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Javzansuren Norvanchig
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WATERSHED-SCALE MODELING FOR WATER RESOURCE SUSTAINABILITY IN THE TUUL RIVER BASIN OF MONGOLIA

A Thesis Presented

By

JAVZANSUREN NORVANCHIG

Submitted to the Graduate School of
The University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2018

Environmental Conservation
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WATERSHED-SCALE MODELING FOR WATER RESOURCE SUSTAINABILITY
IN THE TUUL RIVER BASIN OF MONGOLIA

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Approved as to style and content by:

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Timothy O. Randhir, Chair

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David Bloniarz, Member

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ABSTRACT

WATERSHED-SCALE MODELING FOR WATER RESOURCE SUSTAINABILITY IN THE TUUL RIVER BASIN OF MONGOLIA

MAY 2018

JAVZANSUREN NORVANCHIG, B.S., BANGALORE UNIVERSITY

M.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Timothy O. Randhir

Water scarcity is a prevalent issue all over the world. Growing water abstractions combined with uncertain effects of climate increase competition for scarce water resources worldwide, especially in arid and semiarid regions. It is crucial to assess and manage available water resources to ensure its sustainability. There is a need for integrated water management at a watershed scale. Watershed models are a useful tool to support sustainable water management and investigate effects of hydrologic responses at various scales under climate change conditions and to simulate effects of the management decisions. This study aims to assess the sustainability of water resources in the Tuul River Basin in Mongolia using SWAT (Soil Water Assessment Tool) model to understand ecohydrological processes in the basin. The model is used to analyze the trends in water usage on a watershed and subwatershed basis. The water supply and demand dynamics at each sub watershed levels are analyzed to develop a sustainability index based on specific
criteria of water sustainability. Sustainability index was used for better water management by targeting areas of the watershed.

Using the analysis, strategies for water demand management for the Tuul River basin area were developed. I expect the results of the study with transform water resource situation in the region through better information on the dynamics of the system and will help in alleviating water issues in similar regions of the country and of the world. The model can be a useful tool to support decision makers and to simulate and analyze the effects of water management practices.

Keywords: water resources, water supply, and demand, Tuul river, sustainable water resources
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ABBREVIATED TERMS

ASCE – American Society of Civil Engineers
EFR – Environmental flow requirements
ESA – European Space Agency
FAO – Food and Agriculture Organization
GDEM – Global digital elevation model
GDP – Gross Domestic Product
GIS – Geographic information system
HRU – Hydrological Response Unit
IUCN – International Union for the Conservation of Nature
JICA – Japan International Cooperation Agency
KOICA – Korea International Cooperation Agency
MENA – Middle Eastern and North African countries
MNET – Ministry of Nature, Environment, and Tourism
NAMHEM – National Agency for Meteorology, Hydrology, and Environment of Mongolia
NSE – Nash-Sutcliffe model efficiency
NSOM – National Statistical Office of Mongolia
PBIAS – Percent bias
SWAT – Soil and Water Assessment Tool
SWAT-CUP – Soil and Water Assessment Tool Calibration Uncertainty Procedures
TRB – Tuul River Basin
UN – United Nations
UNESCO – United Nations Educational, Scientific and Cultural Organization
USDA – United States Department of Agriculture Research Service
WA – Available water
WCED - World Commission on Environment and Development
WDM – Water demand management
WDSR – Water Supply Demand Ratio
WTA – Water to availability ratio
WTP – Water treatment plant
CHAPTER 1

WATER SCARCITY AT A GLOBAL AND LOCAL CONTEXT

1.1. Introduction:

The massive rise in demand for water to grow food, supply industries and sustain urban and rural populations has led to a growing scarcity of freshwater in many parts of the world (Ali et al. 2014; Dessu et al. 2014; Sahin et al. 2015; Sarzaeim et al. 2017). In many areas, groundwater is being pumped at rates that exceed replenishment, depleting aquifers and the reducing the base flows of rivers. Aquifer depletion, low or almost non-existing river flows, and increasing level of water pollution are visible indicators of water stress (Postel 2000). Due to less water availability in rivers and lakes, the ecosystem is hugely impacted by the water stress and the life dependent on the system are at the risk of degradation and depletion (Navarro-Ortega et al. 2015). As water is the essential resource for life, all activities that rely on water will be profoundly impacted. Shortage of water creates stress on food and energy production and further contributes to lack of access to clean, fresh water for people.

The populations living in water-stressed conditions will increase 39–49 % by 2071–2100 and the water availability will decline by the end of 21st century (Hoekstra and Mekonnen 2012). Water scarcity in arid and semi-arid regions is a tremendous economic, environmental and social problem. It covers one-third of the world’s land area and is inhabited by almost one billion people, and the higher part thereof is among the most impoverished populations in the world (Johannsen et al. 2016; Wu et al. 2013). In these
areas, water demand increases but the water availability is the also shrinking significantly. Water scarcity creates a burden on the socioeconomic development of the country as there will be less water available to grow crops, sustain livestock and supply drinking water and adequate sanitation to people (Hanasaki et al. 2013).

This phenomenon will be more prominent in developing countries due to their fast-growing economy and rapid urbanization. The population in the urban areas has increased drastically in last few decades. With rapid population growth, water withdrawals have tripled over the previous 50 years and are predicted to increase by 50 % by 2025 in developing countries (UNESCO 2012).

Currently, 54% of the world’s population lives in urban areas, and it is expected to increase to 66 percent by 2050. Africa and Asia are urbanizing faster than the other regions and are projected to become 56% and 64% urban, respectively, by 2050 (United Nations 2014). As a result, cities will face numerous challenges in meeting the needs of their growing urban populations, especially for housing, infrastructure, transportation, energy, and employment, as well as for basic services such as education and healthcare. It further creates stress to existing water supply in urban areas. Many of the urban areas are required to find means to satisfy the growing water demand (McDonald et al. 2014).

In addition to increased water demand for population growth and economic development, the climate crisis also has an enormous impact on water resources. Due to the climate uncertainty, processes influencing the water supply changed over years and it has become an extra challenge to estimate and assess available water resources (Hanasaki et al. 2012(Hanasaki et al., 2012)). Climate change is a significant factor influencing water
supply. It is projected that there will be 10–40% increase in runoff in eastern equatorial Africa, the La Plata basin and high-latitude North America and Eurasia, and 10–30% decrease in runoff in southern Africa, southern Europe, the Middle East and mid-latitude western North America by the year 2050 (Vecchia et al. 2005). Especially in arid and semiarid regions, climate change is projected to increase water scarcity and increase the recurrence and intensity of droughts (Kahil et al. 2015).

As water scarcity is global as well as a local challenge, there is a need for sustainable water management that is best suited for the local context. It requires a holistic approach to analyze the various components of the water supply and demand for the sustainable supply of water.

1.2. Literature review:

1.2.1. Water scarcity

Freshwater scarcity is growing issue in all over the world. As the world population continues to grow and their improved living standards, increased consumption of natural resources is rising global demand for water (Hanasaki et al. 2013; Hoekstra et al. 2012). There have been numerous studies conducted on water shortages under current conditions (Mekonnen & Hoekstra, 2016; Porkka et al., 2014) and future climate change predictions (Faramarzi et al. 2017; Haddeland et al., 2014; Schewe et al., 2014; Johannsen et al. 2016). Based on the calculation of the current trend of consumptive water use, there will be four billion people living in the watershed that experience water scarcity at least one month in a year (Mekonnen and Hoekstra 2016). With the influence of climate change, 0.5 to 3.1
billion people will be exposed to an increase in water scarcity due to climate change by 2050 (Gosling and Arnell 2016). It will increase the number of people living under absolute water scarcity (<500 m³ per capita per year) by another 40% (Jacob Schewe et al. 2014).

Lately, there have been many indicators have been developed to facilitate the assessment of the status of water scarcity across the world. More sophisticated approaches with high spatial resolution have been developed, attempting to incorporate more aspects of water, such as blue water, water quality, green water (soil moisture), and environmental flow requirements (EFR) (Zeng et al. 2013; Mekonnen and Hoekstra 2016). There are several ways to estimate scarcity, such as the ratio of population size to the renewable water supply and the ration of water withdrawals to the renewable supply.

Hoekstra et al. (2012) have used accurate assessment of water scarcity at a global scale using a method that includes estimating consumptive use of water rather than just withdrawals, taken consideration on ecological water needs, and calculated on a monthly basis not yearly at river basin scale for 1996-2005. They compared to water consumption to ecologically available water on a monthly basis. Ecological needs in the river flow were considered as 80% and deducted from the total available water. The water footprints were divided into three main categories; agricultural, industrial and domestic.

-Bluewater print - volume of surface and groundwater consumed as an activity

-Bluewater consumption - the volume of freshwater used and evaporated or incorporated into the product.

They have divided blue water scarcity into four levels (low, moderate, significant and severe). 92% of blue water is consumed by agriculture but vary across water basins and
month to month, and the rest is used for industrial and domestic. There are several basins such as Murray Darling have a water shortage in the dry period when as blue water footprint is highest, but the water availability is the lowest. There are 2.72 billion people face water shortage at least one month of the year in one-half of the river basins included in this study. The authors concluded that monthly estimation provides higher accuracy of water scarcity. With severe water scarcity occurring at least one month per year, the results underline the critical nature of water shortages around the world (Hoekstra et al. 2012).

Mekonnen and Hoekstra (2016) conducted the same study at a finer grid cell with more accuracy. As water scarcity is experienced at the local scale, it is calculated as the ratio of the blue water footprint in a grid cell to the total blue water availability in the cell. Total blue water availability is calculated as the sum of the runoff generated within the grid cell plus the runoff generated in all upstream grid cells minus the environmental flow requirement and minus the blue water footprint in upstream grid cells. It thus accounts for the effect of upstream water consumption on the water availability in downstream grid cells. Monthly blue water scarcity (WS) is classified as low if the blue water footprint does not exceed blue water availability (WS < 1.0); in this case, environmental flow requirements are met. Monthly blue water scarcity is said to be moderate 1.0 < WS < 1.5, significant 1.5 < WS < 2.0, and severe if WS > 2.0. They have found that high scarcity level appears in the highly densely populated area or great irrigated land with low water availability. Moreover, they updated that 71% of the global population (4.3 billion people) lives under conditions of moderate to severe water scarcity (WS > 1.0) at least one month of the year. About 66% (4.0 billion people) lives under severe water scarcity (WS > 2.0) at least one month of the year (Mekonnen and Hoekstra 2016).
Jacob Schewe et al. (2014) mentioned that increasing demand of water puts pressure on available water resources increase, but climate variables are putting additional stress on water supply. They had studied the impact of climate change on global water resources using five different global climate model scenarios and found out that 2°C increases in temperature bring stress to 15% of the global population on water resources which are 40% more compared to just population growth. Jacob Schewe et al. used water crowding index as water scarcity index and water resources to the population at country scale and based on blue water resource, but it does not incorporate the water demand. They have concluded that the population growth and unmitigated climate change plays a significant role in water scarcity and expose a substantial amount of the world population to chronic (1000 m3 per capita annually) and absolute (500 m3 per capita annually) water scarcity (Jacob Schewe et al. 2014).

Hanasaki et al. (2013) executed global water scarcity assessment using high-resolution grid cells. They used Cumulative abstraction to Demand ratio at daily interval under latest socio-economic scenario which includes population, electricity production, and technological change and overall environmental consciousness. The five future situations with substantially different socio-economic conditions were used to analyze water scarcity. These factors were affected by other scenarios such as population, food production, land use, industrial activity, electricity production, technological change, investment in infrastructure, development aid and many others. However, water scarcity, in turn, affects these factors as well. They deducted that mainly due to the economic growth of developing countries, 39-42% of global population will reach severely water-stressed conditions by 2071-2100 (Hanasaki et al. 2013).
There are two types of water scarcity, that are physical which relates to inadequate resources to meet the demand and economical which indicates unaffordability to obtain clean water. Many countries including the U.S., Middle Eastern and North African countries (MENA region) and southeastern European countries, Southern India, Pakistan, Mongolia, Afghanistan, Kazakhstan, Turkmenistan, Uzbekistan, Tajikistan and Western Australia are facing physical water scarcity. Economic water scarcity is experienced in Central and Latin America including Caribbean region, South, and Central Africa, North India, some parts of China and some other Asian countries (Gude 2017).

Zeng et al. (2013) developed an approach for assessing water scarcity considering both water quantity and quality using new water scarcity index and used it for Beijing city in China. They found out that even though Beijing made huge progress regarding the mitigation of the water scarcity by almost 60% from 1999 to 2009, their water scarcity index remained high.

Water scarcity is even more prone to semi-arid regions due to low availability of precipitation. Most of the arid and semi-arid regions are in the developing countries, while the availability of water in adequate quantity and quality is an essential condition to approach sustainable development. There are several studies focused on semi-arid regions of the world (Johannsen et al. 2016; Niu et al. 2014; Rodriguez et al. 2016; Wu et al. 2013).

