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

by

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LIST OF ABBREVIATIONS

AHP	Analytic Hierarchy Process
ANN	Artificial Neural Network
CORDEX	Coordinated Regional Climate Downscaling Experiment
CMIP	Coupled Model Intercomparison Project
DGR	Department of Groundwater Resources
DIW	Department of Industrial Works
ESGF	Earth System Grid Federation
FAO	Food and Agricultural Organization
GCM	General Circulation Models or Global Climate Model
GDP	Gross Domestic Product
GGI	Groundwater Governance Index
GW-MATE	Groundwater Management Advisory Team
IUWM	Integrated Urban Water Management
IWRM	Integrated Water Resources Management
IPCC	Intergovernmental Panel on Climate Change
LDD	Land Development Department
LULC	Land Use and Land Cover
LMB	Lower Mekong Basin
LMR	Lower Mekong Region
NOAA	National Oceanic and Atmospheric Administration
OECD	Organisation for Economic Co-operation and Development
PWA	Provincial Waterworks Authority
QM	Quantile Mapping
RCM	Regional Climate Model
RCP	Representative Concentration Pathway
RID	Royal Irrigation Department
SSP	Shared Socioeconomic Pathway
SWAT	Soil and Water Assessment Tool
SRES	Special Report Emission Scenario
TMD	Thai Meteorological Department
UNDP	United Nation Development Programme
UN	United Nations
USDA	United States Department of Agriculture
USGS	United States Geological Survey

CHAPTER 1

INTRODUCTION

1.1 Background

Globally, the movement of rural settlement to an urban area 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 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 important driver for alteration in the normal functioning of the hydrological cycle, biogeochemical cycle, carbon cycle at the local and global scale (Hua et al., 2020), and while the urban transformation is evolving, the 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 longer 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 the 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, 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 about 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 environment and climate have been greatly affected by the process of urbanization as the multiple human activities alter the consumption pattern of water, energy, food, land, and in-turn pollute the urban environment. But in contrast to this, urbanization is inextricably associated with the economic development quantified as population, income, and output. This demonstrates the significance of urban centers or cities in domestic economics and its requirement to supply the highest quality of 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 major urban public services is the "water supply and sanitation" (H. Jones et al., 2014).

Water, being 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 double character as a "mineral resource" and as a "water resources". Thus, the safe yield of the groundwater depends on both the hydro-geologic 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 (S. 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 (S. 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 LMR 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 of the LMR.

1.3 Research Question

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 surface and groundwater availability?
4. What is the vulnerability of groundwater resources to availability under future multiple stresses in the study area?
5. What would be the possible conflicts in the study area due to the impact of future multiple stresses in groundwater resources?

1.4 Objectives of the Study

The overall objective of the study is to recommend ways for improved groundwater governance in rapidly urbanizing areas of the Lower Mekong Region (LMR) under multiple stresses. The specific objectives are:

1. To assess the current state of groundwater governance in the rapidly urbanizing area of LMR.
2. To predict future change in multiples stresses (climate, land-use, demographic, sectoral demand) under various scenarios.
3. To analyze the impact of climate and land-use change in surface and groundwater availability.

4. To assess the vulnerability of groundwater to availability under multiple stresses.
5. To analyze possible conflicts due to multiple stresses and provide recommendations for improved groundwater governance.

1.5 Scope of the Study

The research covers the following scope:

1. Development of groundwater governance framework in rapidly urbanizing areas.
2. Analyze the current state of groundwater governance in the study area.
3. Project future climate of the study area under multiple climate change scenarios.
4. Project future demographic and land-use change in the study area using the Dyna-CLUE model.
5. Project future sectoral (domestic, industrial, and agricultural) water demand of the study area.
6. Estimate the current and future availability of surface water and spatiotemporal distribution of groundwater recharge under multiple stresses using the SWAT hydrological model.
7. Estimate the current and future groundwater level under multiple stresses on using GMS-MODFLOW - groundwater model
8. Development of groundwater vulnerability to availability framework under multiple stresses in rapidly urbanizing areas.
9. Estimate current and future vulnerability of groundwater resources to availability.
10. Identify the future possible conflicts due to multiple stresses in the groundwater resources and provide recommendations for improved groundwater governance.

1.6 Limitations of the Study

The limitations of the study are:

1. The future demand estimation in the study shall not consider the effect of climate change and urbanization on change in demand.
2. The study shall not consider groundwater vulnerability to pollution and focuses more on quantity aspect.
3. Transboundary aspect of groundwater aquifer shall not be considered in the study.

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 type 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 assessing groundwater vulnerability and groundwater governance included with the concepts of water governance, hydrological and hydrogeological modelling based on the critical review of related literatures.

2.1 Multiple Stresses in Groundwater Resources

Groundwater resources are the huge subsurface reservoirs that are accessible or provides a buffer storage during surface water shortages (Lapworth et al., 2013) and are less vulnerable to drought and degradation in quality when compared to the surface water resources (Schwartz & Ibaraki, 2011). Globally, this complex hydrological system provides 33% of total water withdrawal satisfying the need of 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, Pandey, et al., 2016). These stressors can be natural and human-induced that impacts the sustainability of groundwater resources (J. M. 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, Pandey, 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 urban heat island (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 (R. G. 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 (H. 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).

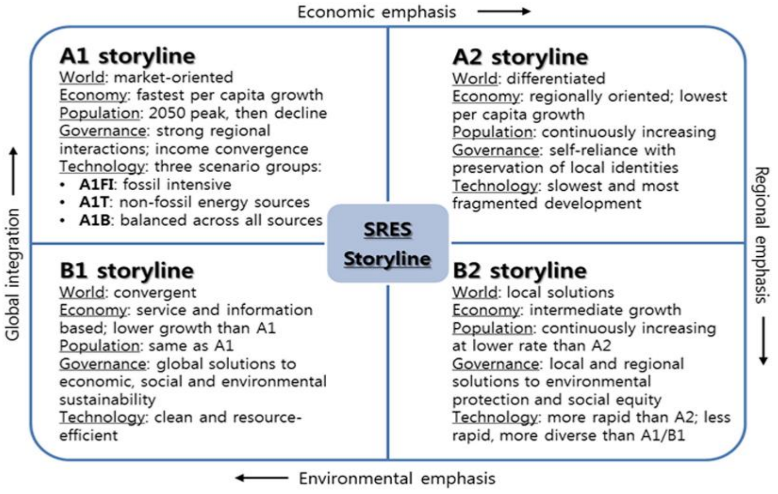
On the other hand, formulating adaptation and management policies as a response to the impact of changing climate at the local level requires finer spatial information, and recent studies have substituted by finer resolution Regional Climate Models (RCMs) produced through the dynamic downscaling of GCMs (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 are 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)



A1 storyline
World: market-oriented
Economy: fastest per capita growth
Population: 2050 peak, then decline
Governance: strong regional interactions; income convergence
Technology: three scenario groups:
- **A1FI**: fossil intensive
- **A1T**: non-fossil energy sources
- **A1B**: balanced across all sources

A2 storyline
World: differentiated
Economy: regionally oriented; lowest per capita growth
Population: continuously increasing
Governance: self-reliance with preservation of local identities
Technology: slowest and most fragmented development

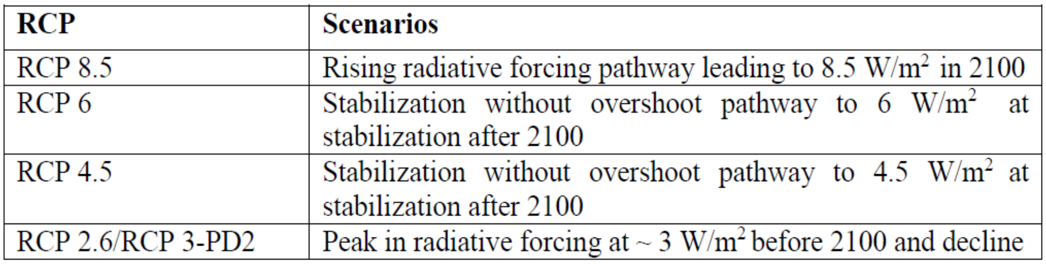
B1 storyline
World: convergent
Economy: service and information based; lower growth than A1
Population: same as A1
Governance: global solutions to economic, social and environmental sustainability
Technology: clean and resource-efficient

B2 storyline
World: local solutions
Economy: intermediate growth
Population: continuously increasing at lower rate than A2
Governance: local and regional solutions to environmental protection and social equity
Technology: more rapid than A2; less rapid, more diverse than A1/B1

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 (Source: Moss et al., 2010)

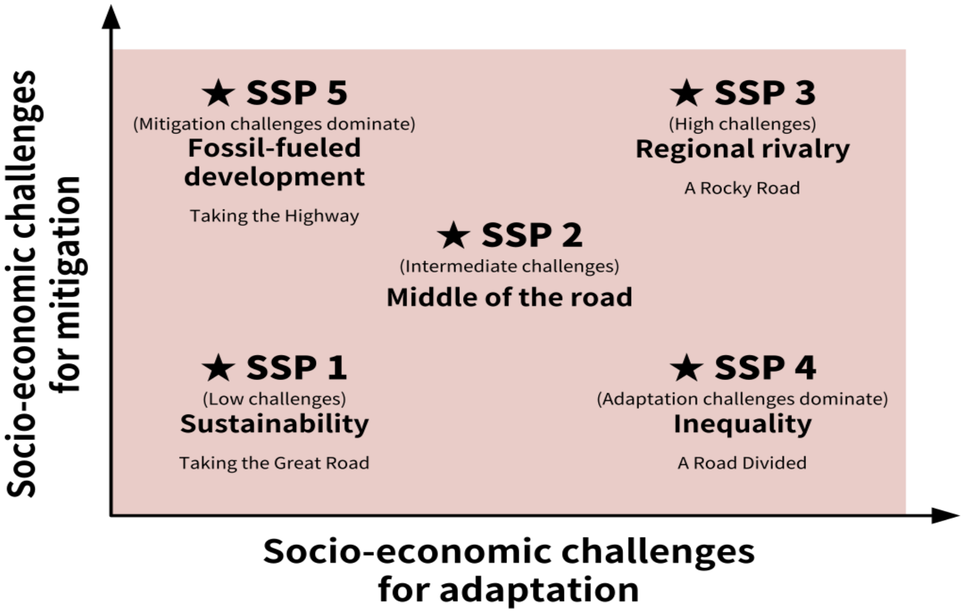


RCP	**Scenarios**
RCP 8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 in 2100
RCP 6	Stabilization without overshoot pathway to 6 W/m^2 at stabilization after 2100
RCP 4.5	Stabilization without overshoot pathway to 4.5 W/m^2 at stabilization after 2100
RCP 2.6/RCP 3-PD2	Peak in radiative forcing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

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

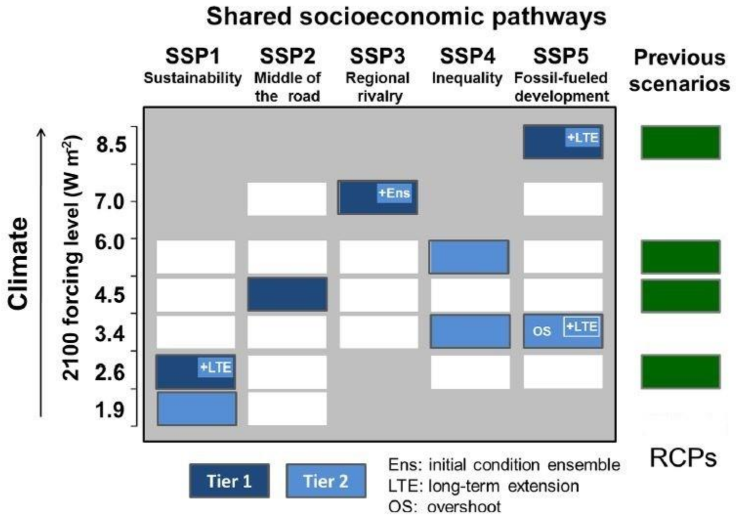


In short, the SSPs describe alternative evolutions of future society in the absence of climate change or climate policy. SSPs 1 and 5 envision relatively optimistic trends for human development, with substantial investments in education and health, rapid economic growth, and well-functioning institutions. 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).

