating changes in the future climatic variables. These are usually representing via three-dimensional grid cells with 250-400 km or greater spatial resolution horizontally with multiple uncertainties (Singh et al., 2019a). The IPCC defines GCMs as "numerical models, representing physical processes in atmosphere, oceans, cryosphere and land surfaces and are the most advanced tools for simulating the response of global climate system to increasing greenhouse gas concentration”. The uncertainties in GCMs observation are mainly due to larger grid size and coarser-resolution failing to accurately provide an estimation of the radiative forcing (Storelvmo et al., 2016). Multiple studies have used a number of GCMs for assessing the impact of climate change in water resources, hydrological flows, and water requirements under future change in climate (Babel et al., 2014; Chun et al., 2009; Deb et al., 2018; Konzmann et al., 2013; Lofgren et al., 2002; Thompson et al., 2013). The accuracy of the GCMs is highly uncertain with finer-scale studies and studies have found inaccurate results in local-scale studies (Chen et al., 2012; Singh & Goyal, 2016). These errors due to multiple factors in GCMs need to be minimized before performing impact studies (Singh et al., 2019a). Two approaches are generally used to minimize the disparity between large and local-scale climate data named as statistical and dynamical downscaling (Maraun et al., 2010). The statistical downscaling approach assumes that the relation between the 20th century’s observation and GCM model output shall hold in the 21st century and thus, the entire method includes the use of the empirical relationship between climate model output and observed high-resolution data (Shrestha et al., 2014).

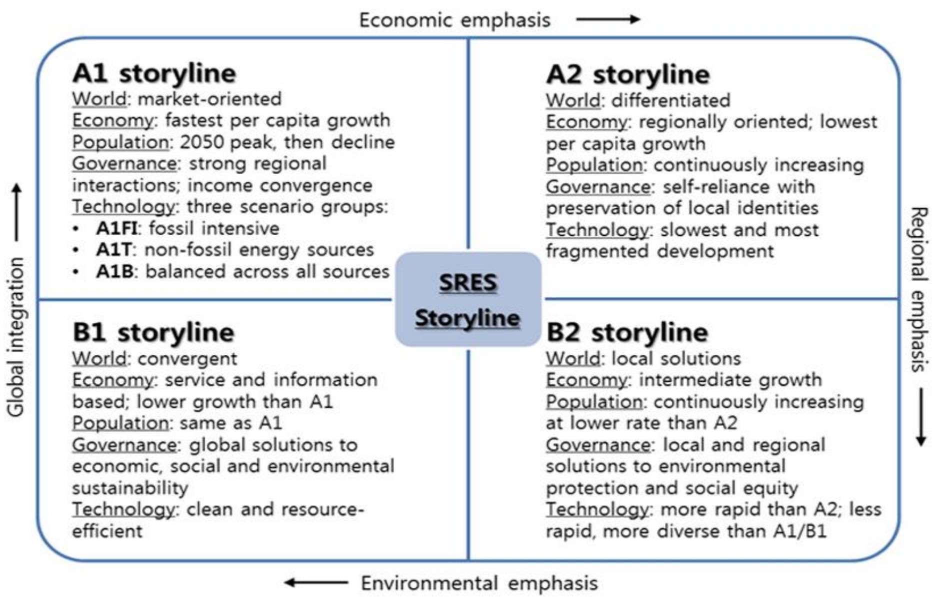
On the other hand, formulating adaptation and management policies as a response to the impact of changing climate at the local level requires finer spatial information, and recent studies have substituted by finer resolution Regional Climate Models (RCMs) produced through the dynamic downscaling of GCMs (Miao et al., 2016). This approach uses lateral boundary conditions for the coarser climate models to generate high-resolution outputs (Fowler et al., 2007) but requires more storage, processing time, and capacity (Shrestha et al., 2014). RCMs as compared to GCMs are better suitable for complicated physiographical areas because of its finer resolution and several studies on groundwater, flood assessment, surface water, land use and land cover change has used outputs from different RCMs to evaluate the impact of climate change (Park et al., 2016; Suh & Lee, 2004; van Roosmalen et al., 2007). The Coordinated Regional Climate Downscaling Experiment (CORDEX) has made available several RCMs (https://cordex.org/) and for the list of RCMs in the Southeast Asia domain (http://www.ukm.my/seaclid-cordex/), list of RCMs, it's driving GCMs and name of contributing institution for the member countries of SEACLID/CORDEX are provided.

2.5.1 Climate Change Scenarios

The Special Report Emission Scenarios (SRES) are storyline approach for the future emission of greenhouse gases where the emission stories are developed based on the socio-economic development included with change in demographics, use of resources, technological advancement, polices and structure of governance. IPCC developed four different families (A1, A2, B1, B2) based on which 40 different scenarios has been developed. These four families are future categorized as more global and economic development aspect and the next is on more regional and environmental emphasized aspects. Figure 2.1 below shows how the storyline for these four families is developed based on assumptions made on economy, governance, technology, population change and aspect (i.e. global, regional, local). These scenarios are used to apply and investigate the driving forces is likely to impact, evaluate the future uncertainties and plan for appropriate adaptation and management strategies (Gregory et al., 2000).

Figure 2.1

Summary of SRES storylines storyline for these four families

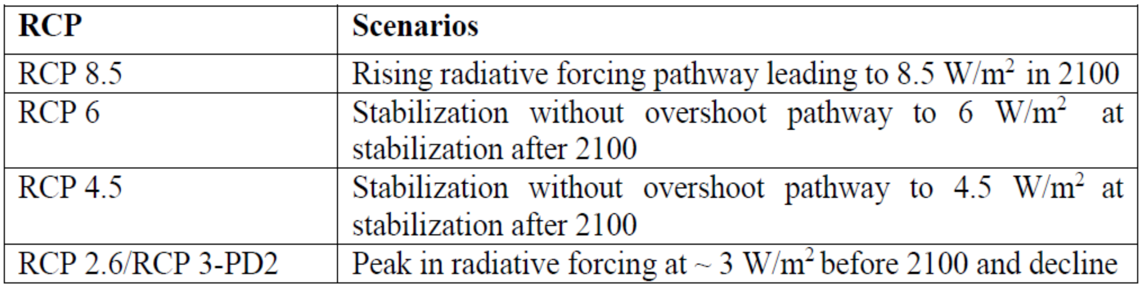


Source: IPCC, 2007

In 2014, the Representative Concentration Pathways (RCPs) replaced the SRES scenarios which adopted "*radiative forcing approach*" (Moss et al., 2010) rather than the previous storyline approach. The RCP scenarios which includes multiple factors like future land-use patterns, global economics, technological advancement, and other environmental factors along with the future likely concentration of greenhouse gases and aerosols. Being subject to the radiative forcing with respect to the time and socioeconomic hypothesis, the RCP scenarios focuses on four different greenhouse gases concentration trajectories which is widely used for impact assessments and develop mitigation strategies figuring out the uncertainties (Moss et al., 2010; Rogelj et al., 2012). Table 2.1 presents the 4 RCP scenarios with respect to the radiative forcing from greenhouse gases concentration up to the 21st century.

Table 2.1

RCP scenarios with respect to the radiative forcing



RCP	**Scenarios**
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100
RCP 6	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100
RCP 2.6/RCP 3-PD2	Peak in radiative forcing at ~ 3 W/m^2 before 2100 and decline

Source: Moss et al., 2010

Shared Socioeconomic Pathways (SSPs) are the climate projection scenarios driven by a new set of emissions and land use scenarios (Riahi et al., 2017) produced with integrated assessment models (IAMs) based on new future pathways of societal development and related to the RCPs. The SSPs were developed over the last several years as a community effort and describe global developments leading to different challenges for mitigation and adaptation to climate change. The specific content of the SSPs comprise five alternative narratives (Figure 2.2) that describe the main characteristics of the pathways in qualitative terms as well as quantitative descriptions for key elements including population, economic growth, and urbanization (O’Neill et al., 2016).

Figure 2.2

Shared Socioeconomic Pathways mapped in the challenges to mitigation/adaptation space

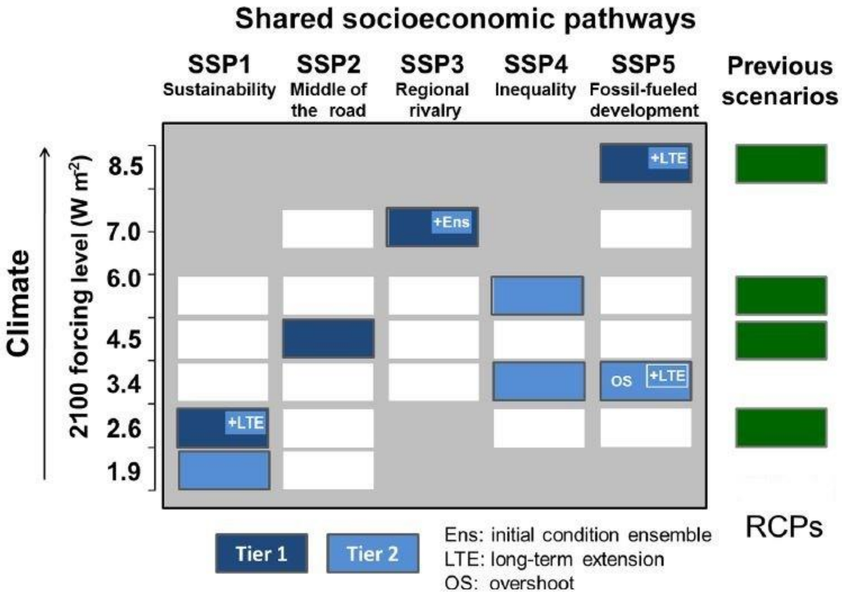
Source: *Van Zalinge et al., 2004*

In short, the SSPs describe alternative evolutions of future society in the absence of climate change or climate policy. SSPs 1 and 5 envision relatively optimistic trends for human development, with substantial investments in education and health, rapid economic growth, and well-functioning institutions. However, SSP5 assumes an energy intensive, fossil-based economy, while in SSP1 there is an increasing shift toward sustainable practices. SSPs 3 and 4 envision more pessimistic development trends, with little investment in education or health, fast growing population, and increasing inequalities. In SSP3 countries prioritize regional security, whereas in SSP4 large inequalities within and across countries dominate, in both cases leading to societies that are highly vulnerable to climate change. SSP2 envisions a central pathway in which trends continue their historical patterns without substantial deviations.

Currently, the Scenario Model Intercomparison Project developed a set of eight pathways of future emissions, concentrations, and land use, with additional ensemble members and long-term extensions, grouped into two tiers of priority which implies new, SSP-based versions of RCPs (Figure 2.3).

Figure 2.3

SSP-RCP scenario matrix



Source: *O'Neill et al., 2016*

2.5.2 Bias Correction of Climate Models

The impact of change in the climatic conditions are frequently computed using the climate models where these models normally requires finer resolution input data. Output from these impact models do not statistically fit with the observed gauging data for a control period and this difference is term as bias (Soriano et al., 2019). The model output for rainfall and temperature often biased mainly due to faulty conceptualization, discretization, and spatial averaging within grid cells (Teutschbein & Seibert, 2012). These biases in the climate model makes the impact studies unrealistic and more complicated (Bergström et al., 2001; Christensen et al., 2008). Thus, the correction of these biases from the climate models through a process to account errors from the model and improves their fitting to observations referred as bias correction of the climate models. Several methods ranging from simple scaling to sophisticated probability mapping are developed for correcting the biases from climate models (Chen et al., 2011; Johnson & Sharma, 2011). Various bias correction techniques such as linear scaling, local intensity scaling, quantile mapping, power transformation approaches etc. have been reviewed, discussed, and applied in many studies (Themeßl et al., 2011; Mpelasoka & Chiew, 2009; Soriano et al., 2019; Teutschbein

& Seibert, 2012). These studies show that all the methods have their own advantages and disadvantages like the liner scaling is based on mean monthly correction but do not account for frequency distribution. Similarly, correcting biases in the mean and variance is handy using power transformation method. Most of these approaches provide an emphasis on correcting rainfall and fit to the observed value irrespective to the extreme value behavior and for correcting the distribution function quantile mapping technique is more useful (Soriano et al., 2019). A study by Teutschbein & Seibert, (2012), to correct the biases of RCMs simulation for the hydrological climate impact assessment showed that all the different correction techniques could correct the mean value but have different capacity in correcting other statistical properties like percentiles or standard deviations but the hydrological simulation from bias corrected input fitted better with the observed values rather than the biased one. Furthermore, studies have also considered the effect of the correction technique on flow frequency curves but the selection of best technique shall be based on the requirement of the application and improvement in the entire timeseries rather than any specific one (Soriano et al., 2019). A study by Shrestha et al., (2017), revealed that the hydrological models' performance has no significant difference between different bias correction techniques.

2.6 Population Projection Techniques

The major share of the current global population currently lives in the cities (Buhaug & Urdal, 2013) and the projection from United Nations, (2018), shows that that the trend is likely to increase to up to 68% by 2050. Urbanization is referred as the rural population to an urban area transforming the built environment (Malik et al., 2017). It is the processes of the increase share of urban population and is mainly governed by the phenomena of reclassification of rural to an urban area, natural growth, and the migration trend (Buhaug & Urdal, 2013). Furthermore, the migration from the rural to urban area as a process of urbanization can be the consequences of few factors one is the increased pressure of population in the rural area leading to rural shortage to the resources, the second can be the impact of the environmental degradation and climate change leading to desertification, droughts, soil salinization etc. affecting the rural livelihood and other factors such as limited opportunities to education, employment, health and other public services (Grimm et al., 2008; Homer-Dixon, 2010). Ayhan, (2018), categorized population projections techniques as mathematical and cohort component projection models. Furthermore, the study also revealed that using past population data to forecast the future total population, mathematical models are handy and useful. In case of the cohort technique, it disaggregates the cohorts and components.

The mathematical models' projects based on the arithmetic or geometric or exponential growth and can be classified as the Linear Model, Geometric Model, Logistic Growth Model, Exponential Model (Ayhan, 2018). The common methods used in applying these mathematical models in projecting the population of the cities are:

Arithmetical increase method assumes the constant rate of population increase and uses the average decadal increase in population from past census and is generally useful for large and old cities where substantial development has occurred. The population (P_i) in this method after i^{th} decade is given by:

$$P_n = P + n.C \qquad \text{Eq.2.1}$$

Where, P is the current population and C is the constant rate of change of population w.r.t time given by

$$C = \frac{dP}{dt} \qquad \text{Eq.2.2}$$

Another common method for projecting population of the cites is the Geometrical progression or increase method which assumes that the decadal percentage increase in population remain constant. In contrast to the Arithmetic method, this method gives higher future increment and is useful in applying new industrial town at the beginning of development. The population (P_i) in this method after i^{th} decade is given by:

$$P_i = P\ (1+ I_G/100)^i \qquad \text{Eq.2.3}$$

Where, P is the current population, i is the number of decades and I_G is the geometric mean in percentage.

Incremental increase method is another popular population forecasting method which is a modified version of the arithmetic increase method and is appropriate for average sized cities having normal increasing growth rate. The method used the increment in the increase of the population is considered on decadal basis. The population (P_i) in this method after i^{th} decade is given by:

$$P_i = P + {}_i.X + \{i\,(i+1)/2\}.\,Y \qquad \text{Eq.2.4}$$

Where, P is the current population, i is the number of decades and X and Y are the average increase and the incremental increase, respectively.

Another popular population forecasting method in the urban areas is the Logistic Curve Method which adopts growth curve characteristics within a limit of socioeconomic opportunities and space. The method is generally used when the population growth rate is not subjected to any exceptional changes and takes place under normal conditions of birth, migration, and deaths. This curve follows the S-shaped curve called as logistic curve. If P_0, P_1, and P_2 are the population of an area at time $t = t_0 = 0$, $t_1$and $t_2 = 2t_1$ respectively over the past, the population after time t (P_t) and saturated population P_{sat} is given by:

$$P_t = \frac{P_{sat}}{1 + e^{(a+b\Delta t)}} \qquad \text{Eq.2.5}$$

$$P_{sat} = \frac{2P_0P_1P_2 - P_1^2(P_0 + P_2)}{P_0P_2 - P_1^2} \qquad \text{Eq.2.6}$$

$$a = \ln(\frac{P_{sat} - P_0}{P_0}) \qquad \text{Eq.2.7}$$

$$b = \frac{1}{n}\ln\frac{P_0(P_{sat} - P_1)}{P_1(P_{sat} - P_0)} \qquad \text{Eq.2.8}$$

Similarly, graphical methods, comparative graphical methods, master plan methods are other methods used in forecasting population of cities.

2.7 Urban Land Use and Land Cover Change Projection

Urbanization is the process of transformation which includes the rapid growth of the urban population included with an increase in demand for urban infrastructures and services. The expansion and the modification of urban land transforming the natural built environment is an important aspect of the urbanization process and this involves both spatial and vertical transformation on natural land cover with the modern service infrastructures and impervious surfaces (Paul et al., 2018). The Land Use and Land Cover Change (LULCC) alters the hydrology, energy balance, biodiversity, habitats cycle, and human livelihoods (Pielke et al., 2011; Trisurat et al., 2010). The impervious surfaces because of change in the land use and land cover impact hydrologic response and increases the surface water runoff, rate of sediment deposits within any catchment, and averts sub-surface infiltration (Sankalp & Sahoo, 2018). The consequences of the LULCC due to the rapid urbanization are reduction in green vegetative cover and excessive use of fossil fuels creating an inconsistency between the creation and utilization of greenhouse gases impacting the carbon cycle (Churkina, 2016). Furthermore, this alteration in natural cover also reduces water seeping capability, accelerates the surface runoff, and rate of sediment deposition thus altering the urban hydrological course and impacting the entire water cycle (Viger et al., 2011). Studies have acknowledged that the LUCCC as one of the key drivers for global climate change (Kumar, 2012; Yao et al., 2015), and the continuation of this trend is likely to alter urban climatic characteristics inducing extreme effects on rainfall, temperature, evapotranspiration and soil water content (Kumar, 2012). The UHI effect is the other major consequence of LULCC in urban areas because of urban rough surfaces and rising temperatures which exposes the urban residents to more heat stress (Chapman et al., 2017). Thus, in the context of rapid urbanization by 2050 as projected by the United Nations, the changes in the trend of urban land use and land cover should be emphasized as it acts as a catalyst for many consequences that result due to urbanization.

The projection of future LULCC is usually done by using different types of land-use change models which preferably quantify the change and predict future use. The LULCC models are the supporting tools to supplement the existing LULC mentalities, analyze the cause and consequences of the change and assist the planners and policymakers for informed decision making (Verburg et al., 2004). The concept of LULCC modelling is mainly based on six different features that are usually deemed to be important while discussing the modelling techniques and these are the level of analysis, the driving factors, the cross-scale dynamics, the temporal dynamics, the spatial interaction, and neighborhood effects and the level of integration of the model (Verburg et al., 2004). The LULCC models can be broadly categorized as spatially and non-spatially explicit (statistical) based models. The statistical model uses a mathematical formula to predict the future change in the land-use change and Markov Model and System Dynamics models are some examples (Akbar et al., 2019; Xu et al., 2016). On the other hand, the spatially explicit models such Cellular Automata (CA) model the Agent-Based model (ABM), Dynamics of Land System model (DLS), and Dyna-CLUE model are used to forecast and analyze the spatial distribution of future land use (Adhikari et al., 2020; Samie et al., 2017; Tian et al., 2016; Trisurat et al., 2019). The study was done by Tang & Di, (2019), used combined multi-temporal Landsat images and the Markov-CA model with the socio-economic dynamics to examine farmland loss in the Delhi, India and the results from the model provided good accuracy and a better understanding of LULC change in past and future but the entire process accumulated the errors of the models from various sources and steps followed and also could not integrate other essential factors such as climate, policies, etc. The Dyna-CLUE model which is the modified version of the CLUE-s model (Castella & Verburg, 2007) can stipulate scenarios for land-use change via the model parameters and successfully used in some countries and continents (Verburg et al., 2008; Y. Wang et al., 2018). This model has the capabilities of not only simulating under multiple land-use scenarios but also takes into account the driving forces for the change, management policies to generate more precise predictions (Wang et al., 2019).

2.8 Sectoral Water Demand Estimation

The process of rapid urbanization has greatly affected the environment and the climate as the various anthropogenic activities modify the utilization pattern of water, energy, food, land, and in-turn pollute the natural environment even though urbanization is intimately interlinked to the socio-economic of the country. This validates the role and importance of urban centers in domestic economics and its obligation to deliver higher quality of services to its inhabitants. So, rapidly urbanizing areas are enormously stressed in delivering multiple (traffic management, education, employment opportunities, waste management, etc.) public-oriented services and among many of the urban public services is the "water supply and sanitation" is one of the important (Bloom et al., 2008; H. Jones et al., 2014). So, urban planners and water managers need to have an informed understanding of sectoral (domestic, industrial, and agriculture) water demand for present and future conditions sustainable management of resources, and delivery of public services. Consistent prediction of the urban water demand offers a scientific basis for strategic (long-term), tactical (medium-term), and operational (short-term) decisions making in water utilities (Donkor et al., 2014). The application of the forecasting discipline in the future estimation water demand faces relatively many challenges mainly due to the multiple hypothesis and variables affecting the demand included with actual filed availability of the baseline data for different sectors (Arbués et al., 2003). Furthermore, the difference in the practice followed by service providers or researchers and forecast periodicities in water demand forecasting significantly makes differences in the methodology and hypothesis used. Several studies used various techniques in estimating domestic, industrial, and agricultural water demand (Joseph et al., 2018; Li et al., 2017; Li et al., 2020). In the study done by (Li et al., 2017), in Shanghai, China estimated the effect of the growth in the population and economics in future needs of public water by extrapolation of previous tendencies and principal component regression analysis creating three scenarios (future GDP and population). Furthermore, the study by (Joseph et al., 2018), used census-based statistical data in estimating future water withdrawal from irrigation, domestic, industrial, and environmental sectors. The same study used several factors such as economic development, production information, qualitative survey in projecting industrial water demand. The review is done by Donkor et al., (2014), on different methodologies and models for forecasting urban water demand shows that multiple methods and applications are used to forecast the demand depending on variables, periodicity, and the forecast horizon of the forecasting agency. Furthermore, the same study concluded that the use of artificial neural networks (ANN) models is handy for short-term demand forecasting which coupled models (econometric models coupled with scenario-based forecasting) is more convenient for strategic forecasting and decision making.

2.9 Hydrological Modelling

Hydrological modelling portrays real-word hydrological system using some physical models and mathematical equations via multiple computer simulations. The model focuses on the individual flows of the entire system and is used for predicting system behavior to various processes using several parameters like climatic variables, catchment topography, land use conditions, and other relevant boundary conditions. In hydrological modelling runoff estimation is a key can be one or both i.e. infiltration and saturation excess (Anees et al., 2016). Estimating a hydrological runoff model developed to estimate runoff is defined through a set of mathematical equations with rainfall and drainage being the major inputs along with watershed topography, soil properties, vegetative cover, and aquifer characteristics (Devi et al., 2015). The process of hydrological modelling consists of replicating actual flow with as minimum errors as possible and a good model is insensitive to any alteration in circumstances. Seiller et al., (2012), defined that the robust hydrological model is insensitive to any change in environmental conditions and is thus competent in replicating its results to different periods than that of only the calibrated and validated period. Devi et al., (2015), classified hydrological models as a lumped and distributed model as a function of time and space, and based on the other criteria the hydrological models can also be divided as deterministic and stochastic models. Furthermore, the additional classification based on the time factor is the static (excludes time) and dynamic (include time) models. The lumped model considers an entire watershed or basin as a single used irrespective of the spatial variability whereas in the distributed models divides the entire catchments into smaller sub-units considering all the spatial processes. The deterministic and the stochastic models differ in terms of the output from the model where the first gives the same output for the set of given input whereas stochastic models produce multiple values of output can be for a single set of given input. Furthermore, these models can be mainly categorized as empirical, conceptual, and physically-based models. Empirical models are also known as the data-driven model as it inputs the information from the currently available data without pondering other characteristics and processes of the system and thus, involving the mathematical equations from the simultaneous input and output time-series. Conceptual models include the semi-empirical equations and portrays the majority of all the components of the system and its processes and are based on connected reservoirs concepts in which rainfall, percolation, infiltrations recharges the system and drainage, runoff, evaporation empties the system. Physically based models which are also known as mechanistic models where the real-world phenomenon is ideally represented mathematically and usually requires morphology of the catchment with initial state data. The choice of these various types of models varies based on the purpose, its application making it more subjective. Studies have found the ANN model to be useful in modelling the complex hydrological processes and used for the estimation of streamflow values (Jimeno-Sáez et al., 2018; Juan et al., 2017; Kumar et al., 2016). Wang et al., (2006), used the HBV model to analyze the impact of climate change on the river discharge whereas other study used other models such as the HSAMI model, NAM model for the same climatic influence in hydrological flows in different areas (Boyer et al., 2010; Thodsen, 2007). Several studies used the WetSpass model for assessing the impact of multiple stresses such as climate and land-use change on surface discharge and subsurface recharge (Dams et al., 2008; Moiwo et al., 2010; Tilahun & Merkel, 2009).

Currently, the "*Soil and Water Assessment Tool (SWAT)*", a semi-distributed model having the capability of continuous simulation and developed by USDA-ARS is being frequently used in hydrological studies in estimation of river flow, modelling of the ungauged basins/catchments, and assessing the impacts on both quantity and quality of water under multiple stresses like climate and land-use changes (Trang et al., 2017). The model is data-driven, it requires a huge quantity of data, its process, and expertise in analyzing the results. However, the model being efficient for simulation of hydrological processes in large basins with an option of splitting the watershed to subunits simulating impacts of both natural and anthropogenic interventions on surface water and sediment yield make it advantageous over other models. Furthermore, a wide range of components like soil and crop characteristics, weather, land-use and management options, nutrient load, etc. can be included in the model. Neitsch et al., (2011), provide a detailed description and insight of the SWAT model. Several research studies have used the SWAT model in hydrological simulation and analyzing the problems for better possible solutions (Alansi et al., 2009; Arias et al., 2014; Piman et al., 2013; Yen et al., 2015).

2.10 Groundwater Modelling

Groundwater modelling is the representation of the sub-surface flow system and is mainly used in the simulation and prediction of the aquifer behavior responding to different conditions at present and the future. The groundwater model represents both the natural subsurface flow within the system and the quality aspects of the system including its movement. Thus, it is a very useful and influential tool in predicting the impacts of hydrological alteration on the aquifer system and used in planning and implementing various water management strategies, protection of groundwater resources, and application of various remediation initiatives based on multi-scenario impact analysis for ensuring sustainable availability of freshwater resources. Baalousha, (2009), stated the classification of groundwater models as (i) physical models, (ii) analogue models, and (iii) mathematical models. Furthermore, the study states that the mathematical models are solved either by analytical methods which are limited to solving simple problems and can be used with less data and the other is the numerical solutions which manages more complex problems and are more effective and simple to use but requires more processing capacity and speed of computers that are being used. The groundwater models or subsurface flow models can be one-dimensional which is mainly used for the vertical flow within the horizontal parallel layers (Olsthoorn, 1985), or can be a two-dimensional models which is mainly used for the two-dimensional flow below the ground and assumes that the conditions in the applied vertical plane is repeated in other parallel planes. Furthermore, the models can also be three-dimensional models which are very sophisticated and involves discretization of the entire domain into smaller cells horizontally and vertically. The parameters in each of the elements/cells are kept constant while may vary with other cells and thus the flow equations are then used to find the flow direction in multiple dimensions.

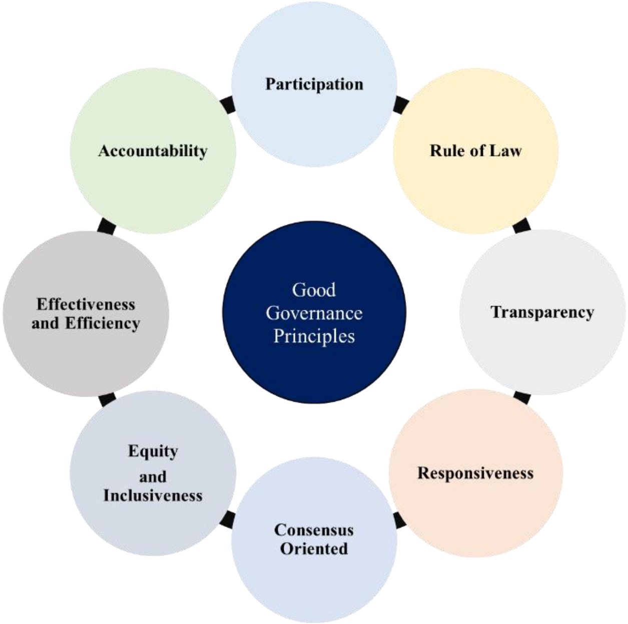
The Groundwater Modeling System (GMS) is a full modelling application for creating and simulating groundwater flows making the entire process more convenient through various processing tools before, during, and after model development. The system supports various subsurface related models such as FEMWATER, MT3DMs, UTEXAS, MODPATH, MODFLOW, etc. as the GMS has a modular interface to simplify the choice of only the needed modelling abilities (Jones, 2001). Furthermore, it also features two-dimensional as well as three-dimensional stratigraphic modeling included with the geo-statistics and the conceptual model. The MODFLOW model from the GMS which is a modular finite-difference flow model is one of the widely used by hydrogeologists around the globe for analyzing the dynamics of aquifer systems and understanding the flow patterns (Shrestha et al., 2020). Several studies have used MODFLOW to simulate the flow through aquifers (Abdalla, 2015; Cheng et al., 2014; Chitsazan & Movahedian, 2015; Qiu et al., 2015; Shrestha et al., 2020).

2.11 Water Governance

The concept of governance is frequently associated with government or the courses of governing. The common and fixed definition of governance is not available as it differs between defining organizations (Landman & Robinson, 2009). The policy paper by (UNDP, 1997), defines governance as "the exercise of economic, political and administrative authority to manage a country's affairs at all levels', which 'covers mechanisms, processes, and institutions through which groups articulate their interests, exercise their legal rights, meet their obligations and mediate their differences". For the OECD, it is 'the use of political authority and exercise of control in a society in relation to the management of its resources for social and economic development,' which 'includes the role of public authorities in establishing the environment in which economic operators function and in determining the distribution of benefits as well as the nature of the relationship between the ruler and the ruled' (OECD, 1995). The three mutual elements of governance regardless of any definition are the process; power (authority); collectively manage community affairs. In general, governance is the process of exercising the authorized power in handling communal concerns. The explanation of governance suggests various options that how and to what extent the authority exercise its power with ethics and norms and the representation of multiple actors (OECD, 2015; UNDP, 1997), making it more extensive to evaluate the quality of governance. Governance is the ability of a governing authority to make and enforce rules in order to deliver public services (Fukuyama, 2013). This implies fair legal frameworks, transparency, accountability, participation of men and women, and so on (Ngobo & Fouda, 2012). Good governance is an approach to government that is committed to creating a system founded in justice and peace that protects an individual's human rights and civil liberties. Participation requires that all groups, particularly those most vulnerable, have direct or representative access to the systems of government. UNESCAP defined eight principles for the governance to be good (Figure 2.4). It assures that transparent process and the views of minorities most vulnerable in society are heard and taken account in decision-making.

Figure 2.4

Principles of good governance

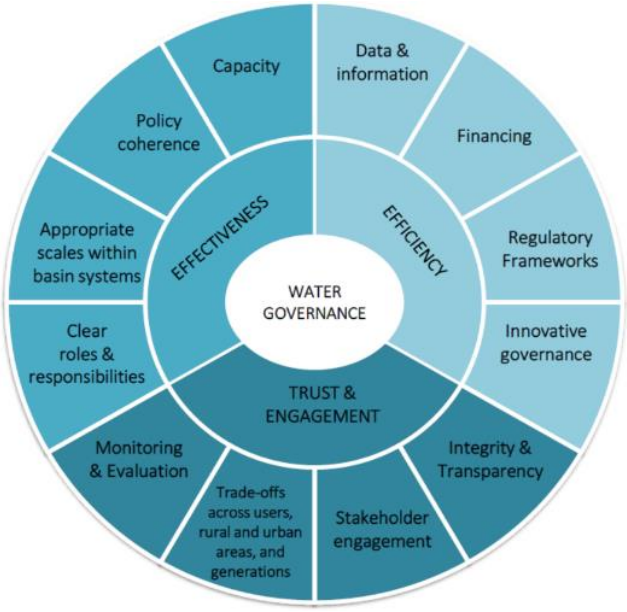


Water, being a renewable natural source is a limited resource that is disproportionately dispersed and is in an extremely pressurized state each day (Zogheib et al., 2018). The situational diversity in finding and using water in space and time makes it challenging to characterize any specific coherent policy for its governance. Water governance is "*the range of political, institutional and administrative rules, practices and processes (formal and informal) through which decisions are taken and implemented, stakeholders can articulate their interests and have their concerns considered, and decision-makers are held accountable for water management*" (Akhmouch & Correia, 2016). The definition differentiates between "*governance*" and "*management*" of water resources where governance of water is a social function which controls and provides direction for the water resources development, management, and its services whereas management are the set of the actions for analyzing and monitoring water resources in-line with the adopted operating measures developed to maintain the desirable condition of the resources.

In recent years, the one major policy level concern worldwide is about water and its good governance as the United Nations has already agreed on making water as the basic human right. Rapid urbanization, environmental issues and changes in the climatic conditions imposes substantial challenges for the effective and sustainable delivery of essential public services related to water and sanitation and environmental safeguard and thus, a probable explanation is likely to be Integrated Water Resources Management (IWRM) or private ownership (Pahl-Wostl, 2009). Water Governance is a complicated long-term affair engaging multiple actors from diverse sectors varying from household, agriculture, industrial sectors of different scales to the multi-level system of the government (Laban, 2007). The effectiveness, efficiency, mutual trust, and engagement required for a good water governance depends on 12 principles (Figure 2.5) as defined by OECD ranging from transparency, stakeholder engagement to monitoring and evaluation with clear organizational structure, policy coherence, adequate information, and regulating frameworks that guide the entire process and the involved stakeholders. The interactions between actors should be considered when promoting local water governance (Laban, 2007).

Figure 2.5

OECD Principles of water governance



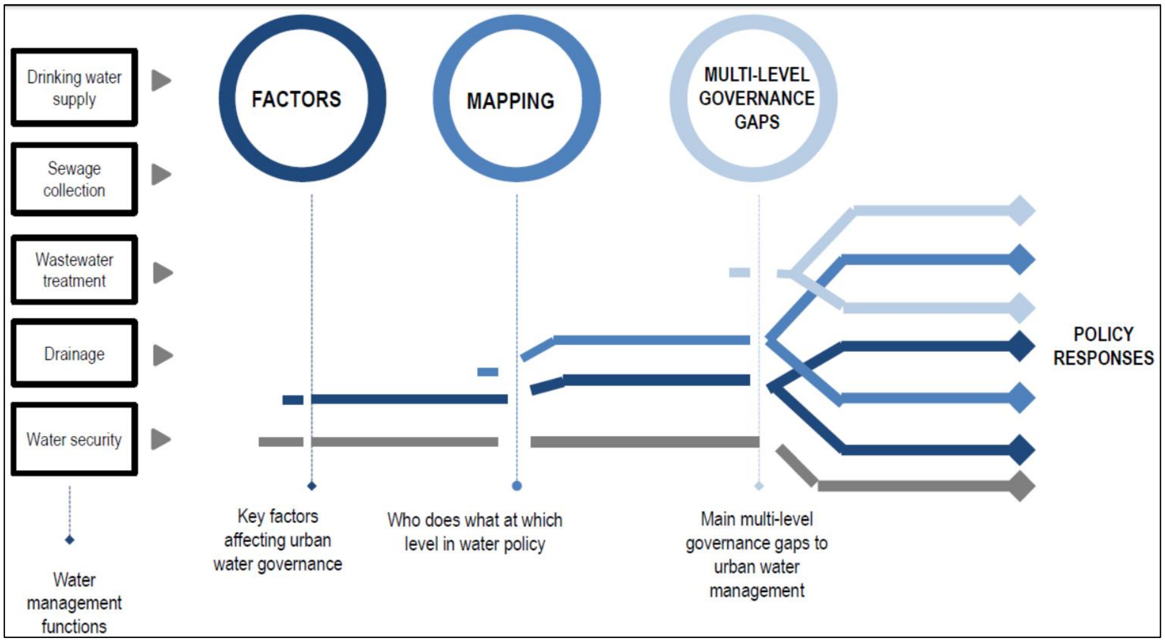
Source: Akhmouch & Correia, 2016

2.12 Urban Water Governance

The United Nations, (2018), projects that the increase in the urban resident to more than 65% by 2050 which is currently more than half the world's population. This signifies a substantial challenge for the management of the water resources and the delivery of essential public services related to water supply and sanitation (Staddon et al., 2017). Thus, there is a need to address these challenges through broader tools and a new integrated approach than the traditional concept of intensive water infrastructure development. A complete approach called "*Integrated Urban Water Management (IUWM)*" that incorporates all the elements of the urban water cycle (Keremane et al., 2017), shall be beneficial in the development of the cities and accomplish sustainable economic, social, and environmental goals. Romano & Akhmouch, (2019), mentioned that the water crisis is mainly a crisis of the governance and often managing this state of crisis become more challenging with insufficient information availability and dissemination, unclear institutional structure, limited capacity, and unclarities in roles and responsibilities. Studies in urban water governance distinguished three different models namely the (i) hierarchical model, (ii) market model, and (iii) network model (de Meene et al., 2011; Romano & Akhmouch, 2019). These models have their features and approaches such as the hierarchical model follow the centralized top-down approach with weaker engagement of the stakeholders in decision-making and implementation processes whereas the market model follows better engagement, ownership, and empowerment of stakeholders in the management processes. Furthermore, the third model i.e. the network model follows a more decentralized approach building cooperation and engagement between multi-sector and multi-actor collaboration for the management and decision-making processes. In practice, "*hybrid models*" are usually followed as cities undergo multiple complexities in addressing water challenges with diverse actors, institutional fragmentation, and distinct system followed by them at different scales. The OECD, (2016), employed an analytical system thinking framework (Figure 2.6) to detect challenges, enhance co-ordination, reduce institutional fragmentation, and bring consistency among relevant policies. The framework integrates the identification of the key internal (water sector) and external (e.g. institutional) factors that influence the effectiveness in decision making in urban water governance. This is followed by an institutional mapping of shared roles and responsibilities at multi-level government entities functioning as a regulatory role, operation role or any other intermediary roles. Furthermore, the frameworks incorporate an appraisal of multiple governance gaps such as communication gaps (between institutions), capacity gaps, financial differences, accountability gaps, information gaps and differences in functional and hydrological boundaries, etc. at the multi-level stage of governance and last but not the least the analytical framework for urban water governance also emphasize on the policy responses for Integrated Urban Water Management (IUWM). These above assessment and challenges identified from the assessment can be responded through the "*3Ps*" framework as developed by the OECD, (2016), which includes the policy, people, and places. The "Policy" coordination within the water sector and cross-sector favors efficient allocation and consumption of water resources in terms of its quality, quantity, and security. The strong engagement of multiple stakeholders i.e. "People" who have share in urban water management is key in building accountability, transparency, trust, and ownership in contributing to integrated water management. In addition to this understanding, the "Place" is crucial in overcoming boundary disparities between cities and its vicinities thus, developing cooperation, partnership, and shared benefits.

Figure 2.6

Analytical framework for assessing water governance in cities



Source: *OECD, 2016*

2.13 Groundwater Governance

Globally, groundwater the most reliant freshwater resource, and the volume of its abstractions is increasing annually (Wada et al., 2014). Managing groundwater resources is a complicated task as it includes various stakeholders and decision-makers with opposing goals and are subject to multiple uncertainties triggered by inadequate data and information (Jakeman et al., 2016). Moreover, climate change and variability are influencing the recharge of groundwater (Taylor et al., 2013), as well as the demand with rapid urbanization. It is usually difficult to conceptualize and understand the hidden groundwater resource and thus its management becomes more complex as compared to the surface water which is fairly understood and managed societally (Jakeman et al., 2016). Additionally, groundwater's use and exploitation are exceedingly scattered in space and largely among private sector such as farmers, suppliers (companies) or local well-owners (de Chaisemartin et al., 2017), and thus, groundwater management is a process of influencing the actions and decisions of multiple actors contrasting from the management of the surface water which where public sector with mega infrastructure development plays a vital role.

Groundwater governance is a complicated process guided by regulatory framework and policies for its allocation, coordination, roles and responsibilities, transparent mechanism across the same or cross-sectors, geographical and jurisdictional borders. Thus, one of the gentle approaches of managing and addressing the water crisis challenges is realizing and understanding the importance of groundwater governance (Closas & Villholth, 2020; de Chaisemartin et al., 2017; Mukherji & Shah, 2005). The process guarantees the sustainable protection and control of the shared resource by supporting the promotion of responsible collective action (Closas & Villholth, 2020). Further, this is aided by the legal regulatory frameworks, policies and plans, effective institutional arrangement, shared information and knowledge, finances, and motivative structure that is aligned to the goal of the society (FAO, 2016). Thus, groundwater governance has appeared as a suitable technique for the management of groundwater resources sustainably with the attention of all the related stakeholders. Responsible use of groundwater with equity, efficiency, and sustainability can only result in effective groundwater management policies that are identified and applied based on the principles of governance (Varady et al., 2013), for the benefit of humankind and dependent ecosystems. The process of the governance of groundwater embraces the enabling framework with the administrative principles for groundwater management (Foster & Garduño, 2013), that defines the clear responsibilities and accountability in the formulation and execution of the policies, plans, and strategies between multi-layers of actors with coordination and interaction between multi-stakeholders. The groundwater governance comprises of four crucial components which includes the "*actors*" engagement and participation at various levels; promising "*legal and institutional framework*"; accurate and broadly-shared "*information & knowledge*"; and "*policies*" and incentive structures aligned with goal (de Chaisemartin et al., 2017). The actors (Figure 2.7) in groundwater governance are the related shareholders who are directly (indirectly) associated with groundwater resource consumption, exploitation, governance, and management. Good groundwater governance involves the inclusion of all diverse character actors (Cruz & Soares, 2018), within a beneficial structure associating individual actions with agreed shared goals. The dynamic involvement of the stakeholders, sense of urgency for governance and management among the actors, clear and undisputed mandate, sufficient capacity and motivation among the government agencies in-charge, motivated and clear understanding of the stakeholders and multi-actors collaborating harmoniously are some of the important aspects while diagnosing these components (FAO, 2016).

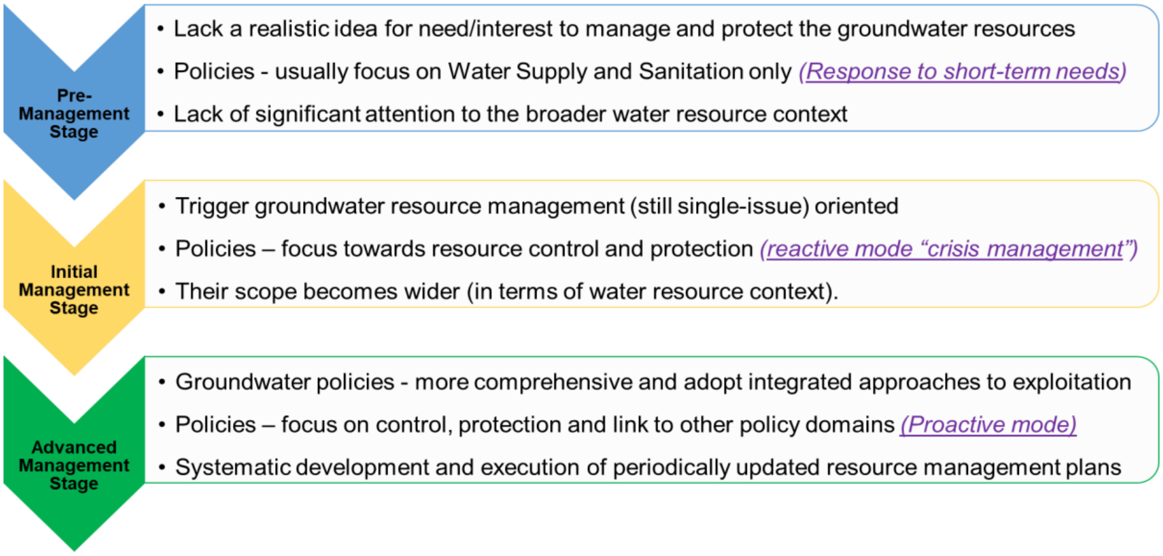
Figure 2.7

Actors in groundwater governance

The second component of groundwater governance is the "*legal frameworks*" which are the legally obligatory standards, within an institutional framework that delineates the roles and responsibilities with alignment of actors with pursued policies and plans (Foster et al., 2010). Laws and regulations are crucial for effective and consistent management of groundwater quality, quantity, and availability. In groundwater governance, the legal frameworks include regulations for ownership and user rights, safeguard from pollution, the role of the state in regulating its use, organizational mandates, rights, and obligations of the different actors, etc. (FAO, 2016). Well-defined regulatory frameworks with clear views on groundwater and its functions, the capacity of agency in-charge in monitoring and enforcing in compliance with the law, and the provisions for harmonization concerning internal as well as international transboundary aquifers are the important aspects while diagnosing these components (FAO, 2016). The third component of the groundwater governance is the "*policies and plans*" which are the set of decisions oriented towards a long-term purpose or to a problem (FAO, 2016). The degree to which they provide the agreed agenda set goals and boundary conditions for action-oriented management plans should be a measure of the governance arrangements. Once policy is formed proper tools, rules, protocols, etc. are required (de Chaisemartin et al., 2017). Groundwater policies and plans are broadly diverse, and this is not only due to differences in location-specific political, cultural, physical, and socio-economic conditions but also in the differences in the stage of advancement (Figure 2.8) of groundwater management and governance.

Figure 2.8

Groundwater policy diversity based on different management stages



- Lack a realistic idea for need/interest to manage and protect the groundwater resources
- Policies - usually focus on Water Supply and Sanitation only *(Response to short-term needs)*
- Lack of significant attention to the broader water resource context

- Trigger groundwater resource management (still single-issue) oriented
- Policies – focus towards resource control and protection *(reactive mode "crisis management")*
- Their scope becomes wider (in terms of water resource context).

- Groundwater policies - more comprehensive and adopt integrated approaches to exploitation
- Policies – focus on control, protection and link to other policy domains *(Proactive mode)*
- Systematic development and execution of periodically updated resource management plans

Optimal groundwater management with clear policies and plans is only possible through the quality of the information and knowledge about the setting, which is the fourth major component of the groundwater governance. A basic information (character, quantity, quality, recharge, development, uses, etc.) on the local systems and its setting (socio-economic, ecological, political, etc.) included with the understanding of the processes of change is crucial as the knowledge established on reliable and sufficient data and information is thus vital to guide groundwater exploitation, management, and protection (FAO, 2016). The information for good groundwater governance should comprise both snapshots of static features (groundwater systems: aquifers/aquitards, physical environment, human communities) and monitoring of dynamic changes (levels, quality, withdrawal volume, demography, etc.) (Cruz & Soares, 2018). This information is then transformed into knowledge through the relevant experts which provides direction to the decision-makers and relevant stakeholders for informed decision making. Additionally, the resulting information and knowledge should be disseminated extensively though multiple online (webinars, online-database) and offline (reports, publications, workshops) platforms.

2.14 Assessment of Groundwater Governance

Governance is frequently associated with government or the courses of governing and thus, it refers to both, procedures for implementing the defined regulations and management of the resources by setting defined objectives, principles, and rules. Globally, all the actors (politicians, authorities, management organizations, private sectors) involved in the management of groundwater have understood the necessity for the long-term employment of sustainable groundwater governance and management practices (Colvin & Saayman, 2007). Groundwater governance "*involves collective action to ensure socially sustainable utilization and effective protection of groundwater resources for the benefit of people and groundwater-dependent ecosystems*" (Foster et al., 2010). It refers to forms of guiding the society beyond policy formation and includes multiple non-state actors (industries, scientists, environmental interests, and other parties interested in groundwater) with an accountable decision-making structures and transparent processes at different levels of the society (Foster & Garduño, 2013). Foster et al., (2010), suggested an enhanced groundwater governance evaluation which entails forming logical typology (Table 2.2) of groundwater bodies based on the resource and supply issues and processes involved during exploitation. Furthermore, a pragmatic arrangement (Figure 2.9) of groundwater bodies is used in considering the utmost typology for groundwater governance status and needs.

Table 2.2

Typology of groundwater bodies with situations and processes involved

Overall Typology of Groundwater Body	Sub-Divisions by Type of Situation or Process Involved #
(1) At Risk of Extensive Quasi-Irreversible Aquifer Degradation and Subject to Potential Conflict Amongst Users ###	(A) Under Intensive Exploitation (provoking land subsidence, saline or polluted water intrusion) ## (B) Vulnerable to Widespread Pollution from Land Surface (depends on aquifer vulnerability and pollutant pressure) ## (C) Undergoing Depletion of Non-Renewable Storage Reserves (normally in aquifers with low contemporary recharge)
(2) Subject to Potential Conflict Amongst Users ### but not at Risk of Quasi-Irreversible Aquifer Degradation	(A) With Growing Large-Scale Abstraction (especially in aquifers with high T/S ratio) (B) Vulnerable to Local Point-Source Pollution (depends on aquifer vulnerability and pollutant pressure) ## (C) With Shared International/Interstate Resources (latter in federal nations with decentralized water management)
(3) Insufficient (or Inadequate Use of) Scientific Knowledge to Guide Development Policy & Process	(A) But Potential to Improve Rural Welfare & Livelihoods (not fulfilling potential role in achieving MDGs) (B) With Presence of Natural Quality Problems (especially with health impacts at low concentrations/eg: As, F) ## (C) But Scope for Large-Scale Planned Conjunctive Use (either for urban water-supply or irrigated agriculture) ##

\# although covered by this typology it may be preferable in practice to treat urban groundwater situations as a separate cross-cutting category

\## in all these cases the intrinsic susceptibility or vulnerability to the given type of problem varies widely with aquifer type

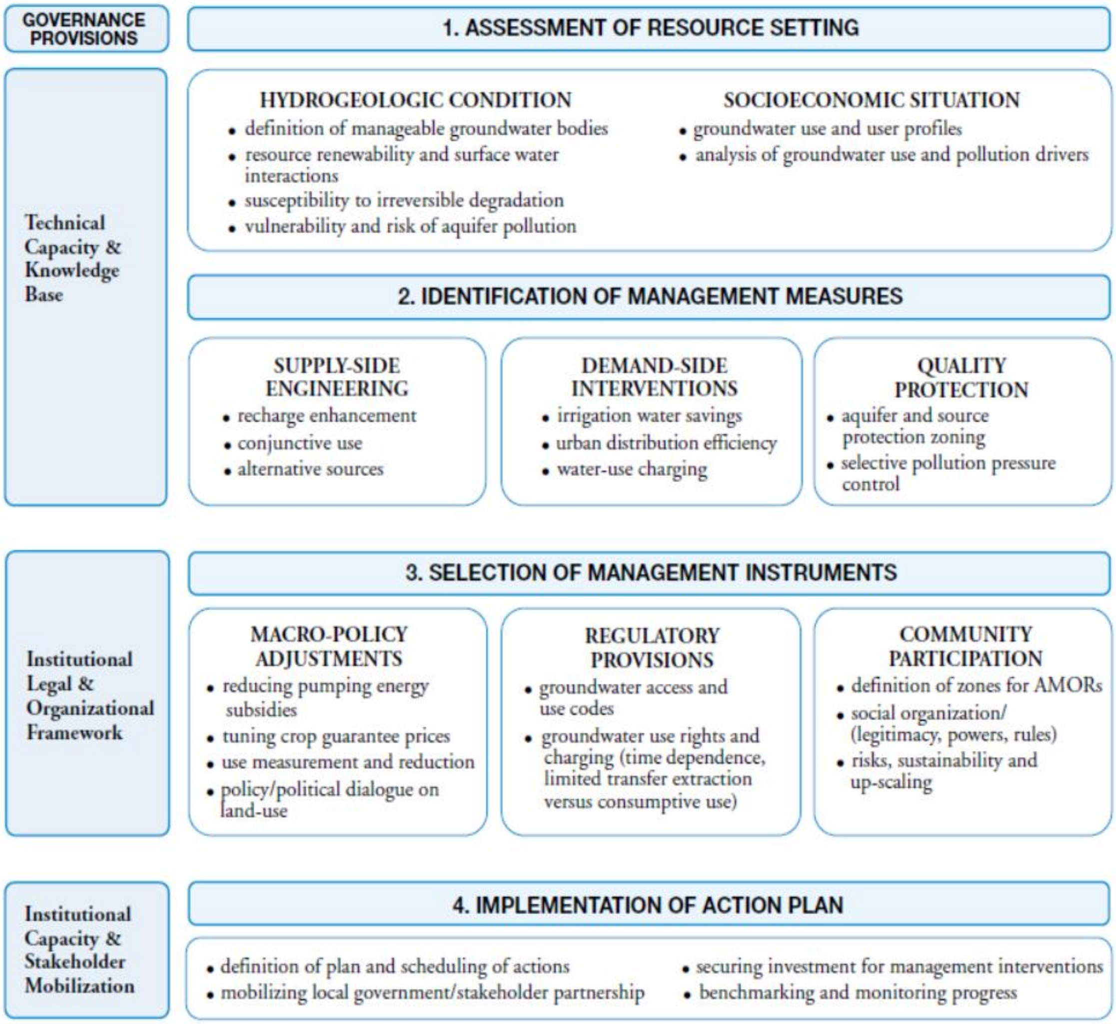
\### users should be taken to include important groundwater-dependent ecosystems

Source: Foster et al., 2010

Action plans for the management of groundwater resources with the investment and intervention on both supply and demand side, a transparent and accountable institutional structure ought to be for the areas or system at risk of irretrievable. The pragmatic framework (Figure 2.9) outlines the explanation and execution of such groundwater management action plan corresponding to the types of governance provisions.