Kahil et al. (2015) estimated water scarcity in the arid and semi-arid region using a hydro-economic model that links a reduced form hydrological component, with economic and environmental components of the arid and semiarid basin in Southeastern Spain to analyze the effects of droughts and to assess alternative adaptation policies. Results indicate that
drought events have significant impacts on social welfare, with the primary adjustments sustained by irrigation and the environment. The authors propose environmental water market policy, where water is acquired for the environment to gather the private benefits of markets while protecting ecosystems. The current water management approach in Spain, based on stakeholders' cooperation, achieves almost the same economic outcomes and better environmental outcomes compared to a pure water market (Kahil et al. 2015).

Rodriguez et al. (2016) analyzed spatial and temporal risks of water shortage in arid and semi-arid regions of Brazil and estimated per capita water use for various levels of risk. They used average monthly water use to assess variation of water availability in the homogenous semi-arid region and found out. This variation of water availability for human consumption in the Brazilian semi-arid region reflects the temporal variability and the spatial variability of rainfall.

Abu-Allaban et al. (2015) used Soil and Water Assessment Tool hydrological model to assess foreseen impacts of climate change on water resources of Mujib, a groundwater basin in Jordan, using ten different scenarios representing dry, normal and wet events. Their findings indicate that dry scenario has a significant impact on annual water precipitation about 20-50% reduction.

Water shortage and scarcity has become colossal challenge all over the world. As water scarcity has temporal and spatial variation, there is a need for better evaluation of the water scarcity at local and regional level. It requires detailed analysis of water supply and demand at watershed and subwatershed level and finds suitable measures to alleviate the water scarcity problems.
1.2.2. Current approaches and needs

The water demand-supply imbalance requires innovative water management practices. To mitigate the water scarcity related problems and satisfy the growing need of water, the sustainable management of water resource is necessary (Xi and Poh 2013).

There have been two main approaches to match the supply and demand of water. Various practical efforts have been made by water managers such as the expanding of construction of water infrastructures over the past century to increase water supply. Augmenting water supply such that finding additional water resource, using an alternate source of water such as rainwater harvesting (Shadeed and Lange 2010; Steffen et al. 2013), desalinization and extracting water from air moisture, etc. However, this alone would not satisfy the all the growing current water demand. Lately, many researchers are focusing on the demand side of the water management for sustainable water resource management. By controlling the water demand, sustainability of water resources can be enforced. This could include approaches such as increasing water efficiency, adapting to the limited water conditions (Ashraf Vaghefi et al. 2015) and reducing water losses (Bijl et al. 2016; Medrano et al. 2015).

Often these practices are implemented at the municipal or regional level, but we need to consider the water sustainability at watershed scale. As there is spatial and temporal variability of the water availability and usage, it is useful to look at the water supply and demand dynamics at the systems level. Water resources are not necessary located according to the municipal or administrative units; it makes more sense to look at the water sustainability in a watershed scale (Boithias et al. 2014). By analyzing the water supply
and demand at watershed scale, watershed managers will be able to understand the spatial as well as temporal variability of the water resources. Therefore, there is a need to analyze both options, water supply augmentation and water demand management at local as well as the national level to understand and find the best suitable opportunities adapted for the local context. Based on the spatial and temporal scale of the water resources and the water demand proper water resource management should be selected to improve the sustainability of the water resources in the watershed.

1.2.3. Water supply augmentation

Many countries in both the developed and developing world face significant problems in maintaining reliable water supplies. These problems are aggravated by the uncertainty of global climate. Growing populations will further increase the demand for water, with limited cost-effective water supply augmentation options (Dharmaratna and Harris 2012). Recently water supply systems have become more challenging to model due to both increased complexity and uncertainty of weather. It is important to know how much water is available for use in the watershed to have sustainable water resources.

There are several methods to augment existing water supply in the watershed; traditional and non-traditional. The traditional water resource enhancement approaches include finding additional resources, building dams for reservoirs. Non-traditional approaches include rainwater harvesting and reuse of stormwater for non-potable purposes, replenishment of groundwater, reclaimed water and desalinization, (Klaysom et al. 2013, Kumar et al. 2016, Bhattacharya 2015). There has been a limited reliance on traditional
water supplies, and also substantial climate change puts an extra challenge on water supply system planning (Milly et al., 2008).

Several studies have considered incorporating non-traditional water sources as alternatives to traditional water sources in the context of urban water supply planning. A survey on assessing water supply augmentation in Australia found that in the long run, a non-traditional method like desalinization provides a more viable, cost-effective and secure bulk water supply alternative when compared to building large rain-dependent dams in semi-arid regions of Australia (Scarborough et al., 2015).

Paton et al. (2014) examined the different non-traditional water supply augmentation measures and concluded that the rainwater harvesting is an expensive option with little gain and not very feasible for arid and semi-arid regions like Adelaide, Australia.

Kumar et al. (2016) assessed the several water augmentation options including reclaimed water and desalination; inter-basin water transfer and sectoral demand management in the water-stressed Mediterranean area of Northern Spain. They deduced that alternative water resources as the most reliable alternative to medium reclaimed water reuse in industry and agriculture and low to medium use of desalination water in domestic and industrial sectors as the best alternative.

When the economic benefits of groundwater replenishment are compared to the seawater desalinization in the city of Perth, Australia, it is found that the aquifer recharge is more reliable and cost-effective solution to increase the urban water supplies efficiently. The economic analysis shows that aquifer banking provides greatest cost saving where there is little loss of the aquifer banked water (Lei Gao et al. 2014).
However, these types of water augmentation methods are cost intensive and face diverse types of challenges such as economic, legal and social (Ghaffour et al. 2013). Even in expensive cities like Sydney, it is found that premature water supply augmentation can reduce the net present value of the welfare of the households by $1900 per household. Unless the water supply augmentation has a long lifetime and low discount rate, there could be large welfare loss (Beh et al. 2014, Grafton et al., 2014).

In developing countries, water supply augmentation is a huge challenge due to limited economic and technical capabilities. (Poustie and Deletic 2014)

Mizyed (2013) studied the challenges in treated wastewater in West Bank which is one of the arid and semi-arid regions of the world. He discusses that even though it is recognized as a strategic option for augmenting water supply, there are many challenges such as legal, socioeconomic implications. It is important to consider economic costs, returns, and benefits of the different qualities of treated wastewater. A social multi-criteria evaluation has been performed to explore the feasibility, desirability, and acceptability of non-traditional water supply technologies in the Metropolitan Area of Barcelona (Spain) and concluded that rainwater harvesting and reclaimed water reuse are the most preferred alternative and the desalination as the least desired option (Domènech et al. 2013).

The water supply augmentation options are challenging and have different output based on the context of the region. In landlocked, precipitation scarce, semi-arid region of Mongolia, water managers should search for sustainable water management options concentrating more on the water demand and efficiency practices that can be suitable for the local context.
1.2.4. Water demand management

The growing demand for water and a limited supply of water brings the question of how to allocate water resources among competing for demand uses during shortage periods has become a significant issue and has attracted much attention from water managers and researchers all around the world (Speed et al., 2013). There have been many efforts to expand construction of water infrastructure over past century to increase water supply. These efforts have effectively alleviated water stresses and have provided massive benefits regarding greater economic returns and fewer water-related disasters. However, the construction of infrastructures often brings unanticipated adverse effects such as migration relocation, reduced runoff, and species extinction. Along with the dramatically growing water demand, increasing supply to meet the future demand is no longer a cost-effective way towards a sustainable future; more proactive water management techniques are required (Gleick et al., 2003).

Demand management measures and policies can achieve considerable water conservation, thus tackling the effects of water shortages, but even more importantly, contributing in this way towards the longer-term goal of sustainable water resources management. A shift toward demand-side management practices is fundamental in the light of increasing population and changing climatic conditions (Dawadi & Ahmad, 2013).

Water demand management (WDM) is essential being part of the challenge to sustain the water resources. The central principle in WDM is “efficient use of water to maintain vital environment flow and to reduce dependence on costly infrastructure projects.”
As there is a specific trend of water demand increase all over the world, the water demand management that is technically and economically feasible and socially acceptable at local context and is crucial for water sustainability. Water demand management initiatives employ various techniques for conserving and making more efficient use of water. An operational definition of water demand management has five different component such as

a) reducing the quantity or quality of water required to accomplish a specific task;

b) adjusting the nature of the mission so it can be achieved with less water or lower quality water;

c) reducing losses in the movement from the source through use to disposal;

d) shifting time from application to off-peak periods, and

e) increasing the ability of the system to operate during droughts. (Brooks, 2006)

Effective water demand management approaches require not only the excellent policy from decision makers but also active public and private participation. (Acheampong et al. 2016)

Kusena et al. (2016) studied the water user participation in water conservation in the city of Gweru, Zimbabwe and reported that the users have significantly low involvement in water conservation training which may have translated into limited water conservation literacy.

Fielding et al. (2013) used smart water metering technology as a tool for behavior change in South East Queensland as to test the effectiveness of demand management interventions which led to significant water savings. But long-term household usage data showed that the reduction in water use resulting from the responses eventually dissipated, with water consumption returning to pre-intervention levels after approximately 12 months.
Lavee et al. (2013) examined the effectiveness of the residential water demand policies in Israel and found that educational policy tools have significant impact water demand, a long-term educational tool had a more substantial effect on residential water consumption than a short-term educational tool. Therefore, the successful education, information, and communication strategies for the public are essential to promote water conservation (Tortajada and Joshi 2013).

There have been several attempts to manage water demand through water conservation and water pricing as well as water policy approaches. Water conservation measures include water metering, installation and retrofitting of water saving technologies in the residential buildings, use of water-efficient technologies and recycling and reusing water (Baki et al., 2018; Ban et al., 2013; Dieu-Hang et al., 2017; Fielding et al., 2013). Water conservation approaches have three main components such as a conservation incentive, conservation measure, and conservation program. A conservation incentive increases customer awareness on the importance of reducing water use. A conservation measure is a device or practice that reduces the demand, and finally, conservation programs include a strategic combination of actions and incentives (Vickers & A.L., 1999). These type of voluntary conservation approaches can have a significant reduction in water demand. However, in the long term, the water consumption can go back to its pre-intervention level approximately after 12 months (Fielding et al., 2013). Therefore, water demand management requires conservation as well as pricing policy together to have more potential impacts.

Steffen et al. (2013) studied the quantity of rainwater harvested at residential parcel and stormwater runoff reduction from the drainage system in 23 cities in seven different climate
regions in the United States. They have used water balance approach to estimate water saving efficiency at a daily time step for multiple variations of rainwater cisterns. The performance depends on the cistern size and climate pattern and in semi-arid regions up to 20% of the runoff volume can be reduced. They concluded that the rainwater harvesting could be used as stormwater management technique at the residential level.

In semi-arid regions, water demand management could be an extra challenging issue to water managers as the water supply is already under stress of the climate conditions, but the demand is more in those areas. Dawadi & Ahmad (2013) found out that the water demand exceeds the available supply in the semi-arid region such as Las Vegas, where it is under stress of climate change and population growth if there is no important demand management policy is implemented. However, with water conservation and water pricing policies, it would be able to meet its water demand well into the future, and the water demand was predicted to reduce by 30-50%.

Hence, water demand management requires multiples scopes and consideration from water managers, including policy and regulation, social and educational outreach, technical advancement and pricing structure. The best combination of the strategy and approach that is suitable for the local socio-economic conditions could be a way to solve the water scarcity in the watershed.

1.2.5. Water sustainability

There is a wide range of definitions of sustainability and sustainable development. One of the most widely used is that of the Brundtland Report, in which it is defined as a
development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). The International Union for the Conservation of Nature defined sustainability as the development that improves the quality of human life while living within the carrying capacity of supporting ecosystems (IUCN, 1991). Although there are many definitions of sustainability, nearly all contain some perception of the future generation and that human society and economy are intimately connected to the natural environment (Caradonna, 2014).

Gleick (2000) defined a sustainable water use as the use of water that supports the ability of human society to endure and flourish into the indefinite future without undermining the integrity of the hydrological cycle or the ecological systems that depend on it. ASCE and UNESCO (1998) defined water resource system sustainability as those water resource systems designed and managed to contribute to the objectives of society entirely, now and in the future, while maintaining their ecological, environmental and hydrological integrity.

In general, the above definitions can be aggregated and is most often associated with issues related to the economic, social and environmental dimensions, which has become known as the Triple Bottom Line (Mihelcic et al., 2003), as an example of sustainability model shown in Figure 1-1.
Figure 0-1. The Triple Bottom Line of the sustainability

It is essential to adopt practices to manage the water resources availability sustainably without altering the socio-economic development. Sustainable water management is a critical component of sustainable development and accounts for similar issues as sustainability. We consider 'sustainable water management systems' to be those that meet the needs of society over the lifetime of the service while also maintaining fundamental ecological functions that support the long-term provision of ecosystem goods, services, and values, including biodiversity maintenance (Poff et al., 2015)

Russo et al. (2014) reviewed sustainable water management in urban, agricultural and natural systems in developed and developing countries. They suggested that the water management of the natural system is the basis of sustainable urban and agrarian management approaches. In developing countries, the primary goal of sustainable water management in urban areas include equitable delivery, reliability and system flexibility,
and growth. The ecosystem in this country requires protection of valued ecosystem services. The challenges for sustainable urban water management in developing countries include intermittent operation, lost or stolen water, rapid urban growth and political conflict. For the ecosystem, economic development priorities constitute a significant challenge. They have also discussed the potential solution for above problems. Institutional improvements, low-tech water capture, and treatment, greywater reuse, cooperation, sharing riparian rights and stakeholder engagement are viable solutions for urban water sustainability, and communication of ecosystem service value is vital for water sustainability (Russo et al. 2014).