2.6 Demographic 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 ith 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 ith 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 ith 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 (C. P. Kumar, 2012). The Urban Heat Island (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 are 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 Assessment of Vulnerability of Groundwater Resources to Availability

Vulnerability is the susceptibility towards the impact of hazards and the definition varies depending on the context and the scholars. Various climatic and non-climatic factors such as population growth, rapid industrialization, urbanization, and increased sectoral water demand has stressed the groundwater (Taylor, 2014; Van der Gun, 2017), thus increasing its vulnerability in the present and future. The IPCC in the fourth assessment report defines vulnerability to climate change as "*the degree to which a system is susceptible to and unable to cope with, adverse effects of climate change, including climate variability and extremes*". Thus, it is a function exposure, sensitivity, and adaptive capacity of a system to current and possible threats (Aslam et al., 2018). Exposure refers to the alteration in climate stimuli to which the system is being exposed, sensitivity is an intrinsic property which refers to the degree of impact on the system being exposed to the threat whereas the adaptive capacity is the ability of the system to bounce back or adjust to the potential damage. The variability in climatic parameters (rainfall, temperature, evapotranspiration) has created a greater challenge in alleviating groundwater vulnerability and the non-climatic factors exaggerate the impact and increase the uncertainties in the assessment. Studies used various locations and its rate of recharge as a benchmark for assessing the groundwater vulnerability to examine seasonal variations such as variation in pumping rates and fluctuation in recharge (Döll, 2009; Segal et al., 2014). The study by (Döll, 2009), assessed global scale groundwater vulnerability to climate change by examining its impact on the recharge and storage and the study discovered that the aquifers in the African regions are highly vulnerable and highly sensitive areas with increased population is likely to decrease in recharge up to 10% by 2050. Segal et al., (2014), analyzed the seasonal recharge patterns in California using stable isotopes and the results concluded increased vulnerability of shallow aquifers due to the alteration in amount groundwater recharge under warmer climatic conditions. The combined impact of climate, population change, urbanization, and industrial development on groundwater resources shows increased abstraction due to increasing demand resulting from water table drawdown (Lutz et al., 2011). Most of the literature limited the scope of the study either to the impact assessment only (Eshtawi et al., 2015; Lutz et al., 2011; Segal et al., 2014). Studies have quantified the intrinsic and specific vulnerability to contamination. These methods are overlay/index method; DRASTIC method; GOD; SINTACS, AVI, DART commonly used when assessing groundwater vulnerability to the quality aspects (Aslam et al., 2018; Luoma et al., 2017). Furthermore, Aslam et al., (2018), proposed an impact modelling and an-index based approach in assessing the groundwater vulnerability to external stressors. Limited studies have adopted the vulnerability of groundwater based on its function as exposure, sensitivity, and adaptive capacity as defined by IPCC. An indicator-based approach is likely to be effective to examine the system vulnerability as a cumulative effect of all the stressors. Babel et al., (2011), applied the indicator-based approach in assessing the vulnerability of freshwater resources where the study selected several indicators for water stress index and adaptive capacity to calculate the vulnerability index.

2.10 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).

2.11 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.

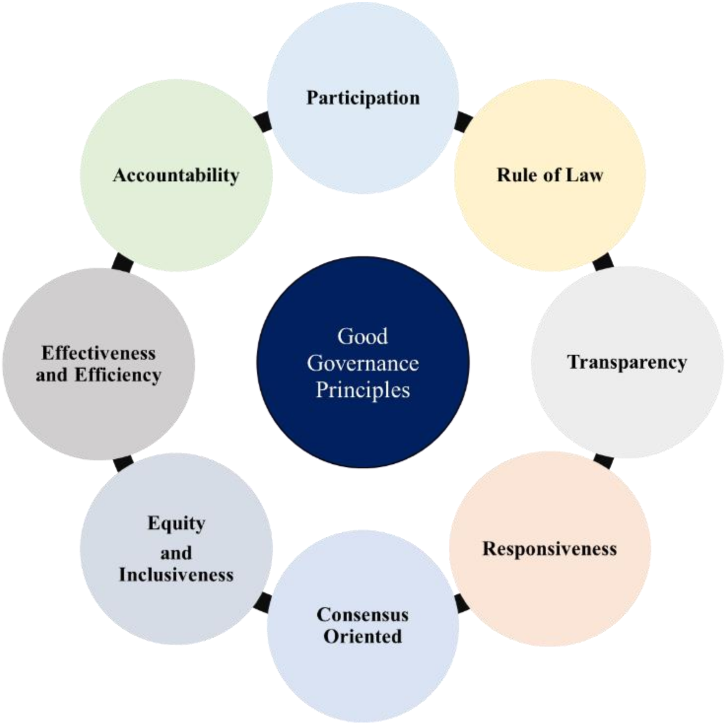
The Groundwater Modeling System (GMS) is a full modelling application for creating and simulating groundwater flows making the entire process more convenient through various processing tools before, during, and after model development. The system supports various subsurface related models such as FEMWATER, 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).

2.12 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

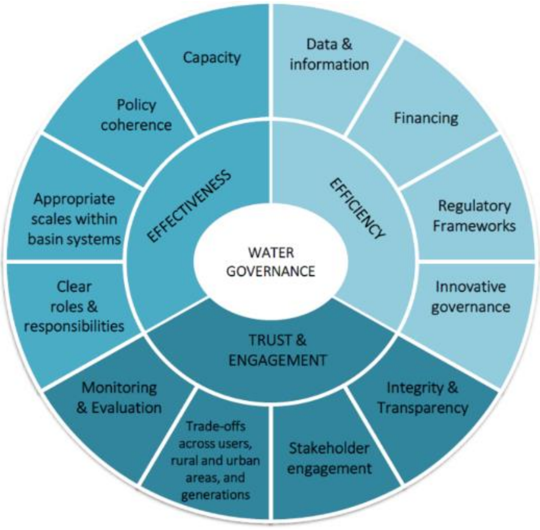


Water, being a renewable natural source is a limited resource that is disproportionately dispersed and is in an extremely pressurized state each day (Zogheib et al., 2018). The situational diversity in finding and using water in space and time makes it challenging to characterize any specific coherent 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)

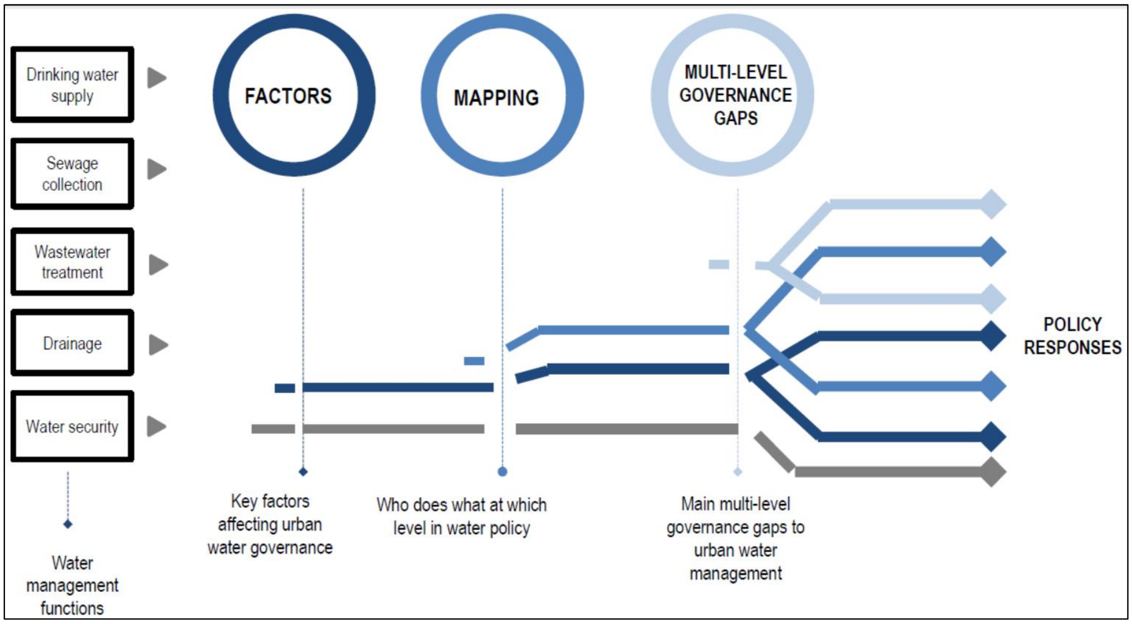


2.13 Urban Water Governance

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)



2.14 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).

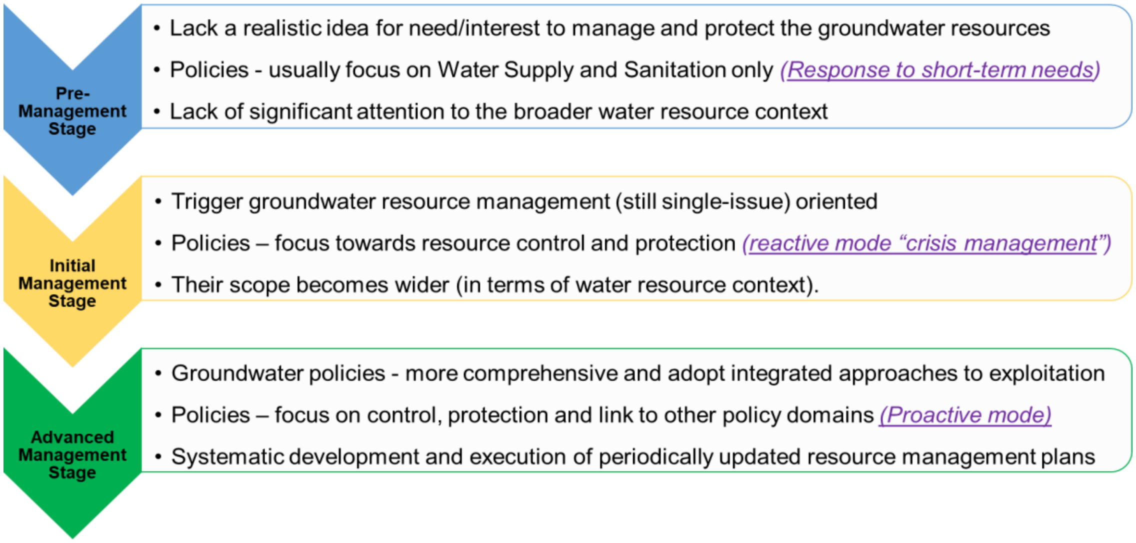
Figure 2.7

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



Pre-Management Stage

- 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

Initial Management Stage

- 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).

Advanced Management Stage

- 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.

2.15 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 (Source: Foster et al., 2010)

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) ##

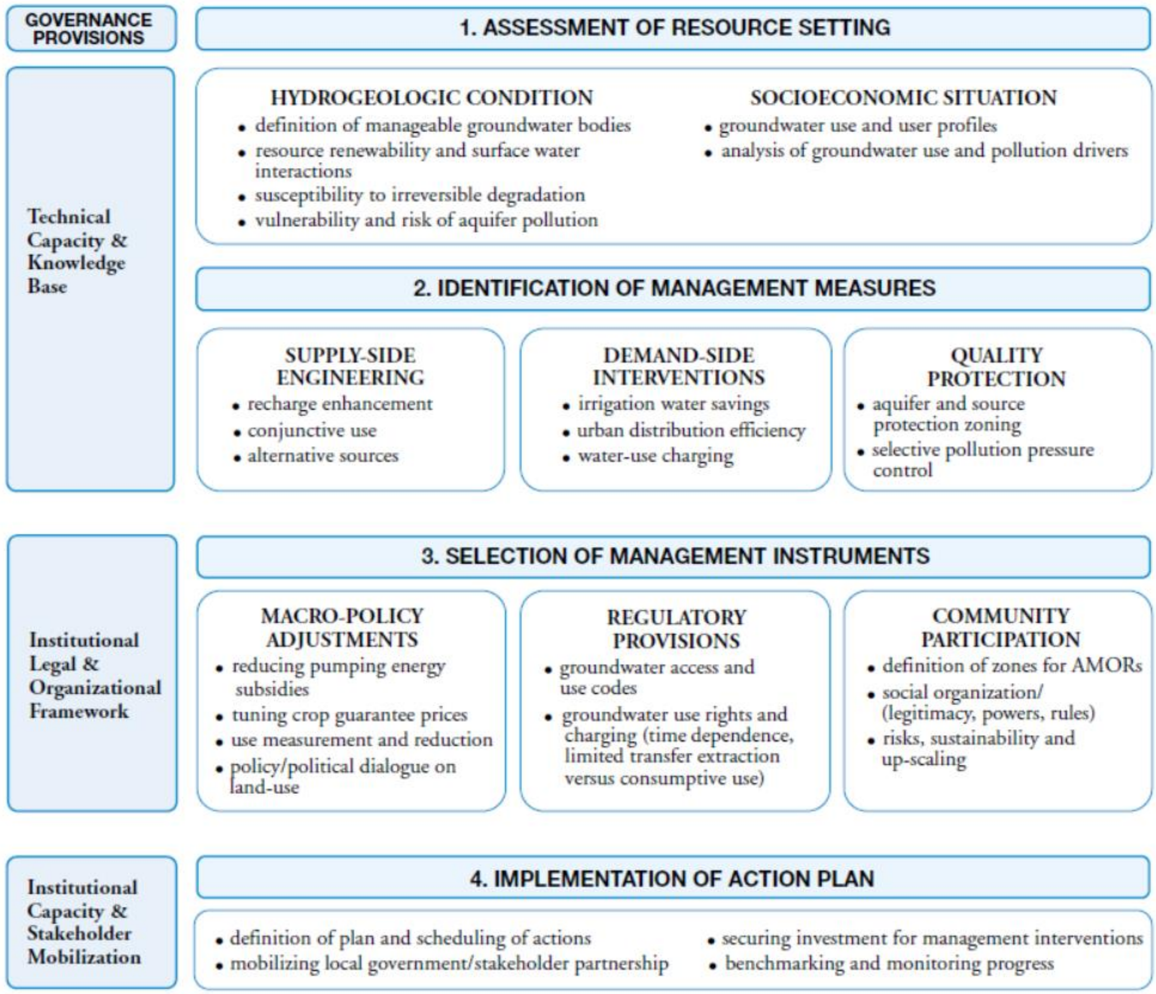
\# although covered by this typology it may be preferable in practice to treat urban groundwater situations as a separate cross-cutting category

\## 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

Figure 2.9:

Pragmatic framework for elaboration of management action plan with corresponding provision of governance (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) outlines the explanation and execution of such groundwater management action plan corresponding to the types of governance provisions. 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 (Source: Foster et al., 2010)

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)

CHAPTER 3

STUDY AREA AND DATA COLLECTION

3.1 Study Area

The study selects Khon Kaen, Thailand as one of the rapidly urbanizing areas in the Lower Mekong Basin. The major concentration of the study shall be on the Khon Kaen Metropolitan Municipality within Muang Khon Kaen district 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 on basin scale.