Figure 2.9

Pragmatic framework for elaboration of management action plan with corresponding provision of governance



Source: *Foster et al., 2010*

Foster et al., (2010), developed a list of benchmarking criteria (Table 2.3) for evaluating the effectiveness of existing governance provisions and capacity for executing the provision. Studies have applied the benchmarks and the rating for assessing and stocktaking the state of groundwater governance in the defined settings (Cruz & Soares, 2018; Pietersen et al., 2011). Also, FAO, (2016), developed and suggested a set of groundwater governance qualitative indicators for global groundwater governance assessment based on '*strong to weak scale*' as the influencing capacity and status.

Table 2.3

Checklist of 'top-20' benchmarking criteria for the evaluation of groundwater governance provision and capacity

Type of Provision/Capacity	No.	Criterion	Rank
Technical	1	Existence of basic hydrogeological maps	
	2	Groundwater body/aquifer delineation	
	3	Groundwater-piezometric monitoring network	
	4	Groundwater-pollution hazard assessment	
	5	Availability of aquifer numerical management models	
	6	Groundwater-quality monitoring network	
Legal and Institutional	7	Water well drilling permits and groundwater use rights	
	8	Instrument to reduce groundwater abstraction	
	9	Instrument to prevent water well construction	
	10	Sanction for illegal water well construction	
	11	Groundwater abstraction and use charging	
	12	Land-use control on potentially polluting activities	
	13	Levies on generation/discharge of potential pollutants	
	14	Government agency as ground-water-resource guardian	
	15	Community aquifer management organizations	
Cross-Sector Policy Coordination	16	Coordination with agriculture development	
	17	Groundwater-based urban/industrial planning	
	18	Compensation for groundwater protection	
Operational	19	Public participation in groundwater management	
	20	Existence of groundwater-management action plan	

In each instance, the criteria should be individually ranked concerning considerations of 'existing provisions' and 'institutional capacity to implement. Rank: (0: non-existent; 1: incipient; 2: acceptable; 3: optimum)

Source: *Foster et al., 2010*

CHAPTER 3
STUDY AREA AND DATA COLLECTION

This chapter demonstrates the study area, the data necessary for the study, and their sources.

3.1 Study Area

The study selects Khon Kaen, Thailand as one of the rapidly urbanizing areas in the Lower Mekong Basin (LMB). The major concentration of the study is on the Khon Kaen center for improved groundwater governance under multiple stresses, but these recommendations for improving groundwater governance of the city shall be done based on a holistic approach by applying the hydrological and groundwater impact assessment.

Khon Kaen province (Figure 3.1) lies in central northeastern, Thailand which is administratively divided into 26 districts. The total area of the province is 10,886 km^2 with the population density of around 166 persons per square kilometers. Geographically, the province occupies part of the Khorat Plateau, and the hydrological boundary of the area is covered by the Chi and Mun rivers flow through it (Figure 3.2). The Mueang Khon Kaen district is the capital of Khon Kaen Province with an area of 953.4 km^2 and the population density of around 437 persons per square kilometers (Figure 3.1). The district accompanies the Khon Kaen Metropolitan Municipality (Figure 3.3) which is the largest city of the province located in north-eastern and one of the fastest-growing secondary cities in Thailand. Although, not the most populous secondary city in the region, Khon Kaen is the regional hub of financial, educational, and administrative activities (Marks, 2019). It is designated as an ‘urban growth pole’ for the northeastern region of Thailand, pouring funds into upgrading the city’s infrastructures which has resulted increase in economic transactions and accelerated urban growth, but with significant social and environmental consequences (Elinoff, 2013). Slum formation, traffic congestion, perennial droughts and biological degradation are now common challenges faced by Khon Kaen. In recent years, global climate change has had observable effects on Khon Kaen (Marks, 2019) resulting dry seasons are becoming much longer and droughts more intense, while heavy rainfall occurs more frequently and causes increasingly destructive flooding.

Figure 3.1

Location map of Khon Kaen province with the administrative boundaries and capital city

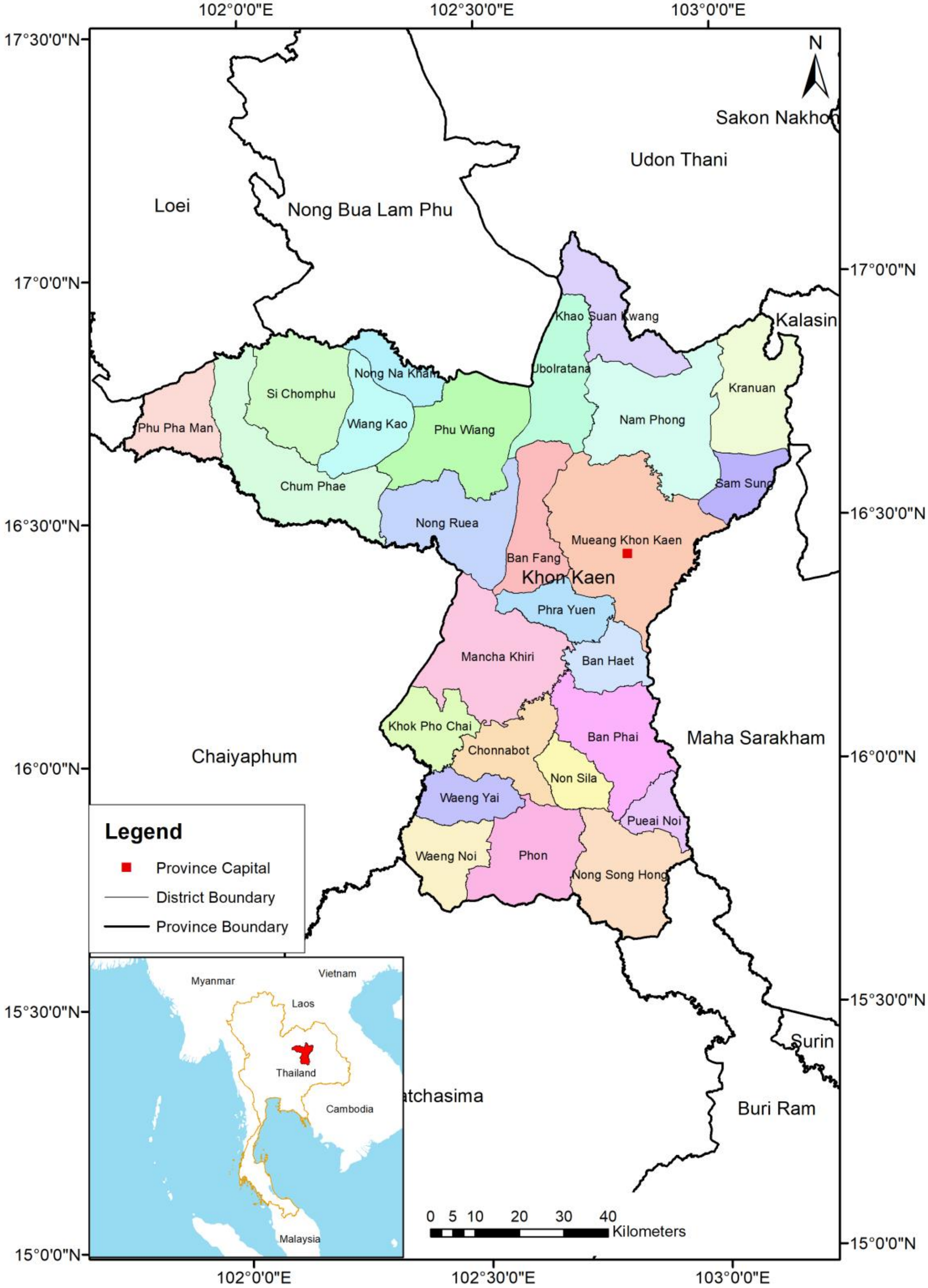


Figure 3.2

Hydrological boundaries of the study area with river network

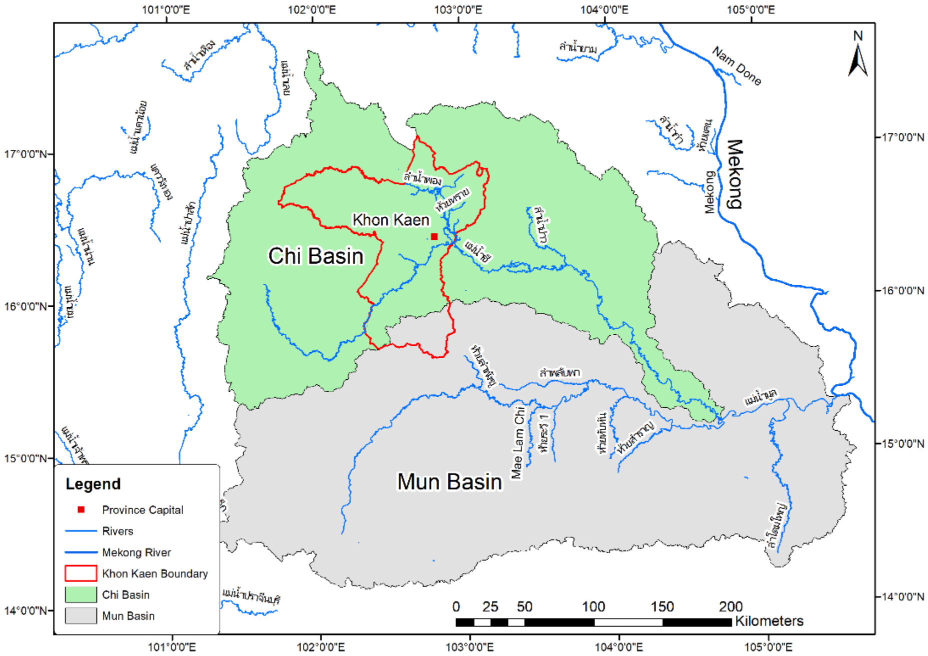
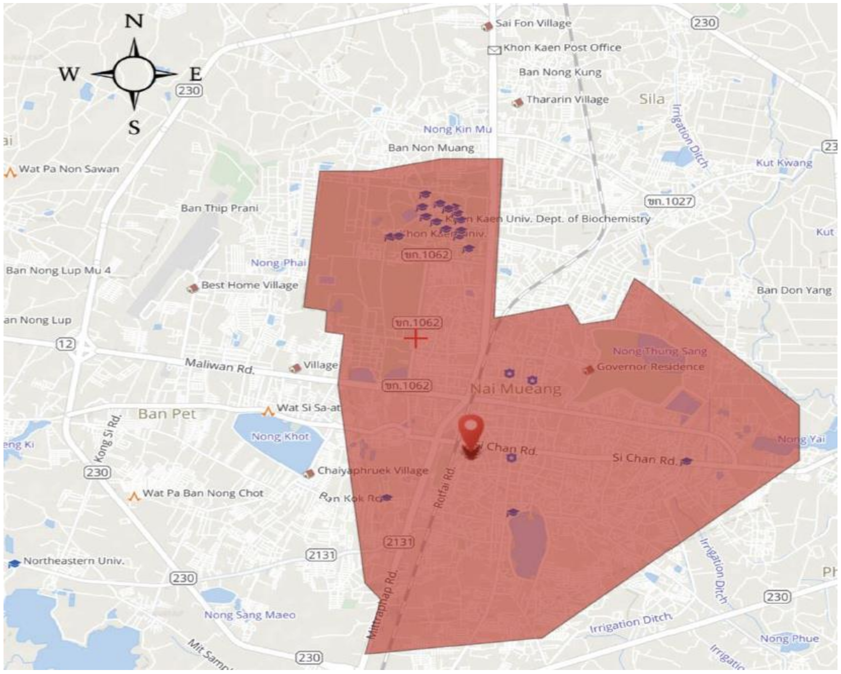


Figure 3.3

Map of Khon Kaen Metropolitan Authority (capital city)



Source: Sudhipongpracha & Dahiya, 2019

Geographically the Khon Kaen Metropolitan Municipality, is situated approximately 450 km northeast of Bangkok and covers an area of 46 km^2 with the population density of around 2488 persons per square kilometers. Furthermore, the higher population density has resulted in increase in urban built up area. Studies shows that urban and built-up areas extraordinarily increased from 58.03 km^2 in 2006 to 131.39 km^2 in 2016 but paddy field and field crop notably decreased from 763.60 km^2 in 2006 to 599.37 km^2 in 2016 (Ongsomwang et al., 2019). The rapid urbanization and increased population density have resulted urban residents and slum dwellers deprived of access to tap water and consequently, must use groundwater for their daily needs. Table 3.1 shows the summary of the characteristics of different administrative levels at Khon Kaen, Thailand.

Table 3.1

Summary characteristics of different administrative level at Khon Kaen, Thailand

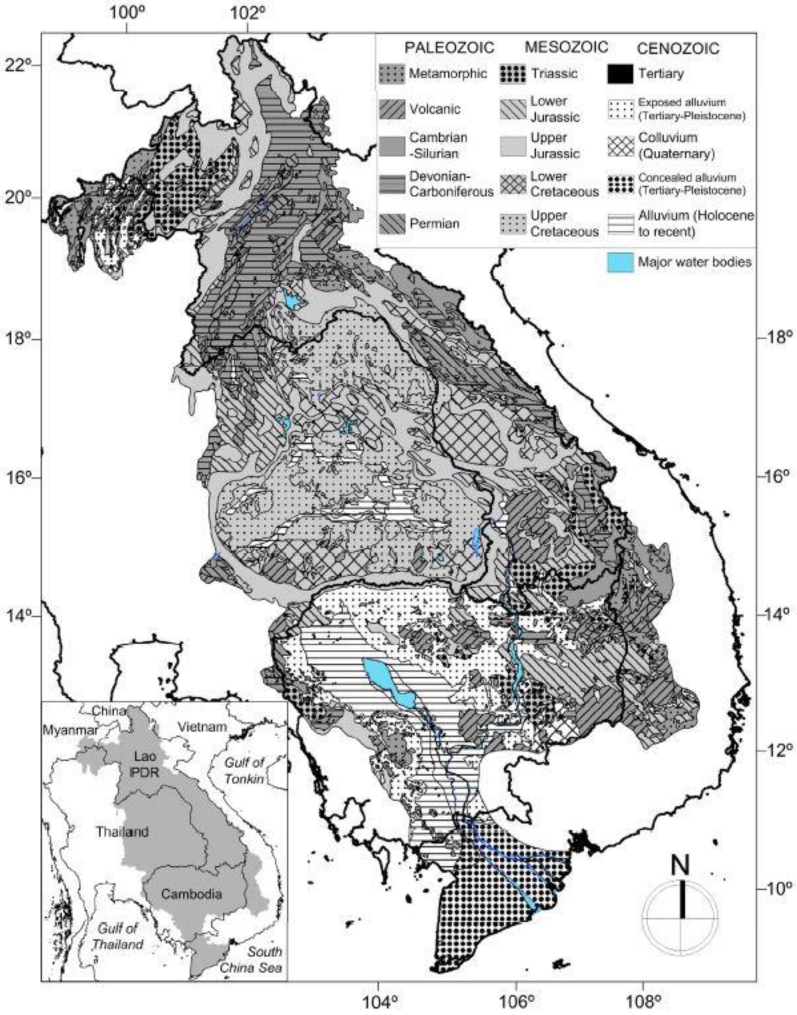
Variables	**Khon Kaen Province**	**Muang Khon Kaen District**	**Khon Kaen Municipality**
Coordinates	16°26'41" N to 102°50'1" E	16°26'18" N to 102°50'20" E	16°26" N to 102°50' E
Area (km^2)	10,886	953.4	46
Population	1.8 Million (2018)	0.40 Million (2017)	0.12 M (2018)
Population Density (person/km^2)	166	437	2600
Average Rainfall (mm/yr)	1246	1246	1246
Average High Temperature (°C)	32.8	32.8	32.8
Average low Temperature (°C)	22.3	22.3	22.3
Average Elevation (m) (above mean sea level)	100-200	100-200	187

3.2 Hydrogeological Units

Four main hydrogeological units (Figure 3.4) can be delineated in the Lower Mekong Basin (LMB). The first is along the eastern and southeastern border of the LMB, volcanic and granitic rocks with water-bearing features (joints, faults, and weathering zones) are overlapped by cemented early Paleozoic metasedimentary rocks with reduced porosity and permeability. The second in the Northern LMB, the porous and permeable late Paleozoic sedimentary rocks, dissected into relatively small blocks by subsequent orogeny, and topped by Mesozoic deposits, supports local groundwater flow systems locally discharging into tributaries of the Mekong River. The third, particularly in the Northeast Thailand consisits deep confined and shallow unconfined aquifers from the Mesozoic are comprised of sandstones. And, the fourth in the Mekong delta Cenozoic alluvial and deltaic sediments of up to 800 m thick form both unconfined and confined aquifers (Lacombe et al., 2017).

Figure 3.4

Geology of the Lower Mekong Basin

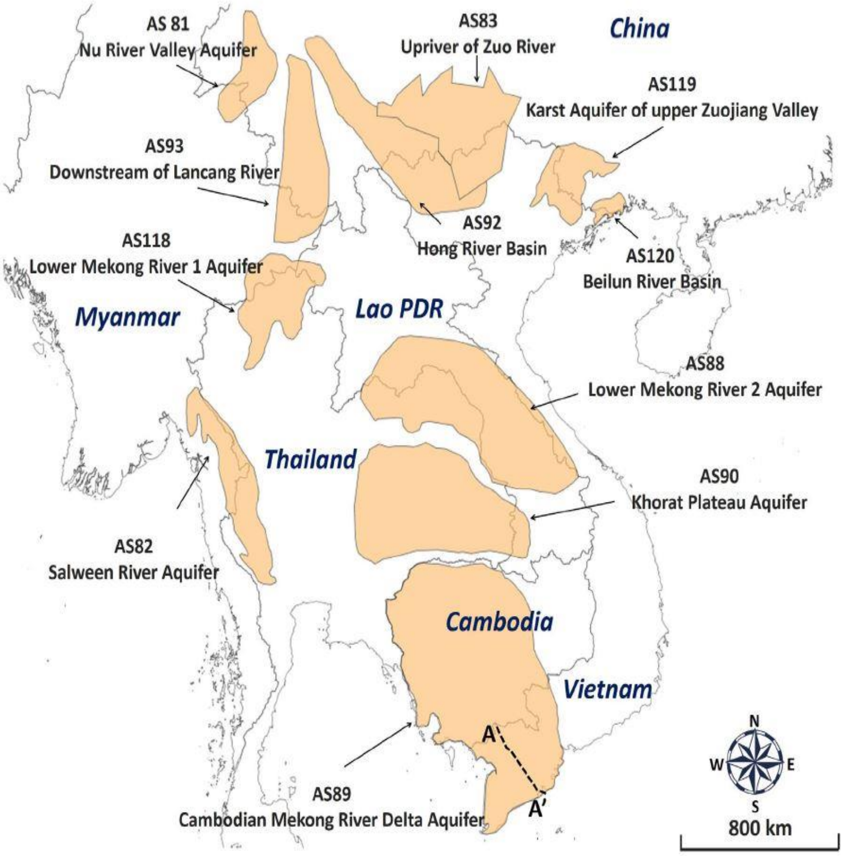


Source: *Lacombe et al., 2017*

In the Lower Mekong Basin, total ground water reserves are thought to be about 100 to 300 km. The study area includes the Khorat Plateau aquifer (Figure 3.5) which is a transboundary aquifer between Thailand and Lao PDR. The area of the aquifer is about 109,000 km^2 and 83.5% is covered in the Thailand. Williamson et al., (1989), observed brackish/saline groundwater due to the existence of salt rock underneath. The strata of the Khorat Plateau aquifer area is mainly composed of limestone, siltstone, shale, sandstone, and Holocene loose sediments. Groundwater in this aquifer is mainly used for the agricultural sector associated with rice paddy or sugarcane cultivation (Lee et al., 2018). Decreasing groundwater levels and deterioration of groundwater quality (salinity), particularly from Thailand, are major concerns threatening a sustainable water supply for irrigation and domestic water demand.

Figure 3.5

Transboundary aquifers in Greater Mekong Subregion and adjacent region



Source: Lee et al., 2018

3.3 Data and Sources

Table 3.2

Data used in the study

Data type	Frequency/Time	Unit/ Format	Resolution	Source
Data used for climate change projection				
Observed Rainfall	Daily/1981-2014	mm	-	Thai Meteorological Department (TMD) {via Hydro-Informatics Institute (HII), Thailand}
Observed maximum and minimum temperature	Daily/1981-2014	°C	-	Thai Meteorological Department (TMD) {via Hydro-Informatics Institute (HII), Thailand}
GCMs data	Daily/1981-2100	mm	-	Earth System Grid Federation (ESGF) data center {via Hydro-Informatics Institute (HII), Thailand}
Data used for land use change projection				
Baseline land use map	2008-2020	Raster	300m* 300m	European Space Agency (ESA CCI)
Restricted area	-	Vector		Open Development Mekong)
Digital Elevation Model (DEM)	-	Raster	90m* 90m	United States Geological Survey (USGS) website(https://earthexplorer.usgs.gov)
Soil Map	-	Vector	-	Food and Agriculture Organization (FAO) website (http://www.fao.org/geonetwork)

Slope	-	Raster	90m* 90m	-
Aspect ratio	-	Raster	90m* 90m	-
River & Road Network	2010, 2015 &2018	Line		Diva GIS (Open Source)
Population density	2010, 2015 &2018	Raster	1km*1km	https://www.cgd.ucar.edu/
Data used for hydrological modelling				
Observed Discharge	Daily/1990-2003 & 2010-2017	m^3/sec	-	Royal Irrigation Department (RID)
Data used for sectoral groundwater abstraction and groundwater level				
Observation/Monitoring well data (Groundwater level)	Yearly/2004-2019	m	-	Department of Groundwater Resources (DGR)
Number of Industries	Yearly/2015-2019	Nos.	-	Department of Industrial Works (DIW)
Industrial water use standard	-	-	-	National Statistical Office of Thailand (http://web.nso.go.th/)
Spatial Population (with scenarios)	Decadal/2000-2100	km	1km*1km	National Center for Atmospheric Research (https://www.cgd.ucar.edu)
Watershed Development Master Plan (Khon Kaen)	2018-2037	-	-	Office of Project Management, Royal Irrigation Department

CHAPTER 4

METHODOLOGY

This chapter expands the approaches employed to attain the study objectives. The chapter consists of the overall methodology followed by the individual methodology of the four specific objectives.

4.1 Overall Methodology

The study's overall objective is to recommend improved groundwater governance in rapidly urbanizing areas (Khon Kaen, Thailand) under multiple stresses. The overall conceptual framework for the study is given in Figure 4.1. First, a groundwater governance framework is developed and applied to the study area to diagnose the current state of groundwater governance and analyze the strength and gaps in different governance components. Then multiple future stresses are projected using different techniques. For climate change, GCM models have been used under 2 SSPs and are analyzed in terms of three timeframes: Near Future (NF), Mid Future (MF) and Far Future (FF). The land use change model Dyna-CLUE is used to project the future land use change of the study area under SSP2-4.5 and SSP5-8.5.

Furthermore, the study used global population datasets projected under the shared socioeconomic pathways for future projection after the baseline validation. The sectoral water demand analysis is done based on the master plan developed for the Khon Kaen Province. Once the multiple stresses are projected, the impact of these multiple stresses is assessed on groundwater availability using SWAT as the hydrological model for groundwater recharge and multiple linear regression for groundwater level. Finally, based on the impact and current state of governance, several recommendations with case studies have been provided for improved groundwater governance. The detailed working methodology for objectives 1-4 are given in Figures 4.2, 4.3, 4.4, and 4.5, respectively.

Figure 4.1

Overall conceptual framework of the study

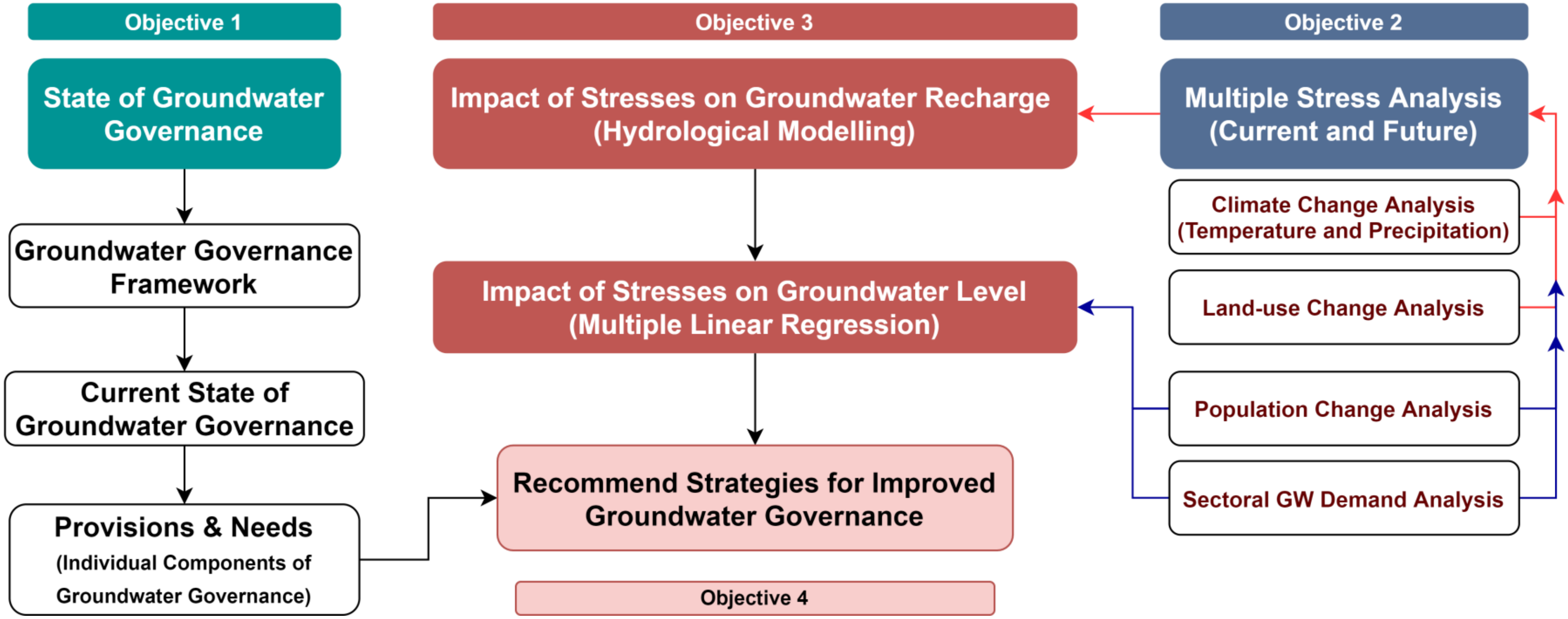


Figure 4.2

Methodological framework to assess the current state of groundwater governance in the rapidly urbanizing area (objective 1)

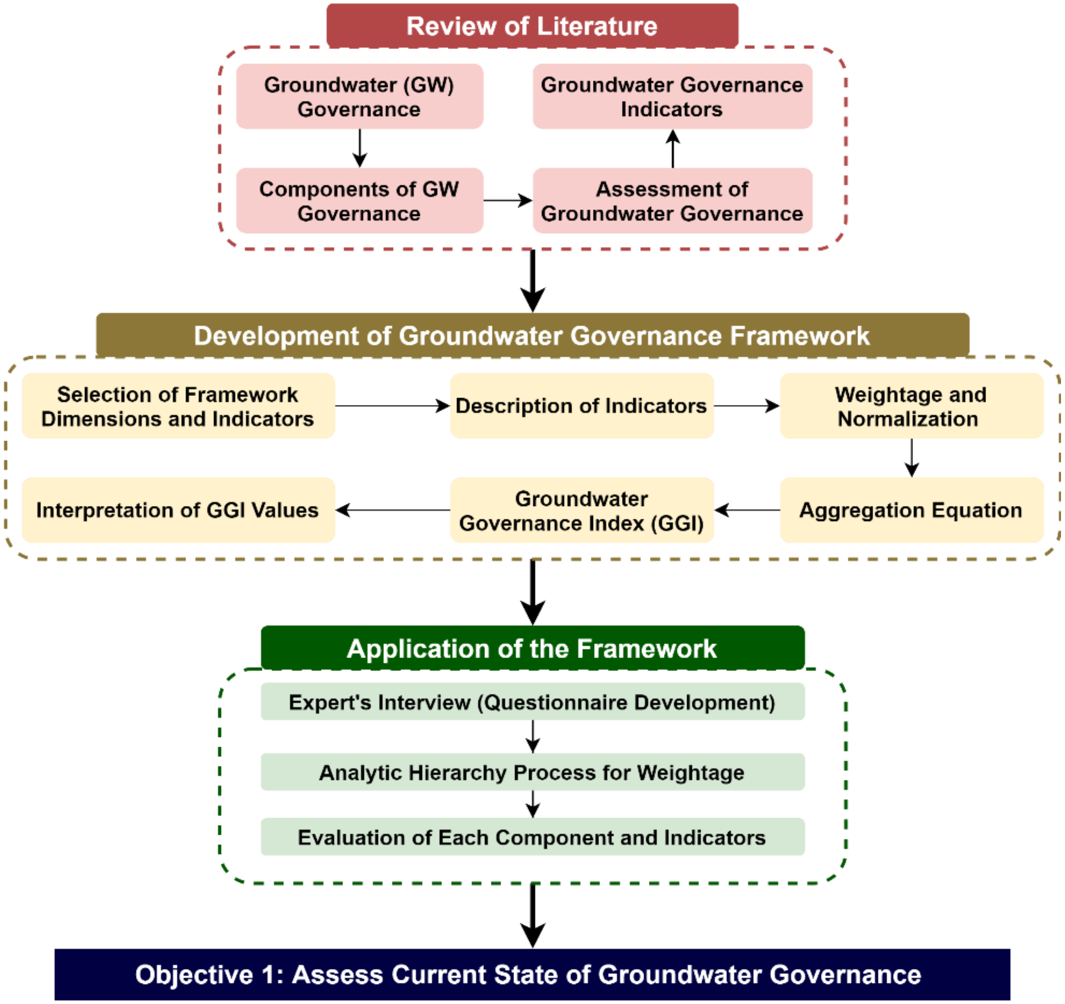


Figure 4.3

Methodological framework to predict future change in multiples stresses (climate, land-use, population, sectoral demand) under various scenarios (objective 2)

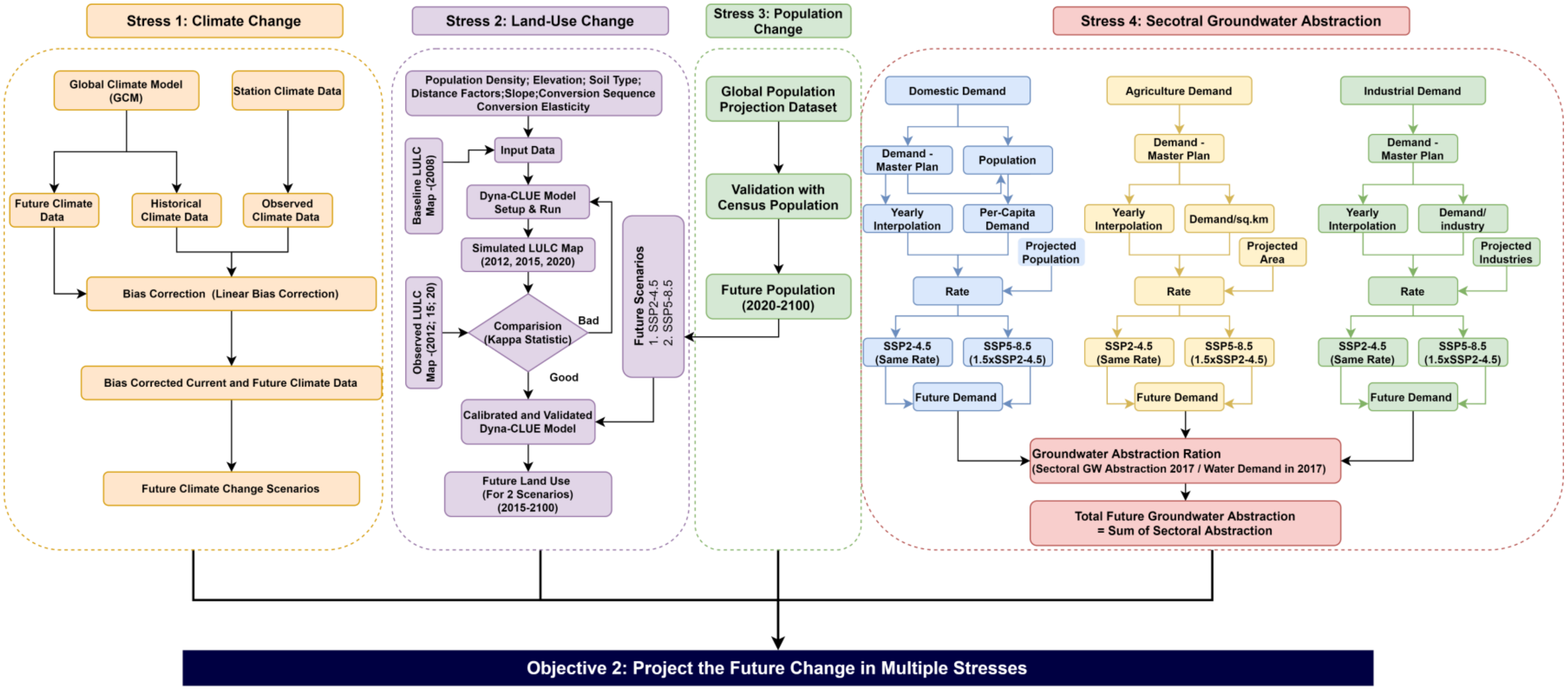


Figure (4.3) continued (Scenario selection)

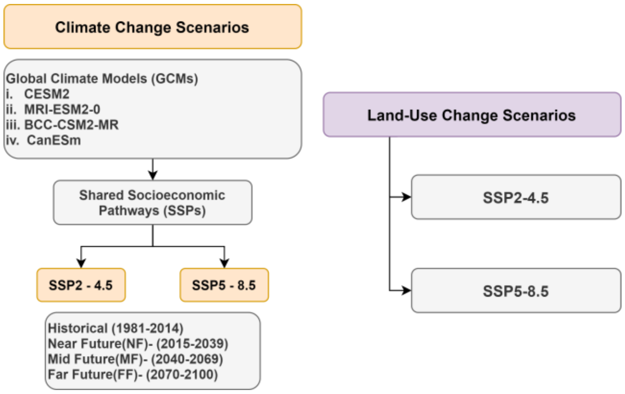


Figure 4.4

Methodological framework to analyze the impact of climate and land-use change in surface and groundwater availability (objective 3)

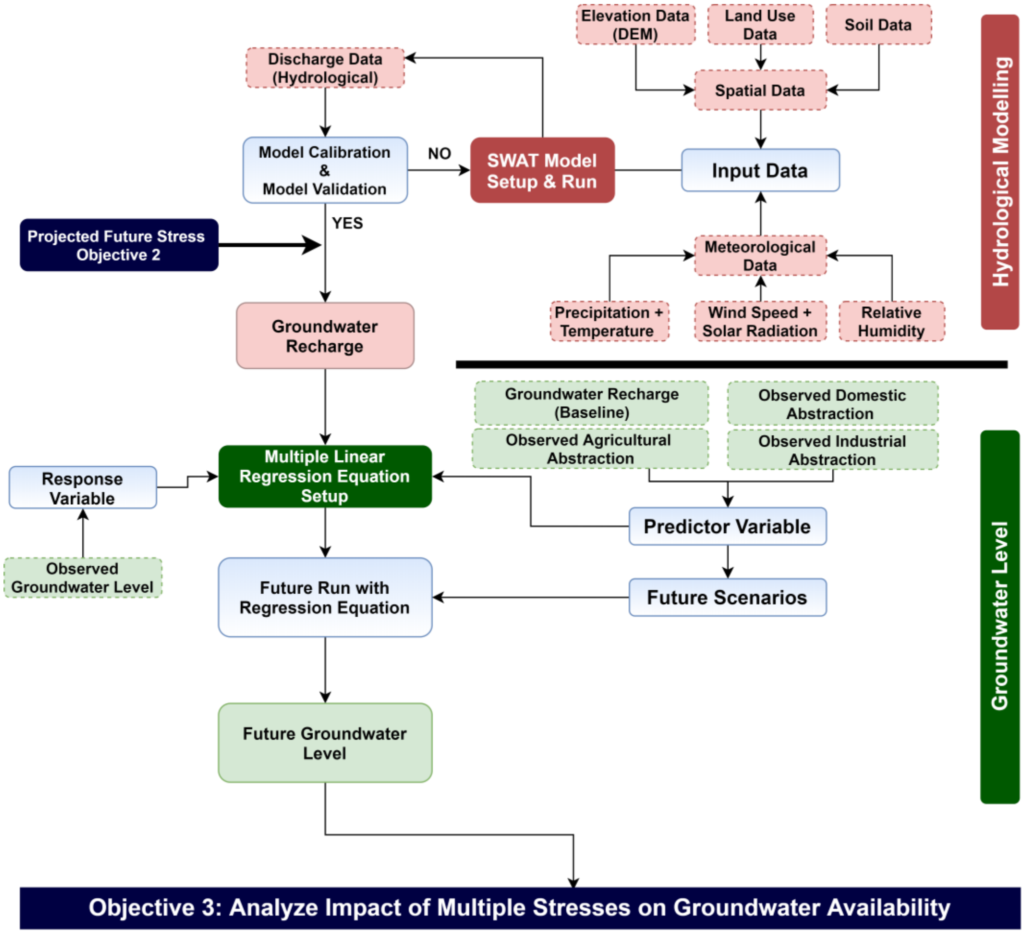
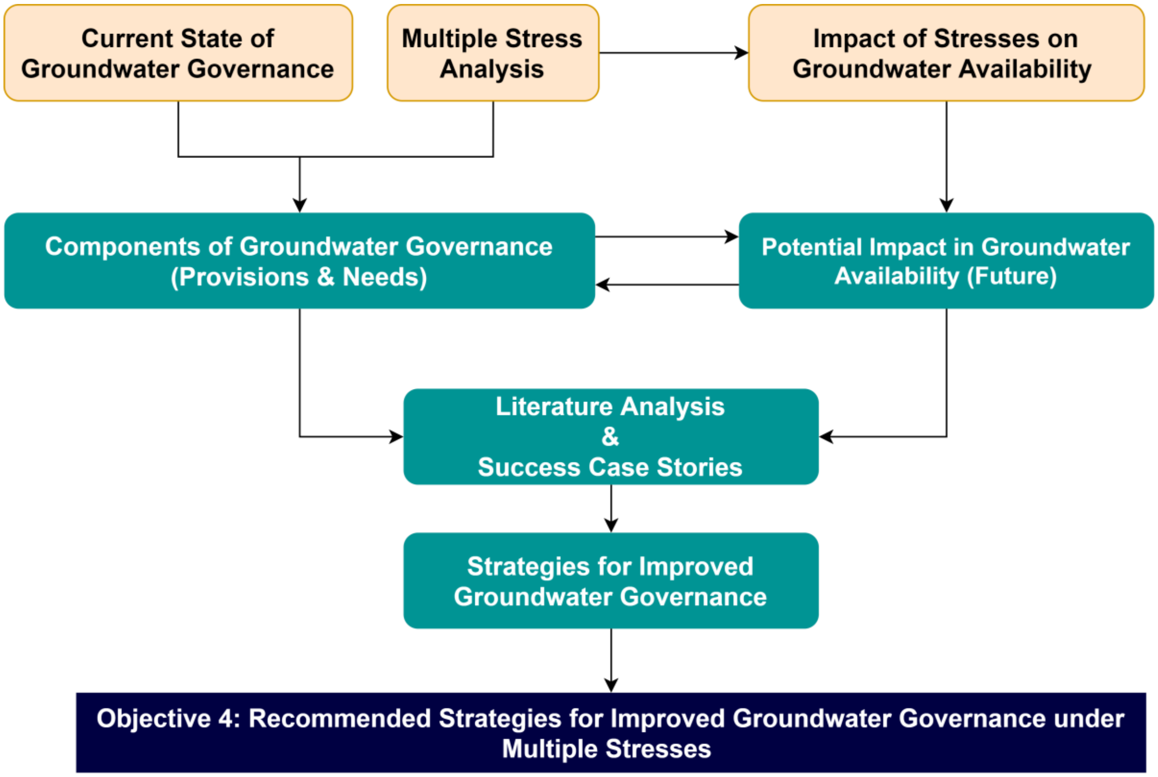


Figure 4.5

Methodological framework to provide recommendations for improved groundwater governance under stresses (objective 4)



4.2 Assessing Current State of Groundwater Governance

The current state of groundwater governance is assessed by developing and indicator-based governance framework, which addresses all four components of groundwater governance.

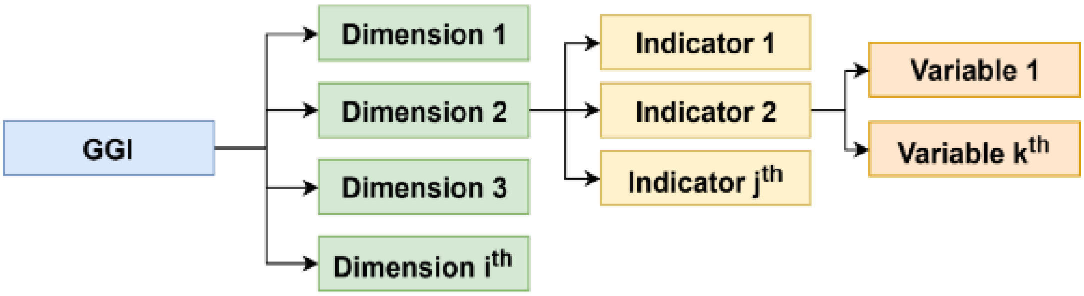
4.2.1 Development of Groundwater Governance Framework

The study develops an inclusive framework for evaluating and quantifying groundwater governance in rapidly urbanizing area using an indicator-based approach. The framework is developed based upon the components of groundwater governance, good governance principles and inclusiveness (gender and right based). The selection of the dimensions, variables, rating criteria and 20 indicators has been done based on the GW-MATE (World Bank) project's groundwater governance benchmarking criteria as developed by Foster et al., 2010 and the 10 gender inclusive indicators (Miletto et al., 2019) has been selected based on the WWAP, 2019. The dimensions and indicators are selected in such a way that they can reflect most of the general situation of groundwater components in any urbanizing area. The mathematical equation for aggregating these framework elements provides a holistic index value known as Groundwater Governance Index (GGI) which provides an general overview of the current state of groundwater governance and a detail diagnosis of strength, gaps and areas of improvements for sound governance and management to the decision makers, managers and related actors.

The structure of the groundwater framework is shown in (Figure 4.6) below, where, GGI is the Groundwater Governance Index, i is the number of Dimensions (D), j is the number of Indicators (I) within in each dimensions and k is the number of Variables (V) within each indicators.

Figure 4.6

Structure of the groundwater governance framework

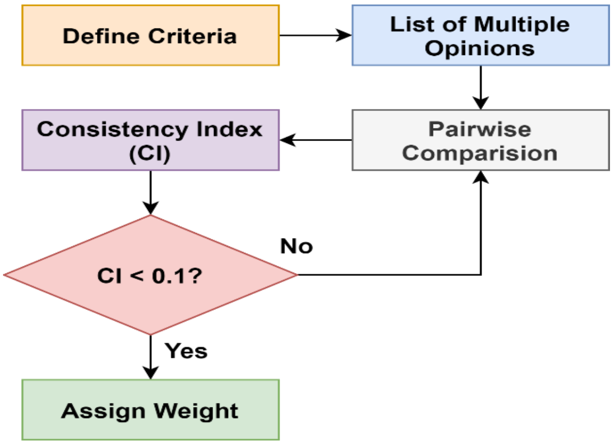


4.2.2 Normalization and Weightage Calculation

The indicators chosen are qualitative, however the rating of each variable within an indicator is quantitative based on a dimensionless rating. Furthermore, after aggregation of all the elements, the final index value range are assigned. So, normalization of the values is not required. Ranking of different elements is a delicate task of the addressing various concerns that may not be related (Blanc et al., 2008) and this may also mislead due to lack of attentions. An informed decision making requires access to information in undertaking decision by combining multiple alternatives. Weights can be allocated according to prioritized issues or statistically determined loads (De Carvalho et al., 2009). The analytic hierarchy process (AHP) is a multi-criteria decision-making process that optimizes the decision according to the prioritized factors. The AHP method introduced by Satty, 1980, establish multi-hierarchy level in solving wide range of unstructured problems. Studies applied AHP method in deriving weights for different dimensions and indicators within an assessment framework (Alawneh et al., 2019; Kamaruzzaman et al., 2018). This study uses of AHP in prioritizing the dimensions of the framework through an expert's opinion. A questionnaire is prepared and sent to experts for their opinion in different dimensions to do a pairwise comparison. Figure 4.7 shows a conceptual framework in applying AHP.

Figure 4.7

Conceptual AHP framework using expert's opinion



The AHP follows a pairwise comparison between different alternative dimensions or elements to determine their relative importance (Alawneh et al., 2019). Once the matrix is constructed for the pairwise comparison the dimensions of the framework is compared using Saaty's scale of intensity (Table 4.1).

Table 4.1

Fundamental scale in AHP method to define the intensity of importance

Rating (Intensity of Importance)	**Meaning**
1	Equal
3	Moderate Strong
5	Strong
7	Very Strong
9	Extreme
2,4,6,8	Intermediate Values

Source: Saaty, 1980

Note: The intensity of importance of each element can only be compared for a pair diagonally (example if X_{12} is equal to 5 than, X_{21} will automatically be equal to 1/5).

Once the pairwise comparison through the developed matrix and the fundamental scale is completed the local priorities is acquired and the outcome's consistency shall be determined to overcome any inconsistencies in the rating by calculating the consistency ratios (CRs) and Consistency Index of each expert using the equation below (Alawneh et al., 2019). If CR < 0.10, then the AHP judgment matrix is consistent which was then aggregated by determining their geometric mean (Alawneh et al., 2019).

$$Consistency\ Ratio\ (CR) = \frac{CI}{RI} \qquad \text{Eq.4.1}$$

$$Consistency\ Index\ (CI) = \frac{\lambda_{max} - n}{n - 1} \qquad \text{Eq.4.2}$$

where, λ_{max} is the the largest eigenvalue of matrix, n=number of elements compared in the questionnaire and RI is the random consistency index which depends on the size of the matrix used (Table 4.2)

Table 4.2

Random consistency index (RI) values used in AHP

Size of Matrix	RI
1x1	0.00
2x2	0.00
3x3	0.58
4x4	0.90
5x5	1.12
6x6	1.24
7x7	1.32
8x8	1.41
9x9	1.45
10x10	1.49

Source: Saaty, 1980

4.3 Projecting Future Stresses on Groundwater

Groundwater is vulnerable to unrestricted exploration and exploitation by humans without considering the wider community's interests (Foster & Garduño, 2013; Megdal et al., 2015). It is a crucial component for the supply of domestic, agricultural, and industrial sectors and ecosystem services as half of the global population uses groundwater as drinking water supply, and in the context of agriculture, about 43% of all water used for irrigation is groundwater (Connor, 2015). Furthermore, it is also a challenging component for effective and efficient management in the context of increased stress and demand. Several studies have enlisted climate change, urbanization (increased population density, higher living standards, increased water-energy-food demand, change in land use and land cover), development of industrial and commercial zones, tourism development as major stressors for groundwater resources, especially in the urbanizing areas (Hutchins et al., 2018; J. M. Lee et al., 2019; Olivares et al., 2019; L. Qiu et al., 2018; Shrestha et al., 2016). This study selects and projects four future stresses (climate change, population change, land use change, and groundwater demand/abstraction change) that are likely to impact the sustainability of groundwater availability in rapidly urbanizing cities.

4.3.1 Climate Change Projection

The long term change in climate or even its short term variability has a great influence in the groundwater environment majorly in terms of its recharge and use which is furthermore modified by the human activities and level of infrastructural and socio-economic development (Taylor et al., 2013). Several studies revealed that the climate change has resulted alteration in rainfall patterns and increase in the temperature posing high risk to groundwater resource (Eslamian & Eslamian, 2017; Meixner et al., 2016; Salem et al., 2018). The study to assess the impact of climate change on groundwater resources done by Shrestha, et al., (2016), in the Mekong Delta aquifer, revealed a decline in groundwater recharge and thus, drop in level and storage resulting due to seasonal change in rainfall and increase in average annual temperature. Projection of future change in climatic parameters are usually done by using climate models. Recently, the finer resolution RCMs generated by dynamic downscaling have replaced the coarser resolution GCMs. But several studies have proved the better performance of GCMs as of RCMs and both models showed significant biases (Gupta et al., 2020; Singh et al., 2019b). Apurv et al., (2015), applied raw Coupled Model Intercomparison Phase (CMIP) 5 GCMs and directly bias corrected rainfall data in Brahmaputra, India.