Thus, as the water sustainability is complex and challenging phenomena, water managers should have a variety of expertise and systematic approach to consider multiple factors.

1.3. Research questions and contribution

Mongolia is facing many water-related problems, such as adverse natural conditions, increasing water withdrawals, limited environmental information and a lack of structures which control the appropriate distribution and protection of water (Menzel et al. 2014). According to the recent study by Government of Mongolia and the Millennium Challenge Corporation (2016), the one of the binding constraint to the economic growth of Mongolia is water and sanitation issues exacerbated by underlying water scarcity issues, driven by an uneven natural distribution of water resources and a semi-arid climate. Domestically, groundwater resources play a vital role in Mongolia’s economy; supporting agriculture, forestry, fishery, livestock production, industrial and domestic water demand and sanitation activities. Water demands are mainly met from the groundwater sources, roughly
80% of the total water consumption (Dolgorsuren, G et al. 2012). The regional effects of global climate change, significant land use changes, a booming mining sector, and growing cities with insufficient and decaying water and wastewater infrastructures result in increasingly unsustainable exploitation. Moreover, contamination of ground and surface water resources is putting at risk both aquatic ecosystems and human health (Karthe et al., 2015).

The country’s capital city Ulaanbaatar is in the Tuul River Basin, and the population growth and industrial activity rapidly intensified during the past two decades. Tuul River Basin has over 46% of the total Mongolian population and is home to 68.4% of entities and organizations that are registered in Mongolia (National Statistical Office 2017). Hence it is the most populated and economically active river basin in Mongolia.

Due to the rapid urbanization, water use increased and the adverse impacts on the environment are running out of control. The Basin suffers from severe degradation including water loss, resource scarcity, and pollution. Ulaanbaatar’s water demand will exceed its existing supply and will be facing water shortages by 2021 under the high-development scenario, and it will be required to draw on additional groundwater sources (Batimaa et al. 2011). Half of Ulaanbaatar’s total water supply is for domestic users, followed by industrial use and agricultural use (Dolgorsuren, G et al. 2012). The population will increase, and the industries will expand, and water demand will continue to grow with these expansions. The supply and demand ratio for water for industrial and domestic use is concerning as current water demand is estimated to double by 2030. Ulaanbaatar is approaching levels where water shortages could become a daily problem (JICA 2010).
Therefore, there is an urgent need for an understanding of water supply and demand conditions and assess proper management practices to overcome this problem.

There have been many attempts to study water supply and demand dynamics in at municipal level (JICA 2010) or whole Tuul River basin on an annual basis until 2012 (Batimaa et al., 2011; Batsaikhan et al., 2011; Dolgorsuren G., 2012), but the temporal and spatial deficits in water supply and demand in the basin and sustainability is not well studied. This study will analyze the water demand and supply using the updated water demand estimation (Ministry of Environment and Tourism of Mongolia, 2015) and assess the sustainability of water resources in its subwatersheds of Tuul River Basin and Ulaanbaatar city. Based on the watershed sustainability criteria will be calculated for each subbasin to assess the vulnerability of the water scarcity issue in the basin. The result of the study could be utilized to support the decision-making process to improve the water resource sustainability in the Tuul River Basin.

1.4. Study objectives

This research aims to understand the current water supply and demand dynamics related to water resource sustainability at subwatershed scale. Tuul River Basin in Mongolia is selected as a study area for being most populated river basin in Mongolia and at substantial risk of water shortage.

The general objective of this study is to develop a watershed model for integrated management to sustain water resources of the Tuul River Basin.
The specific objectives are:

   i. to simulate ecohydrological processes influencing water supplies;
   ii. to assess water demand of the basin and its future trend;
   iii. to evaluate supply-demand dynamics and sustainability at a watershed and subwatershed scales;

1.4.1. Hypotheses (Alternative)

Based on the objectives of the study there are three main hypotheses (alternate) are developed in this study.

   i. The water supply in the Tuul River Basin are influenced by the ecohydrological processes and have a decreasing trend in quantity
   ii. The water demand in the Tuul River Basin has spatial and temporal variation and have an increasing tendency
   iii. Water supply and demand dynamics have variability based on the subbasins as well as administrative units

1.5. Thesis outline

   In this thesis, five chapters are developed according to each objective and organized as follows. Chapter 1 introduced about the current water scarcity problems in a global context as well as the local context of Tuul River Basin and general approaches to reducing water scarcity problems around the world. It also provides a general framework for this study.
Chapter 2 discusses the simulation of ecohydrological processes that influence watershed systems using SWAT model and its related results and discussion using the model. The water supply systems are modeled at the subbasin level and its water balance components are calculated.

Chapter 3 estimated the current water demand in the watershed as well as administrative units in the Tuul River basin using the current statistical reports and the norms on the water demand for unit industrial products, services and human and livestock consumption as well as crops. The results are provided based on the administrative units in the watershed.

Chapter 4 combines the results of Chapter 2 and Chapter 3 and overlays to see how the water demand and the water supply are balancing. The water sustainability index of each subbasin, as well as administrative units, are calculated, and the potential water management practices are suggested in this chapter.

Chapter 5 provides the overall conclusion of this research and offers some insights on potential implications of this study.
CHAPTER 2

SIMULATION OF ECOHYDROLOGICAL PROCESSES INFLUENCING WATER SUPPLIES IN THE TUUL RIVER BASIN

2.1. Introduction

Many countries in both the developed and developing world face significant problems in maintaining reliable water supplies. These problems are aggravated by the uncertainty of global climate. Growing populations will further increase the demand for water, with limited cost-effective water supply augmentation options (Dharmaratna and Harris 2012). It is essential to know quantity water is available for use in the watershed to have sustainable water resources. Water resources systems are complex and influenced many factors such as terrain, precipitation, humidity, air temperature, soil and vegetation type, land use and land cover. Understanding the current hydrologic processes for a watershed is essential to assess future climate and its potential impacts on hydrologic regimes (Hongfu et al. 2012).

Many researchers have been using different methods to assess water resources from simple water balance equations to complex hydrological models that incorporate various components of the water resource system. The development of accurate and informative integrated watershed models that help water managers better understand the issues within their basin at present and in the future is essential. Successful watershed models can lead to the development of timely projects for securing future water resources. Watershed
modeling is a standard tool to understand the behavior of a catchment under dynamic processes (Fiseha et al. 2013). The best model is the one which gives results close to reality with the use of least parameters and model complexity. A model consists of various parameters that define the characteristics of the model. It provides an opportunity to simulate the processes in the watershed and to be able to predict for impacts of the climate, land use, management changes (Devia et al. 2015).

This chapter is mainly focused on the simulation of ecohydrological processes in the watershed. The SWAT watershed model is developed to understand the hydrologic processes in the Tuul River Basin and how those hydrological processes influence the water resources. The model was developed by the USDA-Agriculture Research Service and has been widely used throughout the world for planning and management of water resources. The model components include hydrology, weather, erosion/sedimentation, crop growth, nutrients, pesticides, and agricultural management (Arnold et al. 1998).

2.2. Research questions and contribution

The Tuul River, once known for its immaculate and pristine water and is environmentally degraded in last several decades. The river water is the major water source (max. 94%) in this alluvial aquifer (Tsujimura et al., 2013), which is the major drinking water source for nearly 1.4 million residents of Ulaanbaatar, the capital city of Mongolia. Therefore, water sources and the river flow are the most important for the water supply of Ulaanbaatar city. Unfortunately, the river flow and its floodplain groundwater levels had already shown a decreasing trend over the past two decades as shown in Figure 2-1 (Sukhbaatar et al., 2017).
The other key issues in the Tuul River Basin are presented in the Figure 2-2 below. Upper Tuul River Basin is forested and has issues regarding deforestation due to the expansion of tourism and camping. The Middle Tuul River Basin after Ulaanbaatar city is highly polluted with poorly treated wastewater discharged from Waste Water Treatment Plant (WTP) and in the lower part of the Tuul River Basin, there have been issues regarding overgrazing of livestock and pollution from Zaamar gold mine. (Dolgorsuren et al. 2012).
Figure 0-2. Key issues in Tuul River Basin (Dolgorsuren et al. 2012)

There have been several studies to assess the water resources in the at headwaters (Sukhbaatar et al. 2017) and groundwater abstraction (JICA 2010, Tsujimura et al., 2013) but the subbasin analysis as well as river basin level analysis was not conducted.

Due to the issues mentioned above in the Tuul River Basin, the author of the study would like to find which are the processes influencing water resources and aims to get a better understanding of those processes in the basin and subbasin scale. By analyzing the ecohydrological processes at the subbasin level in the watershed would help water managers to assess the water resources in the basin better.

2.3. Objectives

The objective of this chapter is to simulate ecohydrological processes in the Tuul River Basin and subbasins and analyze the influences of those processes on the water resources.
i. Develop a suitable model to simulate hydrological processes

ii. Analyze the model results at temporal as well as spatial scale

iii. Evaluate the ecohydrological processes influencing the water supply in the Tuul River Basin

2.3.1. Hypotheses (Alternative)

Based on the objectives of the chapter, the following hypotheses are developed in this study.

i. Hydrological models such as SWAT can be used for simulation of processes in the watershed

ii. There is a temporal and spatial variation of water resources in the Tuul River Basin

iii. Ecohydrological processes have an impact on water resources

2.4. Methodology

2.4.1. Study area

Tuul is a river located in central and northern Mongolia. It is 704 km long, with a catchment area of 49,994.3 km². It flows from east to west, covering central parts of Mongolia and is the freshwater source for the country's capital, Ulaanbaatar (Figure 2-3). The waters of the Tuul River are made up of 25% groundwater, 6% melted snow, and 69% rainwater (Dolgorsuren et al. 2012).
The Tuul River flows at the beginning through mountain taiga and forest-steppe region, then down from Ulaanbaatar, the river flows through the steppe region which occupies 80% of the river basin area. The upper part of the river basin has steep rocks and plenty of forests with valleys between mountains of 1-3 km in width. The valley becomes wide at the downstream of Ulaanbaatar and it reaches a width of 8-10 km at Ulaanbaatar city. The geographical coordinates of the point considered as the origin of the Tuul River are 108°13’20” E, 48°30’39” N, the coordinates of the river confluence point are 104°47’52”, 48°56’55”. (Dolgorsuren, G et al. 2012).
• Climate conditions

The Tuul river basin is highly elevated, far from the sea, surrounded by mountains with an elevation range between 2792m and 773m. (Figure 2-4). Hence the climate condition is determined by differences of day and night temperature, long winter, short summer and the most precipitation falls in summer. Summer is dominated by warm, dry air, and thunderstorms land during the summer. At the end of August and the beginning of September a sudden cold is observed, and in the autumn the precipitation decreases. (Dolgorsuren et al. 2012).

![Digital Elevation Map of Tuul River Basin](image)

**Figure 0-4. Digital Elevation Map of Tuul River Basin.**

The Tuul River basin has the continental climatic features that are characterized by a broad variation of annual, monthly and daily temperatures; a low range of air humidity; non-uniform distribution of precipitation; cold and long-lasting winter and warm summer. The rainy period continues from June to August in the upper Tuul River basin, of which rainfall
shares about 90% of the annual precipitation. The Long-term annual average flow of the Tuul River at Ulaanbaatar hydrological station is about 25.6 m$^3$/s. The river freezing in the Tuul River starts during the second week of October, and the maximum ice depth in the river reaches 1.16 m in the middle of February. On average, this phenomenon is sustained for almost 150 days until the middle of April (Dolgorsuren et al., 2012). Sukhbaatar et al. (2017) used the SWAT model to simulate the hydrological processes and climate change impact in the Upper Tuul River Basin and found that there have been cyclic variabilities such as several wet and dry periods. The latest dry period was observed during 1996-2015 where the average air temperature increased, and the precipitation pattern reduced.

- Air temperature

Warming is increasing depending on the geographical location of Mongolia under the global warming pattern, and especially there is high-intensity value in the Tuul river basin. By observation data of meteorological stations in Tuul river basin, the mean annual air temperature increased by 2.0°C from the norm (Figure 2-5). Due to global warming, the number of hot days is increasing. The maximum air temperature since 1940 was observed in the last few years in the Tuul River basin. The annual average air temperature is -0.38 C in the study area. Annual minimum temperature reaches -39.0 C in January, while maximum temperature reaches +37.20 C in July during the summer period (Figure 2-6).
Figure 0-5. Time series of mean daily temperature (gray), annual mean temperature (red) and the trendline (blue) at Ulaanbaatar meteorological station in Tuul River Basin.

Figure 0-6. Monthly maximum, minimum and mean temperature °C at Ulaanbaatar meteorological station in Tuul River Basin (1987-2011)
• Precipitation

The Tuul river basin has the total annual precipitation ranges around 253-275 mm. High mountain or runoff forming area precipitation is more than 350 mm per year. About 85-90% of the total precipitation falls in the vegetation period (Dolgorsuren et al. 2012). In the Tuul River Basin, the total precipitation is changed not so much but the duration of rainfall during the summer season is decreased. The time series date of precipitation (1987-2011) is shown in the Figure 2-7.