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 their administrative boundaries and capital city

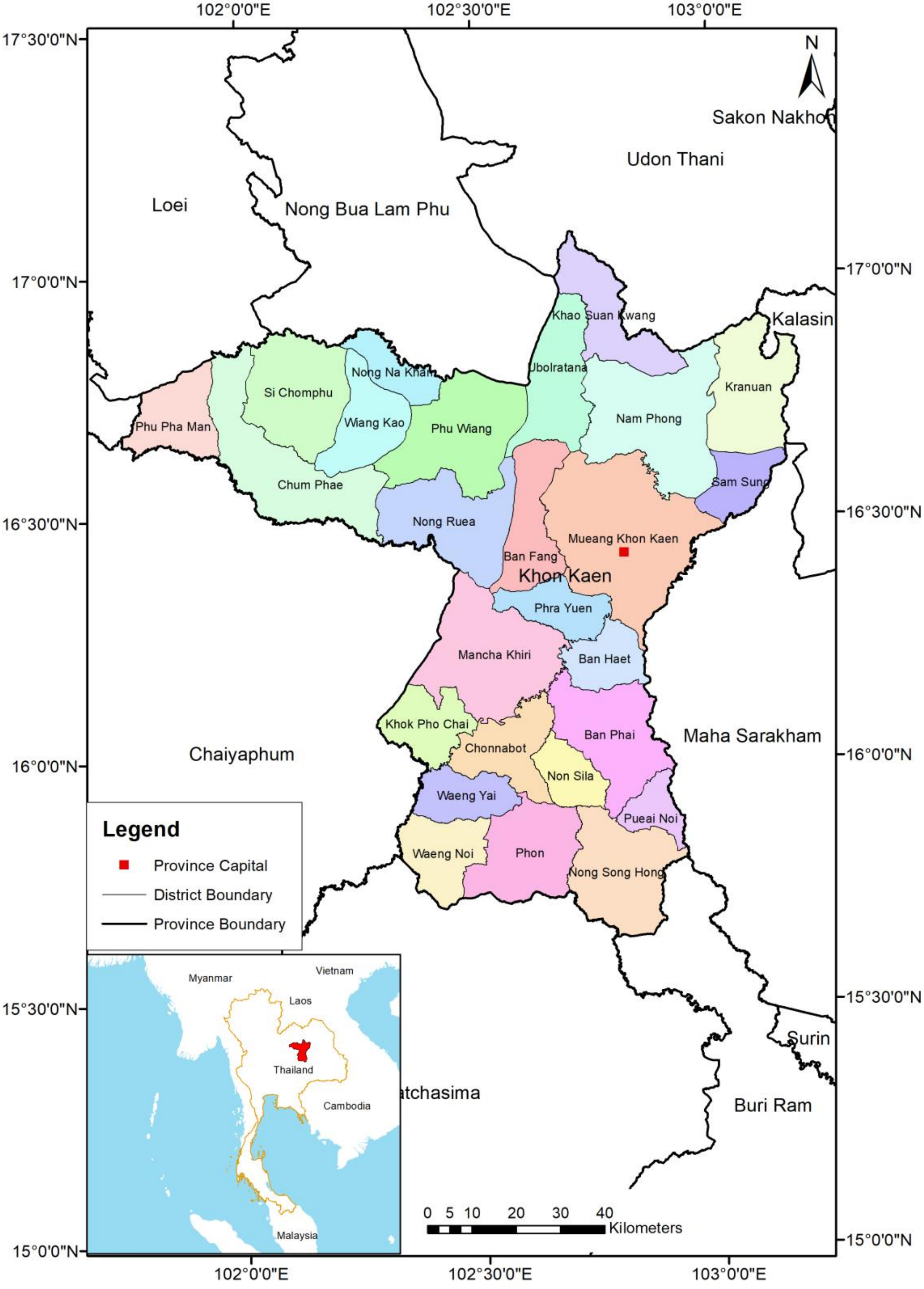


Figure 3.2

Hydrological boundaries of the study area with river network

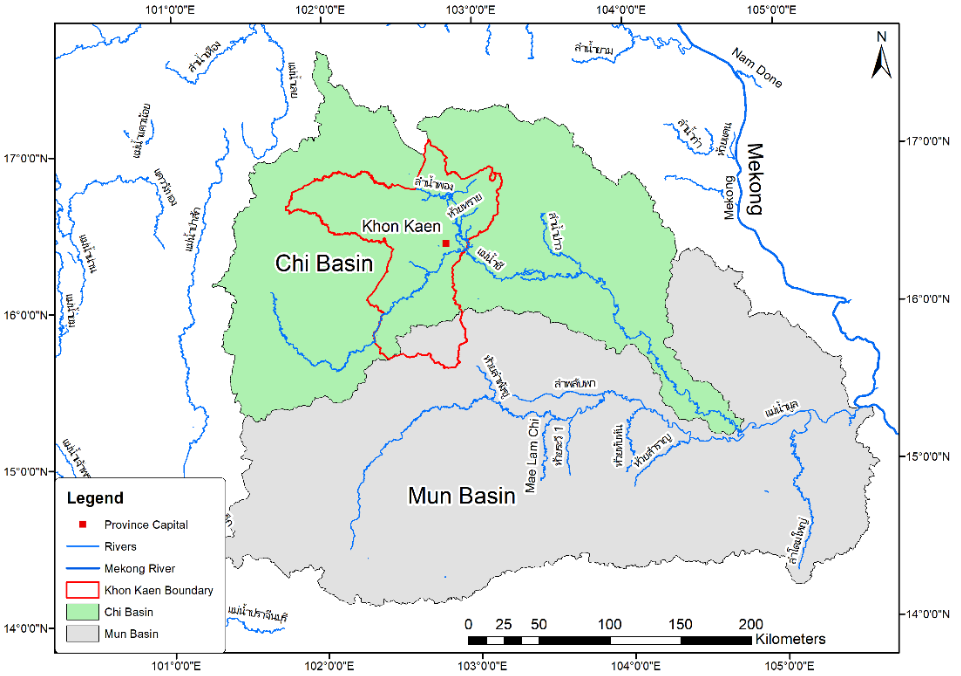
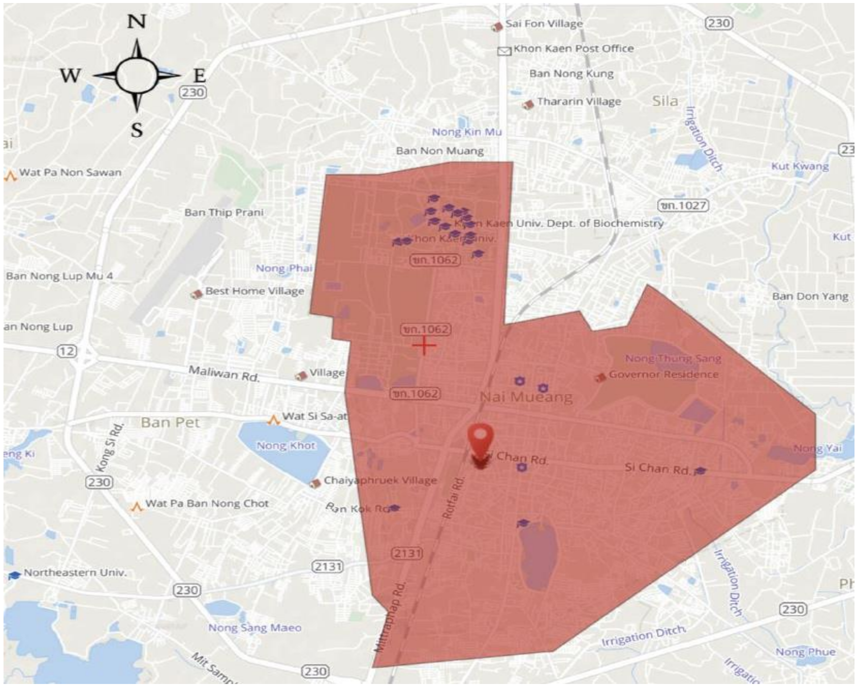


Figure 3.3

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

Summary characteristics of different administrative level at Khon Kaen, Thailand

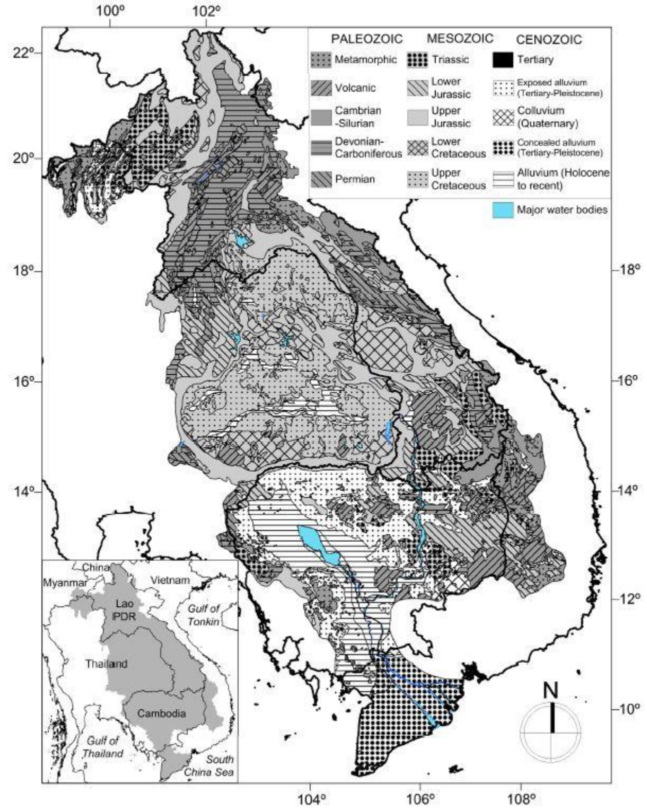
Variables	**Khon Kaen Province**	**Muang Khon Kaen District**	**Khon Kaen Municipality**
Coordinates	16°26'41" N to 102°50'1" E	16°26'18" N to 102°50'20" E	16°26" N to 102°50' E
Area (km^2)	10,886	953.4	46
Population	1.8 Million (2018)	0.40 Million (2017)	0.12 M (2018)
Population Density (person/km^2)	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

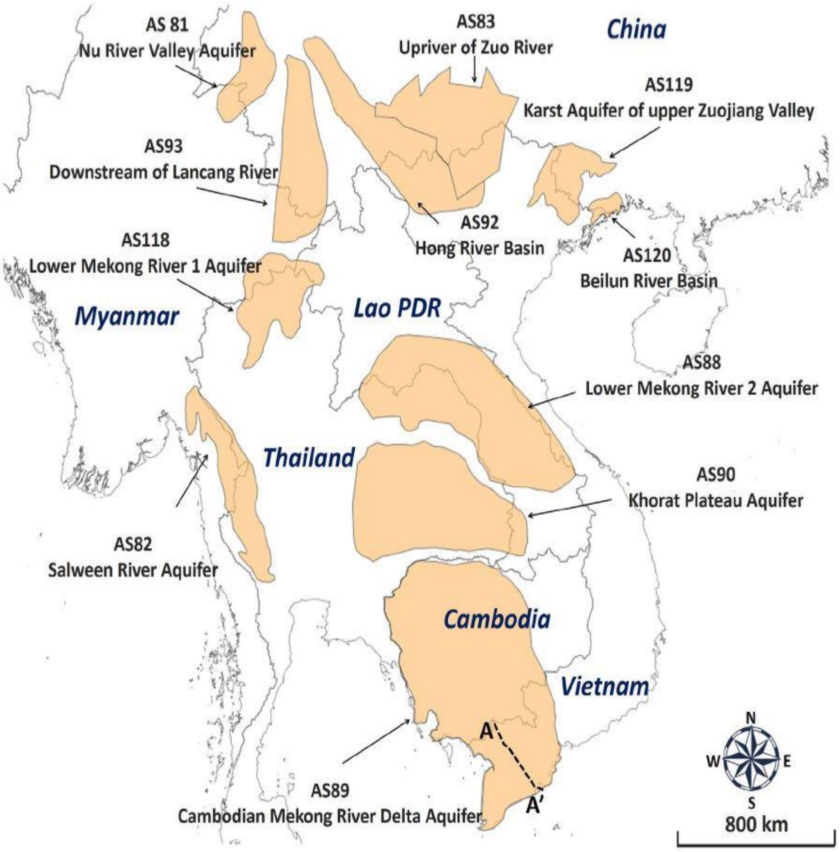
Geology of the Lower Mekong Basin (Source: Lacombe et al., 2017)