Five linearly bias-corrected CMIP-6 GCMs, namely CESM2, MRI-ESM2, BCC-CSM2-MR, GFDL-ESM4 and CanESM5, made available from Hydro Informatics Institute (HII), Thailand under two under two Shared Socioeconomic Pathways (SSP2-4.5 and SSP5-8.5) has been used for analyzing future climatic conditions (Table 4.3). Studies investigating the consequences of climate change using the CMIP6 model are limited in the study area and the region. The climate models selected in this study are based on the data available at the finer resolution, socioeconomic scenarios, and literature-based analysis. Studies have applied these selected CMIP-6 GCMs in Southeast Asia and northeast Thailand for climate change projection assessments (Abatan et al., 2022; Sittichok & Thepprasit, 2022; Supratid et al., 2021). The two SSPs selected are SSP2-4.5 and SSP5-8.5 for assumptions of following the historical trend (medium case) and the optimistic trend of human development trend (extreme case) respectively. Initially, the statistical performance of five linearly bias-corrected data for the historical period (1981-2014) has been evaluated using the statistical performance parameters and the three best performing models for precipitation and temperature has been selected for further analysis.

Table 4.3

List of CMIP-6 GCMs with historical (1981-2014) and future (up to 2100) datasets for precipitation, maximum and minimum temperature) under SSP2-4.5 and SSP5-8.5

S.N.	GCM	Institution	Spatial Resolution
1	CESM2	National Center for Atmospheric Research	0.05°
2	MRI-ESM2-0	Meteorological Research Institute	0.05°
3	BCC-CSM2-MR	Beijing Climate Center	0.05°
4	GFDL-ESM4	Geophysical Fluid Dynamics Laboratory	0.05°
5	CanESM	Canadian Climate Centre	0.05°

4.3.2 Population Change Projection

Urbanization is referred as the rural population to an urban area transforming the built environment (Malik et al., 2017). It is the processes of the increase share of urban population and is mainly governed by the phenomena of reclassification of rural to an urban area, natural growth, and the migration trend (Buhaug & Urdal, 2013). The United Nations, (2018), projects that the people living in the urban areas is likely to increase to up to 68% by 2050. The level of urbanization and change in the population is one of the frequently used indicators in forecasting different trends such as the energy demand and use, poverty use of resources etc. Furthermore, the demand of water and its rate of abstraction can be directly linked with the change in the urban population and thus it is important to understand the growth trend of the urban population future demand and pattern in water-use, land-use and other public services. At the larger scale (national or regional), the coherent component methods are widely used but for cities population there is no single technique dominating. Ayhan, (2018), categorized population projections techniques as mathematical and cohort component projection models. Furthermore, the study also revealed that using past population data to forecast the future total population, mathematical models are handy and useful. The mathematical models' projects based on the arithmetic or geometric or exponential growth and can be classified as the Linear Model, Geometric Model, Logistic Growth Model, Exponential Model (Ayhan, 2018).

The study used the spatially explicit global population dataset (1-km resolution) developed from the Integrated Assessment Modeling (IAM) group of the National Center for Atmospheric Research's (NCAR) and the City University of New York Institute for Demographic Research, which are consistent with Shared Socioeconomic Pathways (SSPs). The datasets have been initially validated with the census population, and then a detailed analysis of the projected total population and urban population under SSP2-4.5 and SSP5-8.5 has been developed.

4.3.3 Land Use Change Projection

Urbanization includes the rapid growth of the urban population included with an increase in demand for urban infrastructures and services. The spatial and vertical modification of the urban natural land and the environment is an important aspect during the process of the urbanization transforming the natural cover with the more impervious surfaces (Paul et al., 2018). This alteration in the Land Use and Land Cover modifies the hydrology, energy balance, biodiversity, habitats cycle, and human livelihoods (Pielke et al., 2011; Trisurat et al., 2010) and thus, should be understood in advance. The projection of the Land Use and Land Cover are generally done by the application of the relevant models which can be broadly categorized as spatially and non-spatially explicit (statistical) based models. The statistical model uses a mathematical formula to predict the future change in the land-use change and Markov Model and System Dynamics models are some examples (Akbar et al., 2019; Xu et al., 2016). On the other hand, the spatially explicit models such Cellular Automata (CA) model the Agent-Based model (ABM), Dynamics of Land System model (DLS), and Dyna-CLUE model are used to forecast and analyze the spatial distribution of future land use (Adhikari et al., 2020; Samie et al., 2017; Tian et al., 2016; Trisurat et al., 2019).

This study uses the Dyna-CLUE model for projecting the future land use change in the study area due to its wide application in detecting change in similar locations (Adhikari et al., 2020; Shrestha et al., 2018). This model is the modified version of the CLUE-s model can stipulate under multiple scenarios for land-use change via the model parameters and also takes into account the driving forces for the change, management policies to generate more precise predictions (Verburg et al., 2008; Y. Wang et al., 2018). In addition to this, the model is easily and freely available in public domain to operate it under user preferences. The model consists of the non-spatial demand and the spatial allocation module. The demand module uses past trend or scenarios to verify the future demand and then and then converts the demand for application by the spatial allocation module (Shrestha et al., 2018). The Dyna-CLUE model considers land use demands, location suitability, neighborhood suitability, spatial restrictions, and conversion parameters as the model inputs. The model uses rainfall, elevation, temperature, slope, geology, soil depth, distance from the road, rail, river, built-up area, crop land, and forest. This study shall use the two observed land-use map of past period in which one of previous period shall be used for development of the model and the next shall be used to compare with the simulated map using the Dyna-CLUE. The verification error shall be computed using Kappa (Eq. 4.3) statistical analysis (Shrestha et al., 2018) given as

$$K = \frac{\Pr(a) - \Pr(e)}{1 - P(e)} \qquad \text{Eq.4.3}$$

where, Pr(a) and Pr(e) are the observed relative agreement (in all raster) and hypothetical probability of chance of agreement, respectively. And K is referred as Kappa which value ranges from 0 to1 (closer to 1 means there is better agreement between simulated and observed maps).

The location suitability and neighborhood suitability for each land use type is calculated by the stepwise logistic regression technique (Eq. 4.4) given as:

$$\log\left(\frac{P_i}{1 - P_i}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \beta_n X_{n,i} \qquad \text{Eq.4.4}$$

where, P_i is the probability of a grid cell for the occurrences of the considered land use features, X_s are the driving factors and β (coefficient) for each factor in the logistic model.

This study uses two SSP scenarios to address the multiple uncertainties related to land use change projection. The first is SSP2-4.5 which assumes that the trend for change in urban land use remains the same until 2050 and then decreases to half. The change in forest area and grassland is assumed to be minimal while the water is constant. The change in the urban area is majorly on the cost of change in the agricultural land. The second scenario is the SSP5-8.5 which assumes rapid urbanization with technological and economic development. The urban land use under this scenario is assumed to increase 1.5 times the area under SSP2-4.5, replacing the agricultural land, while other land uses are similar to the previous scenarios.

4.3.4 Projection of Groundwater Abstraction

The projection of water demand in rapidly urbanizing areas is crucial for effective planning, development, and sustainable management of water resources and urban public services. The study uses the summation of sectoral (domestic, industrial and agriculture) water demand as the total water demand of the selected area. Furthermore, each sector's total share of groundwater is calculated by generating an abstraction ratio based on observed groundwater abstraction to total water demand for a specific 2017.

The study used the Watershed Development Master Plan Report for Khon Kaen province (RID, 2018) to project the future water demand project the sectoral water demand (domestic, agricultural and industrial) water demand (2020-2100) for Khon Kaen province under both the SSPs. An average two-way approach has been used in all sectors of water demand projection. The first approach is calculating the rate (MCM/Year) from the sectoral demand projected in the master plan report through linear interpolation. And the next is the calculation of the rate in terms of projected population, projected agricultural land and projected industries under shared socio-economic pathways (Appendix Table A.1 and Table A.2). The average from both approaches is considered the future sectoral demand. Furthermore, under the SSP2-4.5 scenario, the actual rate calculated is considered for further calculation, while under the SSP5-8.5 scenario, the rate is assumed to increase by 1.5 times the SSP2-4.5 rate. The rate under both scenarios is considered to be constant after 2037.

The study used the per-capita demand (rate) from the census and the projected population included with the interpolation method for domestic demand projection. In the case of agriculture water demand, the study uses demand/sq.km (rate) from the observed and projected agriculture land-use area and the interpolation method. And in the case of industrial demand, the study uses demand/industry (rate) along with the interpolation method to get rates from two different approaches. The number of industries in Khon Kaen, Thailand, is linearly forecasted from the actual number of industries between 2015 and 2019 (Appendix Table A.3).

The sectoral groundwater abstraction is calculated by developing a sectoral abstraction (pumping) to water demand ratio in Khon Kaen, Thailand, for 2017 (Table 4.4). The same ratio has been used to calculate future groundwater abstraction under SSP2-4.5 and SSP5-8.5 scenarios.

Table 4.4

Sectoral groundwater abstraction ratio for Khon Kaen, Thailand in 2017

Sector	Groundwater Abstraction	Water Demand	Groundwater Abstraction Ratio
Domestic	3.19	98.87	0.032265
Agriculture	3.19	6,201.92	0.000514
Industry	10.77	34.11	0.315743
Source:	*(DGR, 2020)*	*(RID, 2018)*	

The equation (Eq. 4.5) for the future groundwater abstraction in domestic sector (G_d), with a total water demand, D_d is calculated by:

$$G_d = 0.032265 * D_d \qquad \text{Eq.4.5}$$

Similarly, the equation (Eq. 4.6) for the future groundwater abstraction in agriculture sector (G_a), with a total water demand, D_a is calculated by:

$$G_a = 0.000514 * D_a \qquad \text{Eq.4.6}$$

Similarly, the equation (Eq. 4.7) for the future groundwater abstraction in industrial sector (G_i), with a total water demand, D_i is calculated by:

$$G_i = 0.315743 * D_i \qquad \text{Eq.4.7}$$

Finally, the total groundwater abstraction {$GWA_{(total)}$} of the city for the selected future time-period shall be given by (Eq. 4.8):

$$GWA_{total} = G_d + G_a + G_i \qquad \text{Eq.4.8}$$

4.4 Hydrological Modelling for Groundwater Recharge Estimation

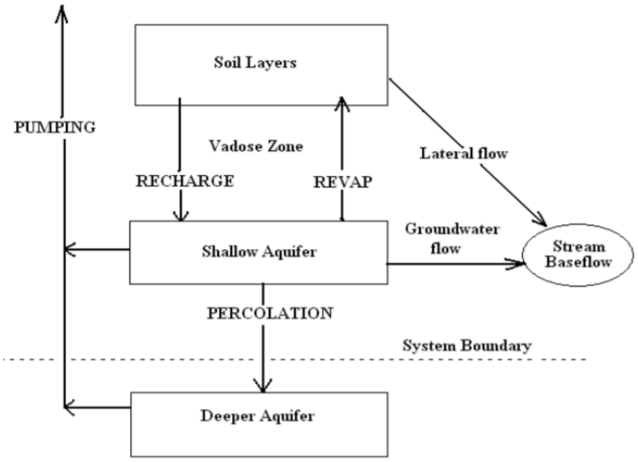
Hydrological modelling portrayal of a real-word hydrological system using some physical models and mathematical equations via multiple computer simulations. In hydrological modelling runoff estimation is a key and is defined through a set of mathematical equations with rainfall and drainage being the major inputs along with watershed topography, soil properties, vegetative cover, and aquifer characteristics (Devi et al., 2015). The choice of these various types of hydrological models varies based on the purpose and its application making it more subjective. Studies have used ANN model and found to be useful in modelling the complex hydrological processes and estimation of streamflow values (Jimeno-Sáez et al., 2018; Juan et al., 2017; Kumar et al., 2016). Moiwo et al., (2010), used WetSpass model for assessing the impact of multiple stresses such as climate and land-use change on surface discharge and subsurface recharge. Several other research studies have used the SWAT model in hydrological simulation and analyzing the problems for better possible solutions (Alansi et al., 2009; Piman et al., 2013; Yen et al., 2015). This study used SWAT Model as the hydrological model to estimate the groundwater recharge in the study area as this model has been extensively used by researchers analyzing the impact of multiple stresses in the watershed hydrology (Arias et al., 2014; Yen et al., 2015).

4.4.1 SWAT Model

The Soil and Water Assessment Tool (SWAT) model being one of the computationally efficient models has been widely around the globe for hydrological analysis (both on quantity and quality aspect). One of the major advantages of the model is its easiness in calibration in data scare areas (Arnold et al., 1998). Furthermore, the model runs in a GIS interface and can also simulate hydrologically connected sub-basins. In this model the shallow aquifers below the soil layers are represented as reservoir and the zone between the soil layer and the aquifer is the vadose zone (Figure 4.8). The detail schematic of representation of groundwater process in the SWAT model is given below:

Figure 4.8

Groundwater Process in SWAT model



Source: Vazquez-Amábile & Engel, 2005

This source of the aquifer for receiving the water is through the process of infiltration from the soil which then percolates to deep aquifer and/or discharges to the nearest stream because of surface water groundwater interaction. The water balance for the shallow aquifer as described by the SWAT model can be given as (Eq. 4.9):

$$waq_{sh,i} = waq_{sh,i-1} - w_{rchg} - Q_{gwf} - w_{dp} - w_{revap} - w_{pp,sh} \qquad \text{Eq.4.9}$$

where,

$\mathbf{waq_{sh,\,i}}$ is the water stored in the shallow aquifer on day i (mmH_2O),

$\mathbf{waq_{sh,\,i-1}}$ is the water stored in the shallow aquifer on day i-1 (mmH_2O),

$\mathbf{w_{rchg}}$ is the recharge entering the shallow aquifer on day i (mmH_2O),

$\mathbf{Q_{gwf}}$ is the groundwater flow or base flow into the main channel on day i (mmH_2O),

$\mathbf{w_{dp}}$ is the water removed from the deep aquifer by pumping on day i (mmH_2O),

$\mathbf{w_{revap}}$ is the water moving into the soil zone in response to water deficiencies on day i (mmH_2O), and

$\mathbf{w_{pp,\,sh}}$ is the water removed from the shallow aquifer by pumping on day i (mmH_2O)

The soil's hydraulic properties and the water table below the ground is the major factor in defining the time for water movement between the vadose zone and the aquifer (Yang et al., 2010). Further, a diffusive process evaporates during the dry period and removes the water from the capillary fringe (a separation between the saturated and unsaturated zone). The loss in water is substituted by the underlying saturated aquifer (Vazquez-Amábile & Engel, 2005). SWAT reports all these as "revap". Revap might occur if the amount of water stored in the shallow aquifer exceeds a threshold value specified by the users. Main groundwater process in SWAT is as shown in figure 4.8.

SWAT simulation are bases on the water balance equation (Eq. 4.10):

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \qquad \text{Eq.4.10}$$

where,

SW$_t$ is the soil water content (mm water) at the end of the time step t (days),

SW$_0$ is the initial soil water content in day i (mm water),

R$_{day}$ is the amount of precipitation on day i (mm water),

Q$_{surf}$ is the amount of surface runoff on day i (mm water),

E$_a$ is the amount of evapotranspiration on day i (mm water),

W$_{seep}$ is the amount of water entering the vadose zone from the soil profile on day i (mm water),

Q$_{gw}$ is the amount of base flow from the shallow aquifer on day i (mm water)

The equation for direct runoff (USDA-SCS, 1972) using the CN method (curve number) is given as (Eq. 4.11):

$$Q_{srf} = \frac{Prcp - 0.2S^2}{Prcp + 0.8S} \qquad \text{Eq.4.11}$$

Where,Q$_{srf}$ is direct surface runoff, Prcp is total rainfall and S is potential maximum infiltration (all in inches). The potential maximum infiltration (S) is calculated using the equation (Eq. 4.12) below:

$$S = \frac{100}{CN} - 10 \qquad \text{Eq.4.12}$$

where, CN is the curve number ($0 \leq CN \leq 100$)

Hooghoudt (1940) portrays the steady-state response of groundwater flow to recharge and the SWAT models follows the same equation (Eq. 4.13) for the calculation of the actual groundwater discharge described as:

$$Q_{gw} = \frac{8000K_{sat}}{L_{gw}^2} * h_{wtbl}$$ Eq.4.13

Rycroft & Smedema, (1983), explained change in the elevation of water table due to non-steady-state response of groundwater flow to periodic recharge as (Eq. 4.14):

$$\frac{dh_{wtbl}}{dt} = \frac{w_{rchrg} - Q_{gw}}{800\mu}$$ Eq.4.14

4.4.2 Performance Evaluation of SWAT Model

The study uses the coefficient of determination (R^2), the Nash-Sutcliffe efficiency (NSE), the percentage bias (PBIAS) and the ratio of root mean square error to standard deviation (RSR) for the evaluation of the SWAT model. These four statistical parameters are widely used in the performance evaluation of hydrological models.

The Coefficient of Determination (R2) is a statistical measure that investigates the strength of the linear relationship between two variables and defines how effectively the model can generate the output. It analyses the proportion of variation (discrepancy) between two variables when calculating the consequence of a given event. The value for the Coefficient of Determination differs from 1–0, with 1 indicating the perfect fit and 0 indicating the poor reliability of the model.

The Nash-Sutcliffe Efficiency (NSE) indicates the degree of fitness between simulated and observed data. The value of NSE can be between -∞ to 1. If the NSE value is 1, it indicates the perfect fit. If the NSE value is negative, the average output value is a better estimate than the model, and predictions are very poor.

The percentage bias (PBIAS) is a statistical measure that provides the average difference between the predicted and the observed value over a specific period. It provides how smaller or larger the predicted values are compared to the observed values. The ideal value of PBIAS is 0, indicating a highly accurate model. The lower the magnitude, the better the accuracy of the model. The overestimation and the underestimation of the model can be identified from the negative and positive values of PBIAS, respectively.

The RMSE-observations standard deviation ratio (RSR) is the ratio of the RMSE and the standard deviation of measured data. The RSR incorporates the advantages of error index statistics and a normalization factor to apply the resulting statics and reported value to various constituents. Lower RSR indicates lower RMSE and better model simulation performance.

The equations (Eq. 4.15 to Eq. 4.18) for the calculation of each statistical parameter are given below:

$$R^2 = \frac{(\sum_{i=1}^{n}\left(Q_i^{obs} - \overline{Q_i^{obs}}\right)(Q_i^{sim} - \overline{Q_i^{sim}}))^2}{\sum_{i=1}^{n}((Q_i^{obs} - \overline{Q_i^{obs}})^2 \sum_{i=1}^{n}(Q_i^{sim} - \overline{Q_i^{sim}})^2} \qquad \text{Eq.4.15}$$

$$NSE = 1 - [\frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs} - \overline{Q_i^{obs}})^2}] \qquad \text{Eq.4.16}$$

$$PBIAS = [\frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right) * 100}{\sum_{i=1}^{n}\left(Q_i^{obs}\right)} \qquad \text{Eq.4.17}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{[\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}]}{[\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - \overline{Q_i^{obs}})^2}]} \qquad \text{Eq.4.18}$$

where, Q_i^{obs} is the observed data, Q_i^{sim} is the simulated data, $\overline{Q_i^{sim}}$ is the mean of simulated data, $\overline{Q_i^{obs}}$ is the mean of observed data and n is the total number of observation

4.5 Estimation of Groundwater Level

Several studies have used MODFLOW to simulate the flow through aquifers (Abdalla, 2015; Cheng et al., 2014; Chitsazan & Movahedian, 2015; Qiu et al., 2015; Shrestha et al., 2020). Groundwater modelling represents the sub-surface flow system and is mainly used in the simulation and prediction of the aquifer behavior responding to different conditions in the present and the future. The groundwater model represents both the natural subsurface flow within the system and the system's quality aspects, including its movement. Furthermore, studies have also used Multiple Linear Regression (MLR) to investigate the groundwater level using multiple factors that impact the level (Sahoo et al., 2013; Wu et al., 2021; Yan et al., 2018). Yan et al. (2018) established a triple linear regression model (rainfall, evaporation, river stage) for predicting the groundwater table and found that the climate is the major factor followed by the river stage. MLR is a statistical technique used to model the relationship between two or more independent variables and a dependent variable. In other words, MLR is an extension of simple linear regression with more than one explanatory variable.

This study analyzed the impact of multiple stressors on groundwater levels using a multiple linear regression model (MLR) to provide a quantified visualization of the future state of groundwater availability in the study area to improve groundwater governance. The predictor variables used for establishing the model are groundwater recharge (as the impact of climate and land-use change from the SWAT model), domestic groundwater abstraction; agricultural groundwater abstraction and industrial groundwater abstraction for a period of 2004 to 2019 with the observed groundwater data from Department of Groundwater Resources, Thailand. A regression equation for the response variable, i.e., the groundwater level (2004 – 2019), has been developed to project the future groundwater level in 6 observation wells in Khon Kaen, Thailand.

The assumptions in the MLR analysis include (a) a linear relationship between dependent and independent variables, (b) no correlation among independent variables, and normal distribution of the residuals (Uyanik and Güler, 2013). The generic equation (Eq. 4.19) of MLR is:

$$y = \beta_0 + \beta_1 x_1 + +\beta_2 x_2 + +\beta_3 x_3 \dots \dots \dots + \ +\beta_n x_n + \in \qquad \text{Eq. 4.19}$$

where,

β_0 = intercept
$\beta_1 x_1$ = one variable and its weight
n = number of variables we have
$\in$ is epsilon

In a linear regression model, the coefficient of determination (R-squared) determines the goodness of fit, showing how much variation in the outcome is explained by an independent variable. This works with only one independent variable. With every added independent variable in the model, the R-squared increases. So, in the case of MLR, R-squared must be adjusted. Adjusted R-squared only increases when the independent variable enhances the model rather than the one obtained by probability.

CHAPTER 5

EVALUATION OF CURRENT STATE OF GROUNDWATER GOVERNANCE

This chapter presents the results of the study's first objective, which is the development and application framework to access the current state of groundwater governance.

5.1 Evaluation of Current State of Groundwater Governance

5.1.1 Development of Groundwater Governance Framework

The study develops a framework for evaluating and quantifying groundwater governance in the rapidly urbanizing area using an indicator-based approach. The framework is developed based on the components of groundwater governance, good governance principles and inclusiveness (gender and right based). The framework consists of 4 dimensions with 30 indicators, and each indicator will be measured based on 2 variables. The variables shall be rated from 0-3, where 0 shows the non-existence level, and 3 shows an optimum level. The selection of the dimensions, variables, rating criteria and 20 indicators has been done based on the GW-MATE (World Bank) project's groundwater governance benchmarking criteria as developed by Foster et al., 2010 and the 10 gender inclusive indicators (Miletto et al., 2019) has been selected based on the WWAP, 2019. The dimensions and indicators are selected to reflect most of the general situation of groundwater components in any urbanizing area.

Furthermore, as the state of groundwater governance is highly based on the local setting, the indicators and ratings can further be contextualized and modified. While the indicators indicate what to measure in the dimensions, the variables describe how they can be measured. The mathematical equation for aggregating these elements provides a holistic index value known as the Groundwater Governance Index (GGI), which provides a general overview of the current state of groundwater governance and a detailed diagnosis of strength, gaps and areas of improvement for sound governance and management to the decision makers, managers and related actors.

The structure of the groundwater framework is shown in (Figure 4.6), where, GGI is the Groundwater Governance Index, i is the number of Dimensions (D), j is the number of Indicators (I) within each dimension, and k is the number of Variables (V) within each indicator.

The groundwater governance framework consists of four dimensions, i.e., Technical, Legal and Institutional, Cross-Sector Policy Coordination and Operational. Each indicator within a dimension shall be evaluated based on the following two variables (i) adequacy of existing governance provisions; (ii) institutional capacity for their implementation. Both variables are rated on a range of 0-3 (Table 5.1), where 0 represents the non-existence state, and 3 represents the optimal state of the measured variables (Foster et al., 2010).

Table 5.1

Groundwater governance framework's variables rating scale

Rating	Level
0	Non-Existent
1	Incipient
2	Acceptable
3	Optimum

The technical legal and institutional, cross-sector policy coordination and operational dimensions of the framework shall consist of 7, 14, 4 and 5 indicators, respectively. The technical dimension is more relevant to the information, knowledge, and dissemination provisions. The second dimension, the legal and institutional dimensions, deals with the legal provisions for groundwater resource regulations. The third dimension is more relevant to the sectoral policies and coordination that directly or indirectly impact groundwater resources. The final dimension is the operational deals with the provision for operational management, end-users access to the resource and participation in managing the resources. The indicators of all the dimensions are selected to provide an inventory of existing provisions and institutional capacity to implement the existing provisions. Tables 5.2 illustrates the different elements of the groundwater governance framework with detailed description of each indicators and their context of application.

Table 5.2

Elements of groundwater governance frameworks with the description of the framework indicators and their context of application

Dimension	S.N	Code	Indicator	Variables	
				AoP	IC
Technical	1	TE1	Existence of basic hydrogeological maps		
	2	TE2	Groundwater body/aquifer delineation		
	3	TE3	Groundwater-piezometric monitoring network		
	4	TE4	Groundwater-pollution hazard assessment		
	5	TE5	Availability of aquifer numerical management models		
	6	TE6	Groundwater-quality monitoring network		
	7	TE7	Vulnerable and Marginalized (V&M) groups specific publications (guide)		
Legal and Institutional	8	LI1	Water well drilling permits and groundwater use rights		
	9	LI2	Instrument to reduce groundwater abstraction		
	10	LI3	Instrument to prevent water well construction		
	11	LI4	Sanction for illegal water well construction		
	12	LI5	Groundwater abstraction and use charging		
	13	LI6	Land-use control on potentially polluting activities		
	14	LI7	Levies on generation/discharge of potential pollutants		
	15	LI8	Government agency as ground-water-resource guardian		
	16	LI9	Community aquifer management organizations		
	17	LI10	Gender-responsive groundwater policies or legal frameworks		
	18	LI11	Gender-inclusive groundwater management agencies (government)		

	19	LI12	Agreements and commitments to cooperation and coordination
	20	LI13	Customary land and water rights for indigenous groups or communities
	21	LI14	Agreements and commitments related to international human rights charters
Cross-Sector Policy Coordination	22	CS1	Coordination with agriculture development
	23	CS2	Groundwater-based urban/industrial planning
	24	CS3	Coordination with tourism development
	25	CS4	Compensation for groundwater protection
Operational	26	OP1	Transparency in groundwater services for all consumers
	27	OP2	Public participation in groundwater management
	28	OP3	Existence of groundwater-management action plan
	29	OP4	Vulnerable and Marginalized (V&M) group inclusiveness in aquifer management organizations
	30	OP5	Vulnerable and Marginalized (V&M) sensitization capacity development (government level)

Varialbles ***AOP: Adequacy of Provision*** ***IC: Institutional Capacity to implement the provision***

Indicator's Source

🟦 *GW-MATE (World Bank; Water Partnership Program) - Foster et al., 2010*

🟧 *World Water Assessment Programme (WWAP) (UNESCO); 2019*

S.N	Code	Description of Indicators and Context
1	TE1	Hydrogeological map of the study area with basic subsurface geologies, aquifers, groundwater table (contours), flow direction, critical zones, etc. The context of the application is to identify the groundwater resources in the study area.
2	TE2	Pragmatic classification of groundwater bodies showing the linkage of characteristics and status of groundwater bodies. The context of the application is to identify the classification of groundwater bodies with typology.
3	TE3	Network setup for monitoring groundwater level, extraction, recharge, and use. The context of the application is to establish resource status and trends.

4	TE4	Groundwater pollution contaminant identification and monitoring pollution hazards from multiple sources like agriculture, industry, solid waste (landfills), mines, etc. The context of the application is to identify quality degradation risk to groundwater.
5	TE5	Availability of (at least) basic process-based model for technical analysis and management solutions of aquifers. The context of the application is for assessment of management measures in critical aquifers.
6	TE6	Network setup for monitoring groundwater quality at aquifers. The context of the application is to detect incipient pollution/salinization to groundwater.
7	TE7	Availability of gender (sex differences) specific knowledge resources (declarations, publications, guidelines etc.) in public domain of groundwater governance and management related government institutions. The context of the application is to identify the dissemination strategy of gender-specific knowledge resources.
8	LI1	Provision of well drilling permits for large scale groundwater users. The context of the application is to identify the groundwater user rights for small scale groundwater users with large users.
9	LI2	Provision of policy instruments for well closure or restricting water abstraction in existing well. The context of the application is to identify the controlling measures for the critical areas.
10	LI3	Provision of policy instruments for controlling of well construction. The context of the application is to identify the controlling measures for overexploited and polluted areas.
11	LI4	Provision for penalizing construction of illegal/ unpermitted water wells. The context of the application is to identify measures for excessive use above permit.
12	LI5	Provision for charging large quantity abstraction and use of groundwater. The context of the application is to identify the provision of “resource charge" on large users.
13	LI6	Provision for constraining land-use activities based on pollution sources that will impact groundwater quality. The context of the application is to identify the measures for restricting groundwater hazards.
14	LI7	Provision of fine/fees in generating and discharging potential groundwater pollutants above the discharge standards. The context of the application is to identify the measures providing an incentive for preventing pollution (for aquifer protection).
15	LI8	Provision of legal frameworks that defines government as the guardian or empowered center to groundwater resources. The context of the application is to identify the measures that empower the government to act on a cross-sectoral basis.

16	LI9	Provision for the formation of community-based aquifer management organizations. The context of the application is to identify the measures that ensure mobilizing and formalizing community participation in aquifer management.
17	LI10	Provision of the groundwater policy framework that identifies and acknowledges the existing differences and inequalities between women and men AND articulates policies and initiatives which address the different needs, aspirations, capacities, and contributions of women and men. The context of the application is to identify the measures that address gender inclusiveness in groundwater management.
18	LI11	Legal provisions for budget allocation on procedures or mechanisms for identifying and integrating gender concerns (through consultations, workshops, meetings). The context of the application is to identify the measures that ensure activities for planning and formulating gender concerns in groundwater governance and management.
19	LI12	Legal provisions for gender-specific staffing ratio (female/male) in different levels in government institutions related to groundwater management. The context of the application is to identify the measures that ensure inclusive decision making in formal groundwater institutions.
20	LI13	Provisions of customary rights to land and water use for indigenous groups or communities. The context of the application is to ensure the measures for inclusive water use right and for minimizing the possible conflicts.
21	LI14	Provision of state ratification/commitments/implementation actions related to human rights charters relevant to groundwater resources right and management. The context of the application is to ensure the measures undertaken for inclusive water-use rights and management.
22	CS1	Provision for coordination with the agriculture sector in managing groundwater resources. The context of the application is to ensure ‘real water-saving’/pollution control.
23	CS2	Provision for coordination with the urban/industrial sector for sustainable quality and quantity management of groundwater resources. The context of the application is to ensure the consideration for conservation and protection of groundwater resources.
24	CS3	Provision of compensation for restricting land use activities that support in groundwater recharge and quality protection. The context of the application is to ensure rewards for constraining land use activities.
25	CS4	Provision of multi-sector (agriculture, water-related industries, enterprises) coordination for sex-disaggregated groundwater use data. The context of the application is to ensure the provision of multi-sectoral groundwater user's gender distribution.

26	OP1	Provision of information on groundwater services (process for good drilling and service charge; non-availability periods with reasons, water tariffs, water delivery schedules, etc.). The context of the application is to ensure the transparency to basic groundwater services.
27	OP2	Provision for active public inclusiveness and support in groundwater management against overexploitation and pollution. The context of the application is to ensure operational effectiveness in controlling exploitation and pollution.
28	OP3	Existence of groundwater management action plan for the aquifer considered with consensus on targets and measures. The context of the application is to ensure the provisioning of a groundwater management action plan with agreed targets and instruments.
29	OP4	Provision of gender inclusiveness (proportion) in terms of positions and responsibility in decision-making processes in local or community aquifer management organizations. The context of the application is to ensure the provision for a balanced decision-making process during the operation of the aquifer.
30	OP5	Provision/implementation of training related to gender inclusiveness in groundwater governance and management at government institutions. The context of the application is to ensure the sensitization of planners and implementors for inclusive management and decision making.

Notes: Multiple aspects covered by the framework

Components of Groundwater Governance	Relevant Dimensions
Actors	Operational; Cross-sector policy coordination; Legal and Institutional
Legal and Institutional	Legal and Institutional
Policies and Plans	Cross-sector policy coordination; Legal and Institutional
Information and Knowledge	Technical
Aspects	**List of Indicators**
Groundwater-Extraction Related	Indicators: 3,5,8,9,10,11,12
Groundwater Quality Related	Indicators: 4,6,13,14,24
Groundwater-Extraction and Quality Related	Indicators: 1,2,15,16,22,23,27,28
Groundwater-Inclusiveness Related	Indicators: 7,17,18,19,20,21,25,26,29,30
Urbanization and Groundwater Related	Indicators: 5,11,12,13,14,22,23,24,25

5.1.2 Aggregation and Interpretation of Groundwater Governance Index

In order to obtain a quantified value of the overall governance index, the values of dimensions, indicators and variables shall be aggregated. The generalized equation for aggregating the framework's elements for the overall governance index is given below. The framework's dimensions, indicators and variables are represented by D, I, and V in the equations, respectively, whereas i, j and k indicate the number of dimensions, number of indicators within each dimension and number of variables within each indicator, respectively.

The aggregation of the variables within each indicator is done by using the formula (Eq. 5.1),

$$I_{ij} = \sum_{k=1}^{n} w_k * V_k \qquad \text{Eq.5.1}$$

where, I_{ij} represents the aggregated value of the jth indicator within ith dimension, w_k and V_k represents the weightage and the rating of the k^{th} variables within that indicator, respectively. Here "n" in the equation represents the total number of the variables (k).

Similarly, the aggregation of the indicators within each dimension is done by using the formula (Eq. 5.2),

$$D_i = \sum_{j=1}^{n} w_j * I_{ij} \qquad \text{Eq.5.2}$$

where, D_i represents the aggregated value of the ith dimension, w_j and I_{ij} represents the weightage of the j^{th} indicator within the dimension and I_{ij} represents the aggregated value of j^{th} indicator within the i^{th} dimension. Here "n" in the equation represents the total number of the indicators (j).

And finally, the overall groundwater governance index is calculated by using the formula (Eq. 5.3),

$$GGI = \sum_{i=1}^{n} wi * Di \qquad \text{Eq.5.3}$$

where, GGI represents overall Groundwater Governance Index, w_i and D_i represents the weightage and the aggregated value of i^{th} dimension. Here "n" in the equation represents the total number of the dimensions (i).

After assessing groundwater governance and quantifying it to obtain an overall groundwater governance index, the index's magnitude is interpreted to give an overview of the current state of groundwater governance in the area. The threshold of the governance index is in a range of 0-3 and described (Table 5.3) as given below:

Table 5.3

Interpretation of the results of groundwater governance index

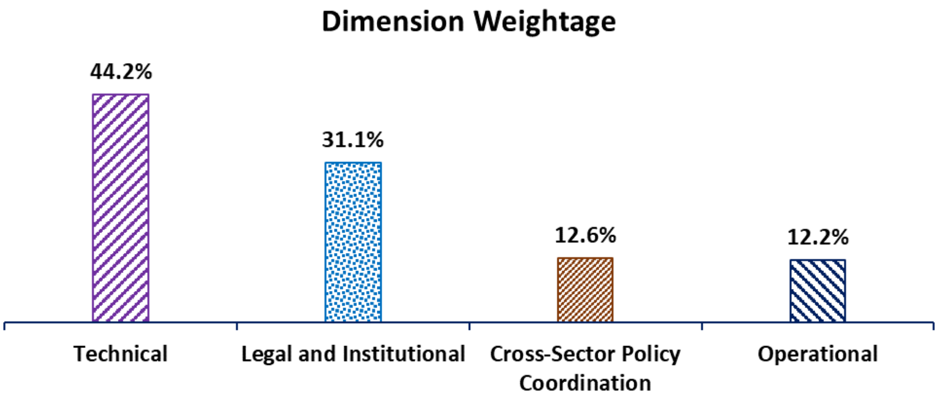
Threshold	State of Governance	Description
0	Non-Existent State of Groundwater Governance	Groundwater governance is in a non-existence state from a dimensional perspective. The country/province/city has no to highly insufficient provisions of technical resources, regulatory and legal outlines, operational plans and policies for cross-sectoral coordination. It faces several issues and conflicts due to the lack of institutional capacity for multi-stakeholder-based governance.
0.01 - ≤ 1	Incipient State of Groundwater Governance	Groundwater governance is in an initial state from a dimensional perspective. The country/province/city has elementary provisions of technical resources, regulatory and legal outlines, operational plans and policies for cross-sectoral coordination. It faces some issues and conflicts due to the basic institutional capacity for multi-stakeholder-based governance.
1.01 - ≤ 2	Acceptable State of Groundwater Governance	Groundwater governance is in a satisfactory state from a dimensional perspective. The country/province/city has fair provisions of technical resources, regulatory and legal outlines, operational plans and policies for cross-sectoral coordination. It faces very fewer issues and conflicts due to the decent institutional capacity for multi-stakeholder-based governance.
2.01 - ≤ 3	Optimum State of Groundwater Governance	Groundwater governance is in the most favorable state from a dimensional perspective. The country/province/city has adequate provisions of technical resources, regulatory and legal outlines, operational plans and policies for cross-sectoral coordination. It faces none to very little issues and conflicts due to the ample institutional capacity for multi-stakeholder-based governance.

5.1.3 Priority and Weightage of Framework Dimensions

The study applied the analytic hierarchy process (AHP) to obtain the weightage of all four dimensions of the groundwater governance framework. A global expert survey has been carried out to obtain the relative weightage of the framework dimensions. Thirty-one responses (42.5%) have been received from the global groundwater experts (77% male and 23% female) representing 15 countries (Australia, Germany, Hungary, India, Japan, Laos, Myanmar, Nepal, Netherlands, New Zealand, Republic of Korea, Sri Lanka, Sweden, Thailand and Vietnam) included scientist/ researchers, policymakers and practitioners.

Figure 5.1

Comparison of groundwater governance framework's dimension weightage obtained from an expert (global) questionnaire survey



The study conducted a consistency ratio (CR) check on all the responses (Appendix Table A.4) and found that only 20 answers had a consistency ratio of less than 20% (i.e., CR≤0.20). The 20 replies majorly (13 responses) included a consistency ratio of less than 10%, and the remaining 7 had CR between 10 and 20%. The selection of CR≤0.20 is based on Satty (1980), who explained the concept of "tolerable inconsistency," which should be below 0.2. Furthermore, many studies have discussed that CR≤0.20 be a tolerable "acceptable level of consistency" as the difference in experts (geographic area, the field of specialization, level of concentration, etc.) is likely to display CR value to some level of internal consistency (Boucher et al., 1993; Dalon, 2008; Rallabandi et al., 2016; Saaty, 1977; Saaty, 1980). Pauer et al., 2017 applied a similar approach (CR≤0.20) to compare different responses in health sector assessment. The combined results from the 20 eligible responses (geometric mean) show that the technical dimension is the most prioritized, with a weightage of 44.2%, followed by the legal and institutional, cross-sector policy coordination and operational dimension, with a weightage of 31.1%, 12.6%, and 12.2% respectively (Figure 5.1). The results show an overall consistency ratio of 4.3% and a high consensus (85.2%) among the individual expert's results (Goepel, 2013).

5.1.4 Quantifying Current State of Groundwater Governance in Khon Kaen, Thailand

An expert-based questionnaire (Appendix Q.1) survey developed based on the groundwater governance framework has been carried out among experts in different institutions related to the governance and management of groundwater in Thailand. The questionnaire has been conducted to receive experts' opinions representing government and non-government institutions at the national, provincial and local levels. Furthermore, the survey also included experts from academic and research institutes involved in groundwater research works in Khon Kaen, Thailand. Overall, 23 expert responses (anonymous) were received, which consisted of 52% of male participants and 48% of female participants who are policymakers, policy implementers/managers, scientists/researchers, practitioners and had an average age of 39 years (27-58 years) and average working experience of 13 years (1-30 years) in groundwater sector.

The rating of each questionnaire has been done based on two variables, "the state of the existing provision and the institutional capacity to implement the provision," and then aggregated accordingly, as mentioned in the methodological section above. The results show (see Appendix Table A.5 and Figure 5.2) that the groundwater governance index (GGI) of Khon Kaen, Thailand is 1.18 "acceptable state of governance" (Table 5.3). The existing state is in a very early stage of a satisfactory state of groundwater governance from a dimensional perspective, as the province has fair provisions of technical resources, regulatory and legal outlines, operational plans, and policies for cross-sectoral coordination. It is likely to face fewer issues and conflicts due to the requirement of additional provisions on multi-stakeholder engagement, operational provision, updates on technical resources and limited institutional capacity for multi-stakeholder-based governance. Furthermore, the results suggest having a thorough multi-perspective analysis to understand current provisions and needs.

Figure 5.2

Groundwater governance framework indicators rating by experts in terms of the adequacy of provision and institutional capacity for its implementation in Khon Kaen, Thailand

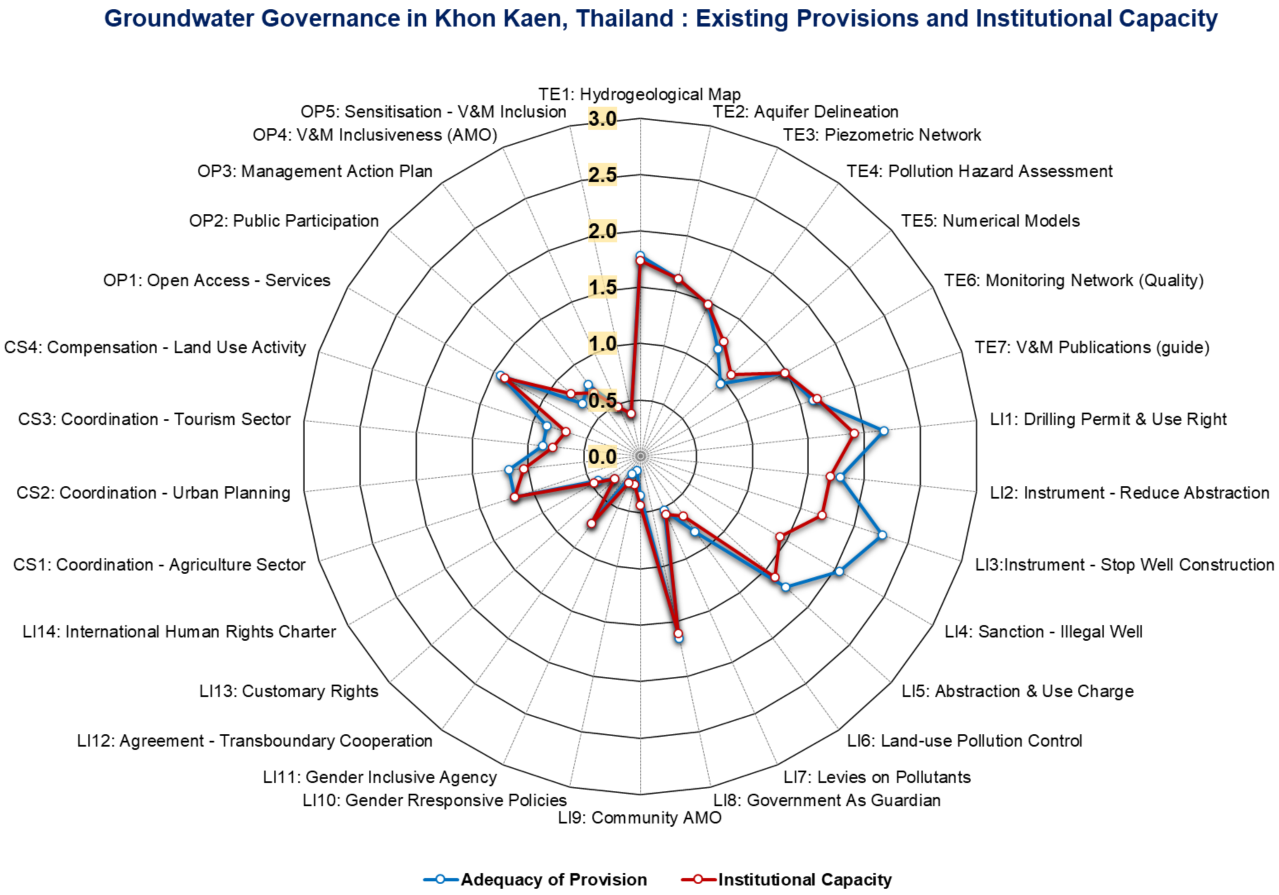
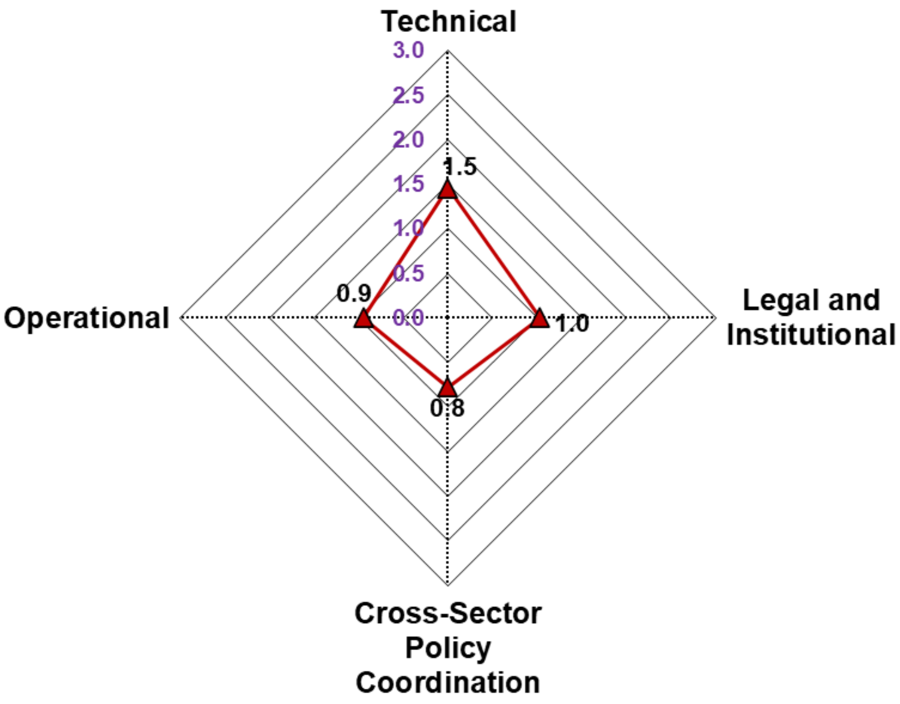


Figure 5.3 below shows the aggregated rating of each dimension for the current state of provisions in groundwater governance of the study area, and the results show an adequate availability of the technical resources as they are the midway between the incipient to an acceptable stage (overall rating = 1.5). Furthermore, the legal and institutional (overall rating = 1.0) and operational dimensions (overall rating = 0.9) are at the initial stages and require further improvements to improve the overall groundwater governance in Khon Kaen, Thailand. The cross-sectoral policy coordination dimension (overall rating = 0.8) has the least provision and institutional capacity for effective governance processes.

Figure 5.3

The experts rating of groundwater governance framework dimensions in Khon Kaen, Thailand



5.1.5 Multi-perspective Analysis of Groundwater Governance in Khon Kaen, Thailand

The radar plot (Figure 5.2) shows the overall status of each indicator of the groundwater governance rated based on the adequacy of current provisions and the institutional capacity to implement the provision in Khon Kaen, Thailand. The result shows a need to improve the institutional capacity in Khon Kaen to implement existing provisions and then upgrade the provisions. Furthermore, in some areas of technical dimensions, such as the provision of the numerical management models, groundwater pollution hazard assessment needs the improvement in the existing provision though there is an acceptable state of capacity available in the current structure. A detailed discussion of the current state of groundwater governance for each dimension is presented below.

The current state of the technical dimension after the aggregation is an acceptable state, with the rating ranging from 1-1.8 for the adequacy of provision and 1.1-1.7 for the institutional capacity to implement the provision (Table 5.4). The result shows a need to improve the provision of the aquifer numerical management model though there is an adequate institutional capacity for implementing it. Furthermore, the provision of the hydrogeological map, delineation of the aquifer, monitoring network, and availability of publications related to the inclusion of vulnerable and marginalized groups in groundwater is approaching a fully acceptable state.

In the case of the legal and institutional dimension, the results (Table 5.4) indicate a clear need to strengthen the institutional capacity in Khon Kaen, though there is an acceptable - optimum level of provision for drilling permits (rating = 2.2), reducing the inappropriate abstraction (rating = 1.8), stopping the illegal well construction (rating = 2.3), sanctions (rating = 2.0), abstraction and use charging (rating = 1.7) etc. Furthermore, the results also suggest a need to improve other vital legal and institutional indicators such as community aquifer management organizations, vulnerable and marginalized inclusive policies and state ratification for transboundary cooperation and human rights charter etc., for improving the legal dimension and overall governance of Khon Kaen. The indicators mentioned above are currently in the non-existence to the initial stage (variables average rating 0.2 to 0.7) in terms of both adequacies of provision and institutional capacity for its implementation.

The third dimension is cross-sector policy coordination. The results show that the provision for coordination with various sectors ranges from 0.9 to 1.2 (Table 5.4). In contrast, the institutional capacity to implement such provisions ranges from 0.7-to 1.2, indicating an (early) incipient stage and displaying the need for coordinating with agriculture, urban and tourism sectors to improve the governance and management of groundwater resources of Khon Kaen.