Figure 0-7. Average monthly precipitation at Ulaanbaatar meteorological station in Tuul River Basin (1987-2011) shown by seasons (grey- winter, green -spring, yellow-summer, orange-fall).
• Evaporation

The main reason of the aridity in the Tuul River basin is global warming. Nowadays the increasing evaporation (E) is causing aridity in the basin. The deficiency of the vegetation water supply affects the vegetation cover. The difference in evaporation and precipitation (E-P) is becoming more substantial since 1990. In the period 1991-2008 compared with the period 1961-1990 mean values decreased by 30% in the runoff forming area of Tuul river basin.

• Soil

Table 0-1. Percentages of soil types in the Tuul River Basin. Source: Dolgorsuren et al. (2012)

<table>
<thead>
<tr>
<th>No</th>
<th>Soil Type</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mountain soil</td>
<td>56.3</td>
</tr>
<tr>
<td>2</td>
<td>Soil of steppe valley and depression</td>
<td>26.2</td>
</tr>
<tr>
<td>3</td>
<td>Low mountains and rolling hills soil</td>
<td>8.3</td>
</tr>
<tr>
<td>4</td>
<td>Soil of humid areas</td>
<td>6.6</td>
</tr>
<tr>
<td>5</td>
<td>Other soils and bare land/water, sand</td>
<td>1.4</td>
</tr>
<tr>
<td>6</td>
<td>Saline soil</td>
<td>1.1</td>
</tr>
<tr>
<td>7</td>
<td>Riparian soil</td>
<td>0.1</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Mountain soils occupy more than 50% of the Tuul River basin area; it is distributed evenly. The mountain soils include mountain drenotaiga, soddy taiga, forest dark, mountain meadow, and mountain dark chestnut soil classes. Along the river meadow swamp cryomorphic, meadow cryomorphic and meadow solonchak soils are distributed. The main
soil types and their percentages are shown in Table 2-1. The soil types in the Tuul River Basin are shown in the Figure 2-8.

![Soil Types in Tuul River Basin](image)

**Figure 0-8. Detailed soil types in Tuul River Basin**

- **Land use**

In the Tuul River basin agricultural land occupies 4560.9 thousand ha or 91.2%, forest 338.6 thousand ha or 6.8%, water 16.1 thousand ha or 0.3%, roads 15.2 thousand ha or 0.3%, urban and local settlement land 72.1 thousand ha or 1.4% (Figure 2-9). It was specified according to the unified land classification of the Mongolian Law on Land. In this estimation, the classification of the land for individual needs includes agricultural land, urban and local settlement area, roads, forests and water (Dolgorsuren et al. 2012).
Figure 0-9. Land use types in Tuul River Basin

2.4.2. Conceptual model

Hydrological models are commonly used to understand a watershed system and its hydrological processes better. SWAT (Soil Water Assessment Tool) is comprehensive models to provide a detailed analysis of water resources, and they are easy to modify any changes in the system (Arnold et al. 1998).

SWAT has been increasingly and successfully used throughout the world for various purposes, e.g., assessment of water resources, planning, and management, the study of impacts of climate change or land use change in both hydrology and water quality (Ficklin et al. 2013) from global to local scales. It is a hydrological model with the several
components: weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer. SWAT can be considered a watershed hydrological transport model (Devia et al. 2015).

It is a semi-distributed, eco-hydrological model developed to assess the effect of management and climate on water supplies, sediments, and agricultural, chemical yields. The model divides the simulation area into subwatersheds and hydrological response units that incorporate unique land use, soil attributes (Abouabdillah et al. 2014). It uses daily meteorological inputs to replicate the watershed mechanisms; the output could be summarized for the monthly or yearly basis for an extended period of simulation. SWAT model is also commonly used for simulation of ungauged watersheds as there are many countries where the hydrological and meteorological monitoring is limited.

Figure 2-10 shows the methodological framework for hydrological estimation components (e.g., surface runoff, percolation, lateral flow, groundwater flow, evapotranspiration, and transmission losses) in SWAT model. The methodological framework includes set of data, pre-processing, model calibration, validation, and the model performance evaluation, and simulation of the hydrological components.
The SWAT model has vast applications and is widely used in various parts of the world for assessment of water resources (Dessu et al. 2014; Jujnovsky et al. 2017), water quality (Abbaspour et al., 2015; Fan & Shibata, 2015), land use changes (Krysanova & Srinivasan, 2015; Neupane & Kumar, 2015; Sajikumar & Remya, 2015; Wang et al., 2014), climate change impacts (Faramarzi et al. 2017; Johannsen et al. 2016).

Although SWAT can require many inputs to simulate the hydrological process, it has been successfully applied in data-limited studies and taking a feasible and useful approach for strengthening water resources management (Fukunaga et al. 2015; Niu et al. 2014).

In this thesis, the following hydrological components were used to simulate hydrology of the study area.

Figure 0-10. Conceptual model
• The hydrological model is based on the following water balance equation (Equation 2-1):

\[ SW_t = SW_0 + \sum_{i=1}^{t} (R_i - Q_i - ET_i - P_i - QR_i) \]

in which \( SW_t \) and \( SW_0 \) are the soil water content at the beginning and end of the day \( i \), \( t \) is the time interval in days, \( R \), \( Q \), \( ET \), \( P \), and \( QR \) are the daily precipitation, runoff, evapotranspiration, percolation, and return flow.

• Surface runoff volume. The following SCS curve number equation (Equation 2-2) is used for predicting surface runoff (USDA-SCS, 1972).

\[ Q = \frac{(R-0.2s)^2}{(R+0.8s)} \]

In which \( Q \), \( R \), and \( s \) are the daily surface runoff (mm), daily rainfall (mm), and retention parameter. The retention parameter varies (1) with watershed because of land use, soil, management, and slope all range and (2) among time due to the variation of soil water content. The retention parameter associated with the curve number (CN) by the SCS formula (Arnold et al. 1998).

• Percolation. This component uses a storage routing technique integrated with a crack-flow model for simulating flow through each soil layer. When water percolates below the root zone, it becomes groundwater as return flow in downstream. The storage routing is based on the following Equation 2-3:

\[ SW_i = SW_{ei} \exp \left( \frac{-\Delta t}{TT_i} \right) \]
in which $SW_0$ and $SW$ are the soil water content at the beginning and end of the day, $\Delta t$ is the time interval (24 h), and $TT$ is the travel time (h) through layer $i$. by subtracting $SW$ from $SW_0$, the percolation can be calculated (Equation 2-4).

$$O_i = SW_i \left[ 1 - \exp \left( \frac{-\Delta t}{TT_i} \right) \right] \quad 0-4$$

where $O$ is the percolation rate (mm·d⁻¹).

- Lateral subsurface and groundwater flow. In the soil profile from 0.0 to 2 m, lateral subsurface flow is estimated simultaneously with percolation. A kinematic storage model is used to calculate the lateral flow in each soil layer. Whereas, groundwater flow to total stream flow is simulated by creating shallow aquifer storage. Return flow from the shallow aquifer to the stream is calculated by as follows in Equation 2-5. (Arnold et al. 1993).

$$q_{lat} = 0.024 \frac{2.S \cdot \sin(\alpha)}{\theta_d L} \quad 0-5$$

In which $q_{lat}$ is lateral flow (mm·d⁻¹), $S$ is drainage volume of soil water (m·h⁻¹), $\alpha$ is slope (mm⁻¹), $\theta_d$ is drainable porosity (mm⁻¹), and $L$ is flow length (m). When the saturated zone increases above the soil layer, water runs back to the surface.

- Evapotranspiration. In the model, three options available for estimating potential ET; Hargreaves (Hargreaves and Samani, 1985), Priestley-Taylor (Priestley and Taylor, 1972) and Penman-Monteith (Monteith, 1965). In this thesis, Penman-Monteith method used for estimating potential evapotranspiration based on the measured and simulated input data (Equation 2-6). This method requires solar radiation, air temperature, relative humidity, and wind speed as the model input.
\[
ET_0 = \frac{0.408\Delta (R_n - G) + \gamma \left( \frac{900}{T + 273} \right) u_2 (e_s - e_a)}{\Delta + \gamma (1 + 0.34u_2)}
\]

where \( ET_0 \) is the potential evapotranspiration (mm day\(^{-1}\)), \( G \) is soil heat flux (MJ m\(^{-2}\) day\(^{-1}\)), \( T \) and \( u_2 \) are mean air temperature (\(^\circ\)C) and wind speed (m s\(^{-1}\)) at 2 m, \( e_s \) and \( e_a \) are saturation vapor pressure (kPa) and actual vapor pressure (kPa), \( e_s - e_a \) is saturation vapor pressure deficit (kPa), \( \Delta \) is the slope of the vapor pressure curve (kPa \(^\circ\)C\(^{-1}\)), \( \gamma \) is psychrometric constant (kPa \(^\circ\)C\(^{-1}\)).

- Actual evapotranspiration. Exponential functions of soil depth and water content are used for predicting actual soil water evaporation and linear function of potential evapotranspiration and leaf area index is used for simulating plant water evaporation (Arnold et al. 1998).

- Snowmelt. When the soil second layer temperature simulated more than 0.0 \(^\circ\)C, snow may be melted, and the following equation 2-7 is used for simulating snowmelt.

\[
SML = T (1.52 + 0.54 SPT)
\]

where \( SML \) is the snow melt rate (mm·d\(^{-1}\)), \( SPT \) is the snowpack temperature (\(^\circ\)C), \( T \) is the mean daily temperature (\(^\circ\)C).

- Transmission losses. In many semiarid regions, river flow and streamflow hydraulically linked with alluvial floodplain groundwater. Lane’s method in USDA (1983) is used to simulate transmission losses that can reduce runoff volumes as flood wave travels downstream (Arnold et al. 1998).
2.4.3. Data collection

Data used in the assessment include climate data (rainfall, air temperature), hydrological (flow rate), spatial (topography, land use, soil). The type and sources the data used in this study are provided in Table 2-2.

Table 0-2. Data types and their sources

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature, precipitation, humidity, wind speed, streamflow</td>
<td>National Agency for Meteorology, Hydrology and Environment Monitoring(NAMHEM)</td>
</tr>
<tr>
<td>Solar radiation</td>
<td>MWSWAT Global weather station data</td>
</tr>
<tr>
<td>DEM</td>
<td>Advanced Spaceborne Thermal Emission and Reflection Radiometer, a spaceborne earth-observing optical instrument (NASA JPL, 2009).</td>
</tr>
<tr>
<td>Soil type</td>
<td>Harmonized World Soil Database from Food and Agriculture Organization</td>
</tr>
<tr>
<td>Land use</td>
<td>European Space Agency (ESA). The GlobCover initiative of ESA</td>
</tr>
<tr>
<td>River basin boundary, river network</td>
<td>Tuul River Basin Authority</td>
</tr>
</tbody>
</table>

2.4.4. Model construction

The ecohydrological model for whole Tuul River Basin and its subwatersheds was developed in this study based on the available data. SWAT (Soil Water Assessment Tool) is used to simulate the hydrological processes in the watershed.

As it has been widely used in scarce data watersheds to simulate the various processes in watersheds, the SWAT model is chosen to simulate and understand the ecohydrological processes in the Tuul River Basin in this study. The SWAT model was previously used for
two watersheds in Mongolia. The effect of subarctic conditions on water resources of Kharaa river basin which is located in the northern part of Mongolia was simulated using SWAT model and found that SWAT satisfactorily reflects stream flow for single years but is not reliable for a more extended period (Hülsmann et al. 2015). Sukhbaatar et al. (2017) developed the SWAT model for Upper Tuul River basin. They analyzed the impact of climate change on hydrological processes in the watershed and found that the model sufficiently predicts the hydrological processes in the watershed and further concluded that the river flow was primarily influenced by precipitation, although air temperature has been significantly increased throughout the latest dry period.

The Tuul River basin was analyzed based on their unique combination of land use, soil type and topographical data that creates HRUs (hydrological response units). Water resources for the Tuul River Basin were simulated from 1996 to 2011 using observed precipitation, temperature, wind speed and air humidity inputs. The streamflow data from 2 stations (Ulaanbaatar and Terelj) in the basin are used to calibrate and validate the simulated results of SWAT model.

SWAT model was developed using the topography, land use, soil and meteorological data. Figure 2-11 illustrates the spatial inputs a) topography, b) land use/cover, and c) soil) and delineated outputs d) land surface slope and e) subbasins. The topography, based on the global digital elevation model (GDEM), has a resolution of 30*30 m. This is generated from the Advanced Spaceborne Thermal Emission and Reflection Radiometer, a spaceborne earth-observing optical instrument (NASA JPL, 2009). Land use/cover data was obtained from the European Space Agency (ESA). The GlobCover initiative of ESA
developed and demonstrated a service for the generation of global land cover maps, based on Envisat MERIS Fine Resolution (300 m) mode data (Arino et al., 2012). The soil map was obtained from MWSWAT which contains Harmonized World Soil Database from FAO (Food and Agriculture Organization). The Basin is divided into 27 subwatersheds based on the unique HRUs (hydrological response units) (Figure 2-11e).
Figure 0-11. SWAT model simulation. a) DEM, b) Land use, c) Soil type, d) Slope and e) Subbasins
2.4.5. Model calibration and validation

The SWAT model performance of calibration and validated by using multiple statistics i.e., the coefficient of determination (R^2), RMSE observations standard deviation ratio (RSR) (Moriasi et al. 2007), and Nash-Sutcliffe model efficiency (NSE) (Nash and Sutcliffe, 1970).

