Projecting water demand and availability under climate change through the application of WEAP in the Nam Ngum downstream area, Laos

by

Phingsaliao Sithiengtham

Student ID: 2176693

Supervisor: Strategic Professor Okke Batelaan

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SUMMARY

Water is one of the most vital resources. Rapidly increasing water demand threatens water resource availability in many regions across the world. Equitable and sustainable water allocation planning is considered important in the context of anthropogenic threats, such as climate change and over extraction. To allocate water efficiently, it is essential to understand the water balance of an area.

The Nam Ngum River Basin (NNRB), Laos was selected as a case study. This research aimed to determine how much water is currently needed and available as well as to project future water demand and availability according to population growth, industrial development, agricultural intensification, and climate change until 2050. The study employed the ‘Water Evaluation and Planning (WEAP)’ model as a key tool to simulate the water balance of the area.

The results reveal that water availability is much more than the current water demand in the Nam Ngum downstream area. The current annual water extraction is around 372.5 million m^3, with primary users being the agricultural (95.7%), domestic (3.8%), and industrial (0.5%) sectors. The water inflow to the area is around 20.66 billion m^3/y, which is coming from the Nam Ngum 1 dam and Nam Lik River inflow (83.6%), rainfall (15.7%), and the Nam Mung 3 dam (0.8%). The Nam Ngum River is also gaining water from groundwater. The river runoff from the area is approximately 19.7 billion m^3/y, which is 53 times higher than the demand. In this case, the amount of water extracted can increase up to 46 times without major environmental flow impacts, whereas 96 m^3/s is preserved for the minimum flow requirement.

In the future, water demand will continue to increase, while water availability will vary according to climate conditions. By 2050, the estimated annual water demand will be approximately 3.3 billion m^3, which will be an increase of 8.9 times relative to the current usage. In a very wet year, the Nam Ngum River runoff from the area is projected to be 48 billion m^3, which is 129 times higher than the current demand. In a wet year, the water availability is estimated to around 90 times higher than the current demand. The minimum river flow is projected to be 250 m^3/s in very dry years. Total river runoff in a very dry year is around 11.4 billion m^3/y equivalent to 30 times the current usage. Thus, in the dry season of an extremely dry year, water might still be adequate to meet the increased demand. However, if the inflow has been halved, the minimum flow requirement of 96 m^3/s might not be met in the year of 2050 if that year experiences a severe drought.

Although sufficient water is currently available, it needs to be managed and allocated properly. The water in the system does not distribute equally to all zones in the Nam Ngum downstream area. Furthermore, anticipated increases in levels of extraction together with projected impacts from

climate change are likely to result in greater demand on water availability. Thus, it is imperative to establish water allocation and sustainable river basin management plans to allocate water for all users equitably and to manage water resources for sustainable use. In addition, further related research should include examination of water quality and the required flow dynamics of the river discharge as important aspects of environmental flows and water availability.

DECLARATION

I certify that this thesis does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; and that to the best of my knowledge and belief it does not contain any material previously published or written by another person except where due reference is made in the text.

Phingsaliao Sithiengtham

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LIST OF ABBREVIATIONS

CFCs:	Chlorofluorocarbons
CH_4:	Methane
CO_2:	carbon dioxide
DC:	Deep Conductivity
DEM:	Digital Elevation Model
DMH:	Department of Meteorology and Hydrology
DTM:	Digital Terrain Model
DWR:	Department of Water Resources
EDL:	Electricity du Lao
FAO:	Food and Agriculture Organisation
GHG:	greenhouse gases
GIS:	Geographic Information System
GoL:	Government of Laos
ha:	Hectare
IPCC:	Intergovernmental Panel on Climate Change
IWRM:	Integrated Water Resources Management
Kc:	Crop coefficient
km:	Kilometre
Lao PDR:	Lao People’s Democratic Republic
LDC:	Least Developed Country
LMB:	Lower Mekong Basin
LSB:	Lao Statistics Bureau
m^3:	Cubic metre
m^3/y:	Cubic metre per year
mm/y:	Millimetre per year
MAF:	Ministry of Agriculture and Forestry
MoIC:	Ministry of Industry and Commerce
MoNRE:	Ministry of Natural Resources and Environment
MRCs:	Mekong River Commission Secretariat
N_20:	Nitrous oxide
NNRB:	Nam Ngum River Basin
NRE:	Natural Resources and Environment
NSE:	Nash-Sutcliffe efficiency

NSEDP:	National Socio-Economic Development Plan
PBIAS:	Percent bias
PEST:	Parameter Estimation
PFD:	Preferred Flow Direction
RCP:	Representative Concentration Pathways
RRF:	Runoff resistance factor
RSR:	The ratio of the root mean square error to the standard deviation of measured data
RZC:	Root Zone Conductivity
SEA START RC:	Southeast Asia System for Analysis, Research and Training Regional Centre
SEI:	Stockholm Environment Institute
SRES:	Special Report on Emissions Scenarios
SWC:	Soil Water Capacity
USA:	United States of America
WEAP:	Water Evaluation and Planning
WRCC:	Water Resources Coordination Committee
WREA:	Water Resources and Environment Agency
Z1:	Initial topsoil layer storage
Z2:	Initial bottom soil layer storage