Table 5.4

Groundwater governance framework dimensions-based indicators rating by experts in terms of the adequacy of provision and institutional capacity for its implementation in Khon Kaen, Thailand

Dimension	Indicator	Variable (Rating)	
		AoP	IP
Technical	TE1: Hydrogeological Map	1.78	1.74
	TE2: Aquifer Delineation	1.61	1.61
	TE3: Piezometric Network	1.48	1.48
	TE4: Pollution Hazard Assessment	1.17	1.26
	TE5: Numerical Models	0.96	1.09
	TE6: Monitoring Network (Quality)	1.48	1.48
	TE7: V&M Publications (guide)	1.61	1.65
Legal and Institutional	LI1: Drilling Permit & Use Right	2.17	1.91
	LI2: Instrument - Reduce Abstraction	1.78	1.70
	LI3: Instrument - Stop Well Construction	2.26	1.70
	LI4: Sanction - Illegal Well	2.04	1.43
	LI5: Abstraction & Use Charge	1.74	1.61
	LI6: Land-use Pollution Control	0.83	0.65
	LI7: Levies on Pollutants	0.52	0.57
	LI8: Government as Guardian	1.65	1.61
	LI9: Community AMO	0.35	0.43
	LI10: Gender Responsive Policies	0.13	0.26
	LI11: Gender Inclusive Agency	0.17	0.26
	LI12: Agreement - Transboundary Cooperation	0.74	0.74
	LI13: Customary Rights	0.30	0.30
	LI14: International Human Rights Charter	0.43	0.48
Cross-Sector Policy Coordination	CS1: Coordination - Agriculture Sector	1.17	1.17
	CS2: Coordination - Urban Planning	1.17	1.04
	CS3: Coordination - Tourism Sector	0.87	0.78
	CS4: Compensation - Land Use Activity	0.87	0.70
Operational	OP1: Open Access - Services	1.43	1.39
	OP2: Public Participation	0.70	0.83
	OP3: Management Action Plan	0.78	0.70
	OP4: V&M Inclusiveness (AMO)	0.48	0.48
	OP5: Sensitisation - V&M Inclusion	0.39	0.39

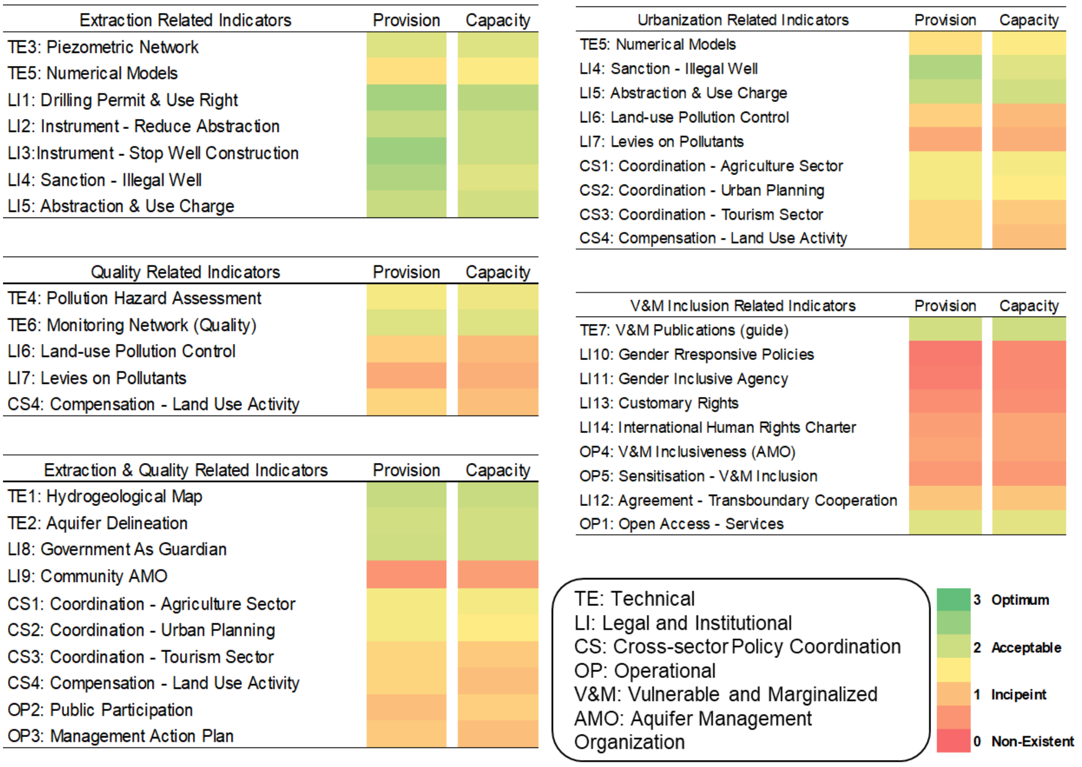
Rank/Rating: 0 = Non-Existent; 1= Incipient; 2 = Acceptable; 3 = Optimum (AoP: Adequacy of Provision; IC: Institutional Capacity

Similarly, the final, i.e., the operational dimension, shows that it is one of the weakest with inadequate provisions and institutional capacity (Table 5.4). The transparency in groundwater services is only one indicator of this dimension in the mid between the initial and acceptable stages in terms of adequacy of provision and institutional capacity for its implementation, with an average score of 1.4. All other indicators range from 0.4 to 0.8 and are approaching the incipient stage. The result indicates a primary need to improve the inclusion and sensitization regarding the participation and involvement of vulnerable and marginalized stakeholders in the aquifer management and a better action plan for groundwater management.

The study further analyzed the current provision and needs based on the groundwater extraction-related, quality-related, combined extraction-quality-related, urbanization-related, and vulnerable and marginalized inclusion-related indicators (Figure 5.4).

Figure 5.4

Experts rating on current provision and institutional capacity under multiple perspectives for groundwater governance in Khon Kaen, Thailand



Extraction Related Indicators	Provision	Capacity
TE3: Piezometric Network	🟩	🟩
TE5: Numerical Models	🟨	🟨
LI1: Drilling Permit & Use Right	🟩	🟩
LI2: Instrument - Reduce Abstraction	🟩	🟩
LI3:Instrument - Stop Well Construction	🟩	🟩
LI4: Sanction - Illegal Well	🟩	🟩
LI5: Abstraction & Use Charge	🟩	🟩

Quality Related Indicators	Provision	Capacity
TE4: Pollution Hazard Assessment	🟨	🟨
TE6: Monitoring Network (Quality)	🟩	🟩
LI6: Land-use Pollution Control	🟨	🟧
LI7: Levies on Pollutants	🟧	🟧
CS4: Compensation - Land Use Activity	🟨	🟧

Extraction & Quality Related Indicators	Provision	Capacity
TE1: Hydrogeological Map	🟩	🟩
TE2: Aquifer Delineation	🟩	🟩
LI8: Government As Guardian	🟩	🟩
LI9: Community AMO	🟥	🟥
CS1: Coordination - Agriculture Sector	🟨	🟨
CS2: Coordination - Urban Planning	🟨	🟨
CS3: Coordination - Tourism Sector	🟨	🟧
CS4: Compensation - Land Use Activity	🟨	🟧
OP2: Public Participation	🟧	🟨
OP3: Management Action Plan	🟨	🟧

Urbanization Related Indicators	Provision	Capacity
TE5: Numerical Models	🟨	🟨
LI4: Sanction - Illegal Well	🟩	🟩
LI5: Abstraction & Use Charge	🟩	🟩
LI6: Land-use Pollution Control	🟨	🟧
LI7: Levies on Pollutants	🟧	🟧
CS1: Coordination - Agriculture Sector	🟨	🟨
CS2: Coordination - Urban Planning	🟨	🟨
CS3: Coordination - Tourism Sector	🟨	🟧
CS4: Compensation - Land Use Activity	🟨	🟧

V&M Inclusion Related Indicators	Provision	Capacity
TE7: V&M Publications (guide)	🟩	🟩
LI10: Gender Rresponsive Policies	🟥	🟥
LI11: Gender Inclusive Agency	🟥	🟥
LI13: Customary Rights	🟥	🟥
LI14: International Human Rights Charter	🟧	🟧
OP4: V&M Inclusiveness (AMO)	🟧	🟧
OP5: Sensitisation - V&M Inclusion	🟥	🟥
LI12: Agreement - Transboundary Cooperation	🟧	🟧
OP1: Open Access - Services	🟩	🟩

TE: Technical
LI: Legal and Institutional
CS: Cross-sector Policy Coordination
OP: Operational
V&M: Vulnerable and Marginalized
AMO: Aquifer Management Organization

🟩 3 Optimum
🟩 2 Acceptable
🟧 1 Incipeint
🟥 0 Non-Existent

The results show that the current provision of the extraction-related governance indicators is acceptable to the optimum state in Khon Kaen, while the quality-related indicators are currently at the initial state and need further improvements in terms of provision and institutional capacity. Similarly, the indicators representing both extraction and quality in groundwater governance and those addressing the governance in urbanizing areas are in a mixed stage. The majority indicate to be in the incipient state. Furthermore, the inclusion-related indicators show an urgent need for adding provisions and institutional capacity for the sensitization and involvement of vulnerable and marginalized groups, customary rights and state ratification for transboundary cooperation in Khon Kaen, Thailand, for improving good groundwater governance and sustainable management.

The water (groundwater) assessment frameworks emphasize the involvement of multiple actors in the planning, decision-making, implementation, monitoring, and evaluation. Furthermore, these frameworks showcase the details of the water system, knowledge, legal and institutional settings, policies and plans, multidisciplinary governance, social welfare, inclusiveness, equity, and sustainable management as the common characteristics required for assessing water governance. However, there is still an absence of a ready-to-use framework to quantitatively evaluate the current state of governance, which would be useful for both technical and nontechnical policymakers, practitioners, and stakeholders in visualizing the prevailing state and plan accordingly (KC et al., 2022). This study developed a modified structure to assess the existing state of groundwater governance, which consisted of four prioritized dimensions (1. Technical; 2. Legal and institutional; 3. Cross-sector policy coordination; 4. Operational) and 30 indicators rated in terms of adequacy of existing provision and institutional capacity to implement, those provisions. The framework has been applied in Khon Kaen, Thailand, a rapidly urbanizing area in the Lower Mekong Region. The results showed groundwater governance is at the "acceptable state" (GGI = 1.18). The existing state is in a very early stage of the acceptable state of governance and needs to improve the institutional capacity to implement existing provisions and improve overall governance. A study by Muenratch et al. (2022) showed that the lower institutional capacity is a key challenge for groundwater management in Khon Kaen, Thailand. Furthermore, the multi-perspective analysis showed that gender mainstreaming in groundwater governance is urgently needed for multi-stakeholder engagement in Khon Kaen, Thailand. The findings are similar to Muenratch et al. (2022), who have emphasized strategies for coordinating key actors at local and aquifer management levels for resource sustainability.

CHAPTER 6

PROJECTION OF FUTURE MULTIPLE STRESSES UNDER SHARED SOCIO-ECONOMIC PATHWAYS (SSPs)

This chapter presents the results of the study's second objective, which is predicting the future change in multiple stresses (climate, land use, population, sectoral demand) under various SSP scenarios.

6.1 Projection of Future Climatic Parameters

6.1.1 Ranking of Bias Corrected Global Climate Models

Five linearly bias-corrected CMIP-6 GCMs, namely CESM2, MRI-ESM2, BCC-CSM2-MR, GFDL-ESM4 and CanESM5, made available from Hydro Informatics Institute (HII), Thailand under two SSPs (SSP2-4.5 and SSP5-8.5) has been used for analyzing future climatic conditions.

Table 6.1

Results for the statistical performance of linear bias correction and ranking of GCMs

	Statistical Results						Ranking				
Variable	Statistical Parameters	CESM2	MRI-ESM-2	BCC-CSM2-MR	GFDL-ESM4	CanESM 5	CESM2	MRI-ESM-2	BCC-CSM2-MR	GFDL-ESM4	CanESM5
Precipitation	R2	0.65	0.66	0.62	0.61	0.69	3	2	4	5	1
	STDV	106.97	106.59	120.27	112.31	100.97	3	2	5	4	1
	RMSE	87.36	86.10	99.09	94.75	80.45	3	2	5	4	1
Maximum Temperature	R2	0.56	0.53	0.59	0.49	0.49	2	3	1	4	5
	STDV	2.31	2.54	2.34	2.51	2.50	1	5	2	4	3
	RMSE	1.60	1.78	1.55	1.85	1.83	2	3	1	5	4
Minimum Temperature	R2	0.55	0.55	0.54	0.53	0.49	1	2	3	4	5
	STDV	2.86	2.93	2.81	2.94	2.89	2	4	1	5	3
	RMSE	2.47	2.50	2.39	2.43	2.52	3	4	1	2	5
						Sum of Ranking	20	27	23	37	28
						Final Rank	***1***	***3***	***2***	***5***	***4***

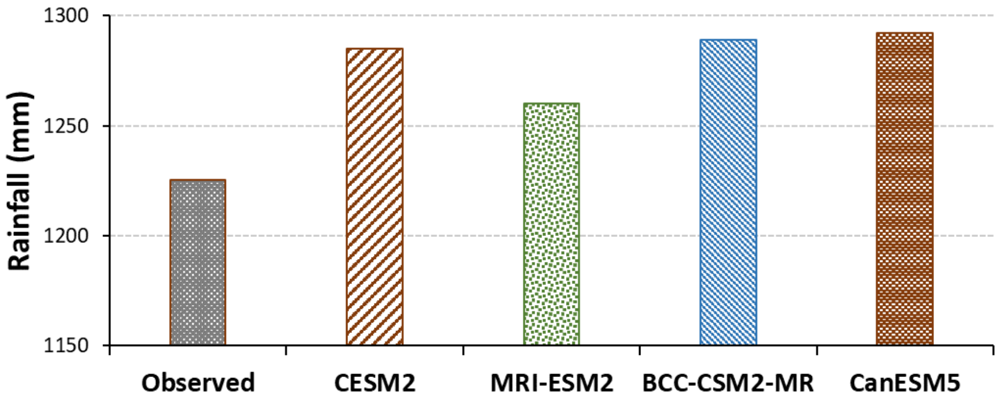
Initially, the statistical performance of five linearly bias-corrected data for the historical period (1981-2014) has been evaluated to rank each precipitation and temperature variable model, which was then future combined to select the four best performing models. The statistical performance of R2, STDV and RMSE for all five RCMs (Table 6.1) after bias correction shows that the three best performing models for precipitation are CanESM5, MRI-ESM2 and CESM2 and for minimum and maximum temperature are CESM2, MRI-ESM2 and BCC-CSM2-MR. So, for further analysis, the study used all four best-performing models for temperature and precipitation. Overall, the statistical performance of the linear bias correction results is similar for all the models where the coefficient of correlation has increased, and the root mean square error for the bias-corrected rainfall data has decreased, and the standard deviation has come closer to the observed deviation.

6.1.2 Performance Check of Global Climate Models

The bias-corrected historical rainfall and temperature of all the four individual GCMs have been compared with the observed rainfall and temperature for the baseline period of 1981-2014 to check the performance of linear bias correction on the individual case.

Figure 6.1

Comparison of GCM's historical average annual rainfall with an observed average annual rainfall of the Chi Mun River basin for the baseline period (1981-2014) after linear bias correction

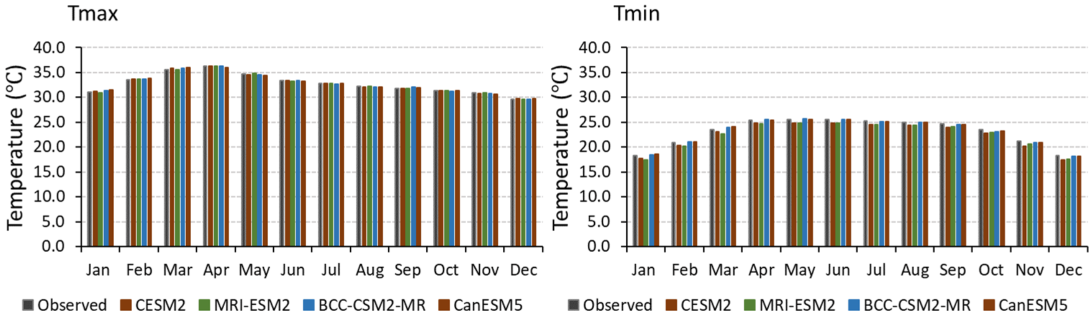


The results for the observed average annual rainfall for the Chi Mun River Basin shown by all the climate models for the baseline period show that the models are overestimated by 35-67 mm after bias correction compared to the baseline 1225 mm annually (Figure 6.1). The MRI-ESM2 models show the least bias of 35mm whereas the CanESM shows the most bias of 67 mm, followed by BCC-CSM2-MR (64mm) and CESM2 (60mm), respectively. Comparatively, it has been observed that the individual GCMs are exhibiting a slight overestimation of the average annual rainfall compared to the observed after linear bias correction.

Similarly, Figure 6.2 shows the performance check for the average monthly, and Appendix Figure A.1 shows the average annual maximum and minimum temperature in Chi Mun Basin. All the GCMs after the linear bias corrections show an average annual maximum temperature of 32.7°C, similar to the observed, while two models, namely BCC-CSM2-MR and CanESM5, overestimate the average annual minimum temperature by 0.5°C as compared to the observed 22.4°C (Appendix Figure A.1). In contrast, majority of the GCM models underestimates the average monthly maximum temperature during January-March by 0.1 to 0.4°C compared to the observed maximum temperature while the CESM2 and the MRI-ESM2 GCM overestimates the average monthly maximum temperature by about 0.7°C (Figure 6.2). Comparatively, the results show that all the GCMs exhibit better estimation of the maximum and minimum temperature after linear bias correction.

Figure 6.2

Comparison of GCM's historical monthly maximum and minimum temperature with an observed monthly maximum and minimum temperature of the Chi Mun River basin for the baseline period (1981-2014) after linear bias correction

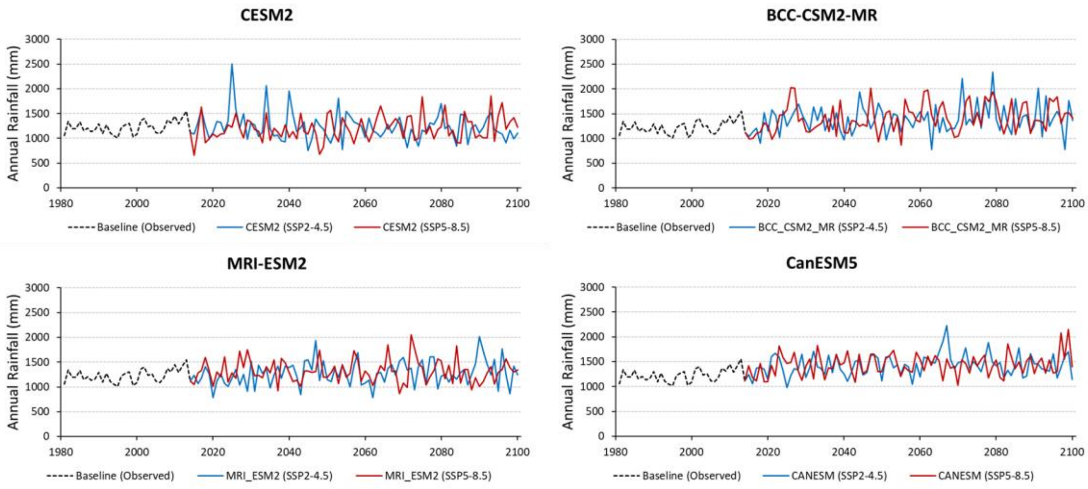


6.1.3 Projection of Future Climate in Chi Mun River Basin

The future rainfall and temperature for each GCMs (CESM2, MRI-ESM2, BCC-CSM2-MR and CanESM5) have been divided into Near Future (NF) (2015-2039), Mid Future (MF) (2040-2069) and Far Future (FF) (2070-2100) under two socio-economic pathways scenarios: SSP2-4.5 and SSP5-8.5. The NF, MF and FF under two SSPs have been compared with the observed baseline (1981-2014). Figure 6.3 below shows the annual rainfall trend plot of Chi Mun Basin for all four GCMs under two SSPs, and the results from the majority of all the GCMs indicate that the annual rainfall is likely to increase under both the SSPs between 2015 to 2100.

Figure 6.3

Projected annual rainfall trend for the Chi Mun River basin (2015-2100) for four GCMs under SSP2-4.5 and SSP5-8.5 scenario



For a detailed analysis of change in annual rainfall, the study compared the projected average annual rainfall (NF, MF and FF) of the Chi Mun basin with the baseline (1981-2014) average annual rainfall under both SSP2-4.5 and SSP5-8.5 scenarios (Table 6.2). The table illustrates that under the SSP2-4.5 scenario, all the GCMs except MRI-ESM2 in NF and CESM2 in FF projects the increase in average annual rainfall from 5% to 20% compared to baseline 1225.37 mm. BCC-CSM2-MR in FF and CanESM5 in MF projects the maximum increase of 20% and 19%, respectively. The overall results further indicate that the MF and FF are likely to increase annual rainfall under the SSP2-4.5 scenario. Similarly, under the SSP5-8.5 scenario, all the GCMs except CESM2 in NF and MF projects the increase in average annual rainfall from 2% to 22% compared to the baseline. BCC-CSM2-MR in FF and CanESM5 in FF projects the maximum increase of 22% and 20%, respectively. The study results agree with Chinvano et al. (2017) and Arunyanart et al. (2017) in Chi River Basin, Thailand. Arunyanart et al. (2017) concluded that climate change in the basin would likely increase the rainfall by 15.76%, 18.37%, and 21.99%, respectively, in NF, MF, and FF. The resulting increment in the rainfall is likely to increase the streamflow in the future in the Chi Mun

River Basin (Li et al., 2021) and, thus, may have increased runoff (due to the increased impervious layer), impacting the shallow groundwater recharge. A similar study conducted in the Chao Phraya Basin in Thailand observed an increase in rainfall and streamflow (Ligaray et al., 2015; Kure and Tebakari, 2012).

Table 6.2

Comparison of projected average annual rainfall (2015-2100) of the Chi Mun River basin with baseline (1981-2014) average annual rainfall under SSP2-4.5 and SSP5-8.5 scenarios

GCMs	Baseline Average Annual Rainfall (mm) (1981-2014)	Projected Average Annual Rainfall (mm)					
		SSP2-4.5			SSP5-8.5		
		NF *(2015-2039)*	MF *(2040-2069)*	FF *(2070-2100)*	NF *(2015-2039)*	MF *(2040-2069)*	FF *(2070-2100)*
CESM2	**1225.3**	1290.0	1237.9	1179.9	1154.1	1199.0	1244.5
MRI-ESM2		1197.3	1293.8	1331.4	1338.3	1298.7	1320.2
BCC-CSM2-MR		1339.1	1342.5	1465.1	1336.1	1402.7	1494.3
CanESM5		1380.2	1458.9	1442.0	1395.6	1450.8	1466.5

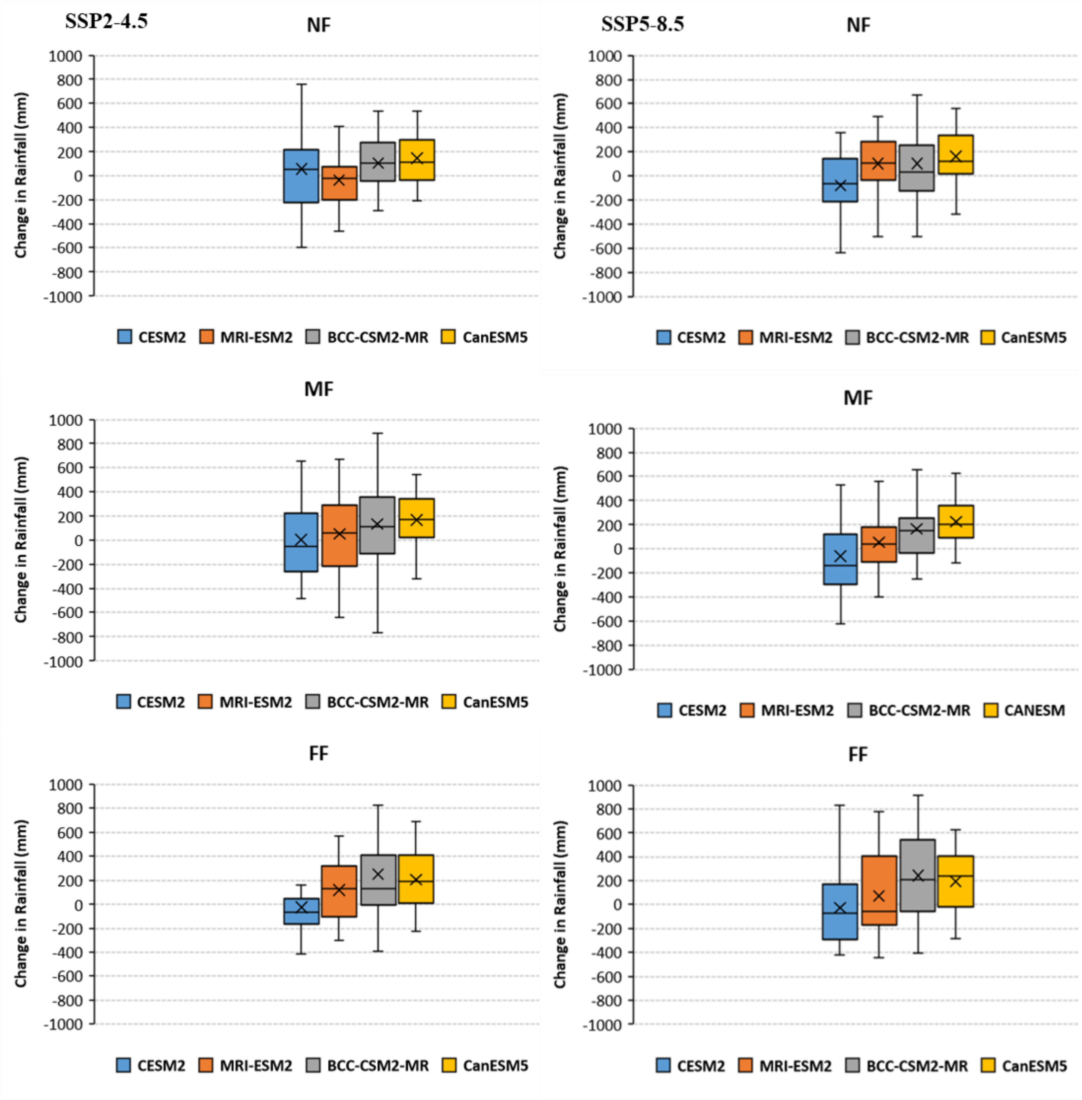
NF (2015-2039); MF (2040-2069); FF (2070-2100)

Change in Annual Rainfall Distribution

The change in the annual rainfall distribution of all four GCMs compared to baseline (Figure 6.4) for Chi Mun River basin shows an increase in mean annual rainfall in all future periods except MRI-ESM2 in NF, CESM2 in MF and FF under the SSP2-4.5 scenario. Furthermore, CESM2 project the maximum variation in change followed by BCC-CSM-2 and MRI_ESM2 models. Moreover, under SSP2-4.5, the climate models in NF, MF and FF are more positively skewed excluding MRI-ESM2 in NF, CanESM5 in MF and CESM2 in FF, which is more negatively skewed. In the case of the SSP5-8.5 scenario (Figure 6.4), most of all, the models are positively skewed, indicating an increase in average annual rainfall in the mid and far future.

Figure 6.4

Comparison of projected change in annual rainfall distribution for Chi Mun River basin (NF, MF,FF) for four GCMs under SSP2-4.5 and SSP5-8.5 scenario

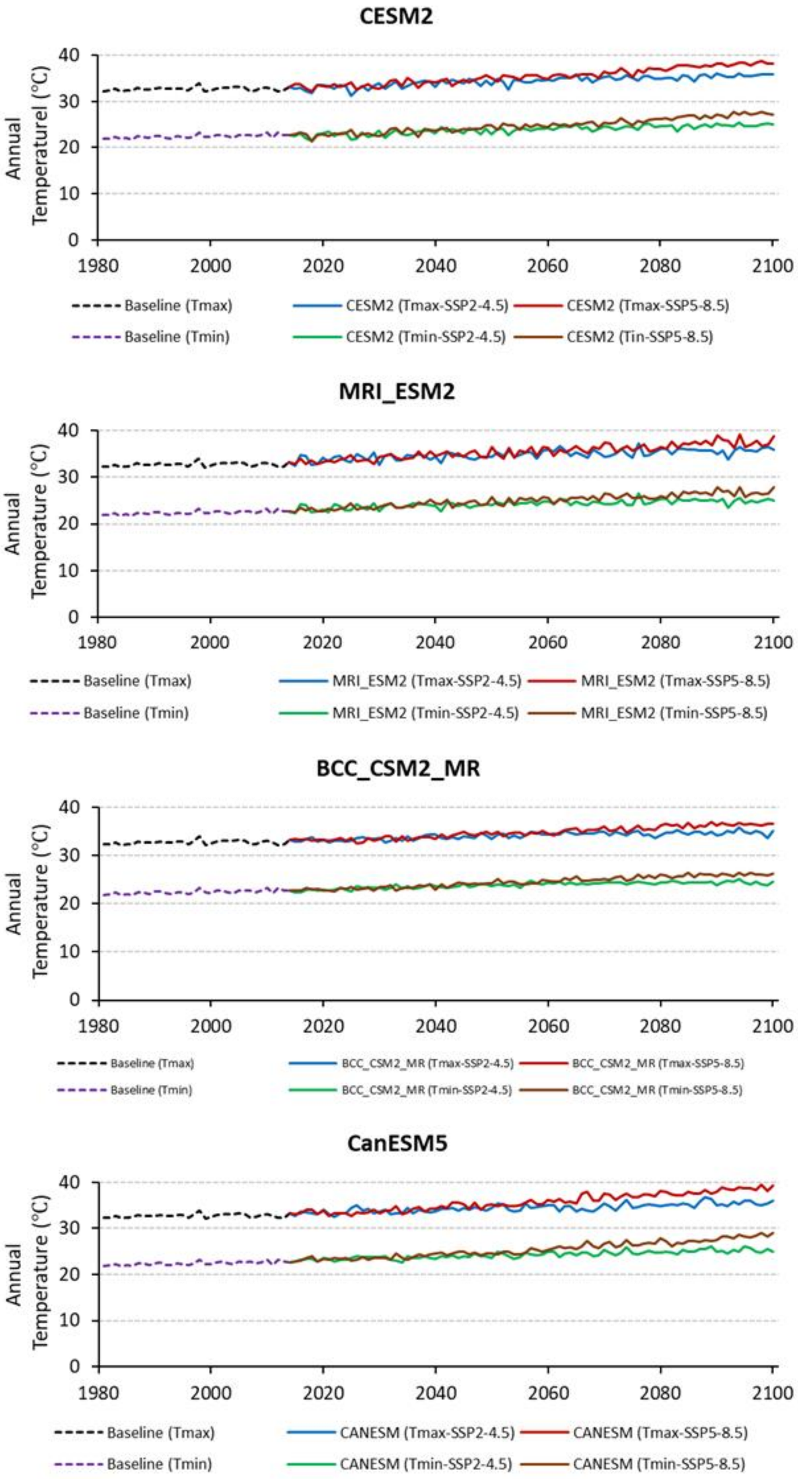


Projection of Temperature of Chi Mun River Basin

Figure 6.5 below shows the annual maximum temperature (Tmax) and minimum temperature (Tmin) trend plot of Chi Mun Basin for all four GCMs under two SSPs. The results show that all the GCMs indicate that the average annual maximum and minimum temperature is likely to increase under the SSP2-4.5 and SSP5-8.5 scenarios between 2015 to 2100. Furthermore, the line graph also indicates that after 2050 (MF), the SSP5-8.5 scenario is likely to have more increase in both temperatures than the SSP2-4.5 scenario. Under SSP5-8.5 scenario, the GCMs CESM2, MRI-ESM2, BCC-CSM2-MR and CanESM5 project maximum temperature up to 38.7°C, 39.2°C, 36.8°C and 39.4℃ and minimum temperature for Chi Mun river basin up to 27.8℃, 27.9℃, 26.5℃ and 29.1℃, respectively.

Figure 6.5

Projected annual maximum and minimum temperature trend for Chi Mun River basin (2015-2100) for four GCMs under SSP2-4.5 and SSP5-8.5 scenario



For a detailed analysis of change in average annual maximum and minimum temperature, the study compared the projected average annual maximum and minimum temperature (NF, MF and FF) of the Chi Mun basin with the baseline (1981-2014) average annual temperature under both SSP2-4.5 and SSP5-8.5 scenarios (Table 6.3).

Table 6.3

Comparison of projected average annual maximum temperature (2015-2100) of Chi Mun River basin with baseline (1981-2014) average annual maximum temperature under SSP2-4.5 and SSP5-8.5 scenarios

GCMs	Baseline Average Annual Maximum Temperature (°C) 1981-2014	Projected Average Annual Maximum Temperature (Tmax) (°C)					
		SSP2-4.5			SSP5-8.5		
		NF	MF	FF	NF	MF	FF
CESM2	**32.7**	33.2	34.4	35.4	33.5	35.1	37.4
MRI-ESM2		34.1	34.9	35.6	33.9	35.4	37.0
BCC-CSM2-MR		33.4	34.3	34.7	33.4	34.7	36.1
CanESM5		33.6	34.4	35.3	33.6	35.5	37.8

NF (2015-2039); MF (2040-2069); FF (2070-2100)

The table illustrates that under the SSP2-4.5 scenario, all the GCMs projects the increase in average annual maximum temperature of 0.5-1.4°C in NF, 1.7-2.2°C in MF and 2-2.9°C in FF compared to baseline of 32.7°C. MRI-ESM2 model projects the maximum increase in all the future periods. Similarly, under the SSP5-8.5 scenario, all the GCMs projects the increase in average annual maximum temperature of 0.7-1.2°C in NF, 2-2.8°C in MF and 3.4-5.1°C in FF compared to baseline of 32.7°C. The most increment is likely to occur in FF as projected by all models, and the CanESM5 in FF projects a maximum of 5.1°C and 2.8°C in MF. Overall, the change in average annual maximum temperature shows that the basin is likely to have increased maximum temperature up to 3°C-5°C as compared to the baseline conditions.

Furthermore, Table 6.4 below compares the projected average annual minimum temperature with the baseline average annual minimum temperature. The results under the SSP2-4.5 scenario shows that all the GCMs projects the increase in average annual minimum temperature of 0.4-1.2°C in NF, 1.5-1.9°C in MF and 2.2-2.9°C in FF compared to baseline of 22.4°C. MRI-ESM2 model projects the maximum increase in NF and MF while CanESM5 projects the maximum increase in the FF. The other models also exhibit a similar trend in the increase in average annual minimum temperature for the basin.

Table 6.4

Comparison of projected average annual minimum temperature (2015-2100) of Chi Mun River basin with baseline (1981-2014) average annual minimum temperature under SSP2-4.5 and SSP5-8.5 scenarios

GCMs	Baseline Average Annual Minimum Temperature (°C) 1981-2014	Projected Average Annual Minimum Temperature (Tmin) (°C)					
		SSP2-4.5			SSP5-8.5		
		NF	MF	FF	NF	MF	FF
CESM2	**22.4**	22.8	23.9	24.7	23.1	24.5	26.5
MRI-ESM2		23.6	24.4	24.9	23.6	24.9	26.4
BCC-CSM2-MR		23.1	24.0	24.4	23.2	24.4	25.8
CanESM5		23.4	24.2	25.1	23.5	25.1	27.4

NF (2015-2039); MF (2040-2069); FF (2070-2100)

Similarly, under the SSP5-8.5 scenario, all the GCMs projects the increase in average annual maximum temperature of 0.7-1.2°C in NF, 2.1-2.7°C in MF and 3.4-5°C in FF compared to baseline of 22.4°C. CanESM5 in projects the maximum increment in all the future periods. Furthermore, the most increment is likely to occur in MF and FF as projected by all models. Overall, the change in average annual minimum temperature shows that the basin is likely to have increased average minimum temperature, which is likely to be more than the change in the average annual maximum temperature indicating more hotter days in the basin. The study results on temperature agree with Chinvano et al. (2017) and Arunrat et al. (2018), indicating an increase in both maximum and minimum temperatures with likely chances of extended warmer periods in Chi River Basin, Thailand. Similarly, another study in different basins of Thailand shows that the spatial distributions of the mean changes in temperature are likely to be more than>4 °C in northern inland regions (Kiguchi et al., 2021) as projected by this study. The resulting increment in the temperature is likely to be more significant in the dry seasons in the Chi Mun River Basin (Li et al., 2021), resulting the increased evaporation and decrease streamflow. Furthermore, this is also likely to impact the shallow groundwater recharge in the region.

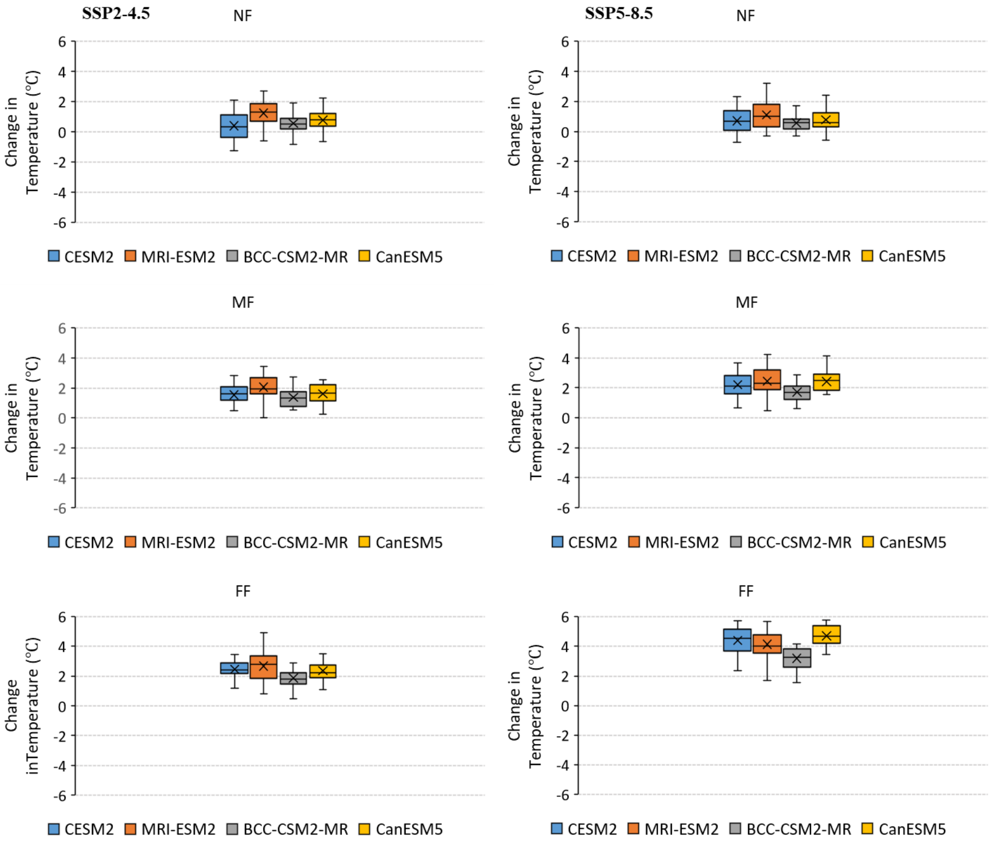
Change in annual temperature distribution

The change in the average annual maximum and minimum temperature distribution of all four GCMs compared to baseline (Figure 6.6) for the Chi Mun River basin shows an increase in mean annual minimum temperature under both SSP scenarios. In both the maximum and minimum temperature and under both the SSPs, all the GCMs are positively skewed, indicating an increase in average annual temperature. In most cases, the MRI-ESM2 climate model shows the maximum variation in change followed by CESM2 climate models in both scenarios. Overall, the average annual maximum and minimum temperature results show that all the models are symmetrically distributed with the mean increment likely to happen more in the mid and far future. Furthermore, the percentage change in minimum temperature is likely to be more than the change in the maximum temperature.

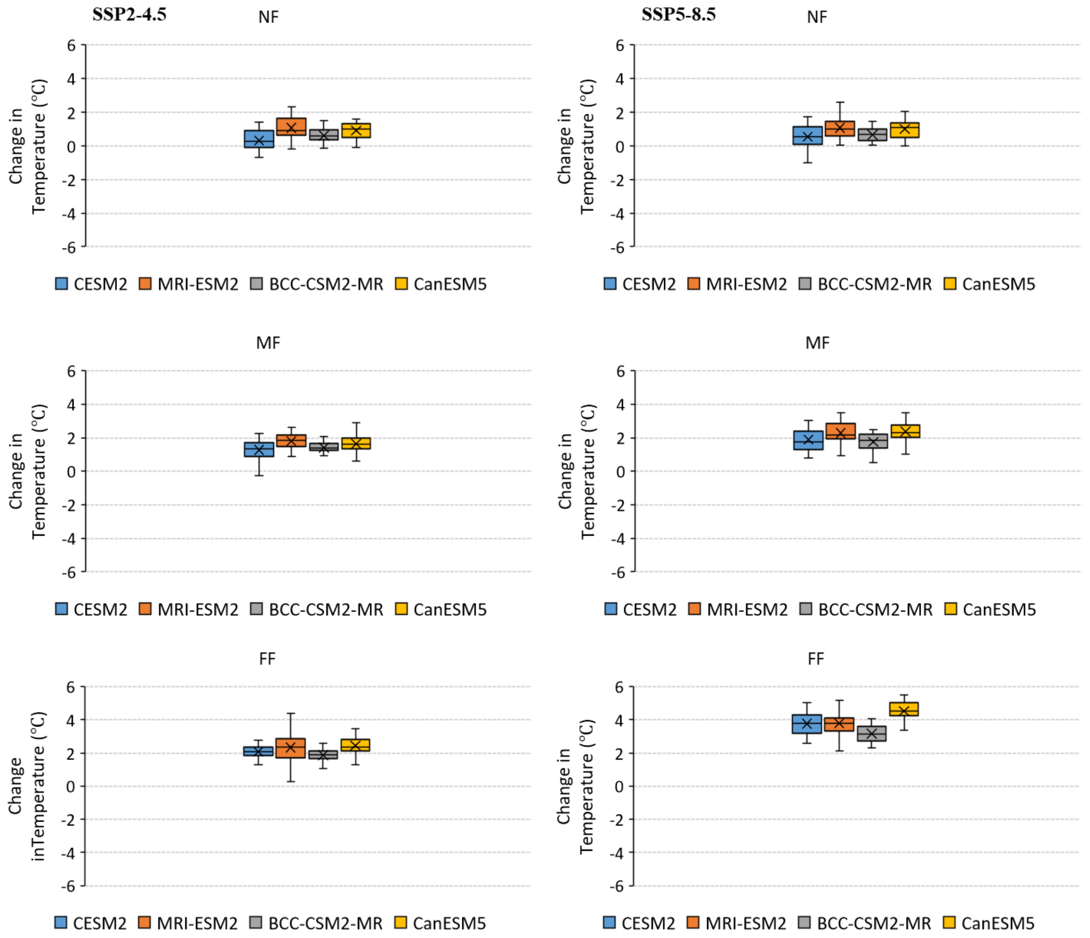
Figure 6.6

Comparison of projected change in average annual maximum and minimum temperature distribution for Chi Mun River basin (NF, MF, FF) for four GCMs under SSP2-4.5 and SSP5-8.5 scenario

Maximum Temperature (Tmax)



Minimum Temperature (Tmin)

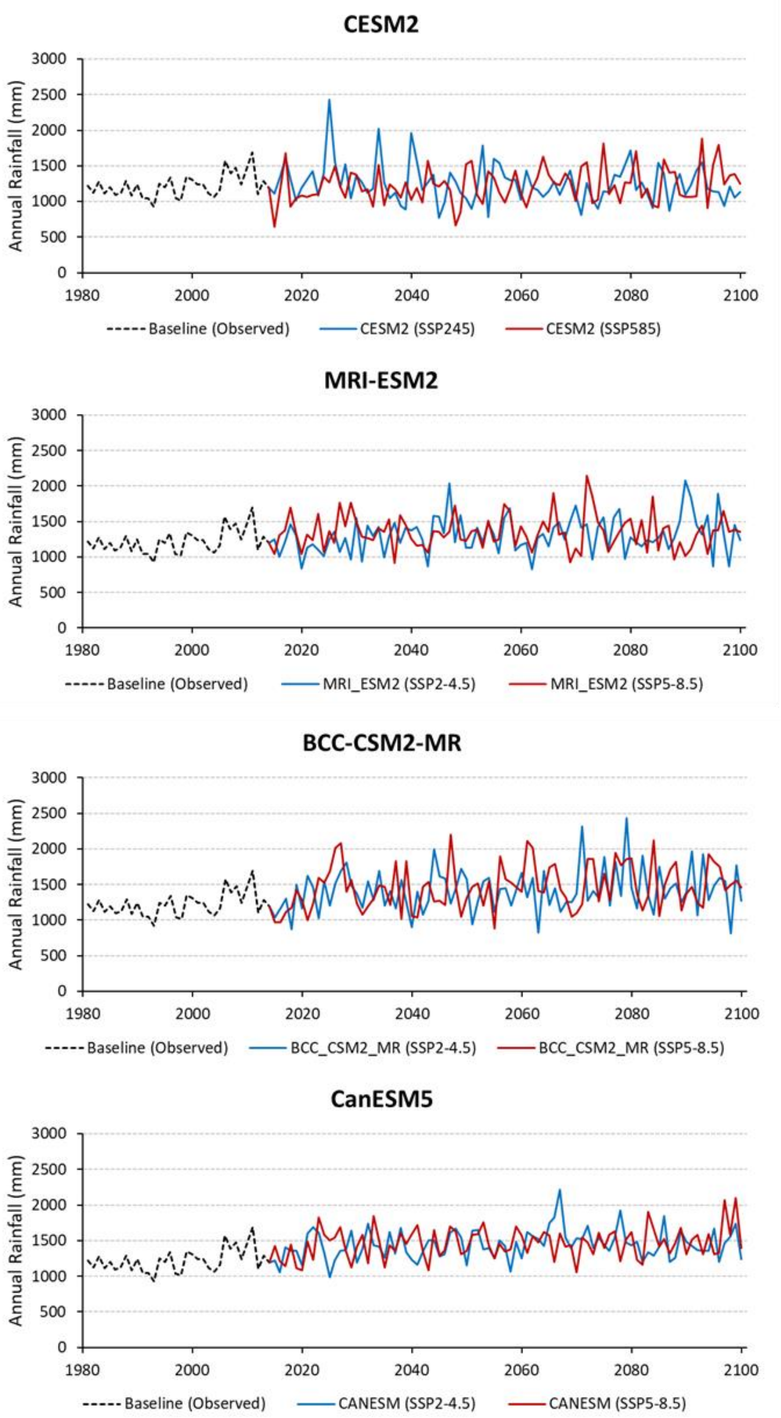


6.1.4 *Projection of Future Climate in Khon Kaen Province*

The study investigates the impact of multiple future stresses on groundwater in rapidly urbanizing areas, and Khon Kaen province is the rapidly urbanizing area in the selected study basin. Further analysis of changes in rainfall trends for the province has also been conducted. Figure 6.7 below shows the annual rainfall trend plot of Khon Kaen Province for all four GCMs under two SSPs, and the results from the majority of all the GCMs indicate that the annual rainfall is likely to increase in Khon Kaen province under both the SSPs between 2015 to 2100. CESM2 in NF under SSP2-4.5 and MRI-ESM2 in MF under SSP5-8.5 show a decreasing trend.

Figure 6.7

Projected annual rainfall trend for Khon Kaen Province (2015-2100) for four GCMs under SSP2-4.5 and SSP5-8.5 scenario



Furthermore, the change in the projected average annual rainfall (NF, MF and FF) of Khon Kaen Province is compared with the baseline (1981-2014) average annual rainfall under both SSP2-4.5 and SSP5-8.5 scenarios (Table 6.5). The results illustrate that under the SSP2-4.5 scenario, all the GCMs except CESM2 in FF projects, the average annual rainfall in Khon Kaen Province is likely to increase from 3% to 23% compared to baseline 1222 mm. Similar to the basin, BCC-CSM2-MR in FF and CanESM5 in MF projects the maximum increase of 23% and 21%, respectively.

Table 6.5

Comparison of projected average annual rainfall (2015-2100) of Khon Kaen province with baseline (1981-2014) average annual rainfall under SSP2-4.5 and SSP5-8.5 scenarios

GCMs	Baseline Average Annual Rainfall (mm) (1981-2014)	Projected Average Annual Rainfall (mm) SSP2-4.5			SSP5-8.5		
		NF	MF	FF	NF	MF	FF
CESM2	**1222**	1311	1260	1203	1175	1219	1276
MRI-ESM2		1217	1330	1368	1363	1335	1349
BCC-CSM2-MR		1363	1374	1506	1386	1451	1534
CanESM5		1390	1474	1465	1411	1477	1497

NF (2015-2039); MF (2040-2069); FF (2070-2100)

The overall results further indicate that the NF, MF and FF are likely to increase annual rainfall under the SSP2-4.5 scenario. Similarly, under the SSP5-8.5 scenario, all the GCMs except CESM2 in NF projects an increase in average annual rainfall from 4% to 26% compared to the baseline. BCC-CSM2-MR in FF and CanESM5 in FF projects the maximum increase of 26% and 23%, respectively. Similar to the SSP2-4.5 scenario, all future periods are likely to have increased annual rainfall compared to the baseline conditions under SSP5-8.5. Additionally, the overall change in the average annual rainfall indicates that rapidly urbanizing area is likely to have slightly more rainfall than the average annual rainfall of the basin.

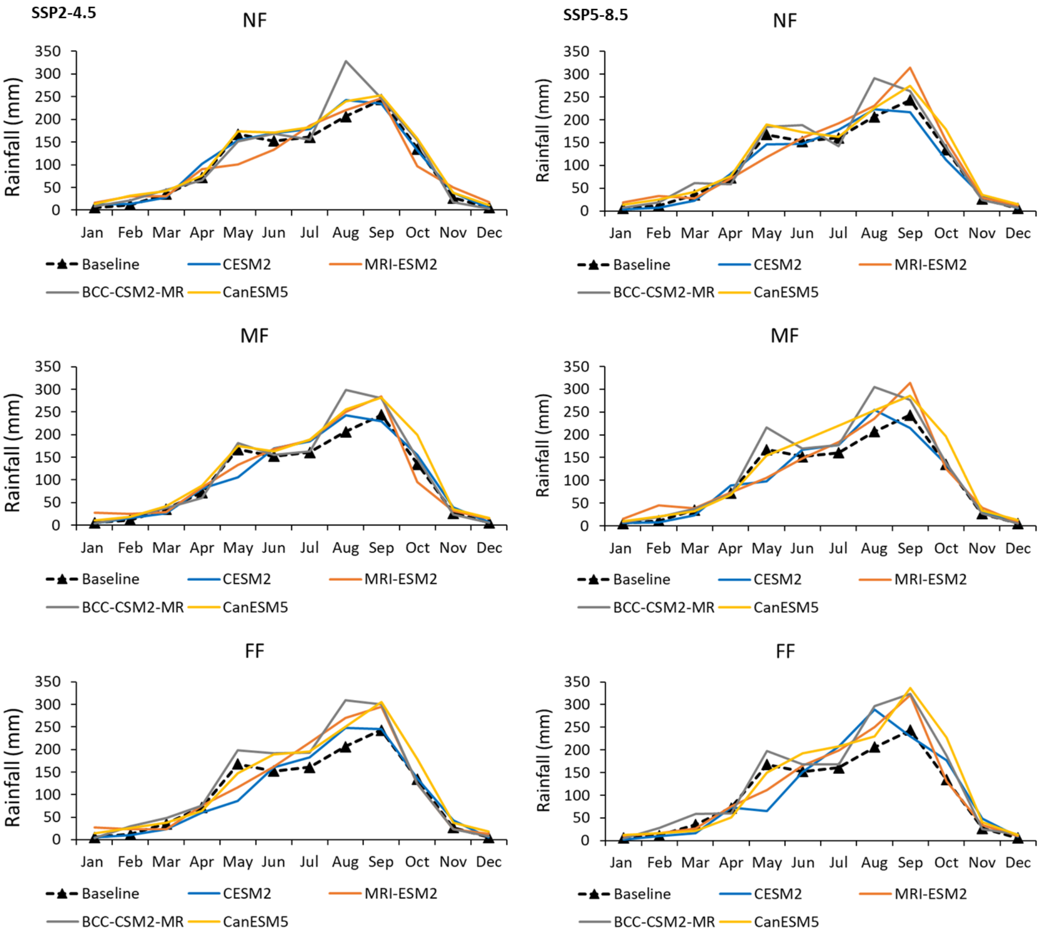
Change in Average Monthly Rainfall

The results for the future average monthly rainfall of the Khon Kaen province compared with the observed average monthly rainfall (baseline) for NF, MF and FF under SSP2-4.5 and SSP5-8.5 scenarios are shown in Figure 6.8. Under the SSP2-4.5 scenario majority of all the models shows that the May month of the wet season (May-October) in all the future period is likely to have decreased rainfall, whereas Khon Kaen is likely to have increased future average monthly rainfall in August as compared to the baseline conditions. Furthermore, the overall results show that most of the GCMs project an increase in average monthly rainfall, mainly in the wet season than the dry season (November-April). The major increase is likely from July to October in MF and FF.