In the Lower Mekong Basin, total ground water reserves are thought to be about 100 to 300 km. The proposed 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 Required for the proposed study

Data type	Frequency/Time	Unit/ Format	Resolution	Source
Data required for climate change projection				
Observed Rainfall	Daily/1981-2014	mm	-	Thai Meteorological Department (TMD)
Observed maximum and minimum temperature	Daily/1981-2014	°C	-	Thai Meteorological Department (TMD)
GCMs data	Daily/1981-2100	mm	-	Earth System Grid Federation (ESGF) data center "or" Hydro-Informatics Institute (HII), Thailand
APHRODITE data	Daily/1981-2014	mm	-	Research Institute for Humanity and Nature (http://www.chikyu.ac.jp)
NOAA climate data sets	Daily/1981-2014	°C	-	NOAA's National Centers for Environmental Information (NCEI) (https://www.ncdc.noaa.gov/cdo-web/)
Data required for land use change projection				
Baseline land use map	2010, 2015 &2018	Raster	30m* 30m	Land Development Department (LDD)
Restricted area	-	Raster	30m* 30m	Land Development Department (LDD)
Digital Elevation Model (DEM)	-	Raster	30m* 30m	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	30m* 30m	-
Aspect ratio	-	Raster	30m* 30m	-
River Network	2010, 2015 &2018	Raster	30m* 30m	Land Development Department (LDD)
Road Network	2010, 2015 &2018	Raster	30m* 30m	Land Development Department (LDD)
Population density	2010, 2015 &2018	Raster	30m* 30m	Land Development Department (LDD)

Table 3.2 (Cont.)

Data Required for the proposed study

Data type	Frequency/ Time	Unit/ Format	Resolution	Source
Data required for hydrological modelling				
Observed Discharge	Daily/1976-2018	m^3/sec	-	Thai Meteorological Department (TMD)
Data required for groundwater modelling				
Observation/Monitoring well data	Monthly/1976-2018	m	-	Department of Groundwater Resources (DGR)
Production/Pumping well data	Monthly/1976-2018	m	-	Department of Groundwater Resources (DGR)
Hydrogeological properties	-	-	-	Department of Groundwater Resources (DGR)
Data required for water demand estimation				
Wind speed	Monthly/1976-2018	m/sec	-	Thai Meteorological Department (TMD)
Solar radiation	Monthly/1976-2018	W/m^2	-	Thai Meteorological Department (TMD)
Relative humidity	Monthly/1976-2018	%	-	Thai Meteorological Department (TMD)
Evaporation	Monthly/1976-2018	mm	-	Thai Meteorological Department (TMD)
Crop calendar	-	-	-	Royal Irrigation Department (RID)/Literature
Area of cultivation	-	ha	-	Royal Irrigation Department (RID)
Irrigation schedule	-	days	-	Royal Irrigation Department (RID)
Sectoral employment	-	-	-	Department of Industrial Works (DIW)
Type of industry, no. & size	-	-	-	Department of Industrial Works (DIW)
Industrial water use standard	-	-	-	Department of Industrial Works (DIW)
Per capita GDP	-	-	-	International Study Report
Water tariff rate	-	-	-	Provincial Waterworks Authority (PWA)
No. of household & size	-	-	-	Land Development Department (LDD)

CHAPTER 4

METHODOLOGY

4.1 Overall Methodology

The overall objective of the study is to provide recommendation for improved groundwater governance in rapidly urbanizing areas of the Lower Mekong Region (LMR) under multiple stresses. The overall conceptual framework for the proposed study is given in Figure 4.1. First, a groundwater governance shall be developed and applied to the study area for the diagnostic of current state of groundwater governance and analyze the strength and gaps in different components of governance. Then multiple future stresses shall be projected using different techniques. For climate change, 3 GCM models shall be used under 2 SSPs and the future shall be divided into three timeframes: Near Future (NF), Mid Future (MF) and Far Future (FF). The land use change model Dyna-CLUE shall be used to project the future land use change of the study area under 3 different scenarios. Furthermore, Logistic curve method shall be used to project the future change in demographics and sectoral demand analysis shall be done to project the future groundwater abstraction in the study area. Once the multiple stresses are projected, the impact of these multiple stresses shall be assessed on surface water and groundwater availability using SWAT as the hydrological model and GMS-MODFLOW as the groundwater model to attain future groundwater recharge and level respectively. Then, finally a vulnerability framework for groundwater resources to availability based on IPCC dimension (exposure, sensitivity, and adaptive capacity) shall be developed to analyze the current and future vulnerability to availability. The major inputs on the framework shall be from the earlier activities done on the study. An AHP approach shall be adopted using expert’s opinion to provide weightage to the indicators. Once, the results of the vulnerability are obtained, the study shall analyze the possible conflicts on groundwater resources based on the strengths and weakness of current state of groundwater governance and future vulnerability to provide recommendation for improved groundwater governance. The detail working methodology for objective 1-5 is given in Figure 4.2, 4.3, 4.4, 4.5 and 4.6, respectively.