CHAPTER 1: INTRODUCTION

1.1. Background and rationale

Water resources play significant roles in livelihood enhancement, economic development, and ecological stability (Goswami & Bisht 2017). All living things in the world need water to survive. Water is a fundamental component of maintaining good health and survival in both animal and plant kingdoms, for growing crops, and for providing employment opportunities (Goswami & Bisht 2017). It is also an essential resource for socio-economic development as it is needed for producing and processing goods and energy, such as hydropower, mining, irrigation, industrial products, and elements of infrastructures (Mogelgaard 2011). In addition, water is vital for maintaining the many ecosystems upon which both animal and plant life depend, as it regulates ecological functions and provides the environmental flow (Arthington et al. 2006).

Even though water is essential, the quantity of and access to fresh water are limited. According to Shiklomanov (1993), there are around 1,386 million km^3 of total water across the world, although only approximately 35 million km^3 or 2.53% is fresh water. Moreover, a large portion of the freshwater, around 68.7%, is in the form of ice and snow, while just around 90,000 km^3 or 0.26% of total fresh water is from lakes and rivers that can be accessed for extraction by humans (Shiklomanov 1993, p. 13).

As fresh water is a limited resource, water use is increasingly competitive, and water scarcity has become an issue in many regions around the world (Mogelgaard 2011). Human water demand is rapidly increasing because of the growth in the world population and rapid infrastructure development that needs water to be supplied (Mogelgaard 2011). However, fresh water resources are being stressed, with the result that water availability is declining and water quality is degrading in many areas (Mogelgaard 2011). For example, the current water demand cannot be met in the Middle East and North Africa regions (Mogelgaard 2011). This may be a result of climate change. The rise in the mean global temperature is resulting in a change of rainfall patterns, and an increase in natural disasters, especially more severe floods and droughts (Arnell 1999; Mogelgaard 2011; Yilmaz & Yazicigil 2011). These issues are challenging many countries in the world including Laos.

Laos is regarded as a nation that is rich in natural resources, especially water resources (DWR 2008). Laos is a landlocked country located in Southeast Asia with an area of 236,800 km^2 (Lao Statistics Bureau 2015, p. 23). The country has a total population of 6,492,228 persons in the

2015 census (Lao Statistics Bureau 2015). Annual renewable water availability per capita is around 55,000 m^3 (DWR 2008, p. 47). However, the water resources are not distributed equally in the country which means that some locations suffer from droughts while others experience flooding. According to DWR (2014), only 2.8% of annual surface water has been utilised while the rest discharges to other countries, such as Cambodia and Vietnam. This is because the management and the storage capacity of water within Laos are limited.

As the utilisation of available water is limited, water use is competitive in many areas. Major development sectors of the country, such as agriculture, hydropower, and mining, are inevitably dependent on water and as a consequence they also trigger significant impacts on water resources (DWR 2008, 2014). In the dry season, many places in the country have been facing water scarcity (DWR 2008). This acts as a catalyst for conflict between different water users, such as hydropower, agriculture, and fisheries as well as the ecosystems. At present, a water allocation plan has not yet been established in Laos and its river basins because of lack of technical and financial support (DWR 2016). However, these water issues have caused changes to public policy which has now recognised the water sector as an integral part of country development (MoNRE 2015a; MPI 2016).

According to the Lao National Water Resources Strategy 2025 and Action Plan 2016-2020 (DWR 2014), the Government has selected 10 out of 64 river basins in the country as priority basins to be managed and developed during 2016-2020. One of them is the Nam Ngum River Basin (NNRB) with an approximate area of 17,000 km^2 (DWR 2008, p. 52). This river basin covers six provinces, namely Xiengkhouang, Luangprabang, Xaysomboun, Vientiane, Vientiane Capital, and Bolikhamxay. There is rapid development in this basin which creates challenges to managing the river system, such as a number of hydropower dams, mining, urban development, population growth, tourism, and agricultural intensification (IDOM & LCG 2013). Groundwater and surface water also exchange across the stream bed, which can lead to vulnerability of available water. In addition, climate change has introduced more stress to water management because natural disasters, such as floods and droughts, are more frequent and severe (IDOM & LCG 2013). These issues are posing threats to water availability in the near future since a water allocation plan is not in place, while at the same time, there is increasing competition amongst water uses in high water demand areas. Therefore, it is imperative to study or assess the current and future water availability and demand in order to provide baseline data for water allocation and basin management planning.

Due to the large area of the basin and constraints of data, this research focused on the downstream area of the Nam Ngum River (Figure 6). This study covers an area of 167,192 ha (1,671.9 km^2), of which 94% overlaps with the Nam Cheng-Nam Souang sub-basin. This sub-basin is one of the five priority sub-basins in the NNRB that the Lao Government has prioritised (Nam Cheng-Nam Souang Taskforce 2015). Most of the agricultural area, around 75% of agriculture in the NNRB, is concentrated in the downstream part (DOI & JICA 2009, cited in Lacombe et al. 2011, p. 7). In addition, there is a high demand for water use by other sectors, such as industries, fisheries, navigation, tourism, and domestic water supply. Thus, water extraction in this area is necessary to be managed and allocated effectively.