- The R^2 value describes the degree of collinearity between simulated and measured data.

R^2 ranges from 0 to 1, with higher values indicating less error variance. (Equation 2-8)

\[
R^2 = \frac{\sum_i(Q_{m,i} - \bar{Q}_m)(Q_{s,i} - \bar{Q}_s)^2}{\sum_i(Q_{m,i} - \bar{Q}_m)^2 \sum_i(Q_{s,i} - \bar{Q}_s)^2}
\]

Coefficient of determination R^2 where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, i is the i\(^{th}\) measured or simulated data.

- NSE: It determines the relative magnitude of the residual variance (“noise”) compared to the measured data variance (“information”). NSE ranges between -\(\infty\) and 1.0, NSE=1 is the optimal value. (Equation 2-9)

\[
NSE = 1 - \frac{\sum_i(Q_{m,i} - \bar{Q}_m)^2}{\sum_i(Q_{m,i} - Q_{s,i})^2}
\]

Nash-Sutcliffe (1970), where Q is a variable (e.g., discharge), and m and s stand for measured and simulated, respectively, and the bar stands for average.
• RSR: RMSE observation standard deviation ratio (RSR) also used, and it is one of the commonly used error indexes. RSR standardizes RMSE using the observations standard deviation of measured data. RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor so that the resulting statistic and reported values can apply to various constituents. The lower RSR (Equation 2-10) is the better the model simulation performance (Moriasi et al. 2007).

\[
RSR = \sqrt{\frac{\sum_{i=1}^{n}(Q_{m,i} - Q_{s,i})^2}{\sum_{i=1}^{n}(Q_{m,i} - \bar{Q}_m)^2}}
\]

Where \(Q\) is a variable (e.g., discharge), and \(m\) and \(s\) stand for measured and simulated values. It varies from 0 to large positive values. The lower the RSR the better the model fit (Moriasi et al., 2007).

<table>
<thead>
<tr>
<th>Performance</th>
<th>(R^2)</th>
<th>NSE</th>
<th>RSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Good</td>
<td>&gt;0.60</td>
<td>0.75 &lt; NSE (\leq) 1.00</td>
<td>0.00 (\leq) RSR (\leq) 0.50</td>
</tr>
<tr>
<td>Good</td>
<td>&gt;0.60</td>
<td>0.65 &lt; NSE (\leq) 0.75</td>
<td>0.50 (\leq) RSR (\leq) 0.60</td>
</tr>
<tr>
<td>Satisfactory</td>
<td>0.50 &lt; NSE (\leq) 0.65</td>
<td>0.60 (\leq) RSR (\leq) 0.70</td>
<td></td>
</tr>
<tr>
<td>Unsatisfactory</td>
<td>&lt;0.60</td>
<td>NSE (\leq) 0.50</td>
<td>RSR &gt; 0.70</td>
</tr>
</tbody>
</table>

Santhi et al. (2001) suggest that the results of the SWAT calibration are acceptable of \(R^2\) and NSE. In addition to that, Moriasi et al. (2007) also summarized overall performance rating for recommended statistics for a monthly time step as shown in Table 2-3.

The SWAT model calibration was conducted using SWAT-CUP (SWAT Calibration Uncertainty Procedures), a program designed explicitly for calibration and validation,
sensitivity and uncertainty analysis of SWAT model (Arnold et al. 2012; Abbaspour, 2015). Several methods linked with SWAT-CUP and Sequential Uncertainty Fitting version 2 (SUFI2) algorithm (Abbaspour et al., 2007) was used for the model sensitive analysis and calibration in this research. The sensitive analysis was conducted to define the influence a set of parameters on river flow in the study area. The obtained model is calibrated and validated using streamflow data from 2 hydrological gauges (Terelj and Ulaanbaatar station) in the headwaters. As there are hydrologic as well as land use changes in the last several years in the basin, the model calibration and validation were conducted using the same period with two hydrological station data. The model was calibrated with 1990-2011 data using the discharge data from the Ulaanbaatar station using statistical methods as provided earlier in Table 2-3. The model validation was conducted using the Terelj station data ranging from 1990-2011 as internal validation. The typical parameters for SWAT model calibration are provided in Table 2-4.
Table 0-4. Parameters for calibration

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 r__CN2.mgt</td>
<td>SCS curve number for moisture condition II</td>
</tr>
<tr>
<td>2 v__ALPHA_BF.gw</td>
<td>Baseflow alpha factor: a direct index of groundwater flow response to changes in recharge</td>
</tr>
<tr>
<td>3 v__GW_DELAY.gw</td>
<td>Groundwater delay time (days): the lag between the time that water exits the soil profile and enters the shallow aquifer.</td>
</tr>
<tr>
<td>4 v__GWQMN.gw</td>
<td>Threshold depth of water in the shallow aquifer required for return flow to occur. Groundwater flow to the reach is allowed only if the depth of water in the shallow aquifer is equal to or greater than GWQMN</td>
</tr>
<tr>
<td>5 v__GW_REVAP.gw</td>
<td>Groundwater revap coefficient: controls the movement of water from the shallow aquifer to the root zone in response to an overlying unsaturated zone</td>
</tr>
<tr>
<td>6 v__ESCO.hru</td>
<td>Soil evaporation compensation factor: determines the depth distribution used to meet the evaporative soil demand</td>
</tr>
<tr>
<td>7 v__CH_N2.rte</td>
<td>Manning’s “n” value for the main channel</td>
</tr>
<tr>
<td>8 v__CH_K2.rte</td>
<td>Effective hydraulic conductivity in the main channel alluvium</td>
</tr>
<tr>
<td>9 r__SOL_AWC(1).sol</td>
<td>Available water capacity of the soil layer: plant available water calculated by subtracting the fraction of water present at the permanent wilting point from that present at field capacity</td>
</tr>
<tr>
<td>10 r__SOL_K(1).sol</td>
<td>Saturated hydraulic conductivity: a measure of the ease of water movement through the soil; reciprocal of the resistance of the soil matrix to water flow</td>
</tr>
<tr>
<td>11 r__SOL_BD(1).sol</td>
<td>Soil bulk density</td>
</tr>
<tr>
<td>12 v__SFTMP.bsn</td>
<td>Snowfall temperature</td>
</tr>
</tbody>
</table>

2.5. Results and discussion

The SWAT model simulated the hydrological processes in each subwatershed for 25 years (1987-2011) period based on the availability of the meteorological station data on a monthly basis, taking initial three years as a warm-up period. After running the model
annual and monthly average basin values are obtained as well as monthly water balance components at every 27 subwatersheds.

The calibration model using the values of the simulated and observed discharge data at Terelj and Ulaanbaatar stream gages are shown in Table 2-5. The model performance of calibration and validation were evaluated using multiple statistics, i.e., the coefficient of determination ($R^2$), RMSE observations standard deviation ratio (RSR), and Nash-Sutcliffe model efficiency (NSE). The statistical values generated during calibration were good ($R^2$, NSE, and RSR) and satisfactory (PBIAS).

<table>
<thead>
<tr>
<th>Table 2-5. Calibration and validation of SWAT model results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Ulaanbaatar (calibration)</td>
</tr>
<tr>
<td>Terelj (validation)</td>
</tr>
</tbody>
</table>

The parameter global sensitivity analysis is conducted in the SUFI2, and the most sensitive parameters are SOL_AWC(1) .sol, GW_DELAY.gw, SOL_K(1).sol, ESCO.hru, CH_N2.rte, and CH_K2.rte. (Figure 2-12).

![Figure 0-12. Global sensitivity of calibrated parameters](image)
The streamflow was calibrated on a monthly basis, and comparisons for the observed and the simulated streamflow at Terelj and Ulaanbaatar watershed are shown in the Figure 2-13. The according to the model results, average annual water balance components in the Tuul River Basin are given below. Average annual basin values:

Precipitation = 277.5 mm, Snow fall = 46.26 mm, Snow melt = 45.79 mm, Sublimation = 0.12 mm, Surface runoff Q = 0.44 mm, Lateral soil Q = 58.14 mm, Groundwater (shallow aquifer) Q = 4.50 mm, Groundwater (deep aquifer) Q = 0.24 mm, revap (shallow aquifer => soil/plants) = 0.66 mm, Deep aquifer recharge = 0.24 mm, Total aquifer recharge = 4.73 mm, Total water yield = 63.31 mm, Percolation out of soil = 4.73 mm, ET = 214.3 mm, PET = 696.0mm, Transmission losses = 0.00 mm, Septic inflow = 0.00 mm and Total sediment loading = 0.16 t/ha. The model simulated precipitation = 277.5 mm and snowfall = 46.26 mm which falls within the range reported by Dolgorsuren et al. (2012) and Sukhbaatar et al. (2017). Moreover, the Tuul River Basin Average has 45.15 annual basin water stress days and 133.79 temperature stress days.
The average monthly basin values are calculated and shown in the Figure 2-14. The maximum amount of rain is simulated in July 76.16 mm which further contributed to the maximum amount of surface runoff 0.12 mm, lateral flow 14.44 mm and water yield 14.77 mm in July and the lowest value of precipitation was observed in January.
The average annual water yield (water yield = surface runoff + groundwater flow + lateral soil flow) was 63.31 mm.

The Hamon PET is calculated based on the day length and air temperature. There are some variations observed in the actual and potential ET measurements as Hamon PET is calculated based on day length and air temperature only, whereas actual ET is also influenced by other factors such as solar radiation, relative humidity, and wind. ET gradually decreased starting from September to January, about deciduous trees shedding of their leaves, reduced demand for ET in September-October and air temperature drop.

When the dormant season started, ET further decreased and reached its minimum in January which can be explained by snow cover accumulated on evergreen trees and ground. As days get warmer in spring and day length increases, ET also increases starting from February.

Then when growing season starts in May, demand for ET increases rapidly. The highest potential ET was observed in July. Starting from July, ET again decreased as air temperature subsided and days get shorter.
Figure 0-14. Annual water balance components in Tuul River Basin

The time series of average monthly discharge, as well as monthly mean air temperature and average monthly precipitation in the Tuul River Basin, are shown in the Figure 2-14. According to the simulation results of the average monthly discharge values in the Tuul River Basin, 1993-1995 was a wet year and starting from 1996 onwards the simulated discharge values are lower than the previous years due to the warmer temperature and lower precipitation.
Figure 0-15. Monthly average discharge, precipitation and mean air temperature values at Tuul River Basin (1990-2011).

The time series of monthly average discharge values at each subbasin in the Tuul River Basin is provided in the Figure 2-15. There is a decreasing trend of monthly discharge over the years since 1996. The annual average monthly discharge values at each subbasin outlets are shown in the Figure 2-16.
Figure 0-16. Time series of monthly average discharge values at each subbasin in the Tuul River Basin

The annual average discharge at each subbasin is spatially represented in the Figure 2-17. The discharge values increase along the river and reach its highest value in subbasin one which is the whole basin outlet.

Figure 0-17. Annual average discharge m3/sec at each subbasin outlets in the Tuul River Basin
Figure 0-18. Annual average discharge m3/sec at each subbasin outlets in the Tuul River Basin

2.6. Conclusions
In this study, the performance of the widely-used SWAT model was evaluated on the Tuul River Basin using split-location calibration and validation techniques on monthly intervals. The model was calibrated at the Terelj and Ulaanbaatar watershed outlets. Calibration and validation were performed with SUFI2 within SWAT-CUP. Both graphical and statistical techniques were used for hydrologic calibration results evaluation. The $R^2$, PBIAS, RSR, and NSE results for the model showed that the SWAT model was able to replicate annual, monthly streamflow values.
A spatial and temporal variation in the discharge in the TRB was observed by the model simulation. The annual average discharge values range from 0.3 m$^3$/s to 96.87 m$^3$/s in the basin.

The river flow was primarily influenced by precipitation and air temperature which has been significantly increased. However, the contribution of precipitation into the actual ET increases and decreases in river flow because of a relatively higher water atmospheric demand (evaporative demand). Therefore, a change in the contribution of precipitation in actual ET and river flow due to a decrease in precipitation has the additional effect of reducing river flow in the study area.
CHAPTER 3

SPATIAL AND TEMPORAL WATER DEMAND IN THE TUUL RIVER BASIN

3.1. Introduction

In many countries of the world, water demand has increased over the last several decades because of demographic and economic growth, changes in lifestyle, and expanded water supply systems (Ali et al. 2014; Bijl et al. 2016; Johannsen et al. 2016; Yates et al. 2005). Globally agricultural water withdrawal amounts to nearly 70% of total water withdrawal, industrial and domestic water withdrawals are about 18% and 13% of total water withdrawal, respectively (Gleick 2014).