Similarly, under the SSP5-8.5 scenario, most of all, the GCMs excluding BCC-CSM2-MR projects decrease in average monthly rainfall during April and May in Khon Kaen, whereas July, August, September during wet seasons is likely to receive more average monthly rainfall. Overall, under the SSP5-8.5 scenario, most of the GCMs projects increased in the average monthly rainfall in both dry and wet seasons and the increment is likely to be more in NF and MF than the NF.

Figure 6.8

Comparison projected average monthly rainfall for Khon Kaen Province (NF, MF, FF) with baseline average monthly rainfall under SSP2-4.5 and SSP5-8.5 scenarios



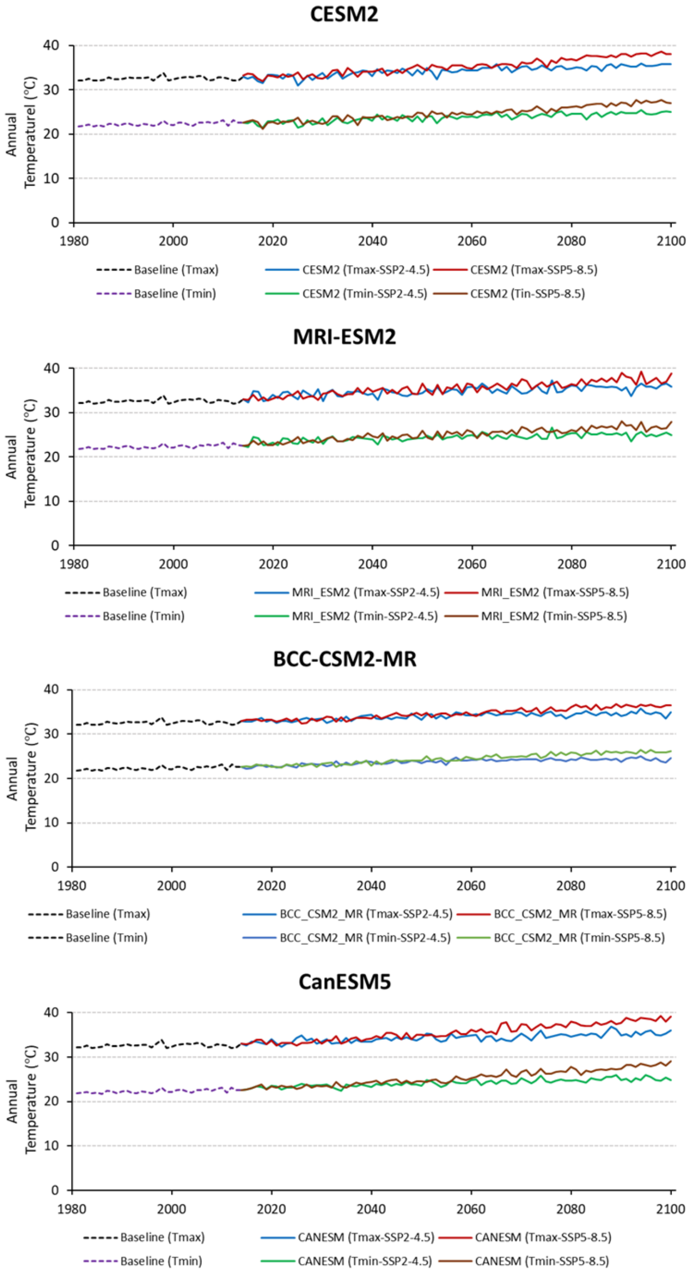
Projection of Temperature of Khon Kaen Province

The average annual maximum temperature (Tmax) and the average annual minimum temperature (Tmin) of the Khon Kaen province for the baseline is 33.8°C and 23.2°C. Figure 6.9 below shows Khon Kaen province's average annual maximum and minimum temperature trend plot for all four GCMs under two SSPs. The results show that all the GCMs indicate that the average annual maximum and minimum temperature is likely to increase under the SSP2-4.5 and SSP5-8.5 scenarios between 2015 to 2100.

Furthermore, the line graph also indicates that the SSP5-8.5 scenario is likely to have more increase in both temperatures than the SSP2-4.5 scenario, mainly from the MF until 2100. Under SSP5-8.5 scenarios, the GCMs CESM2, MRI-ESM2, BCC-CSM2-MR and CanESM5 project maximum temperature up to 38.6℃, 39.2℃, 36.8℃ and 39.2℃ and minimum temperature for Khon Kaen province up to 27.7℃, 28.0℃, 26.4℃ and 29.0℃, respectively. These maximum and minimum temperature trend for the province is similar to that of the basin.

Figure 6.9

Projected average annual maximum rainfall trend for Khon Kaen Province (2015-2100) for four GCMs under SSP2-4.5 and SSP5-8.5 scenario



For a detailed analysis of change in average annual maximum and minimum temperature, the study compared the projected average annual maximum and minimum temperature (NF, MF and FF) of the Khon Kaen province with the baseline (1981-2014) average annual temperature under both SSP2-4.5 and SSP5-8.5 scenarios (Table 6.6). The table illustrates that under the SSP2-4.5 scenario, all the GCMs projects the increase in average annual maximum temperature of 0.4-1.4°C in NF, 1.7-2.2°C in MF and 1.9-2.9°C in FF compared to baseline of 33.8°C. MRI-ESM2 model projects the maximum increase in all the future periods. Similarly, under the SSP5-8.5 scenario, all the GCMs projects the increase in average annual maximum temperature of 0.6-1.3°C in NF, 1.9-2.8°C in MF and 3.4-5.0°C in FF compared to baseline of 33.8°C. The most increment is likely to occur in FF as projected by all models, and the CanESM5 in FF projects a maximum of 5.0°C and 2.7°C in MF. Overall, the change in average annual maximum temperature shows that the basin is likely to have increased maximum temperature up to 3°C-5°C as compared to the baseline conditions and the trend for the province is similar to that of the basin.

Table 6.6

Comparison of projected average annual maximum temperature (2015-2100) of Khon Kaen province with baseline (1981-2014) average annual maximum temperature under SSP2-4.5 and SSP5-8.5 scenarios

GCMs	Baseline Average Annual Maximum Temperature (°C) 1981-2014	Projected Average Annual Maximum Temperature (Tmax) (°C)					
		SSP2-4.5			SSP5-8.5		
		NF	MF	FF	NF	MF	FF
CESM2	**32.6**	33	34.3	35.2	33.4	35	37.3
MRI-ESM2		34	34.8	35.5	33.9	35.4	37
BCC-CSM2-MR		33.2	34.1	34.5	33.2	34.5	36
CanESM5		33.4	34.2	35.1	33.4	35.3	37.6

NF (2015-2039); MF (2040-2069); FF (2070-2100)

Furthermore, Table 6.7 below compares the baseline and projected average annual minimum temperature of Khon Kaen province. The results under the SSP2-4.5 scenario shows that all the GCMs projects the increase in average annual minimum temperature of 0.4-1.4°C in NF, 1.5-2.1°C in MF and 2.0-2.6°C in FF compared to baseline of 23.2°C. MRI-ESM2 model projects the maximum increase in NF and MF while both MRI_ESM2 and CanESM5 projects the maximum increase in the FF. The other models also exhibit a similar increasing trend in the province. Similarly, under the SSP5-8.5 scenario, all the GCMs projects the increase in average annual maximum temperature of 0.7-1.3°C in NF, 2.2-2.7°C in MF and 3.4-5°C in FF compared to baseline of 23.2°C. CanESM5 projects the maximum increment in the mid and far future, while MRI-ESM2 projects the maximum increment in NF and MF. Furthermore, the most increment is likely to occur in MF and FF as projected by all models. Overall, the change in average annual minimum temperature shows that the province is likely to have increased average minimum temperature, which is likely to be more than the change in the average annual maximum temperature indicating more hotter days.

Similarly, the results for the future average monthly maximum and minimum temperature of the Khon Kaen province compared with the baseline for NF, MF and FF under SSP2-4.5 and SSP5-8.5 scenarios are shown in Appendix Figure A.2. Under both scenarios, all the models show that the average monthly maximum and minimum temperature is likely to increase with more increment in the MF and FF. Furthermore, the results also indicate that the dry season (Nov-Apr) is projected to have more increments than the wet seasons (May-Oct). However, all the models during the future period show that the hotter months of baseline (March-June) are likely to have more increments than other months. Overall, under both the SSP scenario, all the climate models projects increased the average monthly rainfall in dry and wet seasons, and the increment is likely to be more in MF and MF than the NF.

Table 6.7

Comparison of projected average annual minimum temperature (2015-2100) of Khon Kaen province with baseline (1981-2014) average annual minimum temperature under SSP2-4.5 and SSP5-8.5 scenarios

GCMs	Baseline Average Annual Minimum Temperature (°C) 1981-2014	Projected Average Annual Minimum Temperature (Tmin) (°C)					
		SSP2-4.5			SSP5-8.5		
		NF	MF	FF	NF	MF	FF
CESM2	**23.2**	22.7	23.8	24.6	23	24.5	26.4
MRI-ESM2		23.7	24.4	24.9	23.6	25	26.4
BCC-CSM2-MR		23	23.9	24.3	23.1	24.3	25.7
CanESM5		23.3	24.1	24.9	23.4	25	27.3

NF (2015-2039); MF (2040-2069); FF (2070-2100)

6.1.5 Statistical Significance Test of Projected Climate Trend in Khon Kaen Province

Rainfall Trend Significance Test

Table 6.8 and Table 6.9 below illustrates the comparison of project rainfall from all four GCMs for Khon Kaen Province, obtained from Mann Kendall test and Sen slope estimate under SSP2-4.5 and SSP5-8.5 scenario, respectively. Under SPP245, Table 6.8 shows that the monthly results are a mix of positive and negative trends in all the GCMs for Khon Kaen Province. The annual rainfall for all the climate models except CESM2 shows that the annual, dry season and wet season rainfall is likely to increase in NF, and the results from BCC-CSM-2-MR projects a non-significant (90% level of confidence) increase in dry season rainfall, whereas the other projected increment is not significant. Furthermore, the CESM2 model shows non-significant decreasing annual rainfall by 11.35 mm/year and a significant decreasing trend during the dry season at a 95% confidence level. In the case of MF, the majority of the models show a non-significant decreasing trend for annual, dry season and wet season, whereas the CanESM5 model shows the increasing trend for all three cases with a significant increasing trend in the annual and dry season at 95% level of confidence. In the case of FF, BCC-CSM2-MR and CanESM5 show a non-significant decreasing trend, whereas the CESM2 and MRI-ESM-2 show the non-significant increasing trend for the annual and wet season. All four models in the FF shows a non-significant decreasing trend during dry seasons in Khon Kaen Province.

Table 6.8

Values of Mann-Kendall test and Sen Slope estimate for projected future rainfall (NF, MF and FF) of Khon Kaen Province under SSP2-4.5 scenario

Time series	1_CESM2 NF (2015-2039)			2_MRI-ESM-0 NF (2015-2039)			3_BCC-CSM2-MR NF (2015-2039)			4_CanSEM NF (2015-2039)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	-0.304		-0.015	-1.238		-0.217	0.350		0.052	0.000		0.005
February	-1.611		-0.150	2.452	*	1.260	1.425		0.444	1.752	+	0.891
March	0.117		0.036	-0.631		-0.405	1.938	+	1.076	0.163		0.153
April	-1.705	+	-2.937	0.490		0.744	-0.070		-0.100	-1.985	*	-1.664
May	-2.079	*	-3.613	0.911		2.171	-0.584		-1.036	-0.257		-0.219
June	-0.210		-0.592	0.724		2.280	1.331		2.859	-0.070		-0.437
July	-0.537		-0.757	0.397		0.665	-0.117		-0.392	0.350		0.586
August	-0.724		-1.434	1.471		1.953	1.565		6.700	1.004		2.269
September	1.518		2.195	-0.257		-0.777	-1.845	+	-4.133	0.677		2.864
October	0.210		0.704	0.117		0.335	-0.257		-1.485	0.537		1.362
November	-0.444		-0.270	1.378		1.102	2.219	*	0.631	-0.257		-0.245
December	-0.350		-0.023	-0.163		-0.035	0.117		0.018	-0.911		-0.153
Annual	-1.611		-11.351	1.144		7.066	1.191		7.211	1.425		7.400
Dry Season	-2.219	*	-5.976	1.285		4.186	1.752	+	3.549	0.397		0.947
Wet Season	-0.817		-3.242	0.817		2.739	0.724		5.634	1.191		7.543

Time series	1_CESM2 MF (2040-2069)			2_MRI-ESM-0 MF (2040-2069)			3_BCC-CSM2-MR MF (2040-2069)			4_CanSEM MF (2040-2069)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	-1.035		-0.038	-1.142		-0.188	-0.285		-0.021	0.999		0.141
February	-0.393		-0.060	-0.785		-0.155	-0.642		-0.126	0.607		0.120
March	-0.178		-0.107	0.892		0.391	-0.464		-0.242	1.534		1.206
April	-1.106		-0.962	0.000		-0.057	0.856		0.290	0.321		0.200
May	-0.821		-1.205	-1.035		-2.093	0.856		1.397	0.214		0.271
June	0.892		1.249	-1.106		-1.669	-0.678		-0.855	-0.678		-0.585
July	0.785		1.005	1.392		1.135	-1.178		-1.871	0.000		-0.018
August	-0.535		-0.842	1.641		2.091	0.856		2.877	0.250		0.391
September	0.107		0.125	-0.285		-0.629	-0.428		-1.370	0.464		0.935
October	0.749		1.863	-0.393		-0.737	-0.357		-0.876	1.641		5.306
November	1.285		0.388	-1.142		-0.164	1.748	+	0.677	1.677	+	0.668
December	-0.393		-0.010	0.250		0.019	1.178		0.079	0.000		0.000
Annual	-0.464		-3.618	-0.500		-2.916	-0.393		-2.096	2.070	*	10.529
Dry Season	-0.535		-1.142	-0.143		-0.104	0.178		0.209	2.034	*	3.486
Wet Season	-0.500		-1.983	-0.642		-3.187	-0.500		-3.078	1.606		6.769
Time series	1_CESM2 FF (2070-2100)			2_MRI-ESM-0 FF (2070-2100)			3_BCC-CSM2-MR FF (2070-2100)			4_CanSEM FF (2070-2100)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	-0.748		-0.024	-1.802	+	-0.251	-1.462		-0.044	0.510		0.081
February	1.360		0.148	0.068		0.018	-1.020		-0.424	0.000		-0.002
March	-1.122		-0.180	-0.510		-0.129	-1.870	+	-1.116	-0.340		-0.215
April	1.326		1.043	-0.306		-0.248	-0.748		-0.509	0.612		0.193
May	-0.374		-0.277	-2.074	*	-3.373	-1.496		-2.993	-2.481	*	-2.442
June	0.000		-0.017	-0.680		-0.952	-0.714		-1.220	-1.802	+	-0.995
July	0.476		0.420	0.782		1.017	-0.136		-0.371	-0.850		-0.783
August	1.190		2.304	0.102		0.224	0.068		0.194	-0.782		-1.062
September	0.510		1.351	0.816		2.238	0.578		2.662	1.802	+	3.061
October	-0.782		-1.580	1.190		2.212	0.238		0.621	0.680		0.883
November	-0.340		-0.255	0.442		0.114	-0.408		-0.158	-1.326		-0.571
December	-1.020		-0.034	-0.646		-0.106	-0.238		-0.005	-1.054		-0.192
Annual	0.238		1.119	0.000		-0.248	-0.408		-3.088	-1.122		-4.478
Dry Season	-0.238		-0.301	-1.258		-1.340	-1.632		-2.603	-0.714		-0.807
Wet Season	0.510		2.546	0.102		1.851	-0.136		-1.061	-1.190		-3.797

Z is the direction of the trend; positive Z is upward and negative Z is downward. ***trend at α = 0.001 level of significance. **trend at α = 0.01 level of significance. *trend at α = 0.05 level of significance. + trend at α = 0.1 level of significance. Sen's slope estimate Q is a true slope of the linear trend of non-parametric data (change/year)

Under the SPP585 scenario, Table 6.9 also shows that the monthly results are a mix of positive and negative trends in all the GCMs for Khon Kaen Province. The annual rainfall, dry season and wet seasons for all the climate models show a non-significant increasing trend in NF except BCC-CSM2-MR, which shows a significant (90% level of confidence) increasing annual trend by 16 mm/year. Similarly, in the case of MF, all the models except CanESM5 for the annual and wet season show a non-significant rainfall trend (MRI-ESM-2 shows a significant increase by 4 mm/year) in Khon Kaen Province. The trend test for FF under the SSP5-8.5 scenario shows a mixed trend with all the models except BCC-CSM2-MR during dry seasons shows the non-significant decreasing trend while MRI-ESM-2 shows the significant decreasing trend by 2.4 mm/year at a 95% level of confidence. Furthermore, MRI-ESM-2 for the annual rainfall of Khon Kaen province and BCC-CSM2-MR for the wet season in FF shows a non-significant decreasing rainfall trend. Overall, the results for the trend analysis shows that the majority of models shows a non-significant decreasing rainfall trend in MF and FF under SSP2-4.5 while a non-significant increasing trend in NF and FF under the

SSP5-8.5 scenario. Furthermore, all models except BCC-CSM2-MR shows that the Khon Kaen province is likely to have lesser rainfall in the dry season during the FF and more rainfall during the NF.

Table 6.9

Values of Mann-Kendall test and Sen Slope estimate for projected future rainfall (NF, MF and FF) of Khon Kaen Province under SSP5-8.5 scenario

Time series	1_CESM2			2_MRI-ESM-0			3_BCC-CSM2-MR			4_CanSEM		
	NF (2015-2039)			NF (2015-2039)			NF (2015-2039)			NF (2015-2039)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	0.117		0.007	2.032	*	0.685	-0.163		-0.008	0.000		-0.001
February	1.144		0.133	-0.771		-0.286	-0.210		-0.037	0.631		0.269
March	1.752	+	0.564	0.350		0.165	0.958		1.032	1.051		0.435
April	0.070		0.075	-0.958		-1.155	0.817		0.730	-0.584		-0.351
May	0.257		0.724	-0.444		-1.084	-0.444		-0.765	0.023		0.132
June	-0.397		-0.516	-0.257		-0.649	0.163		0.444	0.257		0.393
July	0.000		0.003	1.051		1.136	-0.864		-1.381	0.771		1.040
August	0.444		0.346	1.098		2.095	1.191		4.019	1.752	+	3.007
September	0.631		1.118	-0.304		-0.565	1.098		5.092	1.051		4.831
October	0.070		0.154	0.304		0.953	0.163		0.528	-0.584		-1.675
November	2.359	*	1.555	0.304		0.099	1.004		0.512	0.070		0.047
December	-0.584		-0.053	0.490		0.127	1.238		0.113	2.452	*	0.789
Annual	1.098		5.923	0.958		6.279	1.845	+	15.931	1.051		7.122
Dry Season	0.864		1.809	1.191		2.335	0.864		2.569	1.144		1.847
Wet Season	0.631		3.849	0.257		1.202	1.285		14.267	0.771		5.520
Time series	1_CESM2			2_MRI-ESM-0			3_BCC-CSM2-MR			4_CanSEM		
	MF (2040-2069)			MF (2040-2069)			MF (2040-2069)			MF (2040-2069)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	-0.161		-0.004	1.356		0.248	-0.036		-0.003	0.607		0.095
February	-1.035		-0.166	0.357		0.096	1.534		0.454	0.178		0.095
March	0.428		0.127	0.963		0.518	0.821		0.481	-0.428		-0.109
April	0.607		0.650	1.713	+	1.499	1.249		0.872	0.250		0.193
May	0.143		0.155	0.036		0.120	1.356		2.587	0.892		0.860
June	0.321		0.446	1.320		1.890	0.143		0.449	-1.463		-1.475
July	0.178		0.156	-0.214		-0.502	-1.320		-1.653	-1.178		-1.441
August	0.214		0.398	2.248	*	3.093	1.998	*	4.281	1.963	*	2.261
September	1.249		1.209	-1.285		-2.726	-0.107		-0.373	-0.428		-1.032
October	1.606		2.997	-1.070		-1.293	2.177	*	2.929	0.071		0.053
November	0.749		0.294	-1.213		-0.361	0.178		0.058	0.785		0.349
December	-0.357		-0.036	0.535		0.053	-0.892		-0.052	-0.285		-0.038
Annual	1.213		6.464	0.821		4.084	1.249		9.642	-0.107		-0.656
Dry Season	1.035		1.738	1.891	+	3.908	0.999		1.964	0.500		0.940
Wet Season	1.249		4.601	0.107		0.546	1.178		8.379	-0.321		-1.517
Time series	1_CESM2			2_MRI-ESM-0			3_BCC-CSM2-MR			4_CanSEM		
	FF (2070-2100)			FF (2070-2100)			FF (2070-2100)			FF (2070-2100)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	-0.272		-0.007	-0.782		-0.058	0.408		0.024	-0.476		-0.089
February	-1.020		-0.060	-0.306		-0.033	0.306		0.049	-0.204		-0.031
March	-0.782		-0.110	0.238		0.042	0.646		0.605	-0.510		-0.096
April	-0.680		-0.733	-0.680		-0.735	-0.544		-0.332	0.136		0.056
May	-1.564		-1.129	0.374		0.380	0.748		1.024	0.306		0.595
June	0.408		0.803	-0.034		-0.048	-1.258		-2.197	1.326		1.995
July	1.020		0.793	0.374		0.380	-0.136		-0.208	-1.598		-1.469
August	0.884		1.650	0.170		0.348	-0.306		-0.697	-0.034		-0.049
September	0.136		0.379	0.986		2.256	0.204		1.030	0.374		0.899
October	1.156		3.191	-1.020		-1.577	0.340		0.837	1.190		4.047
November	1.224		0.436	-1.292		-0.511	0.476		0.129	0.510		0.196
December	-0.119		-0.008	-2.074	*	-0.187	0.612		0.095	0.000		0.010
Annual	0.714		4.511	-0.340		-1.531	0.068		0.785	1.054		5.095
Dry Season	-0.238		-0.381	-2.244	*	-2.414	0.238		0.361	-0.068		-0.048
Wet Season	0.782		4.742	0.646		3.705	-0.102		-0.771	1.292		5.305

Z is the direction of the trend; positive Z is upward and negative Z is downward. ***trend at α = 0.001 level of significance. **trend at α = 0.01 level of significance. *trend at α = 0.05 level of significance. + trend at α = 0.1 level of significance. Sen's slope estimate Q is a true slope of the linear trend of non-parametric data (change/year)

Maximum Temperature Trend - Significance Test

Table 6.10 and Table 6.11 below illustrates the comparison of the maximum temperature of all four GCMs for Khon Kaen Province, obtained from Mann Kendall test and Sen slope estimate under SSP2-4.5 and SSP5-8.5 scenario, respectively. Under SPP245, Table 6.10 shows that the monthly results are the mix of positive and negative trends in all the GCMs for Khon Kaen Province, with the majority of the positive trends in NF, MF and FF. Under the SSP2-4.5 scenario, CESM2 and BCC-CSM2-MR project a significant increasing maximum temperature trend for the annual, dry, and wet seasons. CESM2 in NF projects about a significant increase of 0.1°C/year at 99% confidence level while BCC-CSM2-MR in NF projects a significant increasing trend of maximum temperature during wet and dry seasons at 95% level of confidence and a significant increase at 99% level of confidence annually. A similar trend is projected in the mid-future by all the climate models where BCC-CSM2-MR projects a significant increase in the maximum temperature trend annually and during the wet season at a 99% confidence level by 0.04-0.05°C/year. Additionally, all the GCMs during the wet season's project a significant increasing trend of maximum temperature at 95 to 99.9% confidence level. In the case of FF, all the climate models project the increasing trend for the maximum temperature annually, wet seasons and dry seasons. Except for BCC-CSM2-MR, all the model projects a significant increasing trend of maximum temperature for annual and wet seasons at 90-99% level in confidence.

Table 6.10

Values of Mann-Kendall test and Sen Slope estimate for projected future maximum temperature (NF, MF and FF) of Khon Kaen Province under SSP2-4.5 scenario

Time series	CESM2			MRI-ESM2			BCC-CSM2-MR			CanSEM5		
	NF (2015-2039)			NF (2015-2039)			NF (2015-2039)			NF (2015-2039)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	1.892	+	0.069	0.724		0.045	0.631		0.029	0.490		0.021
February	-0.023		-0.003	0.864		0.048	-0.117		-0.005	-2.359	*	-0.086
March	2.032	*	0.086	0.958		0.065	0.117		0.007	-0.397		-0.018
April	1.845	+	0.105	1.238		0.080	1.565		0.086	1.471		0.106
May	2.219	*	0.103	-0.257		-0.025	-0.210		-0.014	1.565		0.050
June	1.565		0.058	0.070		0.008	-0.163		-0.010	2.592	**	0.055
July	1.985	*	0.049	0.864		0.021	2.312	*	0.057	1.938	+	0.027
August	2.452	*	0.049	1.144		0.022	-0.724		-0.008	-0.350		-0.006
September	0.304		0.008	2.079	*	0.049	1.331		0.062	-0.210		-0.007
October	1.098		0.031	2.032	*	0.055	2.079	*	0.077	-0.117		-0.009
November	0.958		0.039	1.985	*	0.062	1.051		0.030	1.425		0.050
December	1.938	+	0.095	1.611		0.079	1.285		0.065	0.864		0.054
Annual	2.639	**	0.060	1.098		0.037	3.013	**	0.034	1.004		0.017
Dry Season	2.592	**	0.065	1.752	+	0.072	2.125	*	0.039	0.584		0.014
Wet Season	2.686	**	0.061	0.771		0.025	1.985	*	0.025	1.285		0.017
Time series	CESM2			MRI-ESM2			BCC-CSM2-MR			CanSEM5		
	MF (2040-2069)			MF (2040-2069)			MF (2040-2069)			MF (2040-2069)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q

January	0.500		0.019	0.143		0.008	0.464		0.009	0.250		0.006
February	1.106		0.036	1.570		0.055	1.820	+	0.058	-0.892		-0.043
March	0.250		0.011	0.999		0.044	0.607		0.024	-0.642		-0.021
April	0.963		0.028	0.464		0.010	0.856		0.022	-1.356		-0.064
May	2.105	*	0.088	1.392		0.100	1.035		0.040	0.928		0.026
June	1.106		0.040	2.355	*	0.156	1.927	+	0.058	3.176	**	0.042
July	1.070		0.021	1.320		0.023	3.104	**	0.053	3.854	***	0.036
August	2.676	**	0.048	1.570		0.015	2.284	*	0.048	2.498	*	0.026
September	0.999		0.020	0.928		0.019	1.606		0.045	3.283	**	0.039
October	0.749		0.015	1.249		0.026	1.142		0.033	0.500		0.008
November	1.070		0.048	1.463		0.035	1.070		0.027	0.785		0.017
December	0.607		0.017	0.321		0.010	0.571		0.023	0.214		0.009
Annual	2.391	*	0.029	2.426	*	0.041	3.782	***	0.040	0.642		0.008
Dry Season	1.606		0.025	1.106		0.021	2.105	*	0.023	-0.678		-0.014
Wet Season	2.533	*	0.039	2.533	*	0.055	3.782	***	0.052	3.211	**	0.031

Time series	CESM2			MRI-ESM2			BCC-CSM2-MR			CanSEM5		
	FF (2070-2100)			FF (2070-2100)			FF (2070-2100)			FF (2070-2100)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	2.040	*	0.061	-0.408		-0.015	-0.578		-0.017	1.088		0.064
February	2.583	**	0.066	0.782		0.035	-0.238		-0.010	0.374		0.027
March	1.734	+	0.068	0.680		0.029	1.462		0.041	1.326		0.050
April	-0.204		-0.006	1.190		0.037	0.000		0.001	-0.272		-0.009
May	0.918		0.036	2.583	**	0.174	1.666	+	0.060	2.447	*	0.108
June	0.408		0.015	1.700	+	0.094	1.088		0.017	2.787	**	0.032
July	1.700	+	0.025	-0.102		-0.001	0.714		0.015	1.292		0.010
August	0.544		0.008	1.258		0.018	0.238		0.004	2.481	*	0.025
September	1.326		0.019	1.054		0.018	-0.136		-0.005	0.408		0.004
October	1.870	+	0.049	0.510		0.011	-0.476		-0.015	0.238		0.003
November	-0.136		-0.003	1.156		0.025	0.102		0.006	0.374		0.010
December	-0.374		-0.012	0.102		0.004	-0.408		-0.014	0.646		0.031
Annual	3.093	**	0.029	1.734	+	0.034	1.224		0.011	2.379	*	0.029
Dry Season	2.142	*	0.027	1.190		0.017	0.680		0.007	1.496		0.034
Wet Season	2.176	*	0.033	2.108	*	0.056	1.530		0.016	3.161	**	0.033

Z is the direction of the trend; positive Z is upward and negative Z is downward. ***trend at $\alpha = 0.001$ level of significance. **trend at $\alpha = 0.01$ level of significance. *trend at $\alpha = 0.05$ level of significance. + trend at $\alpha = 0.1$ level of significance. Sen's slope estimate Q is a true slope of the linear trend of non-parametric data (change/year)

Under the SPP585 scenario, as shown in Table 6.11 shows the results are similar to the SSP2-4.5 scenario. The majority of the models show a highly significant increasing trend of maximum temperature in MF and FF for annual, dry and wet seasons of Khon Kaen province. MRI- ESM2 during NF projects highly significant annual and dry seasons increase in maximum temperature by about 0.07°C/year and 0.07°C/year respectively. Similarly, during the three-time series, all the GCMs projects a significant increasing maximum temperature trend in MF at 95-99.9% confidence level. In the case of FF, all the GCMs projects a significant increasing trend at 95-99% level of confidence, excluding MRI-ESM2 during wet seasons, which is significant at a 90% level of confidence. Overall, the results for the trend analysis shows that the majority of models shows that the Khon Kaen province is likely to have a significant increase in maximum temperature under both the SSPs during annual, dry and wet seasons.

Table 6.11

Values of Mann-Kendall test and Sen Slope estimate for projected future maximum temperature (NF, MF and FF) of Khon Kaen Province under SSP5-8.5 scenario

Time series	CESM2			MRI-ESM2			BCC-CSM2-MR			CanSEM5		
	NF (2015-2039)			NF (2015-2039)			NF (2015-2039)			NF (2015-2039)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	0.584		0.028	2.733	**	0.131	-0.210		-0.008	0.817		0.054
February	1.051		0.035	-0.163		-0.012	0.070		0.005	0.210		0.009
March	0.490		0.025	2.452	*	0.110	-0.444		-0.020	0.304		0.015
April	1.051		0.033	3.293	***	0.197	1.938	+	0.077	-0.537		-0.042
May	0.584		0.026	1.471		0.148	-0.397		-0.022	1.985	*	0.075
June	1.238		0.029	0.070		0.003	0.864		0.032	3.060	**	0.050
July	1.004		0.029	0.444		0.011	0.444		0.009	2.919	**	0.042
August	4.087	***	0.067	1.004		0.030	0.631		0.015	2.219	*	0.030
September	1.471		0.027	1.518		0.040	1.144		0.028	0.677		0.015
October	2.312	*	0.070	2.172	*	0.049	1.285		0.060	0.070		0.004
November	1.098		0.056	2.032	*	0.081	0.163		0.010	2.406	*	0.113
December	0.584		0.031	1.658	+	0.084	1.985	*	0.096	1.098		0.047
Annual	1.752	+	0.043	3.620	***	0.073	1.471		0.020	2.125	*	0.028
Dry Season	1.471		0.036	4.087	***	0.092	1.518		0.023	1.191		0.025
Wet Season	1.518		0.040	1.752	+	0.042	1.238		0.023	2.592	**	0.039
Time series	CESM2			MRI-ESM2			BCC-CSM2-MR			CanSEM5		
	MF (2040-2069)			MF (2040-2069)			MF (2040-2069)			MF (2040-2069)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	1.142		0.027	1.713	+	0.069	1.499		0.059	1.463		0.048
February	2.355	*	0.080	2.783	**	0.105	1.570		0.064	1.178		0.041
March	2.426	*	0.088	1.356		0.054	0.785		0.023	1.998	*	0.069
April	2.177	*	0.060	-0.143		-0.011	2.177	*	0.059	1.320		0.075
May	1.677	+	0.063	0.214		0.025	0.714		0.022	1.927	+	0.104
June	1.820	+	0.074	0.678		0.041	1.106		0.022	4.496	***	0.071
July	3.176	**	0.062	2.105	*	0.035	3.640	***	0.055	5.745	***	0.075
August	3.711	***	0.061	1.392		0.021	1.891	+	0.028	5.352	***	0.062
September	3.675	***	0.050	2.391	*	0.048	0.785		0.026	3.925	***	0.066
October	1.641		0.030	2.105	*	0.031	1.035		0.023	3.711	***	0.069
November	0.714		0.025	1.534		0.033	2.391	*	0.062	1.748	+	0.056
December	0.642		0.030	1.570		0.060	1.070		0.032	-0.036		-0.001
Annual	4.032	***	0.051	2.319	*	0.040	4.103	***	0.041	4.068	***	0.058
Dry Season	3.425	***	0.048	2.355	*	0.053	3.568	***	0.047	2.319	*	0.043
Wet Season	3.461	***	0.055	1.392		0.032	3.176	**	0.034	4.425	***	0.072
Time series	CESM2			MRI-ESM2			BCC-CSM2-MR			CanSEM5		
	FF (2070-2100)			FF (2070-2100)			FF (2070-2100)			FF (2070-2100)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	2.889	**	0.080	-0.068		-0.003	0.646		0.030	1.156		0.057
February	2.685	**	0.101	1.938	+	0.087	-0.374		-0.011	3.025	**	0.129
March	2.685	**	0.088	0.646		0.032	1.122		0.057	1.632		0.055
April	3.195	**	0.096	2.278	*	0.104	-0.442		-0.012	2.312	*	0.095
May	4.147	***	0.118	0.850		0.051	2.176	*	0.065	0.952		0.053
June	2.651	**	0.071	1.224		0.085	1.632		0.049	2.583	**	0.051
July	4.283	***	0.084	3.501	***	0.068	3.229	**	0.070	5.269	***	0.073
August	4.453	***	0.079	3.093	**	0.047	2.040	*	0.034	4.691	***	0.071
September	3.637	***	0.093	2.923	**	0.054	1.734	+	0.033	4.759	***	0.082
October	2.210	*	0.064	1.870	+	0.035	0.102		0.004	4.317	***	0.087
November	0.476		0.022	1.258		0.046	1.462		0.056	3.773	***	0.079
December	2.379	*	0.058	0.748		0.037	0.782		0.033	1.870	+	0.072
Annual	5.609	***	0.077	2.651	**	0.051	3.773	***	0.040	4.521	***	0.071
Dry Season	4.453	***	0.072	2.244	*	0.050	2.413	*	0.036	3.943	***	0.080
Wet Season	5.201	***	0.084	1.802	+	0.056	3.909	***	0.048	4.283	***	0.071

Z is the direction of the trend; positive Z is upward and negative Z is downward. ***trend at α = 0.001 level of significance. **trend at α = 0.01 level of significance. *trend at α = 0.05 level of significance. + trend at α = 0.1 level of significance. Sen's slope estimate Q is a true slope of the linear trend of non-parametric data (change/year)

Minimum Temperature Trend - Significance Test

Table 6.12 and Table 6.13 below illustrates the comparison of the minimum temperature of all four GCMs for Khon Kaen Province, obtained from Mann Kendall test and Sen slope estimate under SSP2-4.5 and SSP5-8.5 scenario, respectively.

Table 6.12

Values of Mann-Kendall test and Sen Slope estimate for projected future minimum temperature (NF, MF and FF) of Khon Kaen Province under SSP2-4.5 scenario

Time series	CESM2 NF (2015-2039)			MRI-ESM2 NF (2015-2039)			BCC-CSM2-MR NF (2015-2039)			CanSEM5 NF (2015-2039)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	0.677		0.030	0.584		0.052	1.798	+	0.050	1.378		0.051
February	0.444		0.025	1.144		0.073	0.724		0.026	-0.444		-0.035
March	0.817		0.029	0.911		0.071	1.238		0.040	0.023		0.002
April	1.331		0.031	2.312	*	0.087	1.892	+	0.070	1.238		0.033
May	2.265	*	0.093	-0.117		-0.009	0.257		0.006	2.265	*	0.033
June	1.518		0.035	0.724		0.026	1.471		0.020	4.040	***	0.045
July	2.219	*	0.027	3.013	**	0.027	3.153	**	0.034	3.713	***	0.036
August	3.340	***	0.032	2.966	**	0.029	3.340	***	0.025	2.873	**	0.023
September	1.611		0.017	3.386	***	0.045	0.771		0.015	0.257		0.003
October	1.098		0.040	1.098		0.041	3.200	**	0.069	-1.331		-0.040
November	0.117		0.008	1.798	+	0.071	2.499	*	0.045	0.771		0.038
December	1.378		0.060	1.565		0.090	2.686	**	0.085	1.144		0.038
Annual	2.219	*	0.037	2.032	*	0.052	3.807	***	0.046	2.079	*	0.026
Dry Season	1.378		0.044	2.079	*	0.078	3.620	***	0.063	2.359	*	0.033
Wet Season	2.733	**	0.044	1.611		0.026	3.200	**	0.026	1.658	+	0.017
Time series	CESM2 MF (2040-2069)			MRI-ESM2 MF (2040-2069)			BCC-CSM2-MR MF (2040-2069)			CanSEM5 MF (2040-2069)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	0.178		0.014	0.000		-0.004	-0.071		-0.001	0.178		0.003
February	0.393		0.017	1.713	+	0.055	1.320		0.047	-0.036		-0.001
March	-0.071		-0.008	0.963		0.028	0.749		0.019	0.642		0.012
April	0.428		0.008	0.107		0.004	1.463		0.030	0.036		0.002
May	1.891	+	0.054	1.463		0.080	2.962	**	0.057	1.820	+	0.026
June	1.677	+	0.040	2.712	**	0.086	2.105	*	0.027	3.818	***	0.024
July	1.641		0.021	3.533	***	0.028	2.997	**	0.027	3.675	***	0.028
August	3.533	***	0.032	4.246	***	0.025	2.533	*	0.018	4.210	***	0.026
September	3.176	**	0.024	2.855	**	0.019	1.249		0.018	3.283	**	0.036
October	1.677	+	0.043	0.250		0.005	0.999		0.017	2.070	*	0.056
November	0.856		0.035	1.320		0.038	0.428		0.021	1.499		0.054
December	0.535		0.023	0.250		0.007	1.534		0.035	0.999		0.028
Annual	1.606		0.023	2.855	**	0.031	3.640	***	0.026	2.569	*	0.025
Dry Season	0.821		0.014	1.106		0.011	2.212	*	0.027	1.285		0.020
Wet Season	2.997	**	0.035	3.318	***	0.042	3.640	***	0.026	3.711	***	0.032
Time series	CESM2 FF (2070-2100)			MRI-ESM2 FF (2070-2100)			BCC-CSM2-MR FF (2070-2100)			CanSEM5 FF (2070-2100)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	1.666	+	0.057	-1.360		-0.044	-1.292		-0.031	0.714		0.030
February	1.870	+	0.060	0.170		0.015	-0.918		-0.030	0.272		0.014
March	1.904	+	0.050	-0.170		-0.010	0.680		0.015	1.326		0.038
April	1.020		0.025	0.408		0.017	-0.374		-0.011	0.000		0.002
May	1.326		0.035	2.312	*	0.103	1.190		0.017	2.685	**	0.050
June	0.340		0.009	1.598		0.049	2.074	*	0.018	3.841	***	0.019
July	2.549	*	0.023	0.306		0.003	2.855	**	0.027	3.943	***	0.014
August	1.632		0.011	2.176	*	0.011	1.054		0.012	4.215	***	0.019
September	2.855	**	0.022	1.802	+	0.017	0.646		0.009	2.855	**	0.019
October	1.768	+	0.035	1.326		0.029	-0.748		-0.012	0.136		0.002
November	-0.612		-0.024	1.054		0.031	0.238		0.009	-0.510		-0.014
December	-0.816		-0.041	-0.238		-0.012	-1.088		-0.029	0.204		0.004
Annual	2.719	**	0.020	1.428		0.018	0.374		0.003	2.278	*	0.017
Dry Season	1.768	+	0.023	0.000		-0.001	-0.408		-0.003	0.986		0.019
Wet Season	2.583	**	0.024	2.719	**	0.036	1.530		0.011	2.787	**	0.021

Z is the direction of the trend; positive Z is upward and negative Z is downward. ***trend at $\alpha = 0.001$ level of significance. **trend at $\alpha = 0.01$ level of significance. *trend at $\alpha = 0.05$ level of significance. + trend at $\alpha = 0.1$ level of significance. Sen's slope estimate Q is a true slope of the linear trend of non-parametric data (change/year)

Under SPP245, Table 6.12 shows that the majority of all the models have projected an increase in monthly minimum temperature at a mixed level of significance. Under the SSP2-4.5 scenario, all four GCMs except CESM2 in the dry season and MRI-ESM2 during wet seasons shows a significant increasing minimum temperature annually and both seasons. The level of confidence of the significant trend ranges from 90% to 99.9%. Similarly, in MF, all climate models project a highly significant increase in minimum temperature during wet seasons at 0.02-0.04℃/year. Further, all the models project increasing the annual minimum temperature of Khon Kaen province during MF. Most of these projections are statistically significant at 99-99.9% confidence level, excluding CESM2, which shows a non-significant increasing trend. The FF under the SSP2-4.5 scenario also projects the increase in the minimum temperature in all the time series, but most of the increments are not significant statistically. Furthermore, the results show that Khon Kaen during FF is likely to have a highly significant increase in minimum temperature trend.

Under the SPP585 scenario, as shown in Table 6.13 shows the results are similar to the SSP2-4.5 scenario as the majority of the models shows a highly significant increasing trend of maximum temperature in NF, MF and FF for annual, dry and wet seasons of Khon Kaen province. All the GCMs majorly projected an increase in monthly minimum temperature at a mixed level of significance. Under the SSP5-8.5 scenario, all four GCMs in NF except CESM2 in dry season project a statistically significant increase in minimum temperature annually and seasonally (90-99.9% significance level). Similarly, all the climate models project a statistically significant increase in minimum temperature ranging from 95% to 99.9 % confidence level. The trend is likely to persist similarly statistically in FF, where all models except MRI-ESM2 during dry season show statistically significant increasing minimum temperature. Overall, the results for the trend analysis shows that the majority of models shows that the Khon Kaen province is likely to have a significant increase in minimum temperature under both the SSPs during annual, dry and wet seasons. The major statistically significant projection is likely on MF and FF of the SSP5-8.5 scenario with a highly significant trend during the annual and wet season.

Table 6.13

Values of Mann-Kendall test and Sen Slope estimate for projected future minimum temperature (NF, MF and FF) of Khon Kaen Province under SSP5-8.5 scenario

Time series	CESM2 NF (2015-2039)			MRI-ESM2 NF (2015-2039)			BCC-CSM2-MR NF (2015-2039)			CanSEM5 NF (2015-2039)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	0.257		0.024	2.499	*	0.124	0.304		0.012	0.817		0.036
February	0.444		0.026	-0.257		-0.018	0.350		0.023	0.163		0.012
March	1.144		0.043	2.079	*	0.112	0.444		0.012	1.004		0.049
April	0.817		0.039	3.153	**	0.172	2.219	*	0.060	-0.117		-0.003
May	0.864		0.040	2.125	*	0.122	1.658	+	0.027	2.499	*	0.049
June	1.752	+	0.031	1.098		0.029	1.985	*	0.031	4.461	***	0.032
July	2.359	*	0.032	3.153	**	0.032	1.191		0.012	4.694	***	0.042
August	5.255	***	0.052	2.873	**	0.040	2.312	*	0.026	4.928	***	0.038
September	3.200	**	0.044	3.246	**	0.041	2.125	*	0.052	2.826	**	0.046
October	2.452	*	0.062	1.238		0.043	0.724		0.022	-0.537		-0.010
November	2.639	**	0.111	2.172	*	0.080	0.070		0.002	2.499	*	0.108
December	0.070		0.005	1.518		0.085	2.966	**	0.129	0.911		0.039
Annual	1.752	+	0.046	3.900	***	0.065	3.013	**	0.038	2.919	**	0.037
Dry Season	1.425		0.048	3.340	***	0.090	2.546	*	0.042	2.172	*	0.041
Wet Season	2.452	*	0.041	2.873	**	0.047	3.153	**	0.030	3.713	***	0.037
Time series	CESM2 MF (2040-2069)			MRI-ESM2 MF (2040-2069)			BCC-CSM2-MR MF (2040-2069)			CanSEM5 MF (2040-2069)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	0.178		0.007	1.427		0.067	1.427		0.053	1.927	+	0.086
February	2.284	*	0.062	2.034	*	0.107	1.820	+	0.074	2.248	*	0.074
March	2.248	*	0.070	0.785		0.041	1.927	+	0.052	2.426	*	0.090
April	2.569	*	0.067	0.856		0.028	2.962	**	0.095	2.070	*	0.084
May	2.426	*	0.058	0.749		0.041	2.712	**	0.042	2.783	**	0.086
June	2.748	**	0.067	1.213		0.041	2.890	**	0.025	5.745	***	0.063
July	4.103	***	0.051	3.640	***	0.034	4.710	***	0.044	6.351	***	0.064
August	5.245	***	0.056	4.175	***	0.031	5.424	***	0.056	6.351	***	0.058
September	4.960	***	0.050	2.105	*	0.025	2.712	**	0.038	6.316	***	0.064
October	2.748	**	0.066	1.249		0.024	1.392		0.033	2.783	**	0.056
November	1.035		0.034	0.571		0.021	2.319	*	0.058	1.499		0.060
December	0.321		0.017	1.142		0.044	0.285		0.011	0.000		0.000
Annual	3.889	***	0.052	2.498	*	0.043	4.603	***	0.048	4.496	***	0.065
Dry Season	3.069	**	0.046	2.533	*	0.055	3.640	***	0.052	2.855	**	0.062
Wet Season	4.282	***	0.058	2.177	*	0.038	5.531	***	0.040	5.816	***	0.065
Time series	CESM2 FF (2070-2100)			MRI-ESM2 FF (2070-2100)			BCC-CSM2-MR FF (2070-2100)			CanSEM5 FF (2070-2100)		
	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q	Test Z	Sig.	Q
January	1.904	+	0.070	0.000		-0.003	0.850		0.027	1.598		0.063
February	1.530		0.067	1.802	+	0.070	0.714		0.014	3.093	**	0.140
March	2.583	**	0.085	-0.544		-0.018	1.122		0.053	2.278	*	0.076
April	3.773	***	0.103	2.447	*	0.077	0.034		0.000	2.549	*	0.084
May	4.657	***	0.115	0.816		0.038	3.467	***	0.061	1.972	*	0.067
June	3.433	***	0.069	1.768	+	0.065	2.787	**	0.032	4.181	***	0.058
July	5.473	***	0.072	5.099	***	0.053	4.045	***	0.038	6.493	***	0.060
August	5.643	***	0.069	5.133	***	0.046	4.283	***	0.038	6.425	***	0.068
September	5.643	***	0.077	4.725	***	0.043	3.195	**	0.040	6.561	***	0.066
October	3.569	***	0.091	1.258		0.034	1.224		0.026	4.691	***	0.115
November	0.986		0.039	1.122		0.039	1.360		0.035	3.093	**	0.097
December	1.904	+	0.044	0.306		0.014	1.428		0.047	1.836	+	0.082
Annual	5.813	***	0.080	2.515	*	0.039	3.671	***	0.034	5.099	***	0.083
Dry Season	3.773	***	0.076	1.326		0.029	1.938	+	0.028	4.351	***	0.090
Wet Season	6.357	***	0.083	2.753	**	0.048	5.677	***	0.038	5.541	***	0.072

Z is the direction of the trend; positive Z is upward and negative Z is downward. ***trend at α = 0.001 level of significance. **trend at α = 0.01 level of significance. *trend at α = 0.05 level of significance. + trend at α = 0.1 level of significance. Sen's slope estimate Q is a true slope of the linear trend of non-parametric data (change/year)

6.2 Projection of Future Population

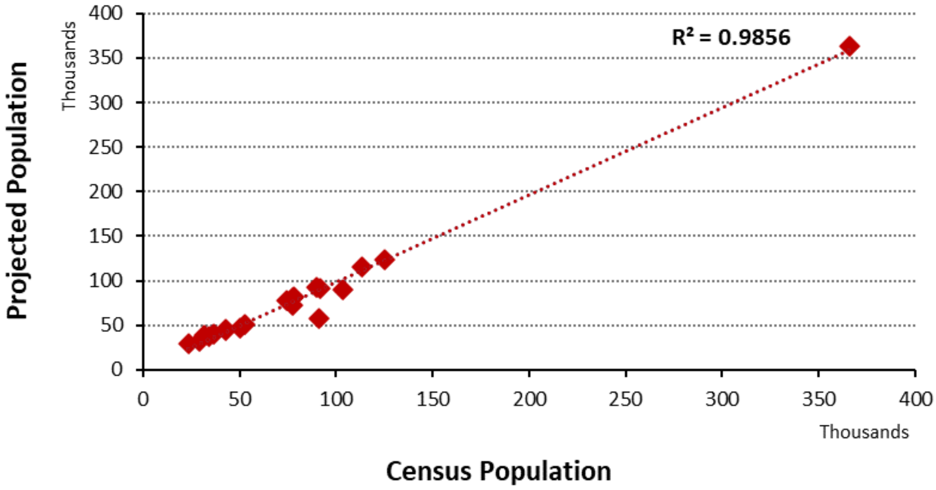
The study used the spatially explicit global population dataset (1-km resolution) developed from the Integrated Assessment Modeling (IAM) group of the National Center for Atmospheric Research's (NCAR) and the City University of New York Institute for Demographic Research, which are consistent with Shared Socioeconomic Pathways (SSPs).

6.2.1 Validation of Global Population Dataset for Khon Kaen Province

The datasets have been initially validated with the census population, and then a detailed analysis of the projected total population and urban population under SSP2-4.5 and SSP5-8.5 has been developed. The number of districts in the Khon Kaen is different (reserve districts) in the past census, while the global dataset used updated 26 districts in the province for the baseline case. Thus, the study utilized 20 matching districts between the 2000 census and modelled data sets covering 93% of the total population to analyze the correlation. The results of the correlation between the census population and the projected baseline population showed the correlation coefficient of about 99% (Figure 6.10).