Figure 4.1

Overall conceptual framework of the study

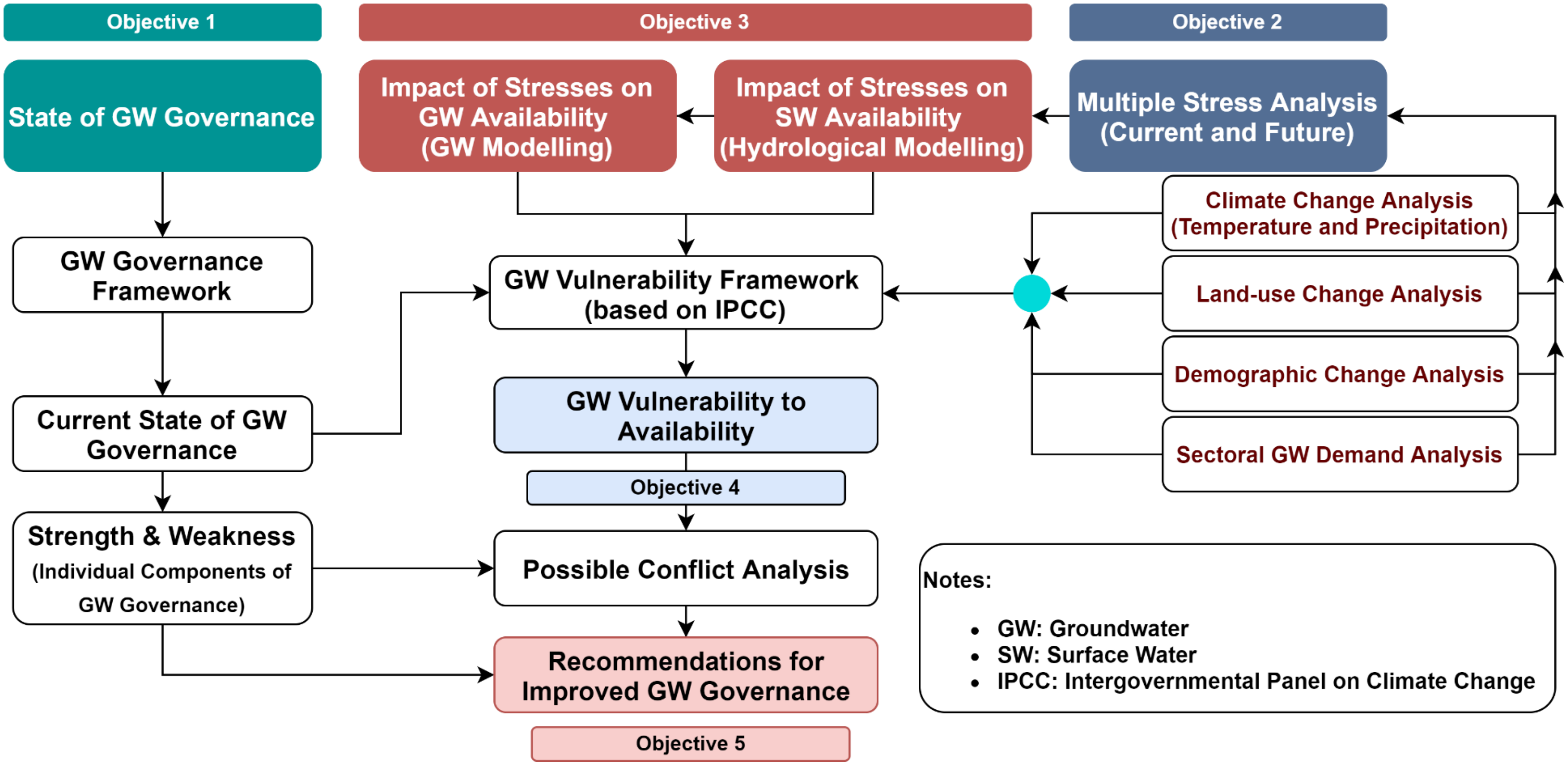


Figure 4.2

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

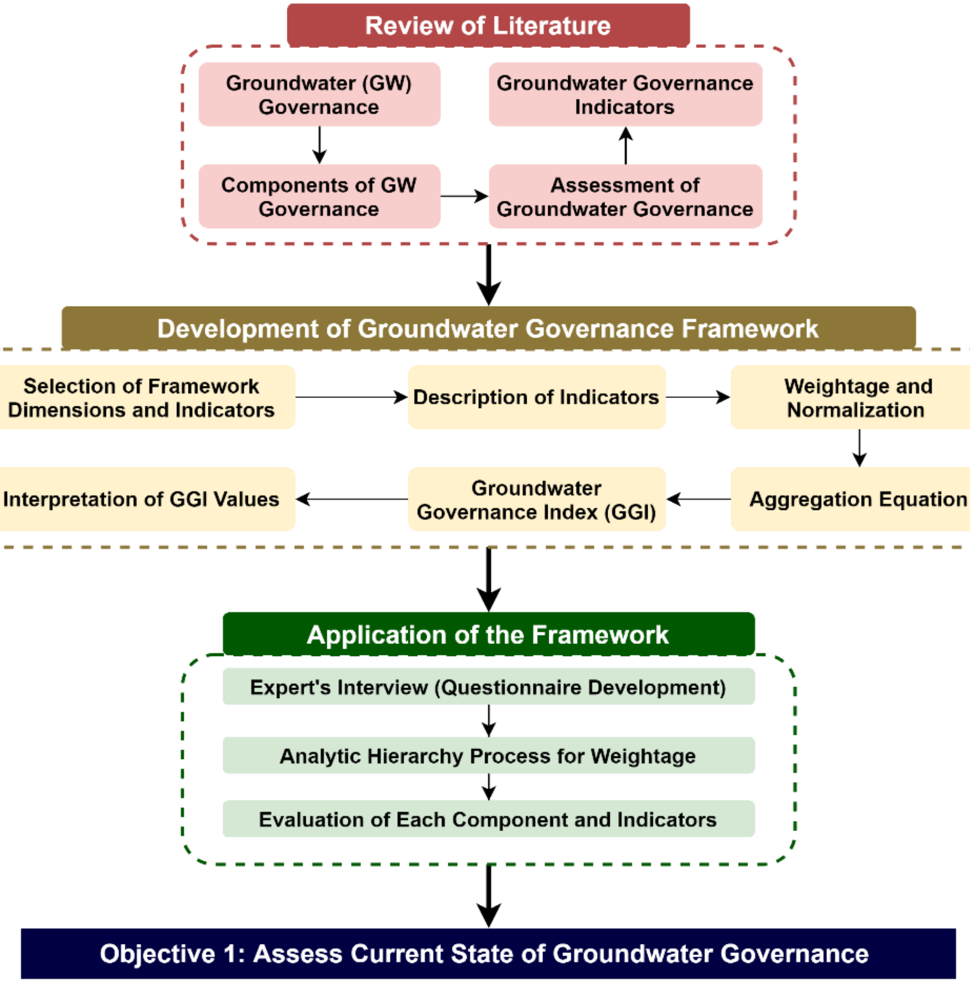


Figure 4.3

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

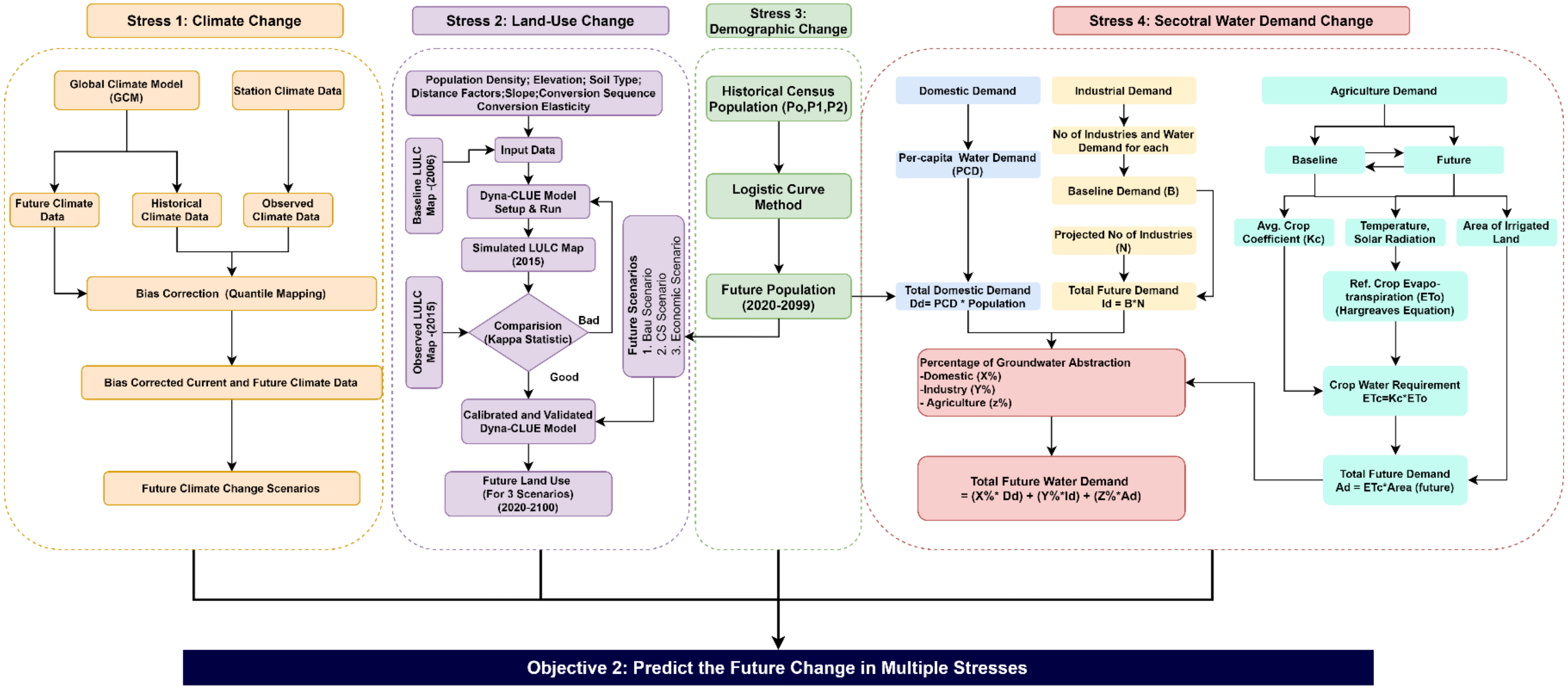


Figure (4.3) continued (Scenario selection)

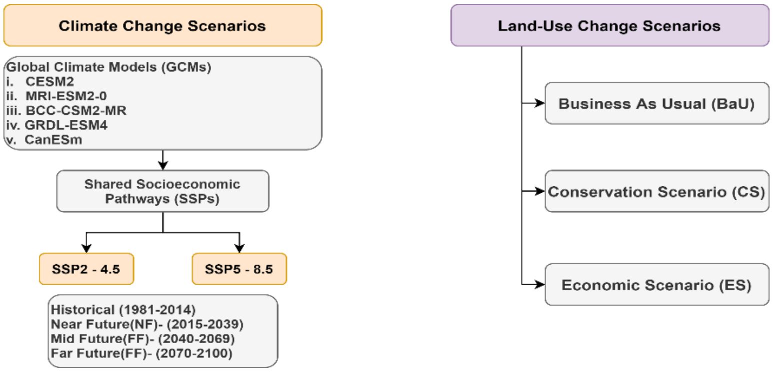


Figure 4.4

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

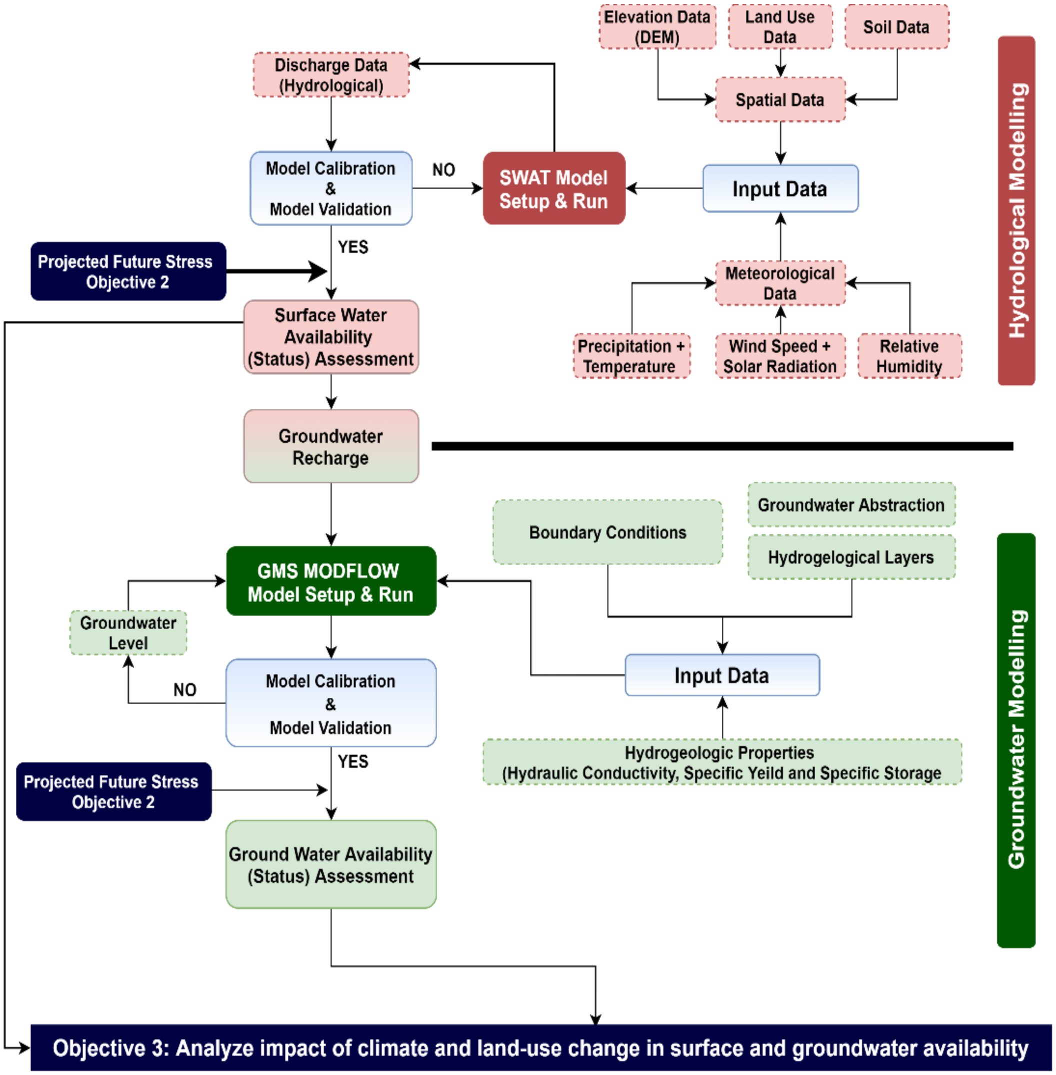


Figure 4.5

Methodological framework to assess the vulnerability of groundwater to availability under multiple stresses (objective 4)

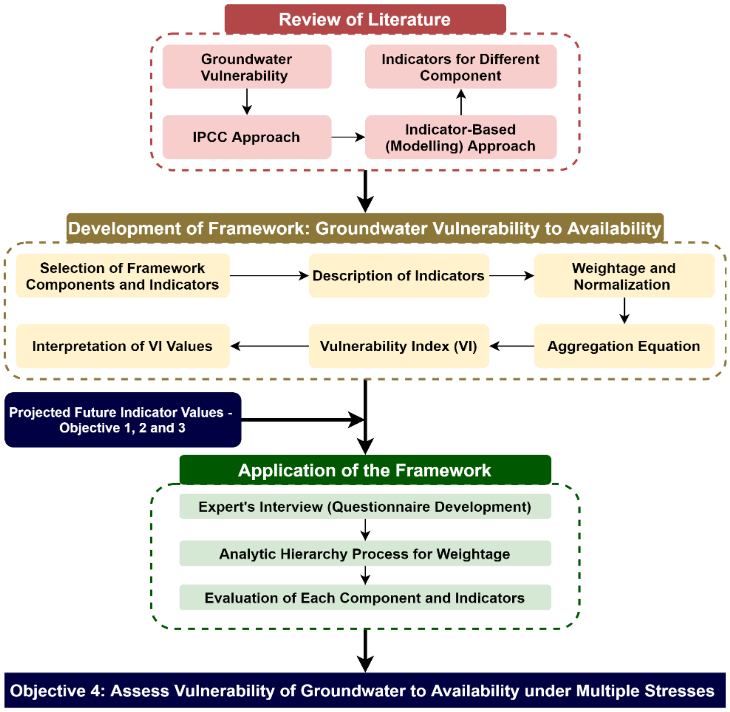
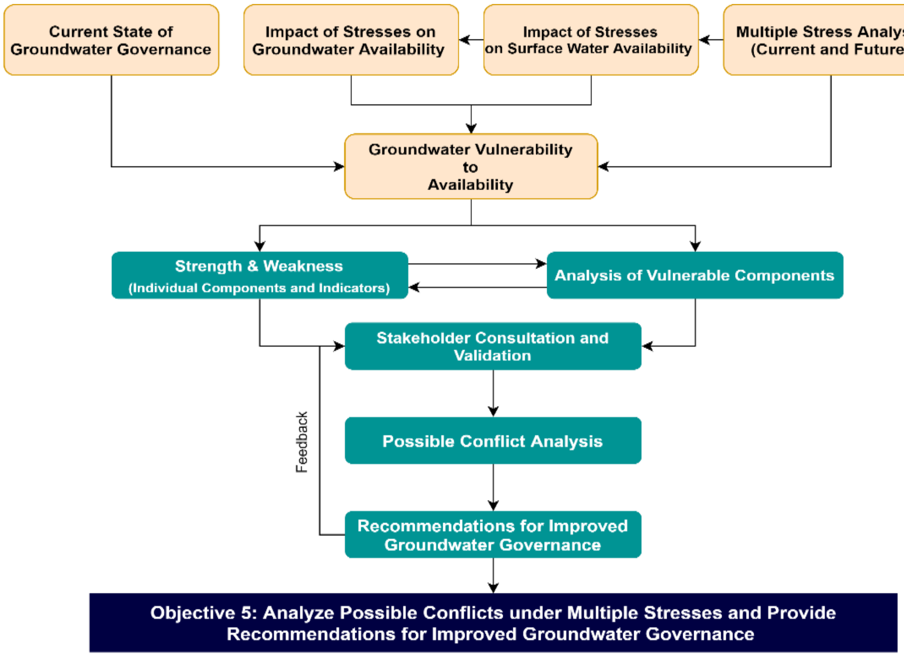


Figure 4.6

Methodological framework to analyze possible conflicts due to multiple stresses and provide recommendations for improved groundwater governance (objective 5)



4.2 Assessing Current State of Groundwater Governance

The current state of groundwater governance shall be assessed by developing and indicator-based governance framework, which shall address all four components of groundwater governance. The detail description on development and application of the framework is given below:

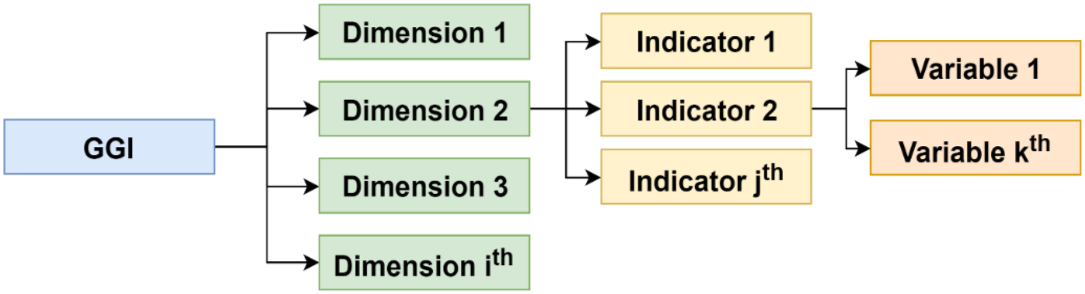
4.2.1 Development of the Framework

The study proposes an inclusive framework for evaluating and quantifying groundwater governance in rapidly urbanizing area using an indicator-based approach. The proposed framework is developed based upon the components of groundwater governance, good governance principles and inclusiveness (gender and right based). The proposed framework consists 4 dimensions with 30 indicators and each indicator will be measured based on 2 variables. The variables shall be rated form 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 in such a way that they can 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 rating can further be contextualized and modified. While the indicators indicate what to measure in the dimensions, the variables describe how it can be measured. The mathematical equations for aggregating these components provides an 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 proposed groundwater framework is shown in (Figure 4.7) 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 4.7

Structure of the groundwater governance framework



4.2.2 Description of the Framework Components and Indicators

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 provision; (ii) institutional capacity for their implementation. Both the variables are rated on a range of 0-3 (Table 4.1) where 0 represents the non-existence state and 3 represents the optimal state of the measured variables.