Water demand is defined as the volume of water required by users to satisfy their needs. It is calculated as water withdrawal minus the return flow from the surface fresh water. The total blue water demand for given period of the year is the sum of sectorial demands (livestock, irrigational, industrial and domestic), the potential consumptive use from available resources. Gross water demand is subsequently reduced to net blue water demand by considering green water availability for irrigation and recycling ratios for the industrial and the domestic sector (Bjil et al. 2016).

The most common water use indicators are water withdrawal and water consumption. Withdrawal is determined as the amount of water removed from the ground or diverted from a water source for use, while water consumption refers to the amount of water that is transpired, evaporated, incorporated into products or crops, or otherwise removed from the water environment (Kenny et al., 2009).
There are several ways to assess water demand. Wada et al. (2011) have calculated the water demand for the year with monthly variation and compared it with water supply estimation. With monthly water demand estimation, water-stressed condition increased by 40% compared to the calculation on an annual basis that indicates the importance of in year variability of water demand.

De Graaf et al. (2014) explored the dynamic attributes of water demand to simulate global water availability which accounts for feedbacks such as return flows of unconsumed water and recharge. In their study, total water demand for irrigation, industry, and domestic use and defines the total abstraction if sufficient water is available. It is mentioned that the abstraction and feedback to river system strongly influence water allocation, especially in irrigated areas (de Graaf, I E M et al. 2014).

Bjil et al. (2016) analyzed non-agricultural water demand using end-use oriented model for electricity, industry and municipal sectors. Since water demand in these sectors is used for different purposes, it is more appropriate to deal with them separately. They included new features such as thermal and water use efficiency and developed two scenarios for 26 regions and concluded that the water demand would increase in developing countries drastically (Bjil et al. 2016).

Dessu et al. (2014) used a defined index method to evaluate water resources concerning demand for limited data watershed of Mara River Basin and analyzed temporal and spatial distribution. They have used SWAT hydrologic system model (Arnold et al., 1998) to estimate water demand and assess water resources to evaluate current water supply and demand status. They estimated the consumptive water demand for six different sectors
(residential, livestock, wildlife, tourism, irrigation and industry) and further reclassified as basic, normal and flood demand using daily consumption estimation. The authors defined the primary demand as the minimum amount of water consumed by humans and wildlife. The normal demand is composed of enhanced human demand, livestock demand, and tourism. The enhanced human demand is the residential water demand more than the basic human need. Flood demand contains irrigation water use and industrial water demand. The assessment of sub-basins' total available monthly volume with the total monthly consumptive demand suggests the natural wildlife reserve and the commercial irrigation areas are highly stressed for six or more months of the year (Dessu et al. 2014).

Boithias et al. (2014) have used supply and demand ratio and estimated under global change (human and climate impact) considering environmental demand under nine global change scenarios and at five spatial scales in Mediterranean basin, Ebro basin in Northern Spain. They have calculated water balance across the basin and highlighted the spatial and temporal mismatches of water supply and demand. Their study shows that water scarcity is usually a local issue (sub-basin to region), but that all demands are met at the most significant considered spatial scale (basin).

The environmental water demand is a key factor determining the proper functioning of riverine ecosystems and associated wetlands. The environmental water demand is the rate of water inflow required for appropriate physical, chemical and biological functioning of an aquatic ecosystem (Sarzaeim et al. 2017).

Sarzaeim et al. conducted the assessment of environmental demand and used representative concentration pathways (RCPs) and (2) downscaling methods and created six different
climatic scenarios for Karkheh river in Iran. Their result indicates that there will be an increase of 0.9-7.7% in average flow under all scenarios. Temporal variation of monthly environmental demand would change under climate change conditions.

As water demand management has multiple components and involves various stakeholders, it requires an integrated tool to represent its complexity fully.

3.2. Research questions and contribution

There have been several studies on water demand assessment in the Tuul River Basin (Dolgorsuren et al. 2012 and JICA). As industrial and drinking water in Ulaanbaatar depend entirely on alluvial floodplain groundwater of the Tuul River. The current exploitable groundwater resources and new measured/indicated/inferred resources will be probably sufficient to supply water demand in Ulaanbaatar until 2021 (Dolgorsuren et al. 2012; KOICA, 2012; Ranen et al. 2014). Therefore, numbers of researchers and feasibility studies have been conducted to define a new water resource that can be sustainable and sufficient for future water demand in Ulaanbaatar. Research on groundwater resources has been conducting within the Tuul River Basin and surrounding river basins, such as Kherlen and Kharaa rivers. The future water demand for Ulaanbaatar has been projected based on the three economic development scenarios—low, medium and high economic development by Dolgorsuren et al. (2012). They concluded that in the Tuul River Basin, future water demand in 2021 is projected to increase by 20 percent, 49 percent and 101 percent in the low, medium and high economic development scenarios respectively. The main drivers for this increase are predominantly the rising industrial water demand, followed closely by the increased necessity of providing drinking water for the population. The study used the
norms and requirements that have been issued in 2009 and using the statistics from 2008-2010. There has not been any study on the water demand assessment in the TRB using the updated water demand requirements with current statistical reports.

This chapter could serve as an update to the previous water demand estimation. The water demand in the TRB will be calculated based on the administrative units and sectors.

### 3.3. Objectives

The objective of this chapter is to assess water demand in the Tuul River Basin to analyze the spatial and temporal variability of it.

i. Assess the water demand of each water utilizing sector in the basin

ii. Assess the sectorial water demand by administrative units

iii. Evaluate the total annual water demand in the Tuul River Basin

#### 3.3.1. Hypotheses (Alternative)

Based on the objectives of the chapter, the following hypotheses are developed in this study.

i. There is spatial and temporal variation in the sectorial water demand

ii. There is a temporal and spatial variation of water demand in the Tuul River Basin

iii. Water demand in the Tuul River Basin has an increasing tendency in quantity
3.4. Methodology

3.4.1. Study area

Tuul is a river located in central and northern Mongolia. The Tuul River Basin covers the territories of 7 districts of Ulaanbaatar city, 37 soums of 5 aimags and occupies a total area of 49774.3 km2. The Tuul River basin covers 65.5% of the Ulaanbaatar city area, 39.8% of Tuv aimag, 20.8% of Bulgan aimag, 6.0% of Uvurkhangai aimag, 4.4% of Arkhangai aimag, 2.2% of Selenge aimag (Figure 3-1).

Figure 0-1. Administrative units in the Tuul River Basin.
Tuv aimag occupies the largest part of the basin area: 59.3% and Selenge aimag occupy the smallest part of the basin area: 1.6%. The administrative units and the percentage of the area of aimags, soums, and cities, which are in the TRB, are presented in Table 3-1.

Table 0-1. Administrative units in the Tuul River Basin and their respective area percentages. Source: Dolgorsuren et al. (2012)

<table>
<thead>
<tr>
<th>Aimag name</th>
<th>Soums or districts name</th>
<th>Percentage of aimag area in the TRB, %</th>
<th>Percentage of soums or districts area in the TRB, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arkhangai</td>
<td>Khashaat</td>
<td>5</td>
<td>83.6</td>
</tr>
<tr>
<td>2</td>
<td>Ugiinuur</td>
<td></td>
<td>17.6</td>
</tr>
<tr>
<td>3</td>
<td>Ulziit</td>
<td></td>
<td>0.02</td>
</tr>
<tr>
<td>Bulgan</td>
<td>Bayannuur</td>
<td>20.5</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>Buregkhangel</td>
<td></td>
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<td>7</td>
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</tr>
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<td></td>
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</tr>
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</tr>
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<td>Chingeltei</td>
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<tr>
<td>44</td>
<td>Sukhbaatar</td>
<td>100</td>
<td></td>
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</tbody>
</table>

Ulaanbaatar City: 7 out of 9 districts of the capital are located in Tuul River Basin. The territory of Bayangol and Khan-Uul districts totally, 98.6-99.9% of the territory of Bayanzurkh, Nalaikh, Sukhbaatar and Chingiltei districts, and 31% of the territory of Songinokhairkhan district belongs to the basin. When estimating socio-economic indicators, the above first six districts are included totally, and Songinokhairkhan district is included except Jargalant village.

Tuv aimag: Zuunmod city as aimag center of Tuv aimag and 11 other soum centers like Altanbulag, Sergelen, Bayan-Unjuul are located in the basin. The territory of Bayankhangai, Undurshireet, and Lun soums totally; 86.7-99.9% of the territory of Altanbulag, Argalant, Bayantsogt, Ugtaal and Zaamar soums; 20.2-74% of the territory of Bayan-Unjuul, Buren, Tseel, Sergelen, Erdene and Erdenesant soums; 0.1-13.1% of territory of 6 other soums belong to the basin. For the economic analysis, demography and economic data were used of Zuunmod city and 16 soums, that have more than 5% of pasture located in the Tuul RB.
Uvurkhangai aimag. 11.2-92.7% of the territory of Kharkhorin, Bayan-Undur, Yusunzuil and Burd soums is located in the basin. The socio-economic estimation was conducted based on these soums. Selenge aimag. The center of Orkhontuul soum and 28% of the soum area are located in the basin. This soum is located near the confluence of the Tuul and Orkhon rivers. This soum is important regarding water management.

The socio-economic analysis of the Tuul River Basin was conducted based on seven districts of Ulaanbaatar City, Zununmod soum, and 28 other soums, which have more than 5% of pasture land inside the basin as suggested by Dolgorsuren et al. (2012).

- Population: The population growth in Ulaanbaatar city and Tuv aimag is provided in the Figure 3-2. The population of Ulaanbaatar city was increasing at a constant rate from 1967 – 1990 and rapidly increased in last 20 years. As the other aimags have less area under the Tuul River Basin and have remote areas, the population in those aimags are very less compared to Ulaanbaatar and Tuv aimag. There are three main types of settlements in the basin; apartments which is connected to central heating and plumbing services and continuous access to water and sewerage, houses which is not connected to the central infrastructure, but has access to public water mains and ger which do not have direct access to water services, so the residents need to travel distances to fetch their water.
Figure 0-2. Population growth of Ulaanbaatar city in Tuul River Basin (1935-2017). Source: NSOM

- Economics: The Tuul River Basin is the most populated and economically active river basin in Mongolia. Water demand in the basin varies by location and time, productivity, and affordability. The main economic and industrial activities are gathered around the Ulaanbaatar city. Tuv and Bulgan aimags have a higher percentage of agricultural operations. Moreover, the economic activities in the Ulaanbaatar city are steadily increasing. The Gross Domestic Product (GDP) in the Ulaanbaatar city and Tuv province are shown in the Figure 3-3. It was growing steadily since 2000 and beginning from 2009 the GDP increased drastically in last several years.
Agriculture: As the main agricultural activity in the Tuul River basin is pastoral farming, the number of livestock in the Tuul River Basin is also in a tendency to increase. The main type of livestock includes camel, horse, cow, sheep, and goat (Figure 3-4). Due to the easier access to the infrastructure and markets, the number of livestock in the basin is increasing, and in 2013 the livestock density was 7.36 livestock/km$^2$ but it drastically increased to 9.09 livestock/km$^2$ in just after 3 years which creates overgrazing problems in the basin and puts pressure on existing water resources (Dolgorsuren et al., 2012). Also, there are several pig and chicken farms in the basin which supply most of the egg and pork products to the Ulaanbaatar city.
Figure 0-4. Number of livestock in the Tuul River Basin. Source: Tuul River Basin Authority

- Farming is one of the essential agricultural production sectors in the basin. The basin is located close to the market. This region has a suitable condition regarding economy and weather. The farming activities are concentrated in the Tuv aimag and Selenge aimag. In 2015, grains, cereals, and fodder crops were planted in 96236.4 hectares, and potato and vegetables were planted in 1672.7 hectares in the Tuul River Basin. (NSOM, 2017)

- Services and public utilities. The number services, as well as type and diversity of service providers, are increasing in the Tuul River Basin (NSOM, 2017). Most of the services and public utilities are concentrated in the Ulaanbaatar city and some limited amount in the Tuv aimag. There are almost 95785 children are in the kindergartens, 397419 students are studying in 112 school or 180 universities, 242 researchers are working in the research institutions and laboratories, 430200 patients receive treatment in the hospitals, 1683 public bathhouses, 1495 cafeterias
and 1849 restaurants and bars are serving daily for the residents of the basin.
(NSOM, 2017)

3.4.2. Methods

The different type of water users (household, industrial, commercial and ecosystems) have different demand based on their needs. This study analyzed the demands of different type of users and their water-related behaviors. Based on the “Norms on water required to achieve the production of the unit product, work and services” issued by MNET (2015) and population growth, land use, the water demand was estimated for various scenarios.

To facilitate estimation of consumptive water demand, the six consumptive water demand sectors (human population, livestock population, large-scale irrigation, lodges and tent camps, mining) proposed by Hoffman et al. (2011) were modified to residential, industrial and agricultural, public services, livestock and environmental and instream flow requirement based on the water requirement of unit product.

The water demand for each sector is analyzed by its subsectors and using the demographic and statistical data. The annual water demand is calculated based on the “Norms on water demand for the unit product, service, and work” which is issued by the Minister of Nature, Environment, and Tourism in 2015. Due to the data availability of the each soums and aimags in the basin, the statistical data of 2015 was used in this study to estimate the annual total water demand of the Tuul River Basin. The annual total water demands for each aimags and Ulaanbaatar city are calculated then further aggregated to estimate the annual
total water demand of the Tuul River Basin. The conceptual model is provided in the Figure 3-5.