Figure 6.10

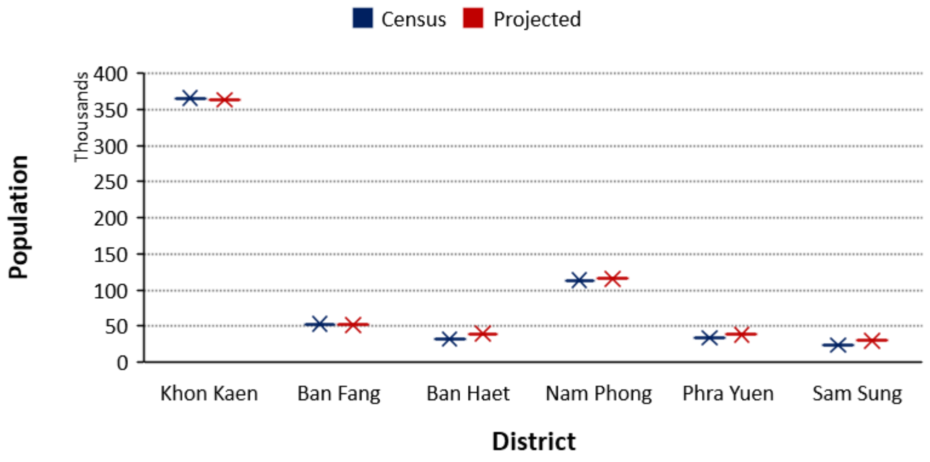
Validation of global population datasets (the baseline year 2000) with the census population (the year 2000) for Khon Kaen Province



Furthermore, as the study is focused on the rapidly urbanized area, the study future compared the census and baseline population for the most urbanized district, i.e., Khon Kaen and its vicinity districts, for further validation. The results (Figure 6.11) from the comparison shows that the projected baseline population is consistent with the census population for Khon Kaen and its vicinity districts.

Figure 6.11

Comparison of global population datasets (the baseline year 2000) with the census population (the year 2000) for Khon Kaen and its vicinity districts

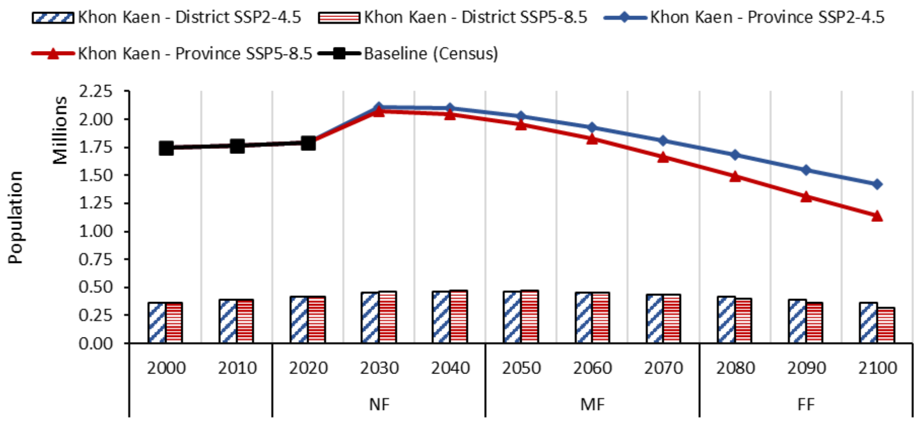


6.2.2 Projection of Future Population in Khon Kaen Province

The projected total population of Khon Kaen province and district under SSP2-4.5 and SSP5-8.5 scenario is shown in Figure 6.12. The population trend in Khon Kaen shows an increasing trend until 2030 and decreasing until 2100. The results show that under both SSPs, the province's population is likely to increase to 2.1 million in 2030 from 1.8 million in 2020. The increment compared to the baseline is expected to persist until 2060 of the MF. The population growth is likely to decrease from 2070 until the end of FF. Furthermore, the population under the SSP5-8.5 scenario is projected to be less than that under the SSP2-4.5 scenario. The results for the change in the population trend agree with the national level projection of the NESDC,MOPH, MSDHS, TSRI & UNFPA, (2019), and the reasons for the declining population in the country is due to the increase in the aging population and low birth fertility rate. Figure 6.12 also shows the projection for the highly urbanized Khon Kaen district under SSP2-4.5 and SSP5-8.5 scenarios. The population in the district is likely to increase 4.6 thousand under the SSP2-4.5 scenario and 4.7 thousand under the SSP5-8.5 scenario compared to the baseline population of 3.8 thousand. Unlike the provincial projection, the SSP5-8.5 scenario project more population in NF and MF. However, the district is also likely to have a decreasing population in late MF and FF gradually.

Figure 6.12

Population projection of Khon Kaen province and district under SSP2-4.5 and SSP5-8.5 scenario



The increase in the population in the highly urbanized district shall increase the population density of the Khon Kaen district and its vicinity districts (Appendix Figure A.3), increasing the increase in water and other demands in rapidly urban areas. Table 6.14 shows the population density of Khon Kaen and its vicinity districts during NF, MF and FF. The results show that the vicinity districts are likely to have a highly denser population in the mid and far future. The population density under the SSP5-8.5 scenario is projected to be more than under the SSP2-4.5 scenario.

Table 6.14

Projected population density of Khon Kaen and its vicinity districts under SSP2-4.5 and SSP5-8.5 scenario

Future	Year	Population Density (Persons/sq. km)			
		SSP2-4.5		SSP5-8.5	
		Vicinity Districts	Khon Kaen District	Vicinity Districts	Khon Kaen District
NF	2020	175	394	181	399
	2030	241	421	410	438
	2040	384	437	785	474
MF	2050	512	448	778	473
	2060	737	451	738	462
	2070	706	436	707	438
FF	2080	662	416	630	404
	2090	609	394	551	363
	2100	560	369	480	320

6.3 Projection of Future Land Use

The study used the ESA CCI land use (300-m resolution) maps from 2008 to 2020 to analyze the historical land-use change trend and project the future land use under SSP2-4.5 and SSP5-8.5 scenarios using the DynaCLUE model. The year 2008 has been used as the input year, and 7 different factors used are mentioned in the methodological section. The results from the model have been validated for the years 2012, 2015 and 2020. Future land-use scenarios under both the SSPs have been developed based on the historical land use change (2012 to 2020) and the SSP storyline. The observed land-use change (2020) in Khon Kaen province shows that the agricultural land covers 89.71% of the total area, followed by the forest (5.28%), water bodies (2.92%), and urban (1.29%) and grassland (0.80%) respectively. Table 6.15 below compares the change in land use from 2012 to 2020 in Khon Kaen, Thailand, and the result shows that the built-up area is rapidly expanding at the rate of 4.28% per year. This increment in the urban area is in the loss of agricultural land and grassland at about 0.05% and 0.19% per year. The forest and water bodies are relatively constant and show a slow growth rate of 0.02% each year.

Table 6.15

Percentage change of different land-use types per year in Khon Kaen, Thailand, for the period 2012 to 2020

Code	Land Use type	Observed Land Use Change (Khon Kaen Province)					
		2012		2020			
		Area (sq. km)	Coverage (%)	Area (sq. km)	Coverage (%)	Change	% Change/year
0	Agricultural Land	9587.8	90.04%	9552.9	89.71%	-34.9	-0.05
1	Forest	561.4	5.27%	562.2	5.28%	0.8	0.02
2	Grassland	86.9	0.82%	85.5	0.80%	-1.3	-0.19
3	Urban (Built-up)	102.1	0.96%	137.0	1.29%	34.9	4.28
4	Water Bodies	310.4	2.92%	311.0	2.92%	0.5	0.02
	Total	**10648.5**		**10648.5**			

The study developed two scenarios (SSP2-4.5 and SSP5-8.5) based on the historical land-use changes and the SSP narratives. Under SSP2-4.5, it is projected that the urban (built-up) land use will follow the same trend until 2050 and slows down afterward to about half of the prevailing rate. The forest and grassland are also assumed to follow a similar trend but will not have any significant change due to current and future restrictions on their conservation. The major implication of the increase in the urban area shall likely be on the agricultural land. Under SSP5-8.5, the rapid economic and technological development is expected to result in faster urbanization, and thus, it is assumed that the rate of change in the urban area is likely to increase by 1.5 times the rate under the SSP2-4.5 scenario in the cost of agricultural land. The forest and grassland follow a similar trend with no significant change in both scenarios. The land use from water bodies under both scenarios is kept constant.

6.3.1 Validation of Projected Land Use using DynaCLUE

The DynaCLUE model has been used to project the future spatial changes in land use under the two SSP scenarios.

Table 6.16

Comparison of observed and simulated land use area, kappa coefficient and overall accuracy for 2012, 2015 and 2020

LU-Code	Land Use (LU)	Area (sq. km)					
		2012		2015		2020	
		Observed	Simulated	Observed	Simulated	Observed	Simulated
0	Agricultural Land	9587.8	9579.4	9553.3	9545.8	9552.9	9545.5
1	Forest	561.4	562.6	560.5	562.7	562.2	563.8
2	Grassland	86.9	87.7	86.9	87.5	85.5	86.0
3	Urban (Built-up)	102.1	101.2	135.8	134.9	137.0	135.5
4	Water Bodies	310.4	308.9	312.0	308.9	311.0	308.9
Kappa Coefficient (k)		***0.96***		***0.93***		***0.92***	
Overall Accuracy		***99.25%***		***98.61%***		***98.52%***	

The simulated results for 2012, 2015 and 2020 have been validated based on the individual change in the area of different landuse, overall accuracy, and the Kappa coefficient, as mentioned in the methodological section. Table 6.16 shows the validation results comparing the observed and simulated land use. The results show a better agreement of the observed and simulated map with an overall accuracy of more than 98% and a kappa coefficient of more than 0.96, 0.93 and 0.92 for 2012, 2015 and

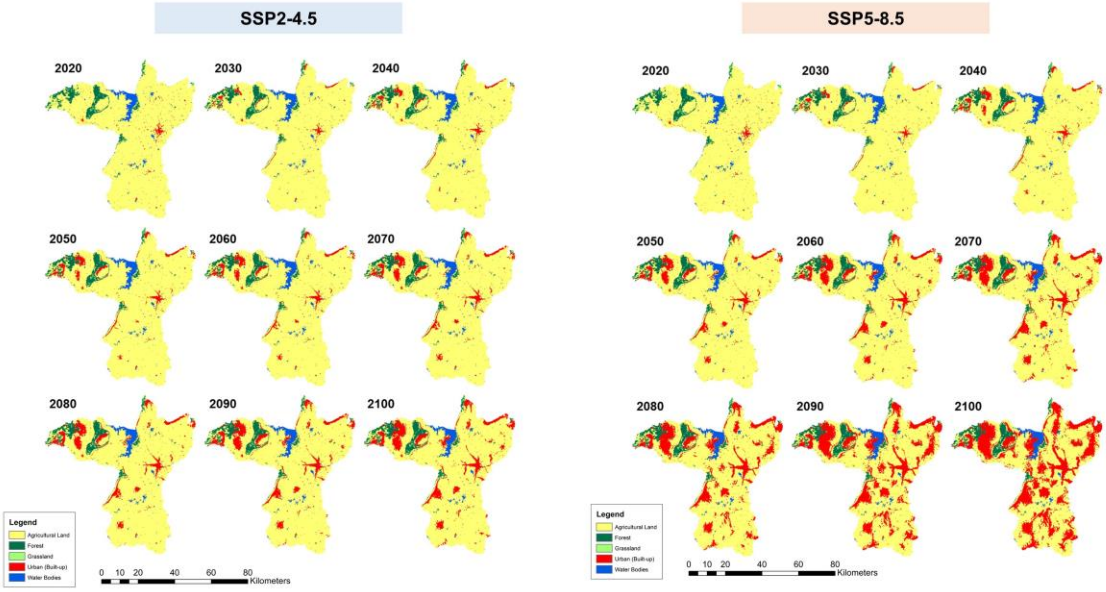
2020, respectively. Several studies have shown that a Kappa index of greater than 0.70 indicates good agreement between observed and model output (Buhay Bucton et al., 2022; Pinsri et al., 2022; Ghimire et al., 2021). Thus, this confirms the better performance of the model developed for projecting future land use in Khon Kaen province.

6.3.2 Projection of Future Land Use in Khon Kaen Province

Figure 6.13 shows Khon Kaen province's projected future land use under the SSP2-4.5 and SSP5-8.5 scenarios for 2020 to 2100. The results (Appendix Table A.6 and Figure 6.13) indicate that the coverage of the built-up area is likely to reach 4.18% in 2050 and 11.23% by 2100. This increment is likely to occur at the expense of the agricultural land, which is projected to decrease to 86.84% in 2050 and 79.81% in 2100 compared to the 89.72% land coverage in 2020. The grassland is expected to cover 0.75% of land by 2050 and 0.68% by 2100, whereas the forest area is likely to remain the same. Under the SSP5-8.5 scenario, the coverage of the built-up area is likely to reach 7.38% in 2050 and 32.39% by 2100. This increment is likely to occur at the expense of the agricultural land, which is projected to decrease to 83.66% in 2050 and 58.69% in 2100 compared to the 89.72% land coverage in 2020. The grassland and the forest are expected to remain similar to SSP2-4.5 until 2100. The trend of land use change in Khon Kaen province projected by the DynaCLUE model agrees with the finding of other studies in Northeastern Thailand (Kuntiyawichai et al., 2020; Ongsomwang et al., 2019). Kuntiyawichai et al. (2020) investigated the change in land use in the Lower Nam Phong River Basin using similar driver variables and found that the built-up area (urban area) to be increasing by 35.5% in the expense of the paddy field (agricultural area) by 2039. Similarly, Ongsomwang et al. (2019), in Khon Kaen city concluded a notable increase in the urban area over the study period replacing the paddy and field crop. The results further indicate rapid urbanization in Khon Kaen regarding land use, resulting in increased impervious cover in the area. The increased imperviousness in the future will likely increase the surface runoff and decrease the amount of shallow groundwater recharge.

Figure 6.13

Projected land-use of Khon Kaen province for 2020 to 2100 under SSP2-4.5 and SSP5-8.5 scenarios



6.4 Projection of Future Groundwater Abstraction

The study used the Watershed Development Master Plan Report for Khon Kaen province (RID, 2018) to project the future water demand under SSP2-4.5 and SSP5-8.5 scenarios, as mentioned in the methodological section above. Table 6.17 below presents the projection of sectoral (domestic, agricultural and industrial) water demand (2020-2100) for Khon Kaen province under both the SSPs. Under the SSP2-4.5 scenario, the domestic water demand of the province is expected to increase maximum up to 114.8 MCM/Year until 2030 and then gradually decrease up to 108.2 MCM/Year in the mid-future (2060). The decreasing trend in the domestic demand continues to 98 MCM/Year by 2100. The agricultural water demand in the Khon Kaen province is expected to increase in the future period. The demand is expected to be 6604.1 MCM/Year, 6806.8 MCM/Year and 6965.8 MCM/Year in 2030, 2060 and 2100, respectively, from 6201.92 in 2017.

Similarly, an increasing trend is projected for industrial water demand in the future. The industrial water demand is expected to be 38.1 MCM/Year, 45.2 MCM/Year and 52.7 MCM/Year in 2030, 2060 and 2100, respectively, from 34.11 in 2017. Under the SSP5-8.5 scenario, the change in water demand for all sectors is expected to increase compared to the SSP2-4.5 scenario and the baseline scenario (2017). The domestic water demand of the province is expected to increase maximum up to 145.8 MCM/Year until 2030 and then gradually decrease up to 133.2 MCM/Year in the mid-future (2060). The decreasing trend in the domestic demand continues to 110 MCM/Year by 2100. The agricultural water demand in the Khon Kaen province is expected to increase in the future period. The demand is expected to be 8333.8 MCM/Year, 8390.9 MCM/Year and 7720.1 MCM/Year in 2030, 2060 and 2100, respectively, from 6201.92 in 2017. Similarly, an increasing trend is projected for industrial water demand in the future. The industrial water demand is expected to be 48.6 MCM/Year, 59.3 MCM/Year and 70.6 MCM/Year in 2030, 2060 and 2100, respectively, from 34.11 in 2017.

Table 6.17

Sectoral Water Demand Projection of Khon Kaen Province under SSP2-4.5 and SSP5-8.5 scenarios

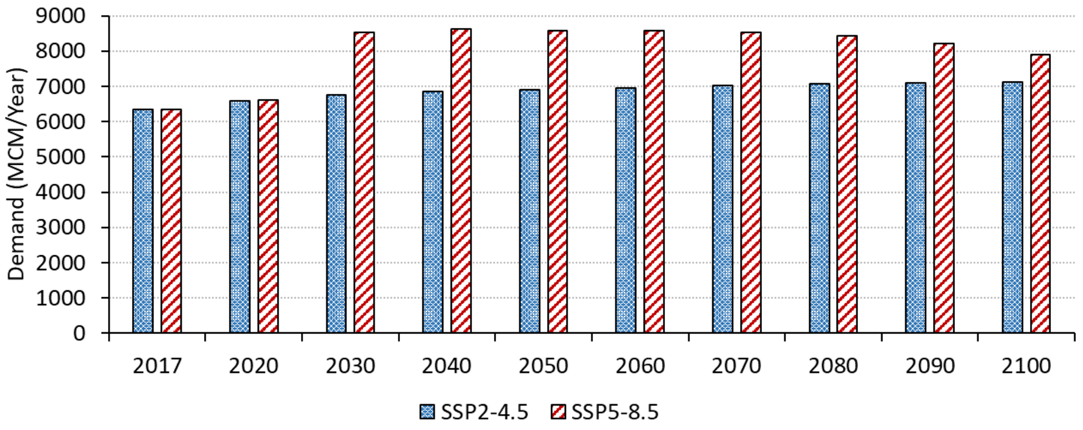
Projected Water Demand (MCM/year)						
Year	Domestic Demand		Agricultural Demand		Industrial Demand	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
2017	***98.87***		***6201.92***		***34.11***	
2020	106.3	106.1	6433.3	6475.9	35.4	35.7
2030	114.8	145.8	6604.1	8333.8	38.1	48.6
2040	110.9	139.3	6697.2	8422.9	41.5	53.7
2050	109.9	137.0	6743.5	8386.9	43.4	56.5
2060	108.2	133.2	6806.8	8390.9	45.2	59.3
2070	105.9	128.2	6862.4	8346.4	47.1	62.1
2080	103.2	122.5	6908.7	8235.1	49.0	64.9
2090	100.5	116.6	6943.8	8037.2	50.8	67.7
2100	98.0	110.7	6965.8	7720.1	52.7	70.6

The total water demand projection for the Khon Kaen province (Figure 6.14) shows an increasing trend under both the SSPs compared to the baseline in 2017. The total water demand in NF is likely to increase to 6849.50 MCM/Year and 8615.90 MCM/Year under SSP2-4.5 and SSP5-8.5 scenarios, respectively, as compared to the baseline demand of 6335 MCM/Year. Similarly, the demand is expected to increase in MF and FF compared to the baseline condition. The trend is expected to decrease from 2080 until the end of the century. The total water demand by 2100 is projected to be 7166.5

MCM/Year and 7901.4 MCM/Year under SSP2-4.5 and SSP5-8.5 scenarios, respectively.

Figure 6.14

Projected water demand of Khon Kaen province for 2020 to 2100 under SSP2-4.5 and SSP5-8.5 scenarios



The study applied the sectoral groundwater abstraction (2017) of Khon Kaen The study applied the sectoral groundwater abstraction (2017) of Khon Kaen province from the Department of Groundwater Resources (DGR), Thailand and the total water demand of the province (RID,2018) to generate the groundwater abstraction ratio and project the future groundwater abstraction in Khon Kaen under SSP2-4.5 and SSP5-8.5 scenarios, as mentioned in the methodological section above. Table 6.18 below presents the projection of sectoral (domestic, agricultural and industrial) groundwater abstraction (2020-2100) for Khon Kaen province under both the SSPs. Overall, the results under both the SSPs show that the industrial groundwater abstraction is expected to increase substantially compared to the abstraction from the domestic and agriculture sectors.

Under the SSP2-4.5 scenario, the groundwater abstraction by the industrial sector is expected to reach up to 13.1 MCM/Year in 2040 compared to 8 MCM/Year in the baseline. The trend is projected to reach 14.9 MCM/Year by the end of mid future and 16.6 MCM/Year by 2100. The groundwater abstraction by the agriculture sector is expected to increase gradually compared to the baseline abstraction. The abstraction is projected to be 3.4 MCM/Year in 2040, 3.5 MCM/Year in 2050 and 3.6 MCM/Year in 2100. The domestic sector is expected to decline in groundwater abstraction between 2020 and 2100 but is still expected to exceed the baseline conditions. The domestic abstraction is projected to be a maximum of 3.7 MCM/Year by 2030 and is then expected to decrease to 3.4 MCM/Year and 3.2 MCM/Year by 2070 and 2100, respectively.

Under the SSP5-8.5 scenario, the groundwater abstraction by the industrial sector is expected to reach up to 17.0 MCM/Year in 2040 compared to 8 MCM/Year in the baseline. The trend is projected to reach 18.7 MCM/Year by the end of mid future and 22.3 MCM/Year by 2100. The groundwater abstraction by the agriculture sector is expected to increase gradually in the future (slightly decreasing trend in FF) compared to the baseline abstraction. The abstraction is projected to be 4.3 MCM/Year until 2050 and 4 MCM/Year in 2100. The domestic sector is expected to increase abstraction and have a decline in groundwater abstraction between 2030 to 2100, but it is still expected to be more than the baseline conditions. The domestic abstraction is projected to be a maximum of 4.7 MCM/Year by 2030 and is then expected to decrease to 4.1 MCM/Year and 3.6 MCM/Year by 2070 and 2100, respectively.

Table 6.18

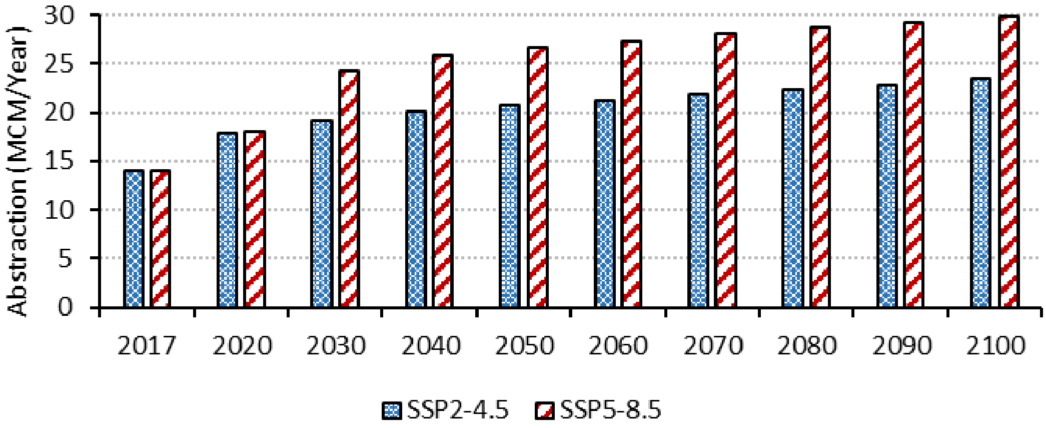
Projected sectoral groundwater abstraction for Khon Kaen Province under SSP2-4.5 and SSP5-8.5 scenarios

Projected Groundwater Abstraction (MCM/Year)						
Year	Domestic		Agricultural		Industrial	
	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5	SSP2-4.5	SSP5-8.5
2017	***3.0***		***3.0***		***8.0***	
2020	3.4	3.4	3.3	3.3	11.2	11.3
2030	3.7	4.7	3.4	4.3	12.0	15.3
2040	3.6	4.5	3.4	4.3	13.1	17.0
2050	3.5	4.4	3.5	4.3	13.7	17.8
2060	3.5	4.3	3.5	4.3	14.3	18.7
2070	3.4	4.1	3.5	4.3	14.9	19.6
2080	3.3	4.0	3.6	4.2	15.5	20.5
2090	3.2	3.8	3.6	4.1	16.1	21.4
2100	3.2	3.6	3.6	4.0	16.6	22.3

The projection of the total groundwater abstraction for the Khon Kaen province (Figure 6.15) shows an increasing trend under both the SSPs compared to the baseline in 2017. The total groundwater abstraction in NF is likely to increase to 20.1 MCM/Year and 25.8 MCM/Year under SSP2-4.5 and SSP5-8.5 scenarios, respectively, compared to the baseline abstraction. A similar trend is projected in MF and FF for Khon Kaen. Under SSP2-4.5, the total groundwater extraction in MF is expected to be 21.8 MCM/Year, and in FF is 23.4 MCM/Year. Furthermore, under the SSP5-8.5 scenario, the total abstraction in MF and FF is likely to be 28 MCM/Year and 29.8 MCM/Year, respectively.

Figure 6.15

Projected groundwater abstraction of Khon Kaen province for 2020 to 2100 under SSP2-4.5 and SSP5-8.5 scenarios



CHAPTER 7

IMPACT OF MULTIPLE STRESSES IN GROUNDWATER AVAILABILTY

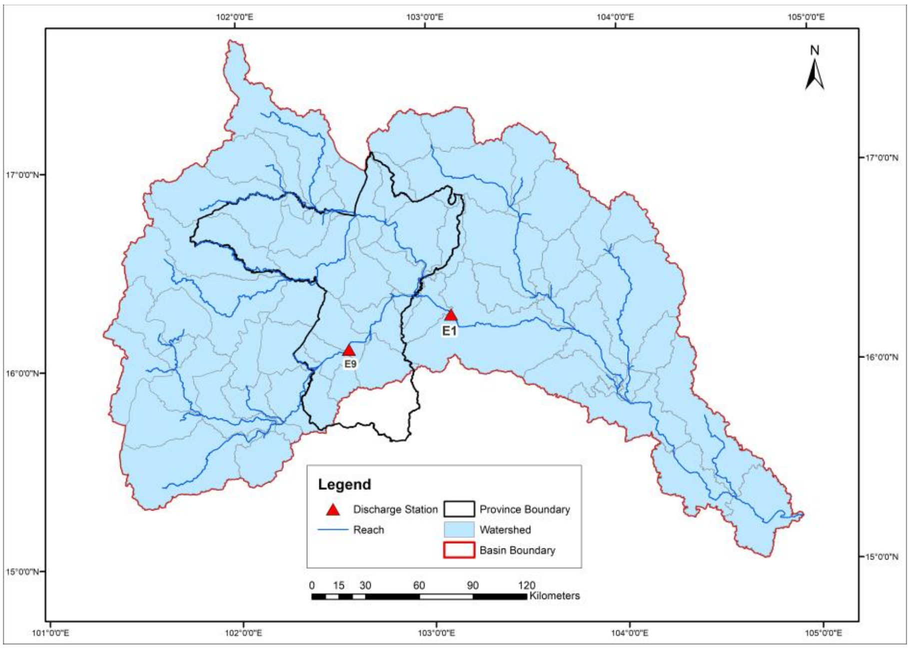
This chapter presents the results of the study's third objective, which is the impact of multiple stresses (climate, land use, population, sectoral groundwater abstraction) on groundwater availability.

7.1 Calibration and Validation of SWAT Model

The spatiotemporal groundwater recharge for Khon Kaen has been generated using the SWAT hydrological model. Initially, the SWAT model covering the watershed area of 51,376.76 km^2 was developed for Chi-River Basin with 61 sub-basins and 2051 Hydrological Response Units (HRUs) with DEM, soil map, land use map and other parameters of the Chi River Basin (Appendix Figure A.4 and Figure 7.1). A sensitivity analysis of the parameters and the calibration process has been done using the SWAT-CUP (SUFI-2) model at the hydrological stations E1 and E9 (Figure 7.2) daily. The hydrological station E1 is the outlet of the Khon Kaen Province, whereas the another is within the province.

Figure 7.1

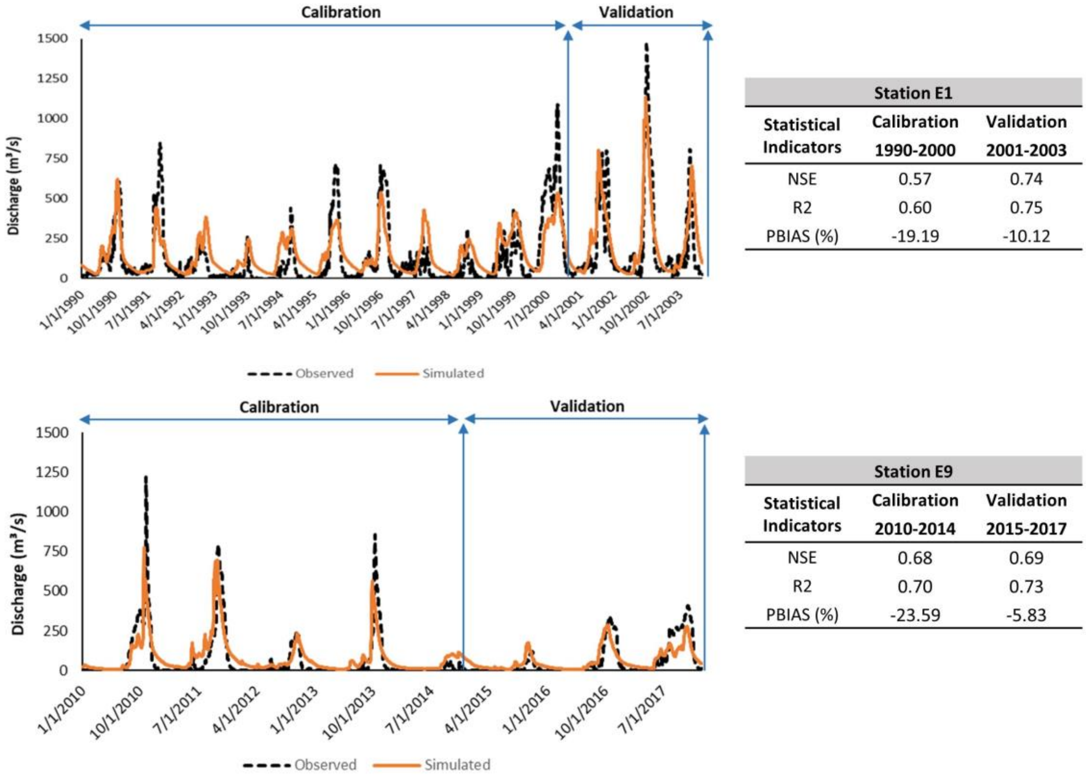
Watershed area of the Chi-River Basin from the SWAT model with sub-basins, Khon Kaen province administrative boundary and hydrological stations



Initially, 500 simulations were conducted for default hydrological parameters, out of which 18 sensitive parameters (Appendix Table A.7) have been selected for performing the calibration and validation of the model. Streamflow at outlets E1 and E9 has been compared with the observed flow for 1990-2003 and 2010-2017, respectively. The statistical performance of the model after the calibration and validation process has been evaluated with NSE, R^2 and PBIAS. The results of the statistical performance (Figure 7.2) for station E1 shows satisfactory performance (NSE = 0.57; R2 = 0.60; and PBIAS = -19.9%) for calibration period of 1990-2000 whereas the model showed a good performance (NSE=0.74; R2=0.75; and PBIAS=--10.12%) for the validation period of 2001-2003 (Moriasi et al., 2007). Similarly, for the station E9 the results shows good performance (NSE=0.68; R2=0.70; and PBIAS=-23.59%) for calibration period of 2010-2014 and a good performance (NSE=0.69; R2=0.73; and PBIAS=-5.83%) of the model is continued in the validation period of 2015-2017. Overall, the model performance is acceptable within the province and at the outlet of the province and thus, is further applied for future projections.

Figure 7.2

Observed and simulated discharge at stations E1 (above) and E9 (below) with the statistical performance during the calibration and validation period



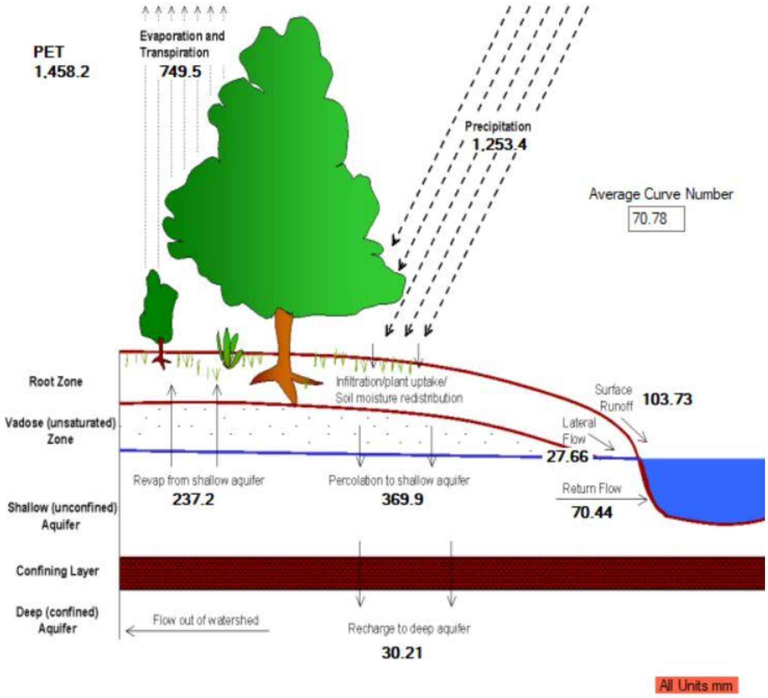
Station E1		
Statistical Indicators	Calibration 1990-2000	Validation 2001-2003
NSE	0.57	0.74
R2	0.60	0.75
PBIAS (%)	-19.19	-10.12

Station E9		
Statistical Indicators	Calibration 2010-2014	Validation 2015-2017
NSE	0.68	0.69
R2	0.70	0.73
PBIAS (%)	-23.59	-5.83

The water balance of the unsaturated zone from the SWAT model shows that the inflow and outflow volumes are nearly the same (Outflow>Inflow by 40.17mm) (Figure 7.3). The slight difference in the water balance is due to the input climate data inconsistency in some stations and the absence of information such as windspeed, relative humidity, solar radiation etc. Overall, the water balance results show that the area's evapotranspiration is about 60% of the rainfall, while the shallow groundwater recharge is around 30%. This is likely because the basin area consists of a larger agricultural area than the other land-use.

Figure 7.3

Sketch of water balance for Chi River basin generated from the calibrated SWAT model



7.2 Impact of Climate Change and Land-Use Change on Groundwater Recharge

The study used the calibrated and validated model to analyze the baseline (1981-2014) and future (2015-2100) groundwater recharge for Khon Kaen Province under SSP2-4.5 and SSP5-8.5 scenarios. The annual groundwater recharge for the baseline and the future period from all four climate models (CESM2; MRI-ESM2; BCC-CSM2-MR; CanESM5) and the ensemble average of all the annual recharge are shown in Figure

7.4 below. Overall, the results show that all the model projects a decreasing trend in the annual groundwater recharge under both the SSPs.

Figure 7.4

Average annual groundwater recharge of Khon Kaen Province for the baseline (1983-2014) and projected from the climate models for the future period (2015-2100)

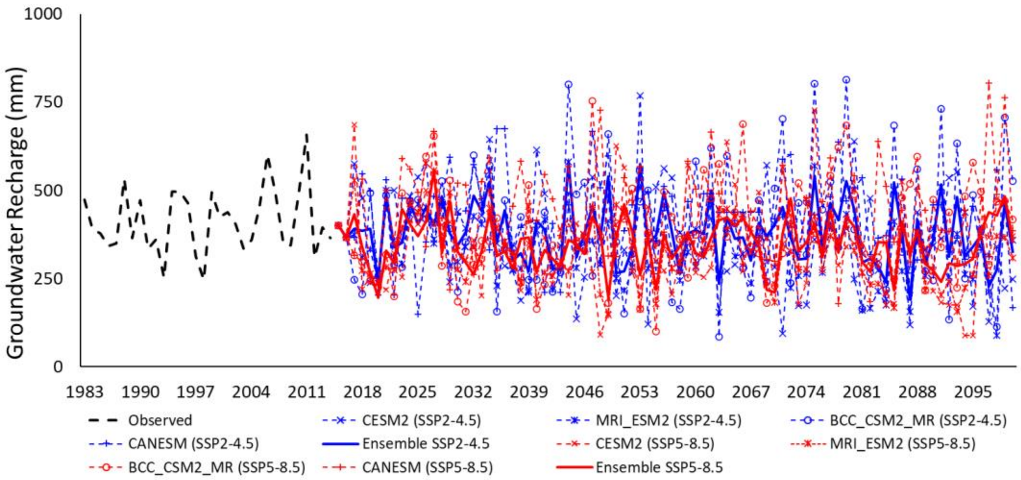


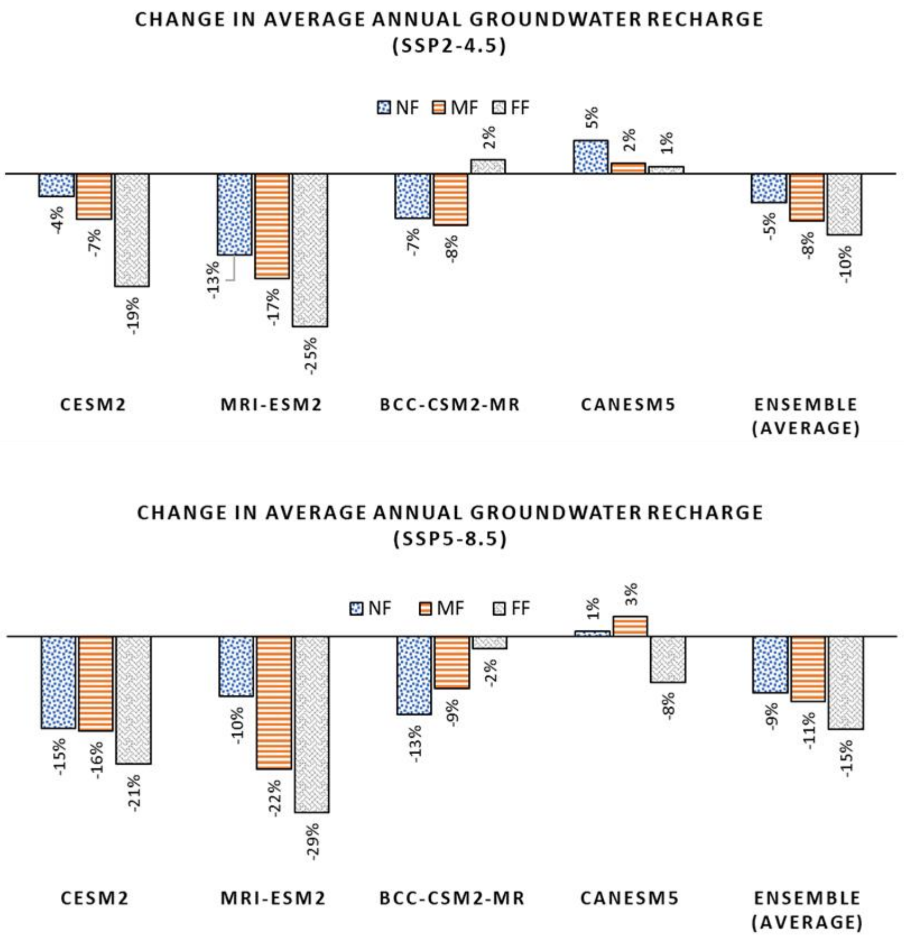
Figure 7.5 below shows the change in average annual groundwater recharge for NF, MF and FF compared to the baseline average annual recharge. The results show that under the SSP2-4.5 scenario, all the climate model except CanESM5 shows a decrease in average annual groundwater recharge by 4-13% in NF, 7-17% in MF and 10-25% compared to the baseline recharge of 412.02 mm/year. CanESM5 predicts an average annual groundwater recharge of 5% in NF, 2% in MF and 1% in FF compared to the annual baseline recharge. Furthermore, BCC-CSM2-MR also projects a 2% increase in average annual recharge during FF. Similarly, under the SSP5-8.5 scenario, all the climate model except CanESM5 shows a decrease in average annual groundwater recharge. But the decrease in the average annual recharge under SSP5-8.5 is likely to be more than the previous scenario. The models project a 9-15% decrease in NF, 9-22% in MF and 8-29% compared to the baseline recharge of 412.02 mm/year. CanESM5 predicts to increase in average annual groundwater recharge by 1% in NF and 3% in MF, while it projects a decrease in average annual recharge by 8% in FF.

Overall, the averagely ensembled results of the annual recharge from all the climate models under the SSP scenarios show that groundwater recharge is likely to decrease more over time, and the decrement is projected to be more under the SSP5-8.5 scenario.

Figure 7.5 below shows that the average annual groundwater recharge in Khon Kaen is expected to decrease by 5% to 8% and then to 10% in NF, MF and FF, respectively (SSP2-4.5) compared to the baseline conditions. The decrement is expected to be 9%, 11% and 15% in NF, MF and FF under the SSP5-8.5 scenario compared to the baseline recharge of 412.02 mm/year. A study by Goofers (2019) showed a similar decreasing groundwater recharge trend under several climate change scenarios in Northeast Thailand. Chi watershed is one of the driest, followed by the Mun and Mekong watershed. The increment in actual evaporation due to a significant increase in minimum and maximum temperature results in fewer recharge available to replace groundwater. Furthermore, the process is exaggerated by the increasing urban area, making the surface more impervious to recharge.

Figure 7.5

Change in average annual groundwater recharge of Khon Kaen Province compared to the baseline period (1983-2014) for NF (2015-2039), MF (2040-2069) and FF (2070-2100) from individual climate models and the averagely ensembled recharge from all models



7.3 Impact of Multiple Stresses on Groundwater Level

The study applied multiple regression in 6 observation wells in Khon Kaen to estimate future groundwater level changes. Four independent variables, namely groundwater recharge, domestic groundwater abstraction, agriculture groundwater abstraction and industrial groundwater abstraction, were used from 2004 to 2019 to generate the equations for the dependent variable, i.e., groundwater level.

The statistics (Table 7.1) results for 16 observation years show a good correlation coefficient between the dependent and the predictor variables. Tapra 5 well shows the least co-relation of 55%, and the Phon well shows the maximum co-relation of 86%. Furthermore, the proportion of variance in the dependent variable coefficient of determination of all the observation well is more than 0.50 excluding Tapra 5 and Tapra 7. However, the standard error in all the wells shows a relatively lesser deviation (0.76 to 1.93 units) from the regression line. Overall, the regression statistics are acceptable as the major objective is to develop a preliminary visualization of future groundwater levels (availability) under stress and provide recommendations for improving the current state of groundwater governance. The regression equations have been generated for all the individual observations using the coefficients and intercepts of all the predictor variables (Table 7.1). A sample of the regression equation for Tapra 1 well is given below:

$$(GWL)fn = -0.0006*Gn + 1.6129*Dn - 0.2563*An - 0.3639*In - 11.7144 \qquad \text{Eq.7.1}$$

where,

(GWL)fn = Future groundwater level for year n;

Gn = Groundwater recharge at year n;

Dn = Domestic groundwater abstraction at year n;

An = Agricultural groundwater abstraction at year n;

In = Industrial groundwater abstraction at year n

Table 7.1

Regression statistics, intercept and coefficient of predictor variables for six observation wells in Khon Kaen province to generate regression equation for groundwater level

Regression Statistics	Monitoring Wells					
	Tapra1	*Tapra2*	*Tapra5*	*Tapra7*	*Tapranao*	*Phon*
Multiple R	0.78	0.76	0.55	0.61	0.65	0.86
R Square	0.61	0.59	0.41	0.48	0.52	0.73
Standard Error	1.71	1.93	1.89	0.80	0.76	1.25
	Coefficients					
Intercept	-11.7144	-11.8963	-5.4139	-6.0013	-7.4871	-12.1626
GWR (G)	-0.0006	0.0012	-0.0019	-0.0022	0.0016	0.0042
Domestic (D)	1.6129	1.6058	1.0937	0.4548	0.3235	1.0239
Agriculture (A)	-0.2563	0.1609	0.1167	-0.2031	-0.2569	1.1454
Industry (I)	-0.3639	-0.6666	-0.3634	-0.0909	0.0193	-1.0106

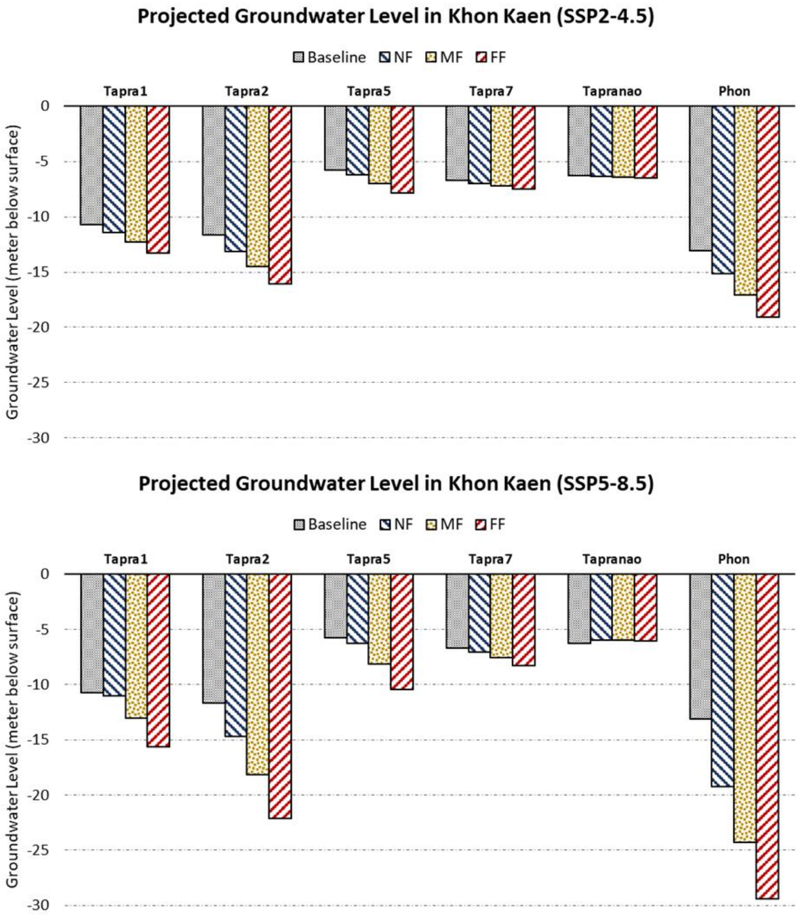
The results of the projected groundwater level in different observation wells at Khon Kaen (Figure 7.6) shows that the groundwater level is likely to decline in all the well due to a decrease in the groundwater recharge (as an impact of climate and land-use change) and increase in sectoral groundwater abstraction. Under the SSP2-4.5 scenario, Phon (2 to 6 m below the surface) and Tapra 2 (1.5 to 4.4 m below the surface) are expected to have a maximum decrease in groundwater level in NF, MF and FF compared to the baseline level. Other observations wells are expected to decrease 0.3-0.7 m, 0.5-1.5 m, and 0.8-2.6 m below the surface in NF, MF and FF, respectively. Tapranao observation shows the comparatively least decrease and is expected to remain the same as the baseline conditions. Under the SSP2-4.5 scenario, the average groundwater level is expected to decrease gradually from 0.8 m to 3 m until 2100.

Similarly, under the SSP5-8.5 scenario, Phon (6.2 to 16.3 m below the surface) and Tapra 2 (3.1 to 10.5 m below the surface) are expected to have a maximum decrease in groundwater level in NF, MF and FF compared to the baseline level. Other observations wells are expected to decrease 0.3-0.5 m, 0.9-2.4 m, and 1.6-4.9 m below the surface in NF, MF and FF, respectively. Under this scenario, the Tapranao observation shows a very increase in groundwater level by 0.2-0.3 m compared to the baseline level. Under the SSP5-8.5 scenario, the average groundwater level is expected to decrease gradually from 1.7 m to 6.3 m until 2100.

Overall, the results show that the impact of climate change and land-use change is likely to lead to a decrease in groundwater recharge and this, when exaggerated by the increased sectoral groundwater abstraction, is likely to lower the groundwater level in Khon Kaen. Goofers (2019) in Northeast Thailand also concluded dropping groundwater table as an impact of climate change and pumping scenarios. Furthermore, the study also showed the impact of pumping (or groundwater abstraction) in the reason is more than the impact of change in local climatic conditions. Thus, groundwater availability in the province is expected to be scarce if the existing trend of urbanization and abstraction continues with the change in climatic conditions. Further, the scarcity is expected to worsen more rapidly if the current trend fastens by only 1.5 times. The results indicate that the situation is likely to bring more pressure to the governance of the resource, and thus, the state of groundwater governance needs a substantial improvement for the sustainable management of the resource.

Figure 7.6

Projection of groundwater level in six observation wells of Khon Kaen province for near, mid and far future under SSP2-4.5 and SSP5-8.5 scenarios



CHAPTER 8

STRATEGIES FOR IMPROVED GROUNDWATER GOVERNANCE

This chapter presents the results of the study's fourth objective, which is to provide strategies for improved groundwater governance under the impact of multiple stresses.

8.1 Current State of the Components of Groundwater Governance

The impact of multiple stresses on groundwater availability (Table 8.1) in Khon Kaen showed that the shallow groundwater recharge would likely decrease. Meanwhile, the possible increase in sectoral groundwater abstraction is likely to lower the groundwater level, pressuring the future governance and management of the resource. The previous section showed that the existing groundwater governance in Khon Kaen is at an (early) acceptable state. In contrast, the future pressure on groundwater availability is likely to increase and lead to possible conflicts for groundwater resource accessibility and use. Good groundwater governance requires multi-actor engagement, explicit regulatory provisions, well-defined policies, and adequate information and knowledge. Thus, the study uses the current state of these four components (multi-actor engagement; regulatory frameworks; policies; information and knowledge) from the groundwater governance framework and recommended provisions for improving the weaker components in the context of future impacts on groundwater availability. Furthermore, the recommendation has been discussed with a successful case study for detailed elaboration.