Table 4.1

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 indicators of all the dimensions shall provide a stocktaking of currently existing provision and institutional capacity to implement the existing provisions. The components of the groundwater governance framework and detail description with context of application has been tabulated in Table 4.2 and Table 4.3, respectively.

Table 4.2

Components of groundwater governance frameworks

Dimension	S.N	Indicator	Variables	
			Adequacy of Provision	**Institutional Capacity**
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		
	7	Availability of gender-specific publications (guide) in Public Domain		
Legal and Institutional	8	Water well drilling permits and groundwater use rights		
	9	Instrument to reduce groundwater abstraction		
	10	Instrument to prevent water well construction		
	11	Sanction for illegal water well construction		
	12	Groundwater abstraction and use charging		
	13	Land-use control on potentially polluting activities		
	14	Levies on generation/discharge of potential pollutants		
	15	Government agency as ground-water-resource guardian		
	16	Community aquifer management organizations		
	17	Gender-responsive groundwater policies or legal frameworks		
	18	Budget allocation for integrating gender concerns		
	19	Gender-inclusive groundwater management agencies (government)		
	20	Customary land and water rights for indigenous groups or communities		
	21	Agreements and commitments related to international human rights charters		
Cross-Sector Policy Coordination	22	Coordination with agriculture development		
	23	Groundwater-based urban/industrial planning		
	24	Compensation for groundwater protection		
	25	Sectoral coordination for sex-disaggregated data		
Operational	26	Transparency in groundwater services for all consumers		
	27	Public participation in groundwater management		
	28	Existence of groundwater-management action plan		
	29	Gender-inclusive participation in aquifer management organizations		
	30	Gender sensitization training at government level		

Indicator's Source:

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

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

Table 4.3:

Description of the framework indicators and its context of application

Dimension	S.N	Indicator	Description of Indicators and Context
Technical	1	Existence of basic hydrogeological maps	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	Groundwater body/aquifer delineation	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	Groundwater-piezometric monitoring network	Network setup for monitoring groundwater level, extraction, recharge, and use. The context of the application is to establish resource status and trends.
	4	Groundwater-pollution hazard assessment	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	Availability of aquifer numerical management models	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	Groundwater-quality monitoring network	Network setup for monitoring groundwater quality at aquifers. The context of the application is to detect incipient pollution/salinization to groundwater.
	7	Availability of gender-specific publications (guide) in Public Domain	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.
Legal and Institutional	8	Water well drilling permits and groundwater use rights	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	Instrument to reduce groundwater abstraction	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	Instrument to prevent water well construction	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	Sanction for illegal water well construction	Provision for penalizing construction of illegal/ unpermitted water wells. The context of the application is to identify measures for excessive use above permit.
	12	Groundwater abstraction and use charging	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	Land-use control on potentially polluting activities	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	Levies on generation/discharge of potential pollutants	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	Government agency as ground-water-resource guardian	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	Community aquifer management organizations	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	Gender-responsive groundwater policies or legal frameworks	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	Budget allocation for integrating gender concerns	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	Gender-inclusive groundwater management agencies (government)	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	Customary land and water rights for indigenous groups or communities	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	Agreements and commitments related to international human rights charters	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.
Cross-Sector Policy Coordination	22	Coordination with agriculture development	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	Groundwater-based urban/industrial planning	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	Compensation for groundwater protection	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	Sectoral coordination for sex-disaggregated data	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.
Operational	26	Transparency in groundwater services for all consumers	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	Public participation in groundwater management	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	Existence of groundwater-management action plan	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	Gender-inclusive participation in aquifer management organizations	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	Gender sensitization training at government level	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

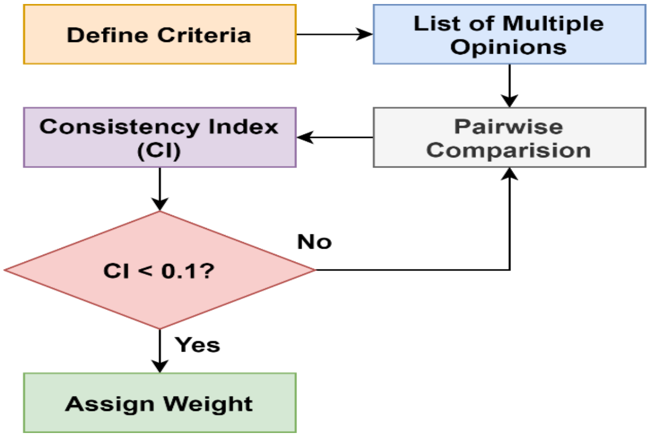
Aspects	List of Indicators
Groundwater-Extraction Related	Indicators: 3,5,8,9,10,11,12
Groundwater Quality Related	Indicators: 4,6,13,14,24
Groundwater-Extraction and Quality Related	Indicators: 1,2,15,16,22,23,27,28
Groundwater-Inclusiveness Related	Indicators: 7,17,18,19,20,21,25,26,29,30

4.2.3 Normalization and Weightage Calculation

The indicators chosen are qualitative, however the rating of each variables within an indicator are rated in a same scale of 0-3 (Table 4.1) : non-existence state (0), incipient state (1), acceptable state (2) and optimum state (3). Furthermore, after aggregation of all the components, the final index value range are assigned in such a way that the range of score is same as earlier. The score values are already in a comparable form (0 being the non-existence and 3 being optimal), so, normalization of the values is not required. Ranking of different components 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 proposes use of AHP in prioritizing the dimensions of the framework through an expert's opinion. A questionnaire shall be prepared and sent to experts for their opinion in different dimensions to do a pairwise comparison. Figure 4.8 shows a conceptual framework in applying AHP.

Figure:4.8

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 shall be compared using Saaty's scale of intensity (Table 4.4).

Table 4.4:

Fundamental scale in AHP method to define the intensity of importance (Source: Saaty, 1980)

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

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).

One the pairwise comparison through the developed matrix and the fundamental scale is completed the local priorities shall be 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).

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

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

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 4.5)

Table 4.5:

Random consistency index (RI) values used *in AHP (Source: Saaty, 1980)*

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

4.2.4 Aggregation Technique for the Groundwater Governance Index (GGI)

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 components of the framework for overall governance index is given below. The dimensions, indicators and variables of the framework are represented by D, I, and V in the equations respectively whereas i, j and k indicates the number of dimensions, number of indicators within in each dimensions and number of variables within each indicators respectively. The sum of total weightage in all cases is equals to 1.

The aggregation of the variables within each indicator is done by using the formula,

$$I_{ij} = \frac{\sum_{k=1}^{n} w_k * V_k}{\sum_{k=1}^{n} w_k} \qquad \text{eq.4.3}$$

where, Iij represents the aggregated value of the jth indicator within ith dimension, wk and Vk represents the weightage and the rating of the kth 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,

$$D_i = \frac{\sum_{j=1}^{n} w_j * I_{ij}}{\sum_{k=1}^{n} w_k} \qquad \text{eq.4.4}$$

where, Di represents the aggregated value of the ith dimension, wj and Iij represents the weightage of the jth indicator within the dimension and Iij represents the aggregated value of jth indicator within the ith 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,

$$GGI = \frac{\sum_{i=1}^{n} wi * Di}{\sum_{i=1}^{n} wi} \qquad \text{eq.4.5}$$

where, GGI represents overall Groundwater Governance Index, wi and Di represents the weightage and the aggregated value of ith dimension. Here “n” in the equation represents the total number of the dimensions (i).

4.2.5 Interpretation of Groundwater Governance Index (GGI) Results

After assessing the groundwater governance and quantifying to obtain an overall groundwater governance index, the magnitude of the index shall be interpreted so that it gives an overview of the current state of groundwater governance in the area. The threshold of the governance index is on a range of 0-3 and described (Table 4.6) as given below:

Table 4.6:

Interpretation of the results of groundwater governance index

Threshold	State of Governance	Description
0 - < 0.5	Non-Existent State of Groundwater Governance	The groundwater governance is at the non-existence state from a dimensional perspective. The country/province/city has no to highly insufficient provisions of technical resources, regulatory and legal outlines, policies for cross-sectoral coordination and operational plans. It faces several issues and conflicts due to the lack of institutional capacity for inclusive multi-stakeholder governance.
0.5 - < 1.5	Incipient State of Groundwater Governance	The groundwater governance is at the initial state from a dimensional perspective. The country/province/city has elementary provisions of technical resources, regulatory and legal outlines, policies for cross-sectoral coordination and operational plans. It faces some issues and conflicts due to the basic institutional capacity for inclusive multi-stakeholder governance.
1.5 - < 2.5	Acceptable State of Groundwater Governance	The groundwater governance is at a satisfactory state from a dimensional perspective. The country/province/city has fair provisions of technical resources, regulatory and legal outlines, policies for cross-sectoral coordination and operational plans. It faces very fewer issues and conflicts due to the decent institutional capacity for inclusive multi-stakeholder governance.
2.5 - ≤ 3	Optimum State of Groundwater Governance	The groundwater governance is at the most favorable state from a dimensional perspective. The country/province/city has adequate provisions of technical resources, regulatory and legal outlines, policies for cross-sectoral coordination and operational plans. It faces none to very little issues and conflicts due to the ample institutional capacity for inclusive multi-stakeholder governance.

4.3 Projecting Future Stresses on Groundwater

Downscaling of RCMs data is not required because, RCMs can determine the local impacts by giving the information of land use and orography (land height) in small scale and giving weather and climate information at resolutions as fine as 50 or 25km. However, there is existence of the logical error in the climate model which cause many faulty concepts causing discretization and dimensional averaging within the grid cell. The crucial need for bias corrections expressively adds doubts in modeling climate change effects. In this study, Quantile mapping approach (QM) will be applied for correcting the biases of RCMs datasets. QM decreases biases of daily temperature and precipitation by coarsely one order of magnitude (Themebl et al., 2012), and it is better than other methods in correcting peak values, especially the 90th percentile (M'Po et al., 2016). The QM is a mapping between two cumulative distribution functions (CDFs); RCMs data and observed data (Themebl et al., 2012). The method corrects the distribution shape of the daily precipitation based on daily constructed pointwise ECDFs (empirical cumulative distribution functions). Both wet and dry days are included in the ECDF estimation. Distribution based QM (Gudmundsson et al., 2012; Teutschbein and Seibert, 2012) as well as Empirical QM (Gudmundsson et al., 2012) are used in correcting precipitation and temperature. In this study, Empirical QM will be used with the 99-percentiles table generated and linear interpolation between them. The QM method was implemented in R language (Venables and Smith, 2012) using package “qmap” (Gudmundsson, 2014). The following equations are used for the quantile mapping technique:

$$P_{his}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{his,m}\left(P_{his,m}\right)\right\rfloor \qquad \text{eq.4.6}$$

$$P_{sim}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{sim,m}\left(P_{sim,m}\right)\right\rfloor \qquad \text{eq.4.7}$$

$$T_{his}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{his,m}\left(T_{his,m}\right)\right\rfloor \qquad \text{eq.4.8}$$

$$T_{sim}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{sim,m}\left(T_{sim,m}\right)\right\rfloor \qquad \text{eq.4.9}$$

Where,

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

The coefficient of determination (R^2), mean, annual rainfall and standard deviation (SD) were considered to evaluate the performance of the bias correction.

4.3.1 Projection of Climatic Parameters

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). In the study by Apurv et al., (2015), applied raw Coupled Model Intercomparison Phase (CMIP) 5 GCMs and directly bias corrected rainfall data in Brahmaputra basin, India.