![Conceptual model of water demand estimation in the Tuul River Basin](image)

**Figure 0-5. A conceptual model of the water demand estimation in the Tuul River Basin**

### 3.4.3. Data collection

For the estimation of the water demand per sector and administrative units, the statistical data was collected from National Statistical Office of Mongolia, Statistics Department Implementing Agency of the Governor’s Office, Statistics Department of Arkhangai, Tuv, Selenge, Bulgan and Uvurkhangai aimags. The norm on water demand for the unit product, work, services was obtained from MNET. The statistics for each administrative unit; soums and districts were calculated and adjusted based on the area percentage of the soums and district in the Tuul River Basin, and whether the soum center is in the Tuul River Basin.
3.5. Results and discussion

Annual water demand in the Tuul River Basin is calculated using the water demand for each administrative units and sectors. The water demand has spatial and time variability based on the sector. The sectorial demands are discussed in detail further below.

- Residential water demand. The total residential water demand in the Tuul River Basin is 53207 thousand m$^3$/year. The 77.2% of total residential water demand corresponds to the apartment residents in Ulaanbaatar city which is 39% of the total population in the basin as their average daily water demand is 200 liters per person. The 21.1% of the total residential water demand is for the ger area residents which is 58.9% of the total population in the basin as they use much less water daily, 25 liters per person due to the limited access to water supply. (Figure 3-6)

![Figure 0-6. Annual residential water demand by aimags (2015)](image_url)
• Industrial water demand

Population growth and an intensive increase of buildings in Ulaanbaatar city are followed by a boost of energy and heat use. As the city rapidly expanded and many industrial, social and apartment buildings were built, energy and heat demand are increasing. In the basin coal fed thermo-power plant are supplying electricity as well as heat. Water supply for the technological demand of the existing thermo-power plants is from some 44 wells established in the alluvial aquifer of the Tuul River floodplain. The highest amount of water demand corresponds to the energy and heat production sector in the Basin which is 22696.5 thousand m³/year. The food production industry is the second largest water user in the industry which is 7937.77 thousand m³/year. Food production industries mainly consist of meat and dairy processing and beverage production. As livestock husbandry is one of the main activity in the basin, 550.46 thousand m³/year water is required for the wool, cashmere, and fur processing sector. (Figure 3-7)
Figure 0-7. Annual industrial water demand by sector in 2015

- Agricultural water demand
  - Livestock husbandry – According to the Norm by MNET (2015), there is seasonal variability in livestock water demand. In the warm summer season, livestock requires more water compared to the frigid winter season. The seasonal water demand for the different type of livestock is provided in the Figure 3-8. Horse, camel, cow have higher unit water demand compared to goat and sheep. For example, an adult horse requires 42 liters of water a day, but water demand for an adult goat or sheep is 3.7 liters per day in summer. Hence, even though the number of horse and cow (340406 and 309374 respectively) are much less than the number of goat and sheep (409468 and 2245232 respectively) water demand for horse and cow are higher due to the almost ten times higher unit water demand.
Therefore, the total water demand for a horse is highest 982455.6 m³ in the summer. As pigs and chicken are in the concentrated farms, they have no seasonal variation in the water demand.

Figure 0-8. Livestock seasonal water demand per livestock type (2015)

According to the administrative units, Tuv aimag has the most number of livestock, hence the higher water demand for livestock. The horse has highest water demand in the Tuv aimag, and the water demand for the cow was the highest in the Ulaanbaatar city. As in Orkhontuul soum of Selenge province, there is a swine farm, the water demand for pig comes higher than the other livestock types. Arkhangai, Bulgan, and Uvurkhangai provinces have similar variation in water demand for the other kind of livestock, water demand for a horse is the highest followed by the sheep and cow. (Figure 3-9)
• Farming – Another water demand intensive activity is farming. In last several years, the Mongolian government has been supporting farmers and promoting farming products. In many areas small-scale farming, greenhouse vegetable planting has taken place in the basin. The most sown plants are grains, cereals, fodder crops, and vegetables. As grains, cereals and fodder crops are not irrigated and depend on the precipitation and weather condition of the growing period only irrigation for the potato and vegetables are calculated in the water demand for irrigation. The highest water demand for irrigation is in Ulaanbaatar city 2205.975 thousand m3/year, followed by the Tuv province 1988.498 thousand m3/year, the
minimum was in Arkhangai aimag 51.173 thousand m3/year. The total irrigation water demand 4638.954 thousand m3/year in the Tuul River Basin. (Figure 3-10)

![Figure 0-10. Annual water demand for irrigation by aimags in the Tuul River Basin (2015)](image)

- Public services

As main public services are centered in Ulaanbaatar city and some in Tuv province, the water demand for public services is negligible in other aimags. Education facilities such as kindergarten and schools have the highest demand for water in the basin followed by restaurant and cafeteria services. The other types of public services such as tourist camps, museums, shops, department stores were not included in the calculation as there is no available data, information on the water demand. The total water demand for public services was calculated based on the available data and was 3136 thousand m3/year. Figure (3-11)
Annual total water demand in the Tuul River Basin was calculated by aggregating the sectorial water demand and presented in the Figure 3-12. The residential water demand was the highest contributing water demand in the water basin which constitutes 46% of the total water demand in the Tuul River Basin. The water demand for the energy and heat production sector was the second highest, 37% of the annual total water demand. Water demand for livestock is 9% of the total water demand and the third highest on the list. The other types of water demand constitute the remaining 8% of the total water demand.
The water demand calculated was further estimated based on the administrative units. Annual total water demand in the Tuul River Basin by administration units and sector is provided in the Figure 3-13. As shown in the Figure 3-13, Ulaanbaatar city has the highest water demand especially for residential and energy, when compared to other aimags and 77.6% of total water demand in the basin. Tuv aimag has the second highest water demand in the basin and 17.6% of the total water demand. The annual water demand by administrative units is presented in the Figure 3-14 with respective amount represented by the blue bubble. As shown in the graph Ulaanbaatar city has the highest amount of water demand despite the comparatively smaller area in the basin.
Figure 0-13. Annual total water demand by sector and administrative units in the Tuul River Basin
Figure 0-14. Total water demand by aimags (blue bubbles)

3.6. Conclusion

In this chapter, the water demand in the TRB is assessed using demographic and statistical data, and government-issued water demand norms. There is a spatial and temporal variation in the sectorial water demand.

The study found that there is a temporal and spatial variation of water demand in the Tuul River Basin. The residential water demand in the TRB was found to be the highest and followed by the water demand for energy and heat production. As those demands are concentrated in the Ulaanbaatar city, the water demand for the city is the highest, 77.6% of the total water demand in TRB. Due to the population and economic growth in the
Ulaanbaatar city and its neighboring areas, the water demand in the TRB is expected to increase further.
CHAPTER 4

EVALUATION OF WATER SUSTAINABILITY AT A WATERSHED AND SUBWATERSHED SCALES

4.1. Introduction

Over the years, population growth and urbanization, industrialization and the expansion of irrigated agriculture are rapidly increasing water demands and put pressure on the water resources (Rees, 1998). Many countries are in a quest for additional water resources to meet their needs.

It is essential to adopt practices to manage the water resources availability sustainably without altering the socio-economic development. Sustainable water management is a critical component of sustainable development and accounts for similar issues as sustainability. We consider 'sustainable water management systems' to be those that meet the needs of society over the lifetime of the service while also maintaining critical ecological functions that support the long-term provision of ecosystem goods, services, and values, including biodiversity maintenance (Poff et al., 2015).

Russo et al. (2014) reviewed sustainable water management in urban, agricultural and natural systems in developed and developing countries. They suggested that the water management of the natural system is the basis of sustainable urban and agrarian management approaches. In developing countries, the primary goal of sustainable water management in urban areas include equitable delivery, reliability and system flexibility, and growth. The ecosystem in this country requires protection of valued ecosystem
services. The challenges for sustainable urban water management in developing countries include intermittent operation, lost or stolen water, rapid urban growth and political conflict. For the ecosystem, economic development priorities constitute a significant challenge. They have also discussed the potential solution for above problems. Institutional improvements, low-tech water capture, and treatment, greywater reuse, cooperation, sharing riparian rights and stakeholder engagement are viable solutions for urban water sustainability, and communication of ecosystem service value is essential for water sustainability (Russo et al. 2014).

We can select the suitable method based on the Local variations, data availability, and socio-political objectives. It is particularly useful for determining estimates of thresholds for sustainable use and allocation.

A sustainability assessment provides scientific support in the decision making for selecting amongst competing for sustainability-enhancing options. Its outcomes can be utilized in a decision-making process that is solution focused, participative, iterative and transparent in its definition of sustainability (Zijp et al., 2016).

For developing countries, Indicator methods are commonly used for evaluating urban water management. Developing successful indicator methods requires continued efforts to quantify the relationships between urban water management and environmental sustainability. Water capture, storage, and reuse are becoming common aspects of sustainable water management systems (Kumar et al., 2016). While traditional capture and treatment systems may be cost-prohibitive for many developing regions, there are low-cost, low-technology treatment systems including constructed wetlands or layering with
indigenous rock materials which can be useful for treating water for reuse (Greenway, 2005). Local conditions and capacity for operation require evaluation to determine the feasibility of a site by site basis.

The governments should aim to develop a holistic framework where policy choices for water management consider the impacts of one sector may have on other sectors and the overall growth and economic development of the country.

Van Leeuwen, (2013) analyzed urban water cycle services in 11 cities; 9 cities in Europe and two cities in Africa using City Blueprint method and calculated the Blue City Index to assess the sustainability of urban water cycles. The results varied among cities, and it was positively related to the Gross Domestic Product(GDP) per person, interest, and involvement of stakeholders in sustainability practices and voluntary participation index and governance indicators.

Venkatesh et al., (2017) argued that simulation and optimization method can be used to find a suitable strategy for long-term operation of the urban water system. They developed WaterMet2 model which can quantify and assess water values of some pre-defined performance indicators by simulating the UWS operation. The established approach is used to the UWS of Kerman City located in the south-eastern part of Iran, which is suffering from decreasing water resources due to overexploitation of groundwater resources.

As there are several methods to assess water sustainability and techniques to improve it, we should consider some options that are suitable for arid and semi-arid regions and low cost and potentially low-tech solutions. Moreover, the proposed alternatives could face
additional characteristics such as they should be feasible in the local context, socio-economically viable and politically acceptable.

4.2. Water sustainability assessment methods

Over the last several decades, there have been multiple attempts to develop methods and indicators to assess the relationship between water consumption and freshwater resources due to the overexploitation of water resources.

The Falkenmark indicator (Falkenmark 1989), which measures per capita water availability, was one of the first attempt to assess water security around the world. While the indicator is straightforward and easy to calculate, it does not account for regional differences by assuming a uniform distribution of water demand globally or within each country. More importantly, it does not account water stress caused by increasing demands from economic development.

Then several studies have assessed water scarcity status at the global scale by comparing per capita water share to the water supply required to achieve food self-sufficiency (Rockström et al. 2009, Kummu et al. 2014, Gerten et al. 2011). Also, a number of indices based on withdrawal-to-availability (WTA) (Vörösmarty et al. 2005, Averyt et al. 2013) or consumption-to-availability (CTA) ratio (Hoekstra et al. 2012, Brauman et al. 2016) have been developed to measure the relationship between human water use and freshwater availability.

In last several years, there have been concerns over freshwater habitat degradation hence the concept “environmental water requirement” (EWR) emerged (Smakhtin et al. 2005).
Previous WTA- or CTA-based indicators were modified by allocating a portion of runoff or streamflow as the EWR (Hoekstra et al. 2011, Smakhtin et al. 2005, Wada 2013). The difficulty of including EWR in water availability indicators is that the exact quantity of water needed to sustain freshwater ecosystems is highly fluctuating, depending on the region and the flow season (Pastor et al. 2014).

Boulay et al. (2014) divided indicators into three main categories on the basis of use-to-resource ratios (WTA or CTA). The categories are anthropocentric, ecocentric and hydrocentric. The anthropocentric indicators take consideration of human use by water availability. The ecocentric indicators compare human consumption with available water after deducting the environmental flow requirement. The hydrocentric indicators use total demand by renewable water availability. Although the Hydrocentric category seems most promising, measurement of renewable water availability at spatial and temporal scales are difficult to estimate, because of the time delay in flow return and broad geospatial variations. Likewise, the Ecocentric category requires assessing the ecosystem/environment water requirement, which often varies and hard to measure consistently. In general, most existing blue and green water availability accounting methods can be classified as either Anthropocentric or Ecocentric indices.