Table 8.1

Average changes in stresses (climate, urban land use, urban population, sectoral groundwater abstraction) and their impact on groundwater recharge and groundwater level in Khon Kaen province under SSP2-4.5 and SSP5-8.5 scenario

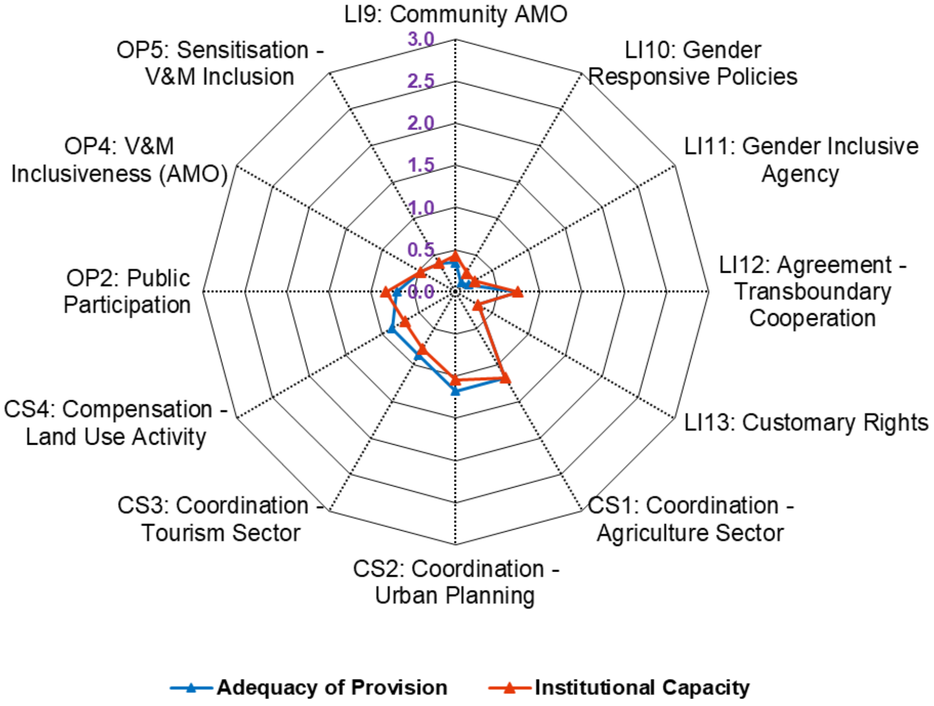
Future Period	SSP	Climate Change			Land Use	Population	(Persons)	Groundwater Recharge (mm/year)	Groundwater Abstraction (MCM/Year)			Possible Descrease in Groundwater Level (m below surface)
		Rainfall (mm)	Tmax (°C)	Tmin (°C)	Urban (Sqkm)	Total	Urban		Domestic	Agricultural	Industrial	
Baseline		***1222.0***	***32.6***	***22.3***	***135.5***	***1,794,531***	***536,467***	***412.0***	***3.0***	***3.0***	***8.0***	***Range = 5.8 to 24.6 m***
NF	SSP2-4.5	8%	0.8	0.9	3%	16%	36%	-5%	19%	13%	51%	- (0.1 to 2)
MF		11%	1.8	1.8	6%	10%	127%	-8%	17%	16%	75%	- (0.1 to 4)
FF		13%	2.5	2.4	11%	-10%	145%	-10%	10%	19%	97%	- (0.2 to 6)
NF	SSP5-8.5	9%	0.9	1	4%	14%	94%	-9%	40%	33%	82%	- (0.3 to 6.2)
MF		12%	2.5	2.4	13%	4%	193%	-11%	45%	44%	129%	- (0.9 to 11.2)
FF		16%	4.4	4.2	32%	-22%	150%	-15%	29%	39%	162%	- (1.6 to 16.3)

8.1.1 Multi-Actors Engagement

The adequacy of provisions and institutional capacity for multi-actor engagement in groundwater governance and management at Khon Kaen, Thailand, is below the incipient stage (Figure 8.1). The future projection from the study (Table 8.1) shows that the urban community is likely to expand in Khon Kaen (increase by 36% to 193%), and the sectoral groundwater abstraction is also estimated to increase (13% to 162%), but the adequacy of legal provisions for involving these multiple actors is very weak at the existing. Currently, provisions for the engaging community, customary rights to water and land, and gender inclusion in formal and informal organizations are very weak (below 0.5). Moreover, the institution also lacks the capacity to implement the current provisions of multiple actors' engagement in groundwater governance processes. Also, the provisions for engaging vulnerable and marginalized groups (likely to be more under stress) at an operational level are near the incipient stage but need substantive preparations for improving the overall groundwater governance. In the case of multi-sector and transboundary engagement, the current state is comparatively at the incipient state (0.7-1.2) and needs further improvement in due course of time.

Figure 8.1

Rating of the indicators for the current state of actor's engagement in groundwater governance of Khon Kaen, Thailand, in terms of the adequacy of provision and institutional capacity for its implementation

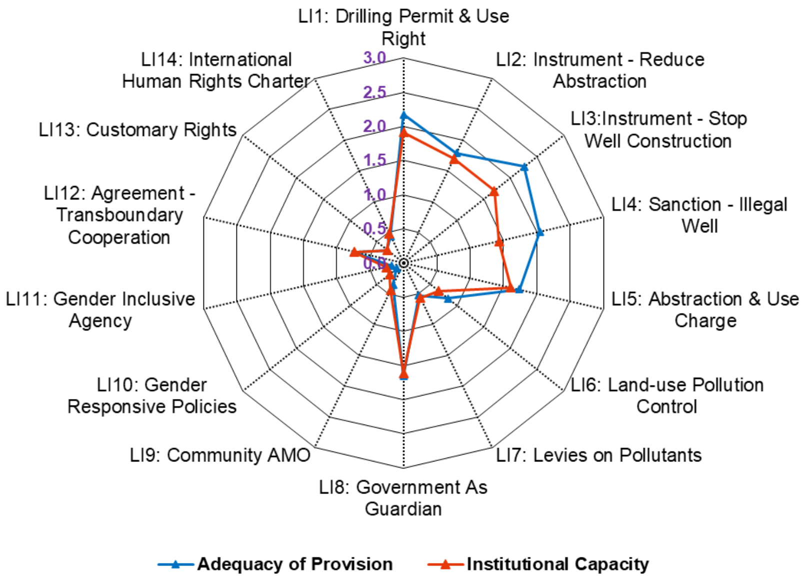


8.1.2 Regulatory Frameworks

The current state of provisions and institutional capacity for regulatory frameworks in groundwater governance and management at Khon Kaen, Thailand, has completed the incipient stage (overall) and is forwarding toward the acceptable stage (Figure 8.2). The legal provisions are a foundation for successfully implementing other requirements in good groundwater governance. The adequacy of provision for drilling permits or reducing the abstractions, water-use charging, and land-use pollution is acceptable to the optimum state (1.5 -2.3), and this will be useful in the context of future increment of urban land-use, pollution and sectoral abstraction.

Figure 8.2

Rating of the indicators for the current state of regulatory frameworks in groundwater governance of Khon Kaen, Thailand, in terms of the adequacy of provision and institutional capacity for its implementation



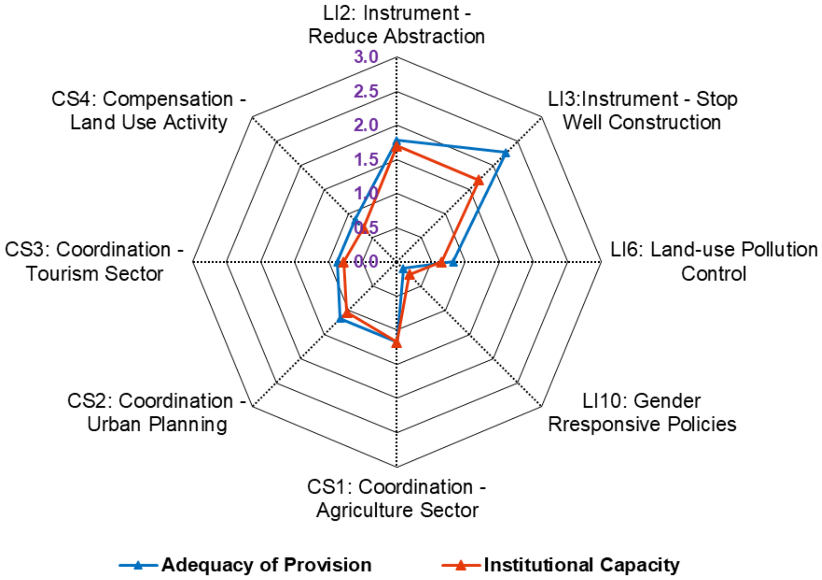
Comparatively, the institutional capacity to implement the existing provisions is lower and needs to be boosted for regular monitoring and compliance. The legal provisions for forming and implementing aquifer management organizations and gender mainstreaming in government agencies and other informal organizations are weaker (less than 0.5) and are likely to impact multi-actor engagement and policies in the governance process. Furthermore, the multiple stress is likely to reduce the groundwater availability in Khon Kaen (Table 8.1), and the right-based conflict for equal access to groundwater resources and the right to water use is likely to occur. Thus, the legal provision and the institutional capacity for customary rights and human rights to water needs to be improved, which is still below the incipient stage.

8.1.3 Policies

The current state of provisions and institutional capacity under defined policies in groundwater governance and management at Khon Kaen, Thailand, is at the incipient stage (overall) and is forwarding towards the acceptable stage (Figure 8.3). The provision of the policies to reduce excessive abstraction or stop the well construction is at an acceptable state (1.7-2.3) and is forwarding towards the optimal state. These provisions will reinforce the improvement of groundwater governance in the future, where it is expected to have increased abstraction and urban demand.

Figure 8.3

Rating of the indicators for the current state of policies in groundwater governance of Khon Kaen, Thailand, in terms of the adequacy of provision and institutional capacity for its implementation



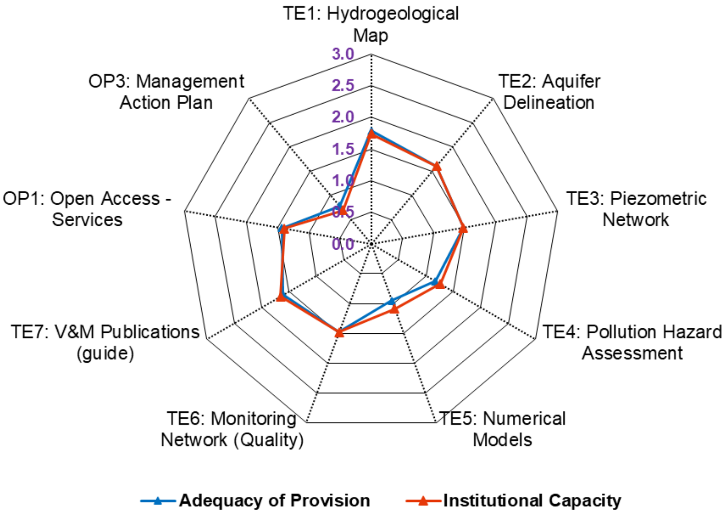
But the policies for coordinating with the urban, agriculture and tourism sector is at an early incipient stage (0.7-1.2) and is likely to be insufficient under future stresses. The policies and institutional capacity for groundwater protection (i.e., compensation land use activity = 0.8) and control of groundwater pollution (land-use pollution control = 0.7) should be improved under possible urban expansion and increased sectoral demand. One of the major improvements in the policy component of groundwater governance is the improved provision of the groundwater policy framework that identifies and acknowledges the existing differences and inequalities between women and men and articulates policies and initiatives which address the different needs, aspirations, capacities, and contributions of women and men.

8.1.4 Information and Knowledge

The current state of provisions for the information and knowledge component in groundwater governance and the institutional capacity for its implementation at Khon Kaen, Thailand, is between incipient and acceptable state (Figure 8.4). The provisions for hydrogeological maps, delineations of the aquifer, groundwater level and quality monitoring are near to the acceptable state (1.5-1.8). Meanwhile, the resources for identifying quality degradation risk to groundwater (hazard assessment = 1.2) and the aquifer management model need to be improved in the context of the projected impact of multiple stresses on groundwater availability. The existing numerical model should be replaced with an integrated numerical model for detailed information about the current and future state of groundwater availability under multiple stresses. The information and knowledge component of groundwater governance in Khon Kaen needs improvement in the operational provision regarding the groundwater management action plan (0.7) for the aquifer, which is in an incipient state. This shall ensure the knowledge of the existing state of groundwater resources among the stakeholders with consensus on targets and measures for sustainable resource use.

Figure 8.4

Rating of the indicators for the current state of information and knowledge in groundwater governance of Khon Kaen, Thailand, in terms of the adequacy of provision and institutional capacity for its implementation



8.2 Recommended Strategies for Improved Groundwater Governance

Strategy 1: Improved Provisions for "Collaborative and Consensus-based Aquifer Management Process for Groundwater Planning and Management"

Groundwater Governance Framework Indicators Covered:

- Community-based Aquifer Management Organizations
- Public Participation
- Management Action Plan

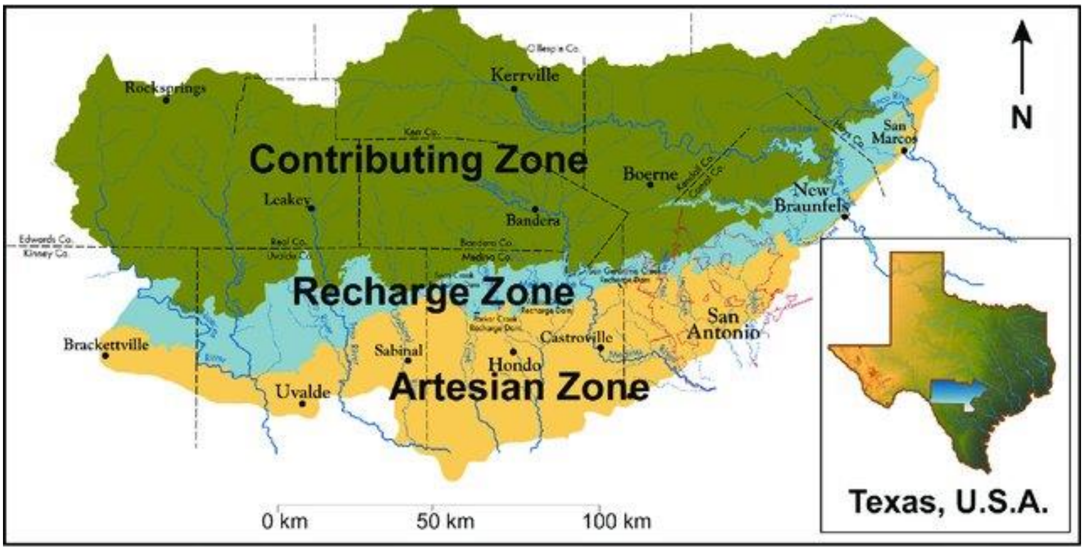
Component of Groundwater Governance Covered:

- Actors
- Regulatory Framework
- Information and Knowledge

Case Study: Texas Edwards Aquifer - A Collaborative and Consensus-based Groundwater Planning

Figure 8.5

The location map of the Edwards Aquifer in Texas, USA (lower right) with the artesian, recharge, and contributing zone



Source: *Stafford et al., 2018*

- Edwards Aquifer (Figure 8.5) in south-central Texas, USA, is the groundwater source serving over 2 million people. As a result of competing interests, a collaborative and consensus-based formal stakeholder participation process was commenced to meet the aquifer's economic, social and ecological needs (Sugg & Schlager, 2017; Votteler & Gulley, 2014).
- Legal enforcement through a Senate Bill directed Edwards Aquifer Authority (EAA) with related institutions of Texas (Department of Agriculture; Parks and Wild Department, Environmental Quality Commission and Water Development Board) to produce Edwards Aquifer Recovery Implementation Program (EARIP) (Gulley & Cantwell, 2013).
- A 26-member steering committee was formed, representing water authority, municipality, industries, a state agency, environmental authority, public utility and agricultural sectors. 13 other interested stakeholders/groups representing the upstream and the downstream interests took part in the process of EARIP proceeding (Gulley & Cantwell, 2013; Sugg & Schlager, 2017).
- Engagement of public organizations with other interested stakeholders and a transparent process facilitated achieving consensus and developing trust among the stakeholders. The stakeholders were also imposed to maintain focus and momentum in resolving issues within the deadline imposed by the Senate Bill. As a result, the stakeholders took ownership of the process, which led to compromises and understanding.
- The main outcome of the process was a consensus-based Habitat Conservation Plan (HCP) that addresses the water abstraction from the aquifer with the need for the protection of the endangered species. The HCP is still under action and provides recommendations, including aquifer storage, quality, habitat protection, and restoration. Most importantly displays the increased trust and ownership of the process among competing stakeholders (Gulley & Cantwell, 2013; Sugg & Schlager, 2017; Votteler & Gulley, 2014).

Strategy 2: Improved Provisions for "Gender Responsive Regulatory Frameworks and Policies" in Formal and Informal Organizations

Groundwater Governance Framework Indicators Covered:

- Gender Responsive Policies
- Gender Responsive Agencies
- Vulnerable and Marginalized Groups Inclusions
- Sensitization of Vulnerable and Marginalized Groups Inclusion

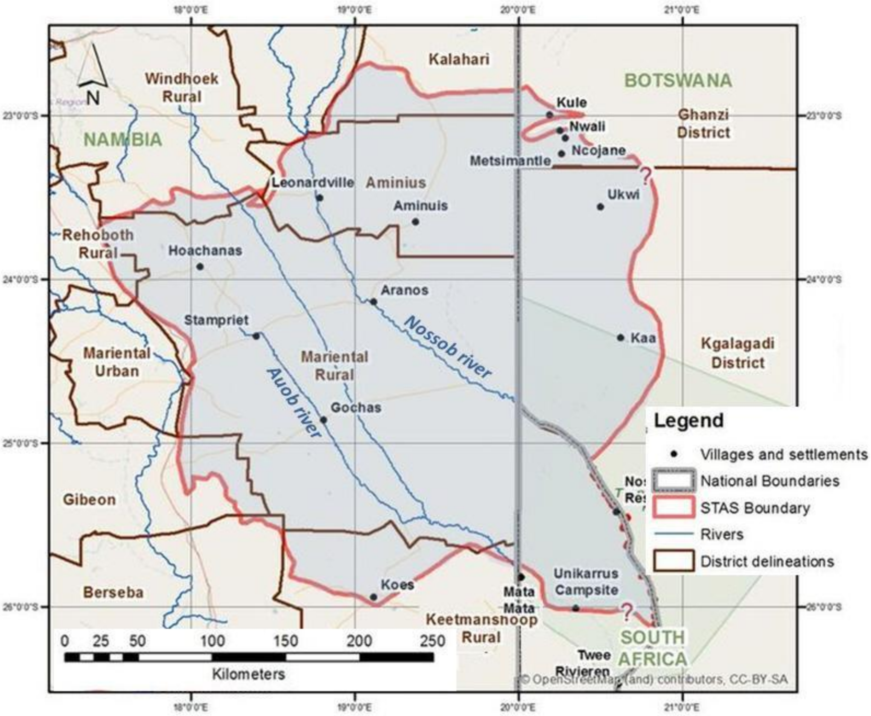
Component of Groundwater Governance Covered:

- Regulatory Framework
- Actors
- Policies

Case Study: Governance of Stampriet Transboundary Aquifer System (STAS)

Figure 8.6

Map of Stampriet Transboundary Aquifer System (STAS) with administrative boundaries



Source:*GGRETA, 2016*

- The Stampriet Transboundary Aquifer System (STAS) covers Namibia, Botswana and South Africa (Figure 8.6), containing two artesian sandstone aquifers and the unconfined Kalahari aquifer (GGRETA, 2016; Kenabatho et al., 2021).
- The sharing countries agreed on a formal structure for aquifer management by establishing a joint technical team under the Orange-Senqu River Commission. The joint technical team provides adequate information for verifying gender mainstreaming in national water-related policies and implementing gender-transformative actions (UNESCO, 2018).
- The joint team involved women and men in decision-making and operational processes at all levels of the formal structure. The STAS gender mainstreamed team created a platform for all to outline and influence the decision-making processes on transboundary issues and governance (Sekwele 2017).
- The second phase of the Groundwater Resources Governance in Transboundary Aquifers (GGRETA) project has further ensured gender mainstreaming in the capacity development for the numerical modelling of the aquifer.
- The major outcome of gender mainstreaming in the STAS is the successful application of the approach in transboundary groundwater governance and management. This involves the involvement of all the genders (especially women) at all the decision-making levels and demonstrating their ability to make strategic decisions in transboundary groundwater management (Kenabatho et al., 2021; Sekwele 2017; UNESCO, 2018).

Strategy 3: Improved Provisions of “Integrated Aquifer Management Model” for Current and Future Status of Groundwater Resources

Groundwater Governance Framework Indicators Covered:

- Aquifer Numerical Models
- Publications on Resource Use and Availability
- Groundwater Level and Quality Status
- Cross-sectoral Coordination
- Transboundary Groundwater Governance

Component of Groundwater Governance Covered:

- Information and Knowledge
- Actors
- Regulatory Framework
- Policies

Case Study: Governance of Stampriet Transboundary Aquifer System (STAS) through Integrated Numerical Modelling

- The Stampriet Transboundary Aquifer System (STAS) covers Namibia, Botswana and South Africa (Figure 8.6), containing two artesian sandstone aquifers and the unconfined Kalahari aquifer (Kenabatho et al., 2021). STAS countries used the prevailing structure of ORASECOM (http://wis.orasecom.org/stas/) to establish the Multi-Country Cooperation Mechanism (MCCM) and joint governance.
- Phase II (2016-2018) of the GGRETA project focused mainly on capacity-building on groundwater modelling and the development of the STAS numerical groundwater model, which also facilitated setting the baseline for establishing a cooperation mechanism for the STAS (Kenabatho et al., 2021).
- STAS MCCM developed a protocol for data collection and feeding and established the information management system (http://wis.orasecom.org/stas/). Further, it also sets procedures for the database maintenance and development STAS numerical groundwater model (which is currently implemented through the United States Geological Survey's (USGS) modular hydrologic model (MODFLOW 6) package in an integrated manner to quantify groundwater flux in the STAS (UNESCO, 2020). The model is being enhanced by using remote sensing data to overcome the data limitations.
- The major outcome of the integrated aquifer model is its applicability to quantifying the STAS resource status for informed decision-making. The vision is to jointly strategize STAS countries on sustainable resource management, including data sharing and developing a strategic action plan (SAP) to address challenges and pull opportunities for sustainable development and use of the aquifer (Kenabatho et al., 2021).

Strategy 4: Improved Legal Framework and Policies on "Land Use Planning and Sectoral Coordination" for Conservation and Management of Urban Groundwater System

Groundwater Governance Framework Indicators Covered:

- Compensation for Land-use Activity
- Levies on Pollutants
- Extraction and Quality Related Indicators
- Cross-sectoral Coordination

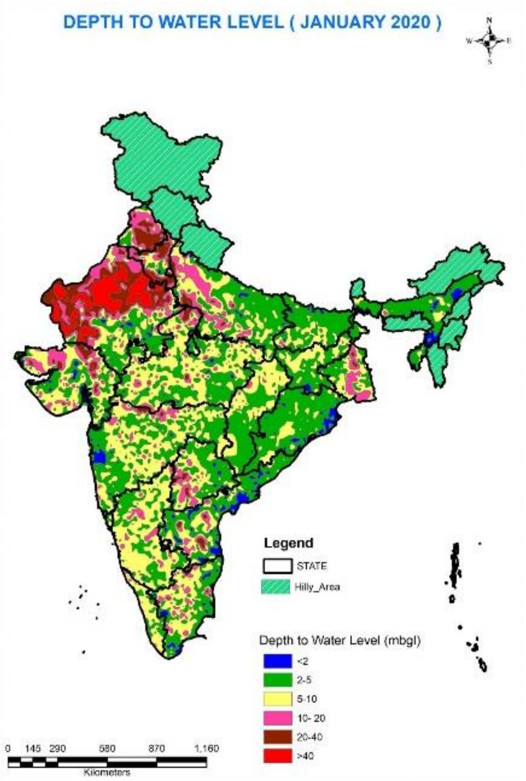
Component of Groundwater Governance Covered:

- Regulatory Framework
- Policies
- Actors

Case Study: Urban Groundwater Management through City Master Planning: Case in Indian Cities

Figure 8.7

Map of India with spatial distribution of groundwater level in different states



Source: *CGWB, 2020*

- About 25% of the world's groundwater extraction is on India mainly for agriculture and drinking supplies making it as the largest groundwater user (World Bank, 2019). Groundwater is the major source for more than half of the cities in India (Figure 8.7).
- In India, the Mumbai Metropolitan Regional Plan (2036), the Master Plan for Delhi (2021), the Master Plan for the city of Bengaluru (2031), a legally binding document, incorporates clear strategies and schemes for conserving the natural environment (forest, air, water, land) and includes sections dedicated to the protection of groundwater (Shinde et al., 2021).
- The Mumbai Metropolitan Regional Plan (2036) instructs that "construction of basements may be allowed subject to the condition that no objection certificate is obtained from the State Ground Water Authority to the effect that such construction will not adversely affect free flow of groundwater in that area".
- The Master Plan for Noida (2031) has the provision of "groundwater storage credits" (as an economic instrument) to ensure recharge and offset high exploitation rate. The plan "requires industries to apply for Zero-Discharge licences making it mandatory for them to install inhouse wastewater recycling plants and use the treated effluent for its operations. Any surplus treated effluent may be used to recharge groundwater resources for which the industries earn storage credits. Hence, the storage credit is equal to the amount of treated wastewater used for groundwater recharge. The industries can then use up these credits to withdraw water for use from permitted recovery wells."

Strategy 5: Improved Provision on "Internal and International Cooperation, Coordination and Right to Water" for Avoiding Conflict and Ensuring Water Availability and Accessibility to All

Groundwater Governance Framework Indicators Covered:

- Agreement - Transboundary Cooperation
- Customary Rights
- International Human Rights Charter

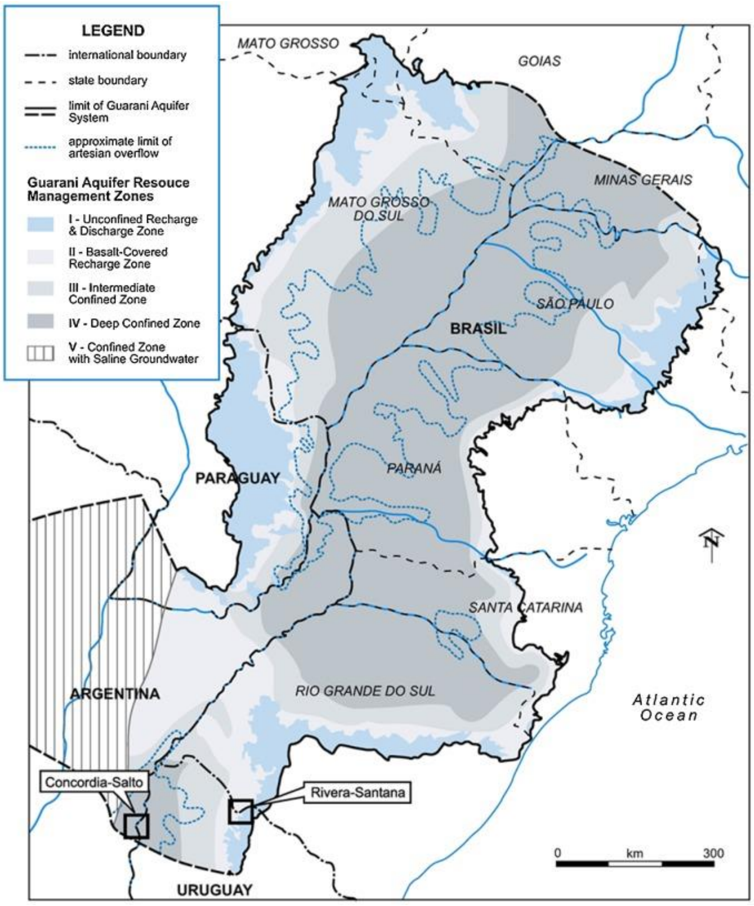
Component of Groundwater Governance Covered:

- Regulatory Framework
- Actors
- Policies

Case Study: Transboundary Groundwater Governance: A Case of Guarani Aquifer Governance

Figure 8.8

Guarani Aquifer System with Administrative Boundaries, System Boundary and Management Zones



Source: *Foster et al., 2009*

- The Guarani Aquifer System is shared by four countries (Argentina, Brazil, Paraguay and Uruguay) in South America (Figure 8.8). The transboundary reservoir has been extensively used for domestic supply, followed by industries, thermal tourism and irrigation (Source: Foster et al., 2009).

- The sharing countries established a management framework for the Guarani aquifer by jointly implementing a project "Project on the Protection and Sustainable Development of the Guarani Aquifer System (PSAG, 2003–2009)" leading to the development of the Strategic Action Plan based on TDA "Transboundary Diagnostic Analysis" (Amore, 2021).
- All four nations signed the "Guarani Aquifer Agreement" in 2010 and ratified it in 2018. The agreement is aligned with UN Draft Articles and "promotes the sustainable development of the aquifer system while solving issues arising between countries." The agreement made provision for a "commission" that administers compliance by all parties based on the principles of the agreement (Tapia-Villaseñor & Megdal, 2021).
- The agreement covers the protection, development, coordination and resource accessibility of entire aquifer in an integrated way providing a specific guideline to all the sharing nations. Article 2 and 3 of the agreement states that "each of the parties has the sovereign right to promote the management, utilization, and monitoring of their portion of the aquifer system as long as they follow the principle of reasonable use." Articles 8 and 12 state, "Data exchange and knowledge improvement are essential" (Amore, 2021; Foster et al., 2009; Tapia-Villaseñor & Megdal, 2021)

CHAPTER 9

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the study briefly with specific conclusions and provides recommendations to policymakers for improving groundwater governance based on study results. Further, it provides recommendations for future research studies as its follow-up.

9.1 Summary

Groundwater is a common-pool resource of global importance. A considerable share of the global population uses groundwater as drinking water supply and for agricultural irrigation, making it a crucial component for supply for domestic, agricultural, industrial sectors, and ecosystem services. Furthermore, the underneath water resource plays a vital role in water security, poverty reduction, and sustainable development of the Lower Mekong Region (LMR). However, the resource's effective and efficient management is challenging in the context of increased climatic and non-climatic stresses. This study evaluates the current state of groundwater governance in a rapidly urbanizing city, Khon Kaen, Thailand, and recommends ways to improve governance based on an evidence-based understanding of groundwater availability under future stresses.

The study developed a framework to assess the existing state of groundwater governance in rapidly urbanizing cities. The framework consisted of thirty indicators incorporated within four dimensions, namely technical (weightage = 44.2%), legal and institutional (weightage = 31.1%), cross-sector policy coordination (weightage = 12.6%), and operational dimension (weightage = 12.2%). The priority and weightage of the dimension were obtained from an expert-based Analytic Hierarchy Process (AHP). Furthermore, the groundwater framework consists of two variables, "adequacy of provision" and institutional capacity to implement its provision, rated from 0-3 (non-existence to optimum level). A set of mathematical equations for aggregating the framework's components delivers a holistic index value known as the Groundwater Governance Index (GGI), providing an overview of the current state of groundwater governance. An expert-based survey shows that groundwater governance in Khon Kaen, Thailand is at an acceptable state (GGI = 1.18) from a dimensional perspective with fair provisions of technical resources and regulatory and legal outlines. Further, the results highlighted the need to improve provisions (including stakeholders, cooperation, water rights, and institutional capacity) to enhance overall groundwater governance.

The study projected the future changes in four stresses (climate, land use, population, and water demand) to analyze their impact on groundwater availability under Shared Socioeconomic Pathways (SSPs). Four linearly bias-corrected CMIP-6 Global Climate Models (GCMs) showed that the annual average rainfall in Khon Kaen province is expected to increase to 13% and 16% under SSP2-4.5 and SSP5-8.5 scenarios respectively. Also, the average maximum and minimum temperature will likely rise around 2.5℃ (SSP2-4.5) and 4.4℃ (SSP5-8.5), making hotter days from April to June. These changes in the future temperature are statistically significant. In the case of land-use change projection, the study used the spatial land-use maps from European Space Agency (ESA) to develop a validated DynaCLUE model for the future forecast. The future land-use projection showed increased urban area by 11% under SSP2-4.5 and 32% under the SSP5-8.5 scenario replacing the agricultural land by 2100. The future population under the SSP2-4.5 and SSP5-8.5 scenarios has been done using a spatially explicit global population dataset validated with the census population. The results show that Khon Kaen will likely increase its population by 2030 (2.1 million). The increment compared to the baseline is likely to persist until 2060 and then is projected to decrease until 2100. The results further indicate that the urban population under both scenarios is expected to increase more than 100% in the mid and far future. The study further projected sectoral and total water demand based on the Khon Kaen province master plan (2017-2037) developed by Royal Irrigation Department (RID). Moreover, each sector’s total share of groundwater is calculated by generating an abstraction ratio based on observed groundwater abstraction to total water demand (2017). The results showed high sectoral abstraction in industrial groundwater abstraction (51-97% under SSP2-4.5 and 82-162% under SSP5-8.5).

The impact of climate and land-use change on groundwater recharge (GWR) has been investigated using SWAT hydrological model. The SWAT model for Chi-River Basin consisted of 61 sub-basins and 2051 Hydrological Response Units (HRUs). A sensitivity analysis of the parameters and the calibration process has been done using the SWAT-CUP (SUFI-2) model at the hydrological stations E1 and E9 daily. The hydrological station E1 is the outlet of the Khon Kaen Province, whereas the another is within the province. The results of the statistical performance for station E1 show satisfactory performance (NSE=0.57; R2=0.60; and PBIAS=-19.9%) for the calibration period (1990-2000), whereas the model showed good performance (NSE=0.74; R2=0.75; and PBIAS=-10.12%) for the validation period (2001-2003). Similarly, for station E9 the results show good performance (NSE=0.68; R2=0.70; and PBIAS=-23.59%) for the calibration period (2010-2014) and good performance (NSE=0.69; R2=0.73; and PBIAS=-5.83%) of the model is continued in the validation period (2015-2017). The results of the impact assessment showed the annual groundwater recharge (baseline: 412 mm/year) decreased over time in Khon Kaen (5%, 8%, and then to 10% in NF, MF, and FF, respectively, under SSP2-4.5), and the decrement is projected to be more under the SSP5-8.5 scenario (9%, 11% and 15% in NF, MF, and FF under the SSP5-8.5 scenario).

The study applied multiple regression in 6 observation wells in Khon Kaen to estimate future groundwater level changes. Four independent variables, namely groundwater recharge, domestic groundwater abstraction, agriculture groundwater abstraction, and industrial groundwater abstraction, were used from 2004 to 2019 to generate the equations for the dependent variable, i.e., groundwater level. The statistical results for 16 observation wells showed a satisfactory performance to develop and apply it for a preliminary visualization of future groundwater levels (availability) under stress and provide recommendations for improving the current state of groundwater governance. The results of the projected groundwater level shows in Khon Kaen showed that the level is likely to decline due to a decrease in the groundwater recharge (as an impact of climate and land-use change) and an increase in sectoral groundwater abstraction. Under the SSP2-4.5 and SSP5-8.5 scenarios, the average groundwater level is expected to decrease gradually from 0.8 m to 3 m and 1.7 m to 6.3 m until 2100, respectively. Overall, the results show that the impact of climate change and land-use change will likely lead to a decrease in groundwater recharge. When exaggerated by the increased sectoral groundwater abstraction, it is likely to lower the groundwater level in Khon Kaen. The results indicated that the situation is expected to bring more pressure on groundwater resources governance. Thus, the state of groundwater governance needs substantial improvement for the sustainable management of the resource.

Finally, the study provided strategies for improving groundwater governance in Khon Kaen, Thailand, with its prevailing state of governance and under the impact of future stresses. The study investigated and used the current state of four components of groundwater governance (multi-actor engagement; regulatory frameworks; policies; information, and knowledge) from the developed framework and recommended strategies for improving the weaker components with a successful case study for detailed elaboration. The results show that most components are at an incipient-acceptable state and indicate an urgent need for improving the provisions and institutional capacity. The investigation found that the inclusion of vulnerable and marginalized groups (actors engagement) in planning and decision-making, provision for integrated aquifer management models, gender responsiveness in the legal frameworks, integration of land-use planning policies, and requirement for adequate framework and structure for transboundary cooperation (internal and international) for improving the overall groundwater governance in urban areas. Conclusively, the study provided five strategies, namely: (1) Improved Provisions for “Collaborative and Consensus-based Aquifer Management Process for Groundwater Planning and Management”; (2) Improved Provisions for “Gender Responsive Regulatory Frameworks and Policies” in Formal and Informal Organizations; (3) Improved Provisions of “Integrated Aquifer Management Model” for Current and Future Status of Groundwater Resources; (4) Improved Legal Framework and Policies on “Land Use Planning and Sectoral Coordination” for Conservation and Management of Urban Groundwater System; (5) Improved Provision on “Internal and International Cooperation, Coordination and Right to Water” for Avoiding Conflict and Ensuring Water Availability and Accessibility to All with successful case studies for improving groundwater governance in Khon Kaen, under multiple future stresses.

9.2 Conclusions

This study evaluated the current state of groundwater governance and the impact of multiple future stresses on groundwater availability in the rapidly urbanizing city of Khon Kaen, Thailand, and provided strategies for improving groundwater under multiple stresses. The conclusions drawn are:

1. A ready-to-use framework to access the current state of groundwater governance in rapidly urbanizing cities was developed. The framework

consisted of 4 dimensions {Technical (w=44.2%); Legal and Institutional (w=31.1%); Cross-sectoral Policy Co-ordination (w=12.6%); Operational (w=12.2%)}, 30 indicators and 2 variables. The framework provides the Groundwater Governance Index (GGI), which represents an overview of the current state of groundwater governance (non-existence - optimal state).

2. The current state of groundwater governance in Khon Kaen, Thailand, is at an “acceptable state” (GGI = 1.18) from a dimensional perspective (Technical=1.5; Legal and Institutional=1; Cross-sectoral Policy Co-ordination=0.8; Operational=0.9) with fair provisions of technical resources and regulatory and legal outlines. Furthermore, the results stressed the need improved provisions for including multiple stakeholders, sectoral cooperation, water rights, and institutional capacity to enhance groundwater governance in Khon Kaen.
3. Future annual average rainfall in Khon Kaen province is expected to increase 8-13% under SSP2-4.5 and 9-16% under SSP5-8.5 scenarios. Similarly, the average maximum and minimum temperatures will likely rise (up to 4.4°C), making hotter days from April to June. The changes in the future temperature are statistically significant.
4. The future land use is projected to have an increasingly urban area (3-11% under SSP2-4.5 and 4-32% under the SSP5-8.5 scenario), replacing the agricultural land by 2100.
5. The population is expected to increase to 2.1 million by 2030 compared to the baseline. The trend is likely to persist until 2060 and then is projected to decrease until 2100. The results further indicated that the urban population is expected to increase 36-145% under SSP2-4.5 and 94-193% under the SSP5-8.5 scenario.
6. The results for total groundwater abstraction showed high sectoral abstraction in industrial groundwater abstraction (51-97% under SSP2-4.5 and 82-162% under SSP5-8.5) compared to baseline 8 MCM/Year. Domestic groundwater abstraction is projected to increase to 19% and 45% under SSP2-4.5 under SSP5-8.5, respectively, until the mid-future. A slight decrement in domestic abstraction is expected in the far future under both SSPs. Similarly, the agricultural groundwater abstraction is likely to increase under both scenarios (13-19% under SSP2-4.5 and 33-44% under SSP5-8.5). The baseline abstractions for both sectors are 3 MCM/Year).

7. The annual groundwater recharge (GWR) in Khon Kaen is expected to be impacted due to climate and land-use change. GWR is projected to decrease over time in Khon Kaen (5%, 8%, and 10% in NF, MF, and FF, respectively, under SSP2-4.5), and the decrement is projected to be more under the SSP5-8.5 scenario (9%, 11%, and 15% in NF, MF and FF respectively, under the SSP5-8.5 scenario).
8. The groundwater level in Khon Kaen is expected to decline due to a decrease under both SSPs. The average groundwater level is expected to decrease gradually from 0.8 m to 3 m and 1.7 m to 6.3 m until 2100, under SSP2-4.5 and SSP5-8.5 scenarios, respectively. Overall, the results showed that the impact of climate change and land-use change led to a decrease in groundwater recharge and increased sectoral groundwater abstraction, further amplifying the lowering of the groundwater level. Furthermore, the impact results indicated an increased pressure on groundwater resources and requires substantial provisions for improving the current and future state of groundwater governance.
9. The current state of four components of groundwater governance (multi-actor engagement; regulatory frameworks; policies; information, and knowledge) showed that majorly all the components are at an incipient-acceptable state (1-2 out of 3). The results indicated an urgent need for improving the provisions and institutional capacity (inclusion of vulnerable and marginalized groups; integrated number models, gender-responsive legal outlines, integration of land-use planning policies, and structure for transboundary cooperation) given the impact of future stresses.
10. The study provided five strategies to improve different components of groundwater governance that shall improve overall groundwater governance under multiple stresses in urban areas. The strategies are included for “collaborative and consensus-based aquifer management process for groundwater planning and management,”; “gender-responsive regulatory frameworks and policies” in formal and informal organizations; “integrated aquifer management model” for current and future status of groundwater resources; legal framework and policies on “land use planning and sectoral coordination” for conservation and management of urban groundwater system; and “internal and international cooperation, coordination and right to water” for avoiding conflict and ensuring water availability and accessibility to all.

9.3 Recommendations

The study proposes the following recommendations to the policy makers and for future research.

9.3.1 Recommendations for Policy Makers

1. The current multi-actor engagement in groundwater governance at Khon Kaen is between non-existent and incipient state. The following are recommendations for improving groundwater governance with the active engagement of all related actors under the impact of multiple future stresses.
    - Develop provisions and strategies to **engage local groundwater users and sectors** (*tourism, industrial, urban, and agriculture*) at aquifer scales (*for domestic and international transboundary management*) in specifying mutually acceptable levels of groundwater depletion and degradation under multi-stress anticipation.
    - Expand **institutional capacity** for improving and implementing existing provisions for the formation of community-based aquifer management organizations (*for ensuring the mobilization and formalization of community participation in aquifer management*); customary rights to land and water use for indigenous groups or communities (*to ensure the measures for inclusive water use right and for minimizing the possible conflicts*) and cross-sectoral engagement (*for multi-stakeholder engagement and cross-sectoral water-use monitoring*)
    - Improve legal provisions for **gender-inclusive staffing ratios** in different levels of groundwater governing institutions and the formation of aquifer management organizations (*including the vulnerable and marginalized groups*).
    - Implement **capacity development and sensitization programs** of key groundwater management agencies and stakeholders to include unrepresented and under-represented actors in planning, implementation, and decision-making processes.
2. The current state of provisions and institutional capacity for regulatory frameworks in groundwater governance and management at Khon Kaen, Thailand, has completed the incipient stage (overall) and is forwarding toward the acceptable state. The following are recommendations for improving

groundwater governance with a favorable legal and institutional framework under the impact of multiple future stresses.

- Expand **institutional capacity** for the execution of existing provisions such as drilling permits (*for groundwater user rights for small-scale groundwater users with large users*); sanctions on illegal well construction (*for controlling excessive use above permit*); groundwater abstraction and use charging (*resource charge on large users*); monitoring of polluters and potential pollutions (*for restricting groundwater hazards, fines or incentive for aquifer protection*) in the context of overexploitation of groundwater resources under stresses.
- Upgrade **regulatory provisions** for improved groundwater quality (land-use control on potentially polluting activities; abstraction and use charging; levies on generation/discharge of potential pollutants; formation of community-based aquifer management organizations).
- Develop **legally binding provisions** for gender-responsive frameworks, policies, and agencies (*to identify and acknowledge the existing differences and inequalities between different gender in formal and informal organizations and articulate initiatives which address the diverse needs, aspirations, capacities, and contributions of all*) in the context of climate change and rapid urbanization.
- Improve the **legal provisions and institutional structure** for international treaties, commitments, and human rights charters for improving cooperation between bordering countries concerning coordinated or joint management of shared aquifers.

3. The current state of provisions and institutional capacity under defined policies in groundwater governance and management at Khon Kaen, Thailand, is at the incipient stage (overall) and is forwarding toward the acceptable state. The following are recommendations for improving groundwater governance with well-defined policies under the impact of multiple future stresses.
    - Improve **policy provisions** for constraining land-use activities based on pollution sources that will impact groundwater quality (*in the context of rapid urbanization*) and **upgrade the provisions of policy instruments** for well closure or restricting water abstraction in existing wells for

controlling the over-extraction (in the context of increasing water demand under multiple stresses).

- Expand **institutional capacity** for effectively monitoring existing and upgraded provisions, such as reducing groundwater abstraction (*for monitoring and controlling abstraction in critical areas*); well construction (*for monitoring and controlling abstraction in overexploited and polluted areas*).
- Promote **intersectoral conjunctive water management policies** for sectoral planning, engagement, coordination, and implementation (*to ensure 'real water-saving/pollution control strategies; ensure the consideration for conservation and protection of groundwater resources; ensure strengthening measures for groundwater extraction and contamination*).
- Establish **provision for policy and planning linkage** with relevant sectors (*tourism, industrial, urban, and agriculture*) and local users from various in restricting land-use activities for groundwater recharge and quality protection with joint anticipation of future groundwater availability and abstraction under several stresses.
- Improve the **provision of gender-responsive groundwater policies** to address gender inclusiveness and the presence of vulnerable and marginalized stakeholders in groundwater governance and management (*within both formal and informal organizations*).

4. The current state of provisions and institutional capacity under information and knowledge in groundwater governance and management at Khon Kaen, Thailand, is between the incipient and acceptable state (overall). The following are recommendations for improving groundwater governance with precise and widely-shared information & knowledge under the impact of future stresses.
    - **Upgrade provisions** for comprehensive and consensus-based groundwater management action plans in the context of rapid urbanization and climate change (*to ensure the provisioning of a groundwater management action plan with agreed targets and instruments*).

- Improve **institutional provisions** for developing an integrated aquifer management model (*integration of surface and groundwater model to assess the impact of multiple climatic and non-climatic stresses*) to quantify resource status for informed decision-making, data sharing, strategic assessment and management measures the aquifer.
- Improve **technical and resource provisions** for detailed identification and assessment of source-based (*agriculture, industry, landfills, mines*) groundwater pollution contaminants and monitoring in the context of rapid urban development (*to generate evidence-based information and identify quality degradation risk to groundwater*).
- Expand and upgrade **institutional capacity** for the development and application of detailed technical resources (*groundwater management action, integrated aquifer management model, and pollution hazard assessments*) for gathering information and transform those to stakeholder's-oriented knowledge products (*for informed management decisions and information sharing*)
- Upgrade **public domain** (user-friendly) of groundwater governance and management-related government institutions for quick access to information (*process for good drilling and service charge, non-availability periods with reasons, water tariffs, water delivery schedules, monitoring networks*) and knowledge resources (*declarations, publications, guidelines, socio-economic reports, climate impact assessments*) to disseminate all required information for stakeholders and to ensure transparency to groundwater services.

9.3.2 Recommendations for Future Research

1. The future study may consider stakeholder engagement and field surveys for the future assumption of climate, land use, population, and water demand scenarios.
2. The current study did not consider groundwater vulnerability assessment. Thus, future research may consider assessing groundwater resources' vulnerability to availability under multiple stresses and the state of groundwater governance.
3. This study assessed the current state of groundwater governance at Khon Kaen city. Future research could utilize this existing framework to evaluate the current state of governance on the entire aquifer level (transboundary level) or

individual assessment on both sides of the aquifer to visualize the overall strengths, gaps, and opportunities for collaboration and sustainable development of the aquifer.

4. The study assessed the impact of multiple stresses on future groundwater availability. An addition of impacts on groundwater quality could be considered in future research.
5. This study has limited its scope by not considering the effect of reservoirs, their releases, and flow from surface water irrigation on groundwater storage. Therefore, investigating the impact of the stresses (climate and land use change) with consideration of existing reservoirs and their scheduling could be considered in future research.
6. The study's groundwater governance framework has not considered the aspect of “self-governance” in communities. New research could incorporate this aspect during the process of framework modification.
7. A modified groundwater governance framework could be developed in future works from the existing one, which shall consist of more dynamic indicators to also address the future state of groundwater governance under multiple stresses.

ORIGINALITY OF THE RESEARCH

The originality of this research is its crucial contribution to the development of the groundwater governance framework. The study developed a unique and well-defined framework for assessing the current state of groundwater governance based on the review of multiple assessment frameworks and the existing gap for a ready-to-use framework. Hence it can be further studied and developed based on specific requirements and utilized in future research work.

LIST OF PUBLICATIONS

- **Journal Publication**

KC, S., Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Groundwater governance: A review of the assessment methodologies. Environmental Reviews, 30(2), 202–216. https://doi.org/10.1139/er-2021-0066

- **Conference Proceedings**

KC, S., Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Developing a Pragmatic Framework for Indexing Groundwater Governance under Stress: Initiative on Groundwater Sustainability in the Lower Mekong Region. Development Research Conference 2022 (DevRes 2022): Transforming Development Research for Sustainability, 22-24 August 2022, Uppsala and Stockholm, Sweden.

KC, S., Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Development of Framework to Evaluate Current State of Groundwater Governance under Urbanization and Climate Change. THA 2022: International Conference on Moving Towards Sustainable Water and Climate Change Management After COVID-19, 26-28 January 2022, Bangkok Thailand (Virtual).

KC, S., Shrestha, S. (2021). Developing a Framework to Benchmark Current State of Vulnerable and Marginalized Groups Inclusion in Groundwater Governance. AGU Fall Meeting 2021, 13-17 December 2021, held in New Orleans, LA.

KC, S., Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2021). Development of Framework to Assess the Groundwater Governance in Transboundary Aquifers of Rapidly Urbanizing Cities. ISARM 2021, 2nd International Conference:

Transboundary Aquifers: Challenges and the way forward, 6-9 December 2021, UNESCO, Paris (Virtual).

- **Seminar Presentations**

KC, S., Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Framework for Indexing Groundwater Governance under Stresses: A Case of Khon Kaen, Thailand. Seminar on *Climate Risks in South and Southeast Asia: Challenges and Opportunities*, Asian Institute of Technology (AIT) and Earth Observatory of Singapore (EOS), 16 June 2022, AIT, Thailand.