This study proposes use of 5 new generation CMIP-6 GCMs (Table 4.7) under two Shared Socioeconomic Pathways (SSPs). The two SSPs selected shall be 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. Since, the CMIP-6 GCMs are new and are on the process of development, the selection of the 3 GCM models shall be done based on the data availability for the study area and for the selected SSPs (Table 4.7). The data for the selected GCMs will be downloaded from Earth System Grid Federation (ESGF) data center https://esgf-node.ipsl.upmc.fr/search/cmip6-ipsl/

Table 4.7:

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

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

Once the GCMs data are made available, the biases in the model data shall be corrected using Quantile Mapping (QM) approach. QM decreases biases of daily temperature and precipitation by coarsely one order of magnitude (Themeßl et al., 2012), and it is better than other methods in correcting peak values, especially the 90th percentile (M'Po et al., 2016). The QM is a mapping between two cumulative distribution functions (CDFs); RCMs data and observed data (Themeßl et al., 2012). The method corrects the distribution shape of the daily precipitation based on daily constructed pointwise ECDFs (empirical cumulative distribution functions). Both wet and dry days are included in the ECDF estimation. Distribution based QM (Gudmundsson et al., 2012; Teutschbein & Seibert, 2012) as well as Empirical QM are used in correcting precipitation and temperature. In this study, Empirical QM will be used with the 99-percentiles table generated and linear interpolation between them. The QM method was implemented in R language using package "qmap" (L Gudmundsson, 2014). The following equations are used for the quantile mapping technique:

$$P_{his}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{his,m}\left(P_{his,m}\right)\right\rfloor \qquad \text{eq.4.10}$$

$$P_{sim}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{sim,m}\left(P_{sim,m}\right)\right\rfloor \qquad \text{eq.4.11}$$

$$T_{his}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{his,m}\left(T_{his,m}\right)\right\rfloor \qquad \text{eq.4.12}$$

$$T_{sim}(d)^* = F^{-1}_{obs,m}\left\lfloor F_{sim,m}\left(T_{sim,m}\right)\right\rfloor \qquad \text{eq.4.13}$$

4.3.2 Demographic Projection using Logistic Curve Method

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).

This study proposes the Logistic Curve Method or Logistic Growth Model in forecasting the population of the rapidly urbanizing area as this approach adopts growth curve characteristics within a limit of socioeconomic opportunities and space (Shrestha et al., 2020). 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 (Ayhan, 2018). 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:

$$P_t = \frac{P_{sat}}{1 + e^{(a+b\Delta t)}} \quad \text{eq.4.14}$$

$$P_{sat} = \frac{2P_0P_1P_2 - P_1^2(P_0 + P_2)}{P_0P_2 - P_1^2} \quad \text{eq.4.156}$$

$$a = \ln(\frac{P_{sat} - P_0}{P_0}) \quad \text{eq.4.16}$$

$$b = \frac{1}{n}\ln\frac{P_0(P_{sat} - P_1)}{P_1(P_{sat} - P_0)} \quad \text{eq.4.17}$$

4.3.3 Land Use Change Projection using Dyna-CLUE

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 proposed the use of 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 statistical analysis (Shrestha et al., 2018) given as

$$K = \frac{\Pr(a) - \Pr(e)}{1 - P(e)} \qquad \text{eq.4.18}$$

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 given as:

$$\log\left(\frac{P_i}{1 - P_i}\right) = \beta_0 + \beta_1 X_{1,i} + \beta_2 X_{2,i} + \beta_n X_{n,i} \qquad \text{eq.4.19}$$

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 proposes three different assumptions to create three scenarios namely Business as Usual (BaU), Conservation Scenario (CS) and Economic Scenario (ES) to address the multiple uncertainties related to land use change projection. The first BaU scenario assumes that the future demand of land shall follow the historical pattern while the second CS scenario assumes that the government prioritize the conservation of forest and ecology in future limiting the change in built-up area. The last scenario (ES) assumes high economic growth trend with higher demand of agricultural land rather than grassland and forest areas.

4.3.4 Projection of Groundwater Demand

The projection of water demand in rapidly urbanizing areas are very crucial for effective planning, development, and sustainable management of water resources and urban public services. The study proposes the summation of sectoral (domestic, industrial and agriculture) water demand as the total water demand of the selected area. Furthermore, the total share of groundwater for each sector shall be assumed to be constant which shall be adopted from the related government agencies and literature reviews.

The domestic demand shall be computed based on the per capita domestic water demand which shall be obtained from the authentic government sources and the related literatures of the selected area. The total domestic water demand (D_d) for any time is given by

$$D_d = Per\ Capita\ Demand * Population \qquad \text{eq.4.20}$$

Where, the projected population for future periods shall be obtained from logistic curve method as discussed in section 4.3.2.

If the current trend of groundwater abstraction in domestic sector is X%, then the future groundwater abstraction for domestic sector (G_d) is given by:

$$G_d = X\%\ of\ D_d \qquad \text{eq.4.21}$$

The industrial demand shall be computed based on the total number of the industries in the areas and the total water demand for each industry for a baseline period which shall be obtained from respective government sources and literatures. The future number of industries shall be predicted based on current trend and government policies in the area which shall then be multiplied by the water demand of each industry in baseline period to obtain future industrial water demand. The total industrial water demand (I_d) for any project future time is given by:

$$I_d = Industries\ Baseline\ Demand * Future\ Number\ of\ Industries \qquad \text{eq.4.22}$$

If the current trend of groundwater abstraction in industrial sector is Y%, then the future groundwater abstraction for industrial sector (G_i) is given by:

$$G_i = Y\%\ of\ I_d \qquad \text{eq.4.23}$$

The agriculture water demand, the reference crop evapotranspiration for the current (baseline) and future period shall be computed using Hargreaves' equation given by:

$$ET_0 = 0.0135\ R_s(T_{mean} + 17.8) \qquad \text{eq.4.24}$$

where, R_s is the incoming short-wave solar radiation and T_{mean} is the projected mean temperature in °C. The, the crop water requirement (ET_c) for baseline and future shall be computed by:

$$ET_c = K_c * ET_o \qquad \text{eq.4.25}$$

where, ET_o is the reference crop evapotranspiration and K_c is the average crop coefficient (K_c) which shall be adopted from literature in the study area. Then, the total agriculture water demand (A_d) for the respective period shall be given:

$$A_d = ET_c * Total\ area\ of\ irrigated\ land \qquad \text{eq.4.26}$$

where, the total area of irrigated land for the respective period shall be obtained by the land-use projection as explained in section 4.3.3 above.

If the current trend of groundwater abstraction in agricultural sector is Z%, then the future groundwater abstraction for agricultural sector (G_a) is given by:

$$G_a = Z\%\ of\ A_d \qquad \text{eq.4.27}$$

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

$$GWA_{total} = G_d + G_i + G_a \qquad \text{eq.4.28}$$

4.4 Hydrological Modelling for the Estimation of Groundwater Recharge

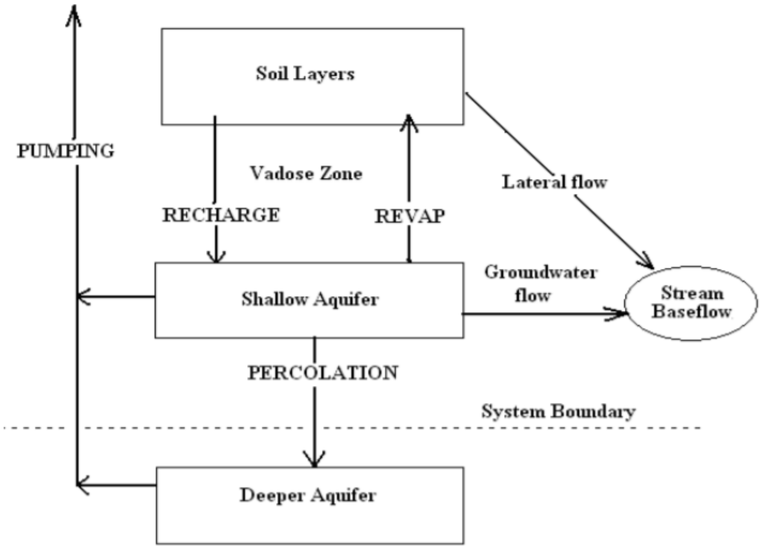
Hydrological modelling portrayal of a real-word hydrological system using some physical models and mathematical equations via multiple computer simulations. In hydrological modelling runoff estimation is a key and is defined through a set of mathematical equations with rainfall and drainage being the 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 proposed to use 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 is represented as reservoir and the zone between the soil layer and the aquifer is the vadose zone (Figure 4.9). The detail schematic of representation of groundwater process in the SWAT model is given below:

Figure 4.9

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:

$$aq_{sh,i} = aq_{sh,i-1} - w_{rchrg} - Q_{gw} - w_{deep} - w_{revap} - w_{pump,sh} \qquad \text{eq.4.29}$$

Where,

$\mathbf{aq_{sh,\,i}}$ is the amount of water stored in the shallow aquifer on day i (mmH_2O),
$\mathbf{aq_{sh,\,i-1}}$ is the amount of water stored in the shallow aquifer on day i-1 (mmH_2O),
$\mathbf{w_{rchrg}}$ is the amount of recharge entering the shallow aquifer on day i (mmH_2O),
$\mathbf{Q_{gw}}$ is the groundwater flow or base flow into the main channel on day i (mmH_2O),
$\mathbf{w_{deep}}$ is the amount of water removed from the deep aquifer by pumping on day i (mmH_2O),
$\mathbf{w_{revap}}$ is the amount of water moving into the soil zone in response to water deficiencies on day i (mmH_2O), and
$\mathbf{w_{pump,\,sh}}$ is the amount of water removed from the shallow aquifer by pumping on day i (mmH_2O)

The time taken by the water to move from the vadose zone to the aquifer depends upon the water table and the hydraulic properties of soil (Yang et al., 2010). The water of the capillary fringe that separates the unsaturated zone and saturated zone is evaporated and removed by diffuse process during the dry period. This part of the water loss is replaced by the movement of water from the saturated aquifer. The deep roots of the plants may also consume water. As water is removed from the capillary fringe by evaporation, it is replaced by water from the underlying aquifer (Vazquez-Amábile & Engel, 2005). SWAT accounts all these as "revap". Revap might occur only 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:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad \text{eq.4.30}$$

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 determining direct runoff using curve number (CN method) is as follow (USDA-SCS, 1972):

$$Q = \frac{P - 0.2S^2}{P + 0.8S} \quad \text{eq.4.31}$$

Where,Q is direct surface runoff (in), P is total rainfall (in), S is potential maximum infiltration (in), which is calculated using the equation below:

$$S = \frac{100}{CN} - 10 \quad \text{eq.4.32}$$

Where, CN is the curve number (0≤CN≤100)

The equation used in SWAT to calculate actual groundwater discharge is derived from the steady-state response of groundwater flow to recharge as described by (Hooghoudt, 1940).

$$Q_{gw} = \frac{8000K_{sat}}{L_{gw}^2} * h_{wtbl} \qquad \text{eq.4.33}$$

Rycroft & Smedema, (1983), described change in water table elevation due to non-steady-state response of groundwater flow to periodic recharge as

$$\frac{dh_{wtbl}}{dt} = \frac{w_{rchrg} - Q_{gw}}{800\mu} \qquad \text{eq.4.34}$$

4.4.2 Performance Evaluation of Hydrological Model

Four most widely used statistical parameter; the coefficient of determination (R^2), the percentage bias (PBIAS), Ratio of root mean square error to standard deviation (RSR) and the Nash-Sutcliffe efficiency (NSE), will be used to evaluate the hydrological model. The Coefficient of Determination (R^2) measures how well a model can reproduce the output. Its value varies from 1–0, with 1 being the best result, and 0 the poorest. The percentage bias (PBIAS) measures the average difference between the measured and simulated value for a given quantity over a specified period. The optimal value of percentage bias is 0 and negative and positive value shows overestimation and underestimation bias of model, respectively. The Ratio of root mean square error to standard deviation (RSR) is the ratio of the RMSE and standard deviation of measured data. The RSR includes the benefits of error index statistics and a normalization factor, so that the resulting statics and reported value can be applied to various constituents. Lower RSR indicates lower RMSE and better model simulation performance. The Nash-Sutcliffe Efficiency (NSE) is used to indicate the degree of fitness between simulated and observed data. The value of NSE can be between $-\infty$ to 1. If the NSE value is 1 it indicated the perfect fit. If NSE value is negative, the average value of output is the better estimate than the model and prediction are very poor. The equations for the calculation of each statistical parameter is given below:

$$R^2 = \frac{(\sum_{i=1}^{n}\left(Q_i^{obs} - \overline{Q_i^{obs}}\right)(Q_i^{sim} - \overline{Q_i^{sim}}))^2}{\sum_{i=1}^{n}((Q_i^{obs} - \overline{Q_i^{obs}})^2 \sum_{i=1}^{n}(Q_i^{sim} - \overline{Q_i^{sim}})^2} \qquad \text{eq.4.35}$$

$$PBIAS = [\frac{\sum_{i=1}^{n}\left(Q_i^{obs} - Q_i^{sim}\right) * 100}{\sum_{i=1}^{n}(Q_i^{obs})} \qquad \text{eq.4.36}$$

$$RSR = \frac{RMSE}{STDEV_{obs}} = \frac{[\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}]}{[\sqrt{\sum_{i=1}^{n}(Q_i^{obs} - \overline{Q_i^{obs}})^2}]} \qquad \text{eq.4.37}$$

$$NSE = 1 - [\frac{\sum_{i=1}^{n}(Q_i^{obs} - Q_i^{sim})^2}{\sum_{i=1}^{n}(Q_i^{obs} - \overline{Q_i^{obs}})^2}] \qquad \text{eq.4.38}$$

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 Future Groundwater Level

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. 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 study proposed MODFLOW model from the GMS (GMS-MODFLOW) to simulate the groundwater level and groundwater balance in the study area. The model is a modular finite-difference flow model and 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).