4.3. Objectives

The objective of this chapter is to assess water supply and demand dynamics in the TRB to analyze the spatial and temporal variability of it.

i. Evaluate the water demand and supply in each subbasin

ii. Assess the water demand and supply in each administrative unit
iii. Evaluate the water resource sustainability in the TRB

4.3.1. Hypotheses

Based on the objectives of the chapter, the following hypotheses are developed in this study.

i. There is spatial and temporal variation in the sectorial water supply and demand dynamic at subbasin

ii. There is spatial and temporal variation in the sectorial water supply and demand dynamic at administrative units

iii. Water sustainability in the Tuul River Basin is under stress

4.4. Methods

The results of Chapter 2 and Chapter 3 will be analyzed to assess the sustainability of the watershed and subbasins based on the assessment of water resources availability and demand, and it will be conducted for whole watershed and its subwatersheds. Average monthly flow volumes that are estimated at the outlet of each sub-basin using calibrated SWAT model will be used as water supply. Then the water supply in the Tuul river basin is aggregated into annual basis. The values are assigned to corresponding subbasins in the GIS shapefile.

Annual water demand values classified by administrative units are joined into the GIS shapefile as well.

GIS overlay tool was used, shapefiles of 27 subbasins with water supply data and six administrative units with water demand data are overlapped to create a new polygon that
has both water supply and demand values. The water supply and demand values for the newly created polygons are further calculated based on the area percentage.

Then, the water demand and available water in each polygon are compared to obtain demand and supply deficit at each subwatershed and administrative unit on an annual basis. Then the water resource indicators as shown below are calculated for each subbasin.

In this study, water demand-supply ratio (WDSR) is given in the Equation 4-1 and calculated for each watershed

\[
WDRS_i = \frac{\sum WD}{WS} \quad 0-1
\]

Where \(i\), which is the fraction of water supply (WS) used for water demand (WD) by each sector \(j\). Moderate and severe water stress occurs above the respective thresholds of 20% and 40%, commonly known as the critical ratio (Alcamo et al., 2000).

The environmental flow requirement (60% of the total water supply) is incorporated into the water supply demand ratio calculation, and when the water demand exceeds the 40% of the total water supply there is a substantial risk of water stress which affects the environmental need for water.

A weighting factor is applied to the WDRS calculated for each watershed to account for variations in monthly or annual flows. Water stress begins when withdrawals rise above 10% of Q. Therefore, it assumed that if WDSR is higher than 0.2, then water stress can be a limiting factor for economic growth. When WDSR is higher than 0.4, water stress is considered elevated risk (Table 4-1).
Table 0-1. Classification of Water Supply Demand Ratio values

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</tr>
<tr>
<td>High</td>
<td>&gt;0.4</td>
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</table>

4.5. Results and discussion

Water scarcity index and water withdrawal to availability ratio are calculated as follows. (Table 4-2). As shown in the table there is variation in the total water supply as well as total water demand by the subbasin. Water supply ranges from 1931.463-611036 m3/year, and water demand ranges from 2.989 m3/year to 39610.121 m3/year. Using the water supply and water demand values at each subbasin, WDSR is calculated using the Equation 4-1. The WDSR values for the subbasins range from 0.01 to 0.59, and the highest value was observed in the Ulaanbaatar city watershed. Ulaanbaatar subbasin and its surrounding areas are under stress based on the water demand and supply ratio. Based on the indicators, subbasin 18 was under high risk of water stress, subbasin 3 and 19 are at medium risk, subbasin 2, 16 and 23 are at moderate risk (Figure 4-1).
Table 0-2. Water Demand Supply Ratio by subbasin

<table>
<thead>
<tr>
<th>Subbasin</th>
<th>Total Supply thousand m3/year</th>
<th>Total Demand thousand m3/year</th>
<th>WDSR</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>611036.000</td>
<td>287.581</td>
<td>0.09</td>
</tr>
<tr>
<td>2</td>
<td>450254.000</td>
<td>23.154</td>
<td>0.13</td>
</tr>
<tr>
<td>3</td>
<td>18497.091</td>
<td>259.555</td>
<td>0.29</td>
</tr>
<tr>
<td>4</td>
<td>34458.749</td>
<td>1339.139</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>63852.073</td>
<td>458.371</td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>36246.200</td>
<td>628.914</td>
<td>0.02</td>
</tr>
<tr>
<td>7</td>
<td>23206.801</td>
<td>244.409</td>
<td>0.02</td>
</tr>
<tr>
<td>8</td>
<td>430940.000</td>
<td>10.675</td>
<td>0.02</td>
</tr>
<tr>
<td>9</td>
<td>416864.000</td>
<td>91.867</td>
<td>0.02</td>
</tr>
<tr>
<td>10</td>
<td>414116.000</td>
<td>191.328</td>
<td>0.05</td>
</tr>
<tr>
<td>11</td>
<td>382903.000</td>
<td>44.109</td>
<td>0.03</td>
</tr>
<tr>
<td>12</td>
<td>1931.463</td>
<td>130.414</td>
<td>0.03</td>
</tr>
<tr>
<td>13</td>
<td>45923.000</td>
<td>516.506</td>
<td>0.03</td>
</tr>
<tr>
<td>14</td>
<td>11501.000</td>
<td>84.138</td>
<td>0.02</td>
</tr>
<tr>
<td>15</td>
<td>101724.044</td>
<td>170.206</td>
<td>0.02</td>
</tr>
<tr>
<td>16</td>
<td>164414.102</td>
<td>39610.121</td>
<td>0.11</td>
</tr>
<tr>
<td>17</td>
<td>67904.000</td>
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</tr>
<tr>
<td>18</td>
<td>194859.790</td>
<td>23851.717</td>
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</tr>
<tr>
<td>19</td>
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<td>20</td>
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<td>42.253</td>
<td>0.03</td>
</tr>
<tr>
<td>21</td>
<td>14515.380</td>
<td>272.160</td>
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</tr>
<tr>
<td>22</td>
<td>334610.276</td>
<td>836.501</td>
<td>0.02</td>
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<td>23</td>
<td>278957.500</td>
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</tr>
<tr>
<td>24</td>
<td>64659.398</td>
<td>72.999</td>
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<tr>
<td>25</td>
<td>18153.600</td>
<td>16.925</td>
<td>0.02</td>
</tr>
<tr>
<td>26</td>
<td>15090.900</td>
<td>565.792</td>
<td>0.01</td>
</tr>
<tr>
<td>27</td>
<td>25337.646</td>
<td>24.350</td>
<td>0.02</td>
</tr>
</tbody>
</table>

When the water demand-supply ratio is calculated based on the administrative units to get a detailed analysis of the water supply and demand dynamics, the Ulaanbaatar city and its surrounding areas have high values of vulnerability (Figure 4-2).
Figure 0-1. Water demand by supply ratio by subbasins in the TRB

Figure 0-2. Water demand by supply ratio by administrative units in the TRB
4.6. Strategies for improving water resource sustainability

Based on the analysis of the WDSR, and the variability of water supply and demand in the basin, water managers should seek integrated approach to solve the water resource sustainability issues. There should be different methods to improve water sustainability in the basin based on the condition of the water supply system and the type of water user.

The author of the study is proposing two main strategies to improve water resources in the Tuul River Basin as mentioned in Chapter 1.2. The strategies should aim to improve the water resources system without creating a burden on a different type of users. Water supply augmentation and water demand management strategies are enforced through best management practices (BMP) and behavioral changes (Figure 4-3).

Figure 0-3. Model strategies to improve water sustainability

As the water supply and demand in the Tuul River Basin vary spatially and temporally, the approaches could be selected based on the priority. The strategies and their suitable locations are presented in Table 4-3.
### Table 0-3. Strategies to improve watershed sustainability in Tuul River Basin

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Action</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Augmentation</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Find new source</td>
<td>Ulaanbaatar</td>
</tr>
<tr>
<td></td>
<td>Land acquisition and protection in the groundwater recharge zones</td>
<td>Headwater</td>
</tr>
<tr>
<td></td>
<td>Recycling grey water in commercial and apartment buildings</td>
<td>Ulaanbaatar</td>
</tr>
<tr>
<td></td>
<td>Recharging groundwater using water harvesting techniques</td>
<td>Ulaanbaatar and Tuv</td>
</tr>
<tr>
<td></td>
<td>Reestablishing forest cover and natural vegetation</td>
<td>Ulaanbaatar and Tuv, and in the headwater</td>
</tr>
<tr>
<td></td>
<td>Building subsurface dams to improve groundwater recharge</td>
<td>Headwaters</td>
</tr>
<tr>
<td>Water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>management</td>
<td></td>
<td></td>
</tr>
<tr>
<td>demand</td>
<td>Installation of water efficient technologies in residential buildings</td>
<td>Ulaanbaatar and Tuv</td>
</tr>
<tr>
<td></td>
<td>Improved pricing strategy</td>
<td>Tuul River Basin</td>
</tr>
<tr>
<td></td>
<td>Use of incentives for installation and/or retrofitting of water-</td>
<td>Tuul River Basin</td>
</tr>
<tr>
<td></td>
<td>efficient equipment</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Leak detection and reduction in unaccounted water</td>
<td>Ulaanbaatar and Tuv</td>
</tr>
<tr>
<td></td>
<td>Public education</td>
<td>Tuul River Basin</td>
</tr>
</tbody>
</table>

- In the headwaters of the Tuul River Basin:

According to the analysis of this chapter, increasing water supply is one of the essential methods for improving water sustainability in the Tuul River Basin. Starting with finding newly available sources to meet the increasing demand and improve groundwater recharge. Even though the headwater is under the protection of Terelj Natural Park, the groundwater recharge zones should be protected from pollution and human intervention. As the
headwaters in the Tuul River Basin is the region with the highest water yield, the percolation, and recharge of groundwater should be the main priority. Building groundwater dam could improve the groundwater recharge and found to be effective as there is minimal evaporation, no major changes to valuable land and generally lower microbiologically contamination concerns (Jamali et al., 2014). Also, the forest cover and natural vegetation could be reestablished to reduce surface runoff and increase the infiltration of surface water. It has been found that moderate tree cover can improve groundwater recharge, and that tree planting and various tree management options can improve groundwater resources (Ilstedt et al., 2016).

- In Ulaanbaatar city and its neighboring regions:

As the 77% of the total water demand is concentrated in the Ulaanbaatar city the main water improving strategy should be focused on this region. The main approach ought to be focused on reducing the residential water use. But there is a disparity between residential water users, the water demand reduction strategies should be applied to apartment residents. The demand in the apartment buildings could be reduced by installing water-efficient technologies such as low-pressure shower heads and dual flush toilet. In new apartment and commercial buildings, installation and use of greywater treatment system should be emphasized to reduce the use of potable water for non-drinking purposes.

Also, there could be incentive policies for installation and application of these types of water-efficient technologies for apartments and commercial buildings to encourage users to further conserve water. This should be complemented by continuous education and promotional activities for users.
4.7. Conclusion

Water supply and demand dynamics of the TRB was analyzed in this chapter. The analysis shows that there is a variability in water supply and demand at subbasin scale. Ulaanbaatar subbasin, the surrounding areas are under stress based on the water demand and supply ratio.

The WDSR values were calculated based on the subbasins as well as administrative units. WDSR values were at high risk in Ulaanbaatar subbasin and moderate to medium risk in the neighboring area of Ulaanbaatar. Subbasin 3 where the mining activities are concentrated was at medium risk.

Therefore strategies for water sustainability is essential in this areas. The potential strategies are discussed in this chapter. There could be two main type of strategies such as water demand management and water supply augmentation, both through best management practices and behavioral change.
CHAPTER 5

CONCLUSION

Due to climate change and increasing water demand as results of growing populations, pressure on available water resources and already exceeds the sustainable amount of water resource utilizing in Ulaanbaatar, the capital of Mongolia. Ulaanbaatar is the highest water usage in the country, and industrial, and drinking water supplies are entirely depending on alluvial floodplain groundwater, which is recharged by the Tuul River water. However, the river flow has been declined in upstream of the river basin and run dry during low flow period surrounding Ulaanbaatar where groundwater production wells occasionally concentrated since 1997. This research contributes to a better understanding of water supply and demand dynamics in the Tuul River Basin. With the available measured long-term records (precipitation, and river flow), a response of the Tuul River flow to changes in precipitation and a near-surface air temperature of the Tuul River Basin have been investigated using Soil Water Assessment Tool (SWAT). The model has been shown to provide a valuable and reliable approach. Moreover, the model could be used as a feasible and appreciate approach for strengthening water resources management in Ulaanbaatar city. According to the SWAT model simulation of the Tuul River Basin, precipitation and temperature and ET were main processes influencing water resources in the TRB. Due to a decrease in precipitation and increase in air temperature during the latest dry period, the study area has suffered by a reduction in the streamflow.

The water demand in the TRB is assessed using demographic and statistical data, and government-issued water demand norms and a spatial and temporal variation in the
sectorial water demand is observed. The residential water demand in the TRB was found to be the highest and followed by the water demand for energy and heat production. As those demands are concentrated in the Ulaanbaatar city, the water demand for the city is the highest, 83.7% of the total water demand in TRB.

Therefore, there is a need for urban water management specifically focused on population and energy and heat production sector. The residential demand management is an ongoing process since 2008, and there have been several approaches to reduce. The methods include pricing policy such as block tariffs and installing water meters. However, there have not been much done in the energy and heat production sector.

Water supply and demand dynamics of the TRB was analyzed based on the administrative units and subbasins. The analysis shows that there is a variability in water supply and demand at subbasin scale. Ulaanbaatar subbasin, the surrounding areas are under stress based on the water demand and supply ratio. To improve the sustainability of the water resources several approaches are discussed based on the locality of the problem.
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