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APPENDIX

Table A.1

Projection of rate of sectoral (Domestic, Agriculture, and Industrial) water demand from Khon Kaen master plan (RID, 2018) using interpolation method under SSP2-4.5 and SSP5-8.5 scenario

Year	Domestic			Agriculture			Industry		
	Total Demand (MCM) *(RID, 2018)*	Rate (MCM/Year)		Total Demand (MCM) *(RID, 2018)*	Rate (MCM/Year)		Total Demand (MCM) *(RID, 2018)*	Rate (MCM/Year)	
		SSP2-4.5	SSP5-8.5		SSP2-4.5	SSP5-8.5		SSP2-4.5	SSP5-8.5
2017	98.87	*0.36*	*0.54*	6201.92	*56.83*	*85.25*	34.11	*0.34*	*0.51*
2022	100.67			6486.08			35.82		
2022	100.67	*0.74*	*1.11*	6486.08	*19.35*	*29.03*	35.82	*0.34*	*0.51*
2027	104.37			6582.83			37.52		
2027	104.37	*0.19*	*0.285*	6582.83	*19.35*	*29.03*	37.52	*0.34*	*0.51*
2037	106.27			6582.83			40.93		
2037	Onwards	*0.19*	*0.285*	Onwards	*19.35*	*29.03*	Onwards	*0.34*	*0.51*

Table A.2

Projection of rate of sectoral (Domestic, Agriculture, and Industrial) water demand from Khon Kaen master plan (RID, 2018) and total population (for domestic demand), total agricultural area (for agricultural demand) and number of industries (for industrial demand under SSP2-4.5 and SSP5-8.5 scenario

	Domestic				Agriculture				Industry			
Year	Population	Total Demand (MCM)	Rate (LPCD)		Agriculture Area (Sq. Km)	Total Demand (MCM)	Rate (MCM/sq. km/Year)		Industries (Number)	Total Demand (MCM)	Rate (L/Industry/Year)	
	(RID, 2018)		SSP2-4.5	SSP5-8.5		*(RID, 2018)*	SSP2-4.5	SSP5-8.5		*(RID, 2018)*	SSP2-4.5	SSP5-8.5
2017	1805910	98.87	149.99	224.99	9545.04	6201.92	0.6498	0.9746	4176	34.11	22378.37	33567.55
2022	1838758	100.67	150.00	225.00	9533.70	6486.08	0.6803	1.0205	4205	35.82	23338.17	35007.25
2027	1758204	104.37	162.63	243.95	9502.20	6582.83	0.6928	1.0392	4222	37.52	24347.35	36521.03
2037	1940932	106.27	150.01	225.01	9416.97	6582.83	0.6990	1.0486	4257	40.93	26341.79	39512.68
		Future Rate	150.01	225.01		Future Rate	0.6990	1.0486		Future Rate	26341.79	39512.68

Table A.3

Projection of the number of industries (2020-2100) in Khon Kaen province using baseline number of industries (2015-2019) and linear interpolation method

Year	Number of Industries	Year	Number of Industries	Year	Number of Industries
2015	*4191*	*2044*	*4281*	*2073*	*4381*
2016	*4175*	*2045*	*4285*	*2074*	*4385*
2017	*4176*	*2046*	*4288*	*2075*	*4388*
2018	*4190*	*2047*	*4291*	*2076*	*4392*
2019	4198	2048	4295	2077	4395
2020	4198	2049	4298	2078	4399
2021	4202	2050	4302	2079	4402
2022	4205	2051	4305	2080	4406
2023	4208	2052	4309	2081	4409
2024	4212	2053	4312	2082	4412
2025	4215	2054	4316	2083	4416
2026	4219	2055	4319	2084	4419
2027	4222	2056	4323	2085	4423
2028	4226	2057	4326	2086	4426
2029	4229	2058	4329	2087	4430
2030	4233	2059	4333	2088	4433
2031	4236	2060	4336	2089	4437
2032	4240	2061	4340	2090	4440
2033	4243	2062	4343	2091	4444
2034	4246	2063	4347	2092	4447
2035	4250	2064	4350	2093	4451
2036	4253	2065	4354	2094	4454
2037	4257	2066	4357	2095	4457
2038	4260	2067	4361	2096	4461
2039	4264	2068	4364	2097	4464
2040	4267	2069	4368	2098	4468
2041	4271	2070	4371	2099	4471
2042	4274	2071	4374	2100	4475
2043	4278	2072	4378		

Table A.4

Responses from the global expert survey with the individual consistency ratio (CR) used in the analytic hierarchy process (AHP) to obtain the priority and weightage of all four dimensions of the groundwater governance framework

Response 1 (CR=4%)					*Response 2 (CR=5%)*					*Response 3 (CR=3%)*					*Response 4 (CR=2%)*				
	D-1	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**
D-1	1	1	2	5	**D-1**	1	1	3	1	**D-1**	1	1	3	2	**D-1**	1	7	7	7
D-2	1	1	4	9	**D-2**	1	1	3	3	**D-2**	1	1	4	5	**D-2**	0.143	1	2	1
D-3	0.5	0.25	1	5	**D-3**	0.333	0.333	1	1	**D-3**	0.333	0.25	1	1	**D-3**	0.143	0.5	1	1
D-4	0.2	0.11	0.2	1	**D-4**	1	0.333	1	1	**D-4**	0.5	0.2	1	1	**D-4**	0.143	1	1	1
Response 5 (CR=0%)					*Response 6 (CR=0%)*					*Response 7 (CR=2%)*					*Response 8 (CR=1%)*				
	D-1	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**
D-1	1	1	1	1	**D-1**	1	5	6	5	**D-1**	1	1	5	7	**D-1**	1	1	5	5
D-2	1	1	1	1	**D-2**	0.2	1	1	1	**D-2**	1	1	8	7	**D-2**	1	1	5	5
D-3	1	1	1	1	**D-3**	0.167	1	1	1	**D-3**	0.2	0.125	1	2	**D-3**	0.2	0.2	1	2
D-4	1	1	1	1	**D-4**	0.2	1	1	1	**D-4**	0.143	0.143	0.5	1	**D-4**	0.2	0.2	0.5	1
Response 9 (CR=10%)					*Response 10 (CR=5%)*					*Response 11 (CR=9%)*					*Response 12 (CR=8%)*				
	D-1	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**
D-1	1	1	5	1	**D-1**	1	3	7	4	**D-1**	1	1	4	1	**D-1**	1	1	3	1
D-2	1	1	5	1	**D-2**	0.333	1	5	3	**D-2**	1	1	5	1	**D-2**	1	1	5	1
D-3	0.2	0.2	1	1	**D-3**	0.143	0.2	1	1	**D-3**	0.25	0.2	1	1	**D-3**	0.333	0.2	1	1
D-4	1	1	1	1	**D-4**	0.25	0.333	1	1	**D-4**	1	1	1	1	**D-4**	1	1	1	1
Response 13 (CR=14%)					Response 14 (CR=12%)					Response 15 (CR=11)					Response 16 (CR=17%)				
	D-1	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**

D-1	1	7	7	6	**D-1**	1	1	3	1	**D-1**	1	1	5	3	**D-1**	1	5	5	5
D-2	0.143	1	5	3	**D-2**	1	1	7	1	**D-2**	1	1	2	4	**D-2**	0.2	1	5	5
D-3	0.143	0.2	1	1	**D-3**	0.333	0.143	1	1	**D-3**	0.2	0.5	1	4	**D-3**	0.2	0.2	1	1
D-4	0.167	0.333	1	1	**D-4**	1	1	1	1	**D-4**	0.333	0.25	0.25	1	**D-4**	0.2	0.2	1	1
Response 17 (CR=16%)					Response 18 (CR=17%)					Response 19 (CR=19%)					Response 20 (CR=5%)				
	D-1	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**		**D-1**	**D-2**	**D-3**	**D-4**
D-1	1	4	3	4	**D-1**	1	5	2	2	**D-1**	1	3	7	7	**D-1**	1	1	3	1
D-2	0.25	1	3	4	**D-2**	0.2	1	2	2	**D-2**	0.333	1	5	5	**D-2**	1	1	3	1
D-3	0.333	0.333	1	4	**D-3**	0.5	0.5	1	2	**D-3**	0.143	0.2	1	9	**D-3**	0.333	0.333	1	1
D-4	0.25	0.25	0.25	1	**D-4**	0.5	0.5	0.5	1	**D-4**	0.143	0.2	0.111	1	**D-4**	1	1	1	1
D-1: Technical Dimension					***D-2: Legal and Institutional***					***D-3: Cross-Sector Policy Coordination***					***D-4: Operational***				

Appendix Q.1

Expert Questionnaire: Groundwater Governance Framework

Study on Assessing Current State of Groundwater Governance

GIRA project "Strengthening Groundwater Governance in Rapidly Urbanizing Areas of the Lower Mekong Region" funded by Stockholm Environmental Institute (SEI), aims to evaluate the current state of groundwater governance in the region and recommend the ways to improve or strengthen the groundwater governance based on evidence-based understanding of groundwater availability, its use and potential conflicts under multiple stresses in the future.

This is a survey aiming to understand experts' perspectives and opinions towards current state of groundwater governance in their region. Further, the questionnaires provide an approach to realize how the groundwater is currently governed, *what are provisions* in terms of Technical, Legal and Institutional, Cross-Sector Policy Coordination and Operational aspect and *what is the institutional capacity* to implement them. If you directly or indirectly work in policy, decision-making, research and implementing side of the groundwater sector, you are kindly invited to participate in this survey.Your contribution is important to understand the current strength, gaps and areas of improvement in groundwater governance and management in the country.
The survey should take about 30 minutes to complete. There are no privacy-related questions. Your responses are anonymous, and the individual study results will be confidential and only used for the research purpose. Data will not be traceable to you and will not be shared with anyone besides the project team. Thank you for your time.
If you have any questions, or if you want the study's final report, please contact sangam@ait.asia or er.saurav.kc@gmail.com.

General information

1. Country: 2. Province:

3. Gender: Male/Female/Prefer Not to Say 4. Age:

5. Highest level of education:
6. Type of occupation:

☐ Policy maker
☐ Scientist/Researcher
☐ Policy implementer/manager
☐ Practitioner
☐ Technical Officer
☐ Legal Officer ☐ Others, pls. specify…………………………………….

7. Type of your organization:

☐ Public Administration
☐ Public Research Institution
☐ Private Sector
☐ Non-governmental development organization
☐ Community based-organization
☐ Others, pls. specify…………………………………….

8. Number of working years:

☐ 0-5 years ☐ 6-10 years ☐ 11-15 years ☐ 15 years and above

9. How do you involve in groundwater sector
☐ Direct
☐ Indirect

Note:

- **Please tick only one box in the each statement (row) of a question.**

SAMPLE

1. Is there any provision for penalizing illegal/ unpermitted water wells?

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☑	☐	☐
Existing Institutional Capacity to Implement the Provision	☑	☐	☐	☐

Interpretation-1: *The result illustrates that there exists a basic provision for penalizing illegal wells but there is no institutional capacity to implement that provision.*

2. Is there any provision for penalizing illegal/ unpermitted water wells?

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☑	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☑	☐

Interpretation-2: *The result illustrates that there exists no provision for penalizing illegal wells but there is acceptable level of institutional capacity to implement if the provision is made available.*

Section A: Technical Aspect in Groundwater Governance

1. **Is there a "Hydrogeological Map" of the entire aquifer available** (with basic subsurface geologies, aquifers, groundwater table (contours), flow direction, critical zones, etc.)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

2. **Are the groundwater bodies been classified with their typologies** (showing the linkage of characteristics and status of groundwater bodies)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

3. **Is there a groundwater-piezometric monitoring network setup for monitoring groundwater level, extraction, recharge, and use?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

4. **Is there any provision for identifying and monitoring the aquifer pollutants from multiple sources** (agriculture, industry, landfills, mines, etc.)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐

Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

5. **Is there a process-based numerical model** (groundwater model) available **for the entire aquifer?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

6. **Is there a groundwater quality monitoring network setup for detecting and monitoring incipient pollution to the groundwater?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

7. **Do the groundwater governing and managing institutions publish knowledge resources** (declarations, publications, guidelines, etc.) **in its public domain that is related to vulnerable and marginalized groups?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

Section B: Legal and Institutional Aspect in Groundwater Governance

8. **Is there any provision of permits for drilling large-scale groundwater wells?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

9. **Is there any provision for closing a well or restricting the volume of abstraction in the existing well at critical zones/areas?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

10. **Is there any provision for controlling the construction of groundwater well?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

11. **Is there any provision for penalizing the construction of illegal/ unpermitted water wells?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

12. **Is there any provision for charging a larger quantity of groundwater abstraction and use** (as a provision of resource charge for large users)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

13. **Is there any provision for restricting land-use activities based on pollution sources that will impact groundwater quality?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

14. **Is there any provision of levies for generating and discharging potential groundwater pollutants above the discharge standards?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

15. **Is there any provision of legal frameworks that defines government as the guardian or empowered center to groundwater resources?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

16. **Is there any policy provision for the formation of community-based aquifer management organizations?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

17. **Is there any policy provision that addresses gender inclusiveness in groundwater management?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

18. **Is there any policy provision for gender-specific staffing ratio (female/male) in different levels of formal groundwater institutions?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

19. **Is there any policy provision for state ratification/ commitments/ implementation actions related to cooperation and coordination among national and/or international transboundary aquifers?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

20. **Is there any policy provision for customary rights to land and water use for indigenous groups or communities?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

21. **Is there any policy provision for state ratification/ commitments/ implementation actions on human rights charters relevant to groundwater resources right and management?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

Section C: Cross-Sector Policy Coordination Aspect in Groundwater Governance

22. **Is there any policy provision for coordination with the agriculture sector in managing groundwater resources** (to ensure water-saving/pollution control)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

23. **Is there any policy provision for coordination with the urban/industrial sector in managing groundwater resources** (to ensure the consideration for conservation and protection of groundwater resources)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

24. **Is there any policy provision for coordination with the tourism sector in managing groundwater resources** (to ensure groundwater supply, quality, and strengthening measures for groundwater extraction and contamination)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

25. **Is there any policy provision of compensation for restricting land use activities that support in groundwater recharge and quality protection?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

Section D: Operational Aspect in Groundwater Governance

26. **Is there any provision of information on basic groundwater services (**process for good drilling and service charge; non-availability periods with reasons, water tariffs, water delivery schedules, etc.)**?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

27. **Is there any policy provision for public participation in operational groundwater management against overexploitation and pollution?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

28. **Is there existence of a groundwater management action plan for the aquifer considered with consensus on targets and measures?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

29. **Is there any policy provision for including representatives from Vulnerable and Marginalized (V&M) groups in different positions and responsibilities** (in decision-making processes) **in local or community aquifer management organizations?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐
Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

30. **Is there any provision/implementation of capacity development activities related to Vulnerable and Marginalized (V&M) inclusiveness in groundwater governance and management at formal government institutions?**

Statement	Not at All	Basic	Acceptable	Full
Existing Provision	☐	☐	☐	☐

Existing Institutional Capacity to Implement the Provision	☐	☐	☐	☐

Section E: Key Challenges and Barriers in Groundwater Governance

31. **Please write down your own statement on the existing conflicts in groundwater resources with in your region?**

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

32. **Please write down your own statement regarding key challenges related to groundwater governance and management in your region?**

……………………………………………………………………………………

……………………………………………………………………………………

……………………………………………………………………………………

***********Thank you for your kind cooperation!***********

Table A.5

Assessing current groundwater governance index (GGI) of Khon Kaen Thailand using the groundwater governance framework and expert-based evaluation

Type of Provision/ Capacity	Code	Indicator	Average Rating		Aggregation		GGI Value (Weighted)
			Adequacy of Provision	Institutional Capacity	Variable	Dimension	
Technical	TE1	Existence of basic hydrogeological maps	1.78	1.74	1.76	**1.5**	**1.18**
	TE2	Groundwater body/aquifer delineation	1.61	1.61	1.61		
	TE3	Groundwater-piezometric monitoring network	1.48	1.48	1.48		
	TE4	Groundwater-pollution hazard assessment	1.17	1.26	1.22		
	TE5	Availability of aquifer numerical management models	0.96	1.09	1.02		
	TE6	Groundwater-quality monitoring network	1.48	1.48	1.48		
	TE7	Vulnerable and Marginalized (V&M) groups specific publications (guide)	1.61	1.65	1.63		
Legal and Institutional	LI1	Water well drilling permits and groundwater use rights	2.17	1.91	2.04	**1.0**	
	LI2	Instrument to reduce groundwater abstraction	1.78	1.70	1.74		
	LI3	Instrument to prevent water well construction	2.26	1.70	1.98		
	LI4	Sanction for illegal water well construction	2.04	1.43	1.74		
	LI5	Groundwater abstraction and use charging	1.74	1.61	1.67		
	LI6	Land-use control on potentially polluting activities	0.83	0.65	0.74		
	LI7	Levies on generation/discharge of potential pollutants	0.52	0.57	0.54		
	LI8	Government agency as ground-water-resource guardian	1.65	1.61	1.63		
	LI9	Community aquifer management organizations	0.35	0.43	0.39		
	LI10	Gender-responsive groundwater policies or legal frameworks	0.13	0.26	0.20		
	LI11	Gender-inclusive groundwater management agencies (government)	0.17	0.26	0.22		
	LI12	Agreements and commitments to cooperation and coordination	0.74	0.74	0.74		
	LI13	Customary land and water rights for indigenous groups or communities	0.30	0.30	0.30		
	LI14	Agreements and commitments related to international human rights charters	0.43	0.48	0.46		
Cross-Sector Policy Coordination	CS1	Coordination with agriculture development	1.17	1.17	1.17	**0.8**	
	CS2	Groundwater-based urban/industrial planning	1.17	1.04	1.11		
	CS3	Coordination with tourism development	0.87	0.78	0.83		
	CS4	Compensation for groundwater protection	0.87	0.70	0.78		
Operational	OP1	Transparency in groundwater services for all consumers	1.43	1.39	1.41	**0.9**	
	OP2	Public participation in groundwater management	0.70	0.83	0.76		
	OP3	Existence of groundwater-management action plan	0.78	0.70	0.74		
	OP4	Vulnerable and Marginalized (V&M) group inclusiveness in aquifer management organizations	0.48	0.48	0.48		
	OP5	Vulnerable and Marginalized (V&M) sensitization capacity development (government level)	0.39	0.39	0.39		

Figure A.1

Comparison of GCM's historical average annual maximum and minimum temperature with an observed average annual temperature of the Chi Mun River basin for the baseline period (1981-2014) after linear bias correction

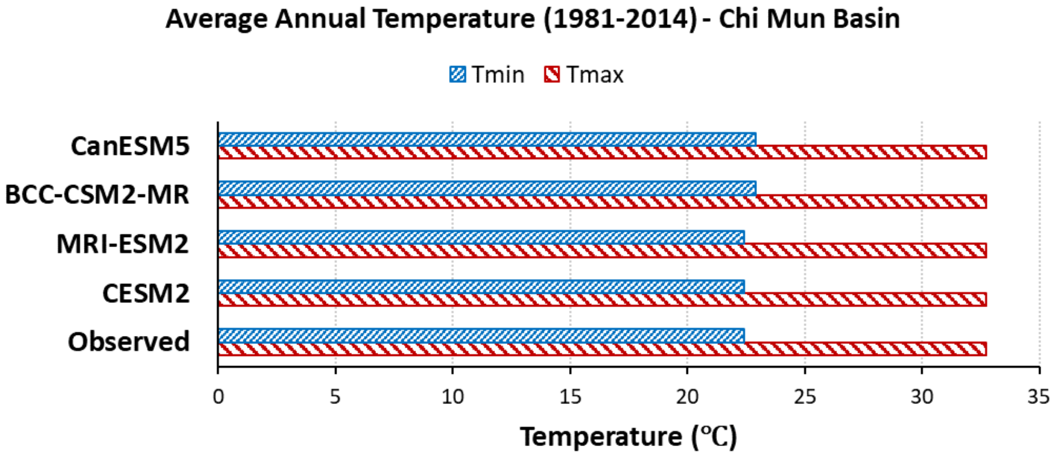
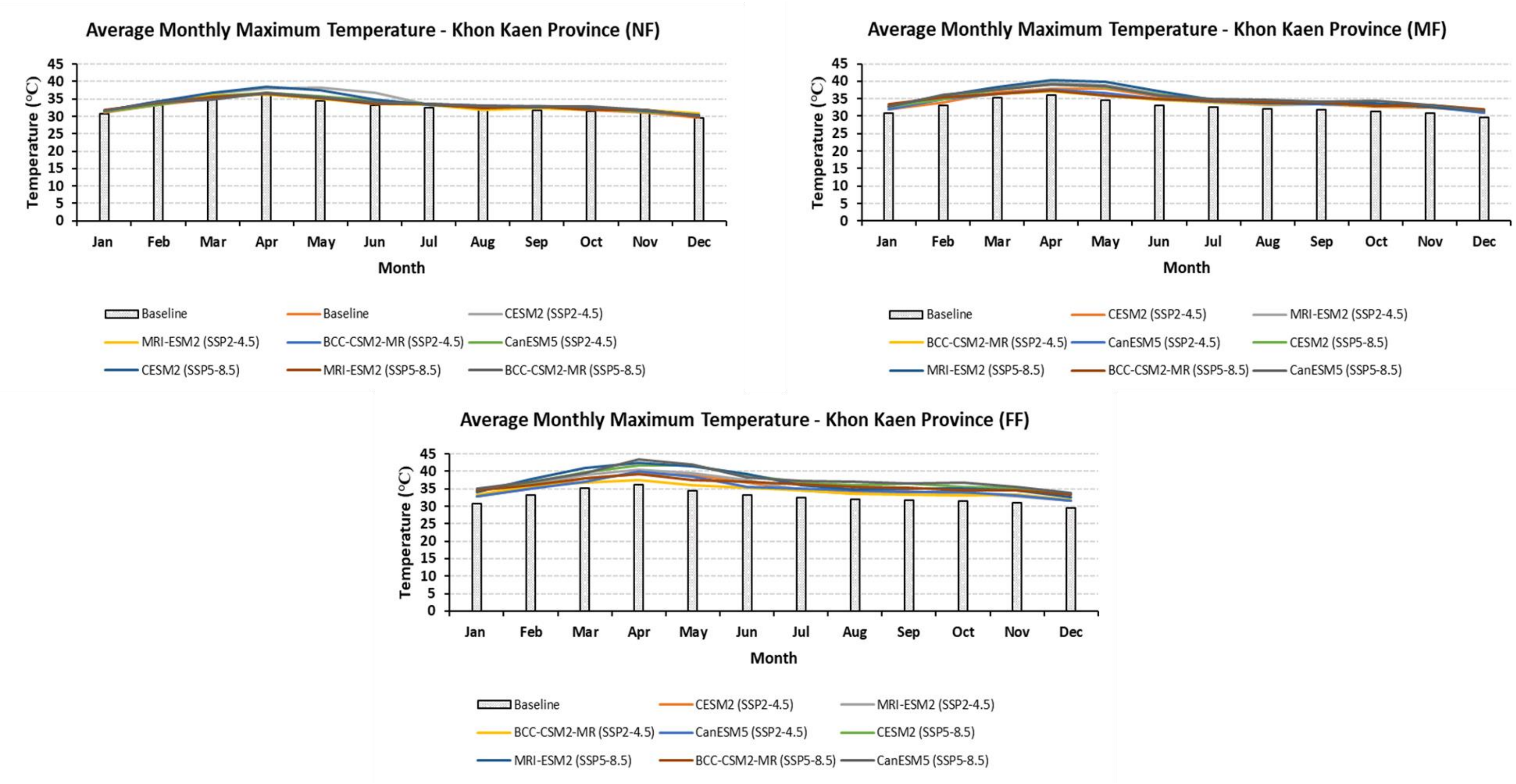
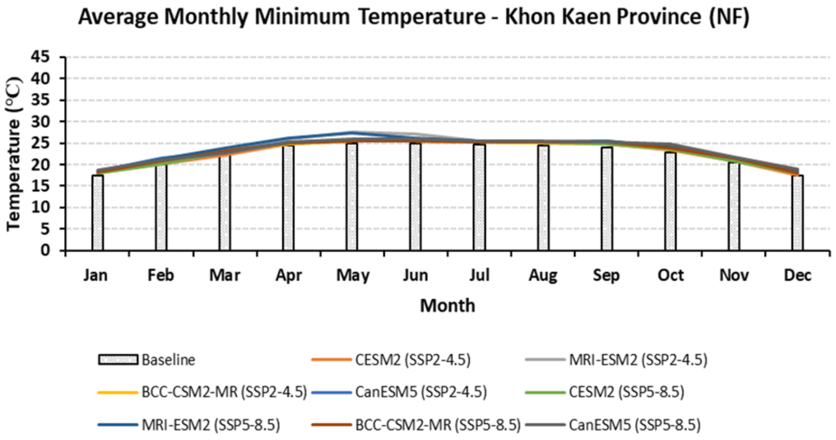
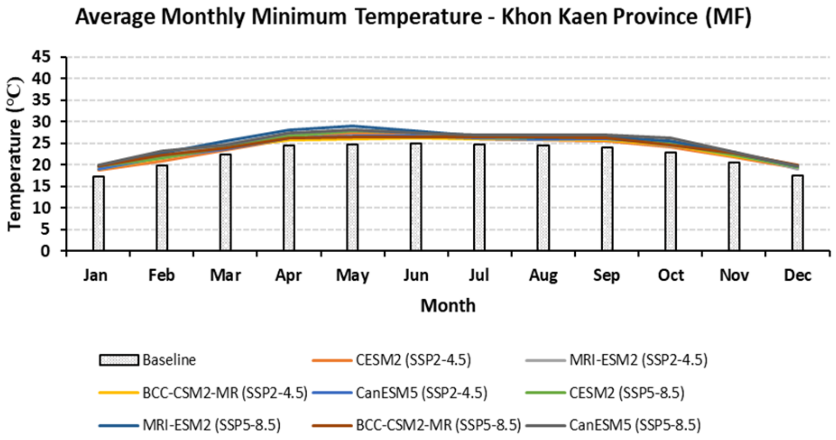


Figure A.2

Comparison of projected average monthly maximum and minimum temperature for Khon Kaen Province (NF, MF, FF) with baseline average monthly temperature under SSP2-4.5 and SSP5-8.5 scenarios




Average Monthly Minimum Temperature - Khon Kaen Province (NF)
Temperature (°C)
45
40
35
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Baseline
CESM2 (SSP2-4.5)
MRI-ESM2 (SSP2-4.5)
BCC-CSM2-MR (SSP2-4.5)
CanESM5 (SSP2-4.5)
CESM2 (SSP5-8.5)
MRI-ESM2 (SSP5-8.5)
BCC-CSM2-MR (SSP5-8.5)
CanESM5 (SSP5-8.5)


Average Monthly Minimum Temperature - Khon Kaen Province (MF)
Temperature (°C)
45
40
35
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Baseline
CESM2 (SSP2-4.5)
MRI-ESM2 (SSP2-4.5)
BCC-CSM2-MR (SSP2-4.5)
CanESM5 (SSP2-4.5)
CESM2 (SSP5-8.5)
MRI-ESM2 (SSP5-8.5)
BCC-CSM2-MR (SSP5-8.5)
CanESM5 (SSP5-8.5)

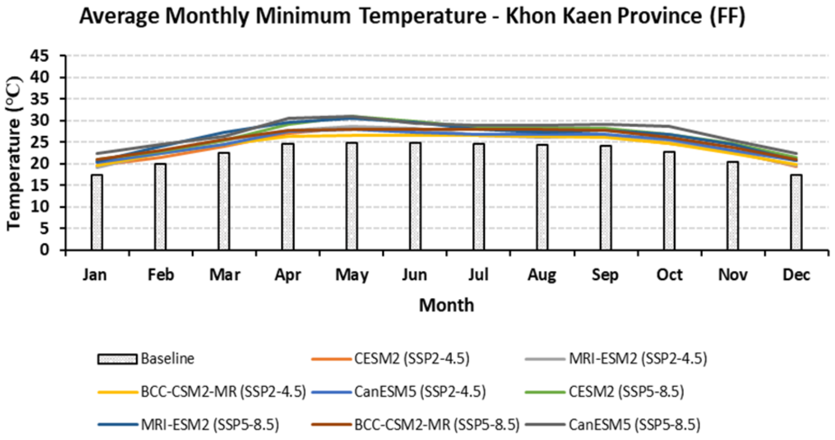

Average Monthly Minimum Temperature - Khon Kaen Province (FF)
Temperature (°C)
45
40
35
30
25
20
15
10
5
0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month
Baseline
CESM2 (SSP2-4.5)
MRI-ESM2 (SSP2-4.5)
BCC-CSM2-MR (SSP2-4.5)
CanESM5 (SSP2-4.5)
CESM2 (SSP5-8.5)
MRI-ESM2 (SSP5-8.5)
BCC-CSM2-MR (SSP5-8.5)
CanESM5 (SSP5-8.5)

Figure A.3

Projected population density of the Khon Kaen Province (NF, MF, FF) with districts under SSP2-4.5 and SSP5-8.5 scenario

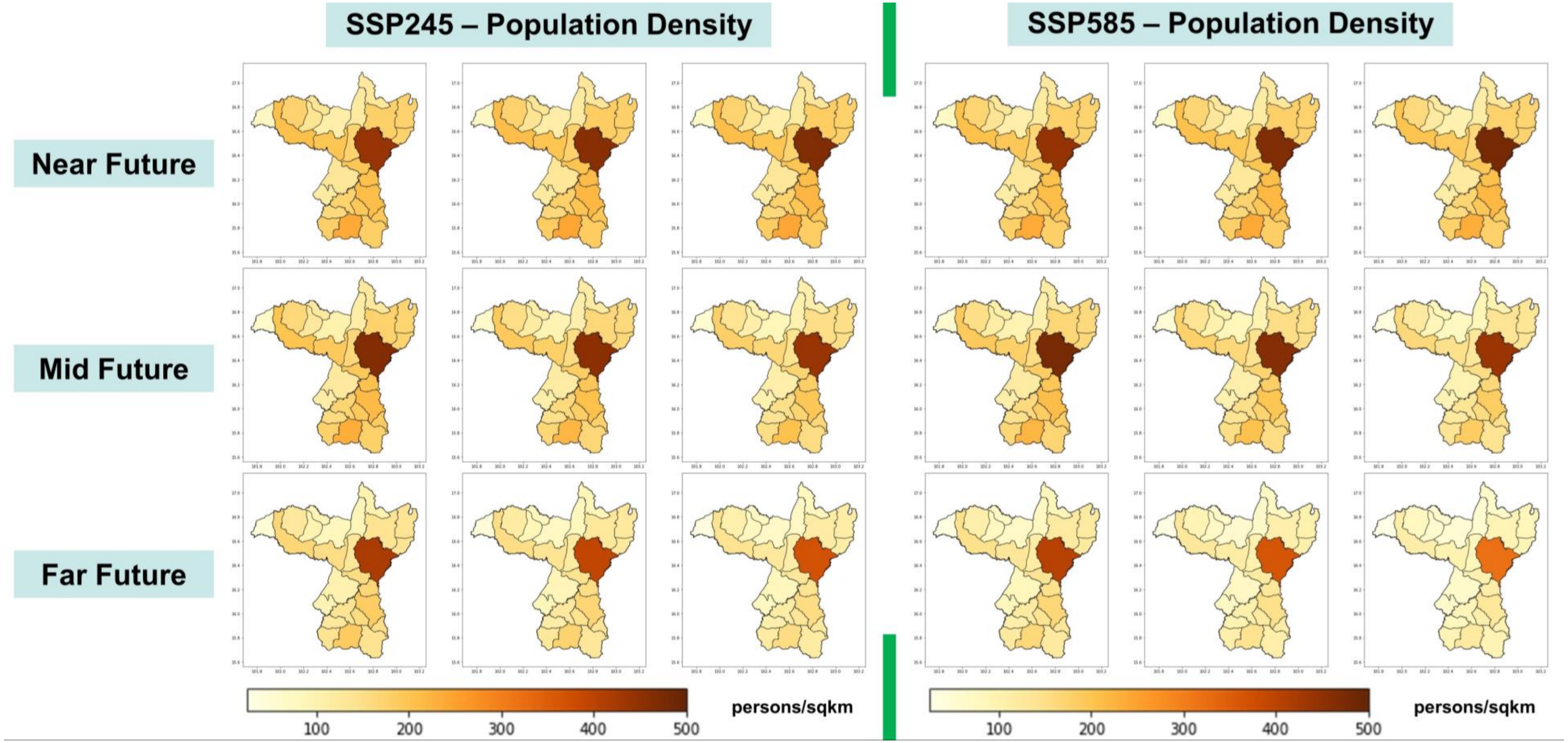


Table A.6

Comparison of projected land use and their share in Khon Kaen Province (2020-2100) under SSP2-4.5 and SSP5-8.5 scenarios

Area (Sqkm) - SSP2-4.5					
Year	Agricultural	Forest	Grassland	Urban	Water
2020	9545.5	563.8	86.0	135.5	308.9
	89.72%	*5.30%*	*0.81%*	*1.27%*	*2.90%*
2030	9479.9	564.5	85.1	201.4	308.9
	89.10%	*5.31%*	*0.80%*	*1.89%*	*2.90%*
2040	9384.3	565.2	82.2	299.2	308.9
	88.20%	5.31%	0.77%	2.81%	2.90%
2050	9240.0	566.3	79.9	444.6	308.9
	86.84%	*5.32%*	*0.75%*	*4.18%*	*2.90%*
2060	9144.4	566.7	78.8	541.0	308.9
	85.95%	*5.33%*	*0.74%*	*5.08%*	*2.90%*
2070	9026.6	567.7	77.5	659.1	308.9
	84.84%	5.34%	0.73%	6.19%	2.90%
2080	8882.3	569.2	75.5	803.9	308.9
	83.48%	*5.35%*	*0.71%*	*7.56%*	*2.90%*
2090	8705.8	571.8	74.8	978.5	308.9
	81.82%	*5.37%*	*0.70%*	*9.20%*	*2.90%*
2100	8492.0	572.1	72.3	1194.4	308.9
	79.81%	*5.38%*	*0.68%*	*11.23%*	*2.90%*
Area (Sqkm) - SSP5-8.5					
Year	Agricultural	Forest	Grassland	Urban	Water
2020	9545.5	563.8	86.0	135.5	308.9
	89.72%	*5.30%*	*0.81%*	*1.27%*	*2.90%*
2030	9437.7	564.8	83.4	244.9	308.9
	88.70%	*5.31%*	*0.78%*	*2.30%*	*2.90%*
2040	9246.2	565.9	79.7	438.9	308.9
	86.90%	*5.32%*	*0.75%*	*4.13%*	*2.90%*
2050	8900.8	566.6	77.9	785.5	308.9
	83.66%	*5.33%*	*0.73%*	*7.38%*	*2.90%*
2060	8631.6	568.4	75.2	1055.6	308.9

	81.13%	*5.34%*	*0.71%*	*9.92%*	*2.90%*
2070	8269.9	568.8	73.5	1418.6	308.9
	77.73%	*5.35%*	*0.69%*	*13.33%*	*2.90%*
2080	7780.8	569.6	72.0	1908.5	308.9
	73.13%	*5.35%*	*0.68%*	*17.94%*	*2.90%*
2090	7126.6	571.2	70.0	2563.0	308.9
	66.98%	*5.37%*	*0.66%*	*24.09%*	*2.90%*
2100	6244.8	572.9	67.1	3445.9	308.9
	58.69%	*5.38%*	*0.63%*	*32.39%*	*2.90%*

Figure A.4

DEM, Soil Map and Land-use Map of Chi River Basin used in the SWAT hydrological modelling

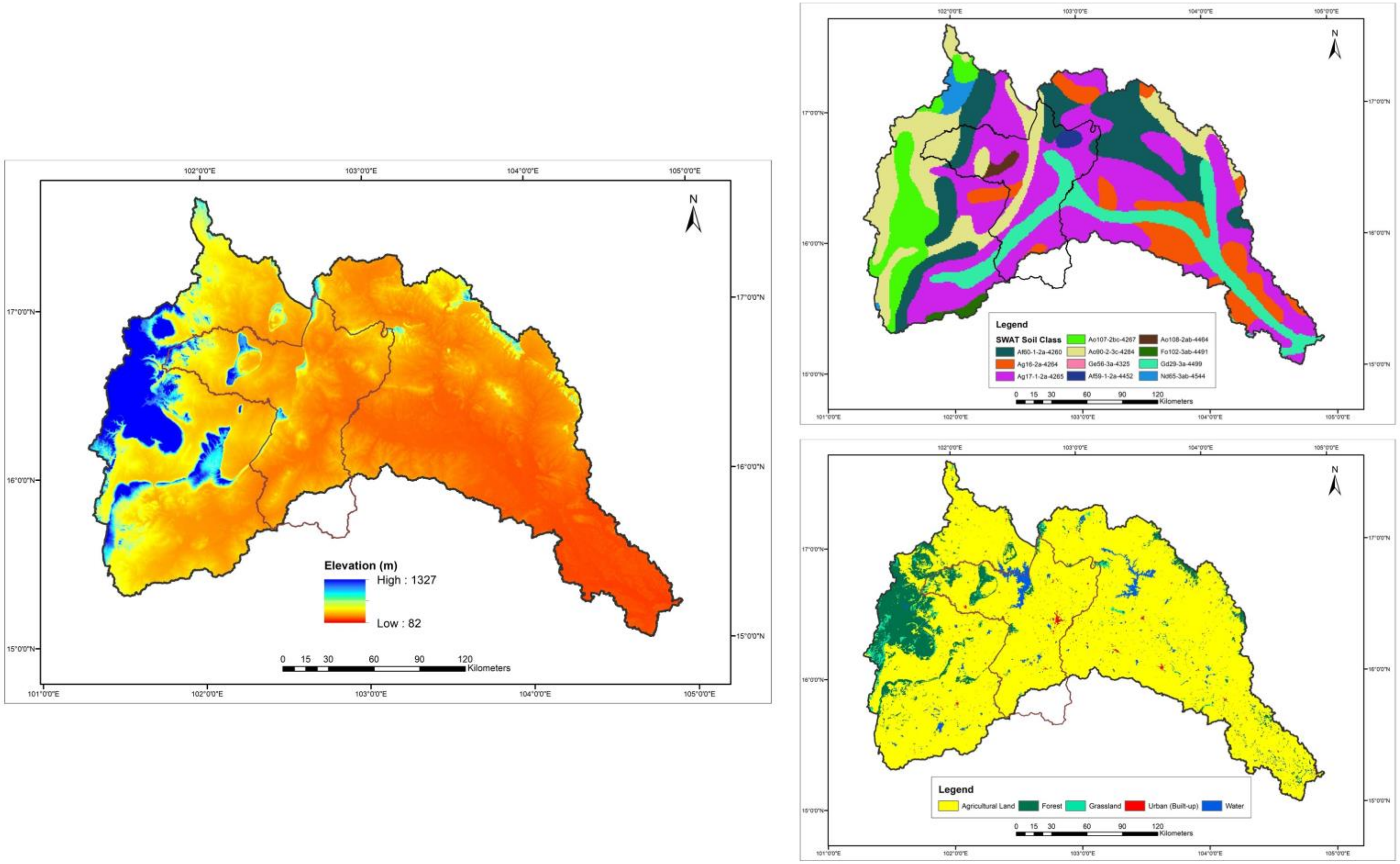


Table A.7

Selected sensitive parameters (with fitted values) for the calibration and validation of the SWAT model at outlets E1 and E9 using observed flow for 1990-2003 and 2010-2017, respectively.

S.N	Parameter_Name	Description of Parameter	Fitted_Value	Min_value	Max_value
1	R__CN2.mgt	SCS runoff curve number f	-0.0615	-0.1028	-0.0203
2	V__GW_DELAY.gw	Groundwater delay (days).	36.5059	35.2385	37.7734
3	V__ALPHA_BF.gw	Baseflow alpha factor (days).	0.9952	0.9927	0.9977
4	V__GWQMN.gw	Treshold depth of water in the shallow aquifer required for return flow to occur (mm).	2724.2703	2651.7080	2796.8325
5	V__GW_REVAP.gw	Groundwater "revap" coefficient.	0.1948	0.1930	0.1966
6	V__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm).	53.9648	33.4091	74.5204
7	V__RCHRG_DP.gw	Deep aquifer percolation fraction.	0.0764	0.0708	0.0819
8	R__SOL_BD(..).sol	Moist bulk density.	0.2719	0.2636	0.2802
9	R__SOL_AWC(..).sol	Available water capacity of the soil layer.	-0.0613	-0.0718	-0.0509
10	R__SOL_K(..).sol	Saturated hydraulic conductivity.	-0.1034	-0.1059	-0.1010
11	V__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium.	247.2091	245.7573	248.6608
12	V__LAT_TTIME.hru	Manning's "n" value for the main channel.	96.8381	95.8978	97.7785
13	V__CANMX.hru	Maximum canopy storage.	91.4048	90.7954	92.0142
14	V__ESCO.hru	Soil evaporation compensation factor.	0.0463	0.0108	0.0819
15	V__EPCO.hru	Plant uptake compensation factor.	0.5556	0.5300	0.5813
16	R__SURLAG.bsn	Surface runoff lag time.	0.2466	0.2327	0.2604
17	V__CH_N2.rte	Manning's "n" value for the main channel.	0.0667	0.0634	0.0701
18	V__ALPHA_BNK.rte	Baseflow alpha factor for bank storage.	0.1508	0.1174	0.1841

CURRICULUM VITA

Curriculum Vitae (CV)

PERSONAL DETAILS

Family Name:	**XX**	Sex:	**Male**	Nationality:	**Nepalese**
Given Name:	**XXXXX**	Status:	**Student**	Date of Birth:	**17/08/1987**

ADDRESS

Current Address:	Asian Institute of Technology, Klong Luang, Pathumthani 12120, Thailand	Mobile Number:	+66945799919
Address (Nepal):	Old Sinamangal-32, Kathmandu	Landline Number:	+9779841316673

EMAIL ADDRESS: XXXXX

ACADEMICS

Dates	**Institution & Place**	**Area of Study**	**Degree**
Aug 2019 to Present	Asian Institute of Technology (AIT), Thailand	**Water Engineering and Management**	Doctoral in Engineering
2017 to 2019	Asian Institute of Technology (AIT), Thailand	**Water Engineering and Management**	Master’s in Engineering
2006 to 2010	Tribhuwan University / Kantipur Engineering College/ Nepal	**Civil Engineering**	Bachelor’s Degree in Civil Engineering

PUBLICATIONS

Journal Articles

- Dhungana, S., Shrestha, S., Van, T. P., **KC, S**., Das Gupta, A., & Nguyen, T. P. L. (2022). Evaluation of gridded precipitation products in the selected sub-basins of Lower Mekong River Basin. Theoretical and Applied Climatology, 1-18. Publisher: Springer. **Impact Factor: 3.410.**

- Bucton, B.G. B, Shrestha, **S., KC**, S., Mohanasundaram S., Virdis, G.P.S., Chaowiwat, W. (2021). Impacts of Climate and Land Use Change on Groundwater Recharge under Shared Socioeconomic Pathways: A Case of Siem Reap, Cambodia. Journal of Environmental Research. Publisher: Elsevier. **Impact Factor: 8.431.**

- Pinsri, P., Shrestha, **S., KC**, S., Mohanasundaram, S., Virdis, G.P.S., Nguyen, T. P. L., Winai, C. (2021). Assessing Climate Change, Land Use Change, and

Abstraction Scenarios Impacts on Groundwater Resources in Tak Special Economic Zone, Thailand. Journal of Environmental Research. Publisher: Elsevier. **Impact Factor: 8.431.**

- **KC, S.,** Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Groundwater governance: A review of the assessment methodologies. Environmental Reviews, 30(2), 202–216. Publisher: Canadian Science Publishing. **Impact Factor: 5.547**

- Fernando N.S., Shrestha, S., **KC, S.,** Mohanasundaram, S. (2021). Investigating Major Causes of Extreme Floods Using Global Datasets: A Case of Nepal, USA & Thailand. Progress in Disaster Science. Publisher: Elsevier. **Cite Score: 7.2.**

- **KC, S.,** Shrestha, S., Ninsawat, S., & Chonwattana, S. (2021). Predicting flood events in Kathmandu Metropolitan City under climate change and urbanisation. Journal of Environmental Management. Publisher: Elsevier. **Impact Factor: 8.91.**

- Shrestha, S., **KC, S.** (2021). Groundwater solutions to climate change in urbanizing cities. Technology: Smarter Solutions, 9-16. Link

- Pathak, D.R. & **KC, S.** (2016). Municipal solid waste generation, composition, and material recovery in Kathmandu Valley, Nepal. Waste Management. 54. II-III.

<u>Conference Papers:</u>

- **KC, S.,** Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Developing a Pragmatic Framework for Indexing Groundwater Governance under Stress: Initiative on Groundwater Sustainability in the Lower Mekong Region. Development Research Conference 2022 (DevRes 2022): Transforming Development Research for Sustainability, 22-24 August 2022, Uppsala and Stockholm, Sweden.

- **KC, S.,** Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2022). Development of Framework to Evaluate Current State of Groundwater Governance under Urbanization and Climate Change. THA 2022: International Conference on Moving Towards Sustainable Water and Climate Change Management After COVID-19, 26-28 January 2022, Bangkok Thailand (Virtual).

- **KC, S.,** Shrestha, S. (2021). Investigating Major Causes of Frequent Flooding in Highly Urbanized Metropolitans Using a Quali-Quantitative Approach. AGU Fall Meeting, 13-17 December 2021, New Orleans, USA (online).

- Bucton, B.G. B, Shrestha, S., **KC, S.,** Mohanasundaram S., Virdis, G.P.S., Chaowiwat, W. (2021). Impacts of Climate and Land Use Change on the Groundwater Recharge in Siem Reap, Cambodia. AGU Fall Meeting 2021, 13-17 December 2021, New Orleans, LA (online).

- **KC, S.,** Shrestha, S. (2021). Developing a Framework to Benchmark Current State of Vulnerable and Marginalized Groups Inclusion in Groundwater

Governance. AGU Fall Meeting 2021, 13-17 December 2021, held in New Orleans, LA (online).

- **KC, S.**, Shrestha, S., Nguyen, T. P., Das Gupta, A., & Mohanasundaram, S. (2021). Development of Framework to Assess the Groundwater Governance in Transboundary Aquifers of Rapidly Urbanizing Cities. ISARM 2021, 2nd International Conference: Transboundary Aquifers: Challenges and the way forward, 6-9 December 2021, UNESCO, Paris (Virtual).

- Fernando N.S., Shrestha, S., **KC, S.,** Mohanasundaram, S. (2021). Investigating Major Causes of Extreme Floods Using Global Datasets: A Case of Nepal, USA & Thailand. Progress in Disaster Science. Second International Symposium on Disaster Resilience and Sustainable Development, 24-25 June 2021, Thailand (Online).

LANGUAGE COMPETENCY

Nepali: Fluent (Native)	English (Excellent)	Hindi: (Good)

COMPUTER COMPETENCY

- Website (WordPress) (developed and managed web content http://wem.ait.ac.th/)
- Social Media Handling (WEM Facebook page and YouTube Channel)
- Proficient in Microsoft Office Packages and Google tools
- Proficient in application of Water Resources and Climate Models

MEMBERSHIPS AND INVOLVEMENTS

- Nepal Engineering Council -6825 "Civil" "A"
- Nepal Engineers' Association -11182 "Civil"
- Member of Appraisal Panel – Subject Expert [CADP/CAA (2012/13) – ADB funded project]
- Chairperson: SU Sports (AIT/Student Union/ January 2018)

EXTRACURRICULAR ACTIVITIES

- **Young Rapporteur on "World Water Week 2021"** for "Building Resilient Societies" organized by Stockholm International Water Institute (SIWI), Sweden (Online: August 23-27, 2021)

- **Young Panel Discussant** in the workshop "**Opportunities and Challenges for a Blue Economy in Asia-Pacific Region in Covid-19 World**" jointly organized by The Energy and Resources Institute (TERI), Konrad Adenauer Foundation (KAS), and AIT (Online: February 2021)

- Course on **"WTR001: Water: Addressing the Global Crisis"** offered by SDGAcademyX, an online learning initiative of SDG Academy and the Stockholm International Water Institute (SIWI) through edX (Online: 09 June 2020 – 22 August 2020 – Partially Funded) Course Completion Verification: https://courses.edx.org/certificates/cb52a5aee0804701bc15d4eda4c256c8

- Training course on **"Questioning as we learn - An introduction to critical thinking"** by INASP, an international development organization in the UK (Online: 16 June - 13 July 2020) Course Completion Verification: https://moodle.inasp.info/mod/customcert/verify_certificate.php (Code: cNVrYdZBw3)

- Training course on **“Research Writing in the Social Sciences”** by INASP, an international development organization in the UK and AuthorAID (Online: 6 April - 25 May 2020) Course Completion Verification: https://moodle.inasp.info/mod/customcert/verify_certificate.php (Code: VP2Atqaksx)

- Training course on **“Global Navigation Satellite System (GNSS – T151-40)”** jointly organized by Geo-Informatics Center, Asian Institute of Technology (GIC/AIT), Center for Spatial Information Science, The University of Tokyo (CSIS/UT) and International Committee on Global Navigation Satellite Systems (ICG) at Thailand (06 -10 January 2020 - Fully Funded)

- **“World Youth Forum (WYF) – 2019”** conference and workshop at Sharm El-Sheikh, Egypt (December 12-17, 2019 – Fully Funded)

- International Symposium on **“Climate Change Impacts, Vulnerability, and Adaptation: Asian Perspective”** organized by Asia-Pacific Network for Global Change Research (APN) and Asian Institute of Technology, Thailand (16 – 18 October 2019 – Fully Funded)

- “**Asia Climate Week- InterFLOOD Asia”** conference and exhibition organized by Media Generation Ventures Ltd., United Kingdom in Singapore (27 - 28 March 2019 – Partially Funded)

- International Symposium on “**Disaster Resilience and Sustainable Development**” organized by the Asian Institute of Technology, United Nations University and ProSper.Net, Thailand (7 - 8 March 2019 – Fully Funded)

- **International Course of “Solid Waste Management 2014”** for policymakers and project managers in the Asia Pacific region organized by International Urban Training Center, supported by UN-HABITAT & Gangwon Province, Republic of Korea (23-30 April 2014 – Fully Funded)

WORK EXPERIENCE

Date	Position/ Duties	Organization
2019/08- Present	Early Career Researcher (Doctoral Candidate) **Project:** Strengthening Groundwater Governance in Rapidly Urbanizing Areas of Lower Mekong Region (GIRA) Project (SEI, Asia)	**Water Engineering and Management** Asian Institute of Technology, Thailand Advisor: Prof. Sangam Shrestha email: sangam@ait.asia
2021/12- 2022/03	Intern	**Asia-Pacific Network for Global Change Research (APN)**, Japan Advisor: Mr. Xiaojun Dengemail: xdeng@apn-gcr.org

2018/03- 2019/04	Student Assistant (Part-time Masters Student)	**Water Engineering and Management** Asian Institute of Technology, Thailand Advisor: Prof. Sangam Shrestha email: sangam@ait.asia
2014/07- 2017/07	Value Chain and Rural Infrastructure (VCRI) Expert	Ministry of Agriculture Development **Raising Incomes of Small and Medium Farmers Project (RISMFP)** **(ADB G0233-NEP)** PMU**,** Nepalgunj, Nepal Project Director: Mr. Gokarna Raj Aryal email: gokarnaaryal013@gmail.com
2013/07- 2014/06	Engineer (Consultant) & Member: Bid Evaluation Committee	Ministry of Urban Development **Solid Waste Management Technical Support Center (SWMTSC),** Nepal Executive Director: Dr. Sumitra Amatya email: drsumitraamatya@gmail.com
2012/02- 2013/06	Rural Infrastructure Specialist/ Project Engineer & Member: Appraisal Panel (Subject Expert) Commercial Agriculture Alliance (CAA) Component 1- CADP	Ministry of Agriculture Development **Commercial Agriculture Development Project (CADP)** **(ADB-G0063Nep)** PMU, Biratnagar, Nepal Project Director: Mr. Tek Bahadur Bam email: tb_bam@yahoo.com
2011/02- 2012/01	Engineer	Ministry of Local Development **Solid Waste Management Technical Support Center (SWMTSC),** Nepal Executive Director: Dr. Sumitra Amatya email: drsumitraamatya@gmail.com

REFERENCES

Academic Reference	**Prof. Sangam Shrestha** Program Chair Water Engineering and Management, Asian Institute of Technology Pathumthani 12120, Thailand	Relationship: Advisor Email: sangam@ait.asia
Professional Reference	**Dr. Basant V. Thapa** Deputy Team Leader Raising Income of Small & Medium Farmers Project (RISMFP) (ADB funded Project)	Relationship: Technical Team Leader Email: bvt_thapa@yahoo.com
Professional/ Academic Reference	**Dr. Dhundi Raj Pathak** Director Engineering Study & Research Center Kathmandu, Nepal	Relationship: Lead Author (Research Publication) and Technical Advisor (SWMTSC) Email: drpathak@esarcnepal.com

CERTIFICATION

I, the undersigned, certify that, to best of my knowledge and belief, this biodata correctly describes my qualification, my experience, and myself. I understand that any willful misstatement described herein may lead to my disqualification or dismissal if any engaged.

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