4.5.1 Governing Equation for GMS-MODFLOW Model

The MODFLOW model was developed to simulate the movement of the water flow below the ground. Using 3D finite difference method, groundwater flow model can simulate several different types of aquifers. The governing equation for 3D groundwater flow is based on the law of mass balance and Darcy's law. This modelling can be performed in both steady state and transient state conditions. Fluxes are constant during the simulation period in steady state while they vary both in space and time in fully transient modelling.

3D groundwater flow through porous medium is governed by the following equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} - W \qquad \text{eq.4.39}$$

Where,

K_x, K_y, K_z are values of hydraulic conductivity along x, y and axes,
h is the hydraulic head,
W is flux per unit volume, representing sink and/or sources of water,
S_s is specific storage of the aquifer.

Solution of the equation is obtained by using a block centered finite-difference approximation. Eq.4.39 when combined with boundary and initial conditions, describes transient flow in a heterogeneous and anisotropic medium provided that the principal axes of hydraulic conductivity are aligned with the coordinate directions. For steady state conditions the term on the right-hand side of the equation reduces to zero.

The flow regime is represented by blocks made of grids (plan view) and layers (side view). Each block is assumed to have uniform medium properties and employ the above eq.7 to calculate the head of the layers. When, at the end of iteration, the head rises above the top elevation of the layer, the layer is confined while vice-versa for unconfined layer (Anderson et al., 2015). Consequently, the heads in the uppermost layer could rise infinitely as the model assumes no upper limit for the uppermost layers.

4.6 Assessing Vulnerability of Groundwater to Availability

The IPCC in the fourth assessment report defines vulnerability to climate change as "*the degree to which a system is susceptible to and unable to cope with, adverse effects of climate change, including climate variability and extremes*". Thus, it is a function exposure, sensitivity, and adaptive capacity of a system to current and possible threats (Aslam et al., 2018). Various climatic and non-climatic factors such as population growth, rapid industrialization, urbanization, and increased sectoral water demand has stressed the groundwater (Taylor, 2014; Van der Gun, 2017), thus increasing its vulnerability in the present and future. Aslam et al., (2018), proposed an impact modelling and an-index based approach in assessing the groundwater vulnerability to external stressors. Babel et al., (2011), applied the indicator-based approach in assessing the vulnerability of freshwater resources where the study selected several indicators for water stress index and adaptive capacity to calculate the vulnerability index.

The study proposes a dynamic indicator-based framework to access vulnerability of groundwater resources to availability. The proposed framework has adopted the vulnerability of groundwater based on its function as exposure, sensitivity, and adaptive capacity as defined by IPCC. The detail description on the framework is given below:

4.6.1 Description of the Framework

The proposed framework consists of 3 components namely, exposure, sensitivity and adaptive capacity as defined by IPCC. Furthermore, each component contains 3 different indicator that addresses the component. The exposure components describe the current and future situations to which a system is being exposed. The second component sensitivity links to the intrinsic properties of the aquifer describes the measure of whether and how the system is likely to be affected by a given change under future stresses. The third component of the framework is the adaptive capacity and refers to the ability of the system to respond to changes caused by the multiple stresses. Table 4.8 below shows the detail of the vulnerability framework with indicators, its functional relationship with vulnerability and the pathways.

Table 4.8

Structure of the groundwater vulnerability framework with components, indicators with functional relationship

Component	Indicator	Representation for	Indicator-Vulnerability (Functional Relationship)	Pathways	Source
Exposure	Change in Rainfall (%)	Extent of Climate Change and Variability	↑ ↓	(Increased rainfall intensity increases groundwater recharge due to greater infiltration or may decrease recharge due to higher runoff)	Mayer's et al. (2011); Seeboonruang (2016); Wallace et al. (2012)
	Change in Groundwater Recharge (%)	Risk of Reduced Quantities	↓	Reduced recharge reduces groundwater quantity	Dennis & Dennis (2012); Luoma et al. (2016)
	Population Density (Persons/km^2)	Risk of Pressure in Groundwater	↑	Increase in Population increases the demand for water and thus groundwater abstraction	Mayer's et al. (2011)
Sensitivity	Amount of Groundwater Recharge (m^3)	Availability of Groundwater to cope up with Domestic, Industrial and Agricultural Need	↓	Higher recharge increases groundwater quantity	Dennis & Dennis (2012); Luoma et al. (2016)
	Transmissivity (m^3/day/m)	Change in groundwater quantities	↓	Less transmissivity means less recharge and less contribution to groundwater quantity	Seeboonruang (2016)
	Amount of Sectoral Demand	Risk of increased pumping and reduced quantities	↑	Increased sectoral demand increases groundwater pumping	Zume & Tarhule (2011)
Adaptive Capacity	Economic Capacity (GDP Per Capita)	Ability to Access Resources and Technology	↓	Higher economic stability higher the adaptation	Pandey et al. (2010); Babel et al. (2011);
	Human Capacity (Working age population + Educated people) (%)	Availability of Social Resources and Flexibility in Adaptation	↓	Higher social resources higher adaptation to stress	Pandey et al. (2010); Babel et al. (2011);
	State of Groundwater Governance	Governance Provisions and Capacity for Management to secure Availability and Access	↓	Good governance higher adaptive capacity	Mayer's et al. (2011)

Note: ↑Direct Proportionality (Increase); ↓Inverse Proportionality; ↑ ↓Mixed Proportionality (Increase/Decrease)

4.6.2 Normalization and Weightage Calculation

This study proposes the vulnerability index for each subbasin, and the range of this numerical value shall be between 0 to 1 from low to severe vulnerability. Before computing the VI, the values of indicators should be normalized. The min-max approach is used for normalization of indicators. For two types of functional relationship different formulas are used. The equations for the direct (eq. 4.40) and inverse (eq. 4.41) relationship shall be:

$$NV_{ij} = \frac{Yij - Ymin}{Ymax - Ymin} \qquad \text{eq.4.40}$$

$$NV_{ij} = \frac{Ymax - Yij}{Ymax - Ymin} \qquad \text{eq.4.41}$$

Where, NVij = Normalized value of the j^{th} indicator for the i^{th} component ; Y_{ij} = Actual values of the j^{th} indicator for i^{th} component; Y_{max} and Y_{min} = maximum and minimum values of all the units considered

The study proposes to apply AHP in prioritizing the indicators and to assign weights to different indicators of the framework through an expert's opinion as described in section 4.3.2. In the case of the weight for the component, equal weight for all the three components shall be given in the framework.

4.6.3 Aggregation Technique for Vulnerability Index (VI)

The study proposes to apply AHP in prioritizing the indicators and to assign weights to different indicators of the framework through an expert's opinion as described in section 4.3.2. In the case of the weight for the component, equal weight for all the three components shall be given in the framework.

$$C_i = \sum_{j=1}^{n} W_j * NV_{ij} \qquad \text{eq.4.42}$$

Where,

C_i = Aggregated value of the ith component; W_j = Weightage of the selected jth indicator for ith component; NV_{ij} = Normalized value of the jth indicator for the ith component

$$VI = \sum_{i=1}^{n} W_i * C_i \qquad \text{eq.4.43}$$

Where,

VI = Vulnerability Index; W_i = Weightage of the selected ith component;

C_i = Aggregated value of the ith component

4.6.4 Interpretation of Vulnerability Index (VI) Results

After assessing the groundwater governance and quantifying to obtain an overall groundwater governance index, the magnitude of the index shall be interpreted so that it gives an overview of the current state of groundwater governance in the area. The threshold of the governance index is on a range of 0-3 and described (Table 4.9) as given below:

Table 4.9:

Interpretation of the results of groundwater governance index

VI - Value	Vulnerability	Interpretation
0.0-0.2	**Low**	The groundwater system is healthy in terms of availability, development practice, governance process, and management capacity to multiple stresses. The system is applying sustainable groundwater resource development, governance, and management practice. No serious change in policy and governance mechanism is required. However, there is still a possibility for adjusting policies to moderate issues identified in one or two aspects while assessing different components of the vulnerability index structure.
0.2-0.4	**Moderate**	The groundwater system is generally in good condition in terms of availability, development practice, governance process, and management capacity to multiple stresses. The system is toward the realization of sustainable groundwater resource development, governance, and management practice. However, it may still face several challenges due to multiple stresses, lack of human, economic, and governance capacity. Therefore, the policy adjustment to upgrade the system should be focused based on the challenges identified in one or two or all the aspects while assessing different components of the vulnerability index structure.
0.4-0.7	**High**	The groundwater system is under high stress in terms of availability, development practice, governance process, and management capacity to multiple stresses. The system requires great efforts for strong policy design, technical and managerial support to deal with high pressure due to multiple stresses, lack of human, economic, and governance capacity. Therefore, a long-term strategic development and management policy should be made based on the challenges identified while assessing different components of the vulnerability index structure.
0.7-1.0	**Severe**	The groundwater system is highly degraded in terms of availability, development practice, governance process, and management capacity to multiple stresses. The system requires restoration with great efforts and high commitment from all the actors for strong policy design, technical and managerial support. Therefore, a long-term strategic and integrated water resources development and management policy with the involvement from international, national, and local agencies should be made based on the challenges identified while assessing different components of the vulnerability index structure.

CHAPTER 5

EXPECTED OUTPUTS

5.1 Expected Outputs

The following outputs are expected at the end of the proposed study:

- Development of groundwater governance framework for rapidly urbanizing areas of Lower Mekong Basins addressing social equality, human-rights, conflicts, and gender dimensions.
- Detail diagnostic of current state of groundwater governance in Khon Kaen, Thailand with its strengths, gaps, and areas of improvement.
- Projection of future change in climatic parameters under different Shared Socioeconomic Pathways (SSPs).
- Projection of future population change and changes in land-use under different scenarios.
- Projection of future sectoral and overall groundwater demand in the study area.
- The spatial and temporal distribution of groundwater recharge, its level and water balance under multiple stresses such as climate change and land use change.
- Development of dynamic groundwater resources vulnerability to availability framework in terms of exposure, sensitivity, and adaptive capacity.
- Estimation of current and future groundwater resources vulnerability to availability under multiple stresses.
- Identification of possible conflicts in groundwater resources availability, accessibility, and management under multiple stresses with recommendations for improved groundwater governance in Khon Kaen, Thailand.

CHAPTER 6

RESEARCH TIMELINE AND BUDGET

6.1 Research Timeline

Table 6.1

Research Timeline

Activities	2020								2021												2022											
	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Literature Review	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
Development of Groundwater Governance Framework	🟩	🟩	🟩	🟩	🟩	🟩	🟧																									
Advancement to Candidacy (ATC) Exam (Proposal Defense Exam)						🟦																										
Secondary (hydrological, hydrogeological, and other) Data Collection							🟧	🟧																								
Groundwater Governance-Questionnaire Development and Interview						🟧	🟧	🟧																								
Result Analysis for Current State of Groundwater Governance (Objective-1)								🟧	🟧																							
Future Climate Change Projection								🟧	🟧	🟧																						
Future Population Change Projection										🟧																						
Future Land-Use Change Projection										🟧	🟧	🟧																				
First Progress Exam												🟦																				
Future Groundwater Abstraction Projection												🟧	🟧	🟧																		
Analysis of Results for Future Projection of Multiple Stresses (Objective-2)														🟧	🟧	🟧																
Hydrological Model Development																🟧	🟧	🟧														
Second Progress Exam																		🟦														
Groundwater Model Development																		🟧	🟧	🟧	🟧											
Analysis for Impact of Multiple Stresses in Surface and Groundwater (Objective-3)																					🟧	🟧	🟧									
Development of Groundwater Resources Vulnerability to Availability Framework	🟩	🟩	🟩	🟩	🟩	🟩	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧																
Groundwater Vulnerability-Questionnaire Development and Expert's Opinion																🟧	🟧															
Third Progress Exam																							🟦									
Result Analysis for Groundwater Vulnerability to Availability (Objective-4)																		🟧	🟧	🟧	🟧											
Stakeholder Consultation for Result Validation and Possible Conflict Analysis																						🟧	🟧									
Recommendations for Improved Groundwater Governance																							🟧	🟧								
Compilation of Results and Discussion and Writing of Dissertation Report																						🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧			
PhD Dissertation Final Exam																															🟦	
Manuscript Preparation										1st													2nd				3rd			4th		

Note: 🟩 **Completed** 🟧 **To be Done** 🟦 **Exam**

6.2 Research Budget

The estimated budget for the research work is shown in the table 6.2

Table 6.2

Research Budget

Description	**Budget in Thai Baht (THB)**		
	2020-21	**2021-22**	**Total**
Data Purchase (meteorological, hydrological, hydro-geological, topographic, land-use, sector water use data etc.)	15,000	8,000	**23,000**
Domestic Travel to Study Area	2,500	2,500	**5,000**
Accommodation and Local Transport	3,000	3,000	**6,000**
Logistics (Printing and Photocopy)	5,000	6,000	**11,000**
Other Miscellaneous	2,500	2,500	**5,000**
Grand Total	**28,000**	**22,000**	**50,000**

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