1.2. Goal and Objectives

The goal of this research is to evaluate the water status in the Nam Ngum downstream area, contributing to equitable water allocation and sustainable river basin management planning.

The specific objectives of the research are as follows.

1). To assess the current water availability and water demand for different sectors, such as agriculture, industry, and municipality, in the Nam Ngum downstream area.
2). To project water quantity and water extraction in the Nam Ngum downstream area against climate change, population growth, industrial development, and agricultural intensification until 2050.
3). To simulate groundwater and surface water interactions in the Nam Ngum downstream area.

1.3. Research questions

This research sought to answer the following questions.

1). How much water is flowing in and out of the Nam Ngum downstream area and what are the sources of water input?
2). How much water is currently needed by each user group, particularly agricultural, industrial, and domestic sectors, in the Nam Ngum downstream area?
3). What is the predicted water demand and availability in the Nam Ngum downstream area in 2050, taking into account climate change, industrial development, population growth, and agricultural intensification?
4). How much of the recharge to the aquifer and discharge from the aquifer to rivers occurs in the Nam Ngum downstream area?

1.4. Scope of study

This study focused on the water balance in the Nam Ngum downstream area. The precise study area is a hydrological boundary delineated from the Vernkham streamflow gauge to the Pakkayoung streamflow gauge of the Nam Ngum River, and hereafter this is called the 'Nam Ngum downstream area' or the 'study area' (Figure 6). The water balance was simulated with a software model named 'Water Evaluation and Planning – WEAP' (SEI 2019b). The study employed the climate and hydrological data from 2010 to 2016 as a baseline and simulated future change until 2050. The assessment of water demand and availability was considered for the Nam Ngum downstream area as a whole rather than looking at each specific area individually. Due to data and time constraints, water quality was not a focus of this research.

1.5. Structure of the thesis

The thesis consists of five key chapters as follows.

Chapter 1: Introduction

This chapter presents general background and main problems of water resources management and allocation at global, national, and river basin levels. In addition, the goal and objectives of the research as well as the research questions are also stated in this chapter.

Chapter 2: Literature review

This chapter critically synthesises existing literature related to the topic and the study area. The reviews include water balance, water allocation, climate change, Lao water management, and WEAP. These literature sources are mainly from journal articles, books, reliable websites, and government documents.

Chapter 3: Data and methodology

This chapter covers the study area, data, and methodology. It elaborates on how the study area was delineated and its background, how the data were collected and analysed, and how the WEAP model was set up and run.

Chapter 4: Results and discussion

This chapter presents the findings of the research emphasising the results of the data collection and the WEAP simulations. These results are interpreted and discussed with regard to the facts, causes, possible consequences, and plausible options based on existing literature and previous research.

Chapter 5: Conclusion and recommendations

This chapter summarises the key aspects of the research thesis and research limitations, and includes recommendations for future water governance in the area and further research in the same field.

CHAPTER 2: LITERATURE REVIEW

2.1. Water balance

Water is generally balanced and it moves through its cycle in different forms across the globe (Kumar n.d; Oliver & Oliver 2013). Precipitation falls as rain or snow before infiltrating to aquifers as groundwater and running off towards the oceans and then it evaporates into the atmosphere condensing into clouds before falling down again (Marine Science Education Centre n.d; NASA nd; URI n.d).

For a given area, for example at a river basin scale, calculations and analysis are required to quantify the amount of water for each component of the water balance. Goyal et al. (2018, p. 299) argue that, in order to manage available water resources effectively, it is essential to have accurate information on the water balance. A very simple water balance is that the input equals the output plus the change in storage (Goyal et al. 2018; Kumar n.d; Stauffer 2018).

$$\textit{Input} = \textit{Output} + \textit{Change in Storage} \qquad \textbf{Equation 1}$$

There are many sub-components involved in the water balance equation depending on different areas and conditions. Generally, the input includes precipitation (rainfall and snow), groundwater inflow, and surface water inflow (diversion); the output consists of river runoff, water extraction and consumption, groundwater outflow, evaporation (from water bodies, reservoirs, or tanks), evapotranspiration (from forests and crops); the change in storage might account for the water stored or lost in soils, plants, rivers, wetlands, and reservoirs.

Each component in the water balance is inter-related and affects each other (Goyal et al. 2018). Xu and Singh (1998) contend that only three to five parameters of water data might be adequate to estimate other missing data by monthly water balance models in humid zones. In the absence of piezometric measurements or isotopic tracers, Pellicer-Martínez and Martínez-Paz (2014) employed water balance models to estimate groundwater inflows and outflows for the Segura River Basin in south-eastern Spain. Andrews, Gross and Hutton (2016) simulated subtidal streamflow at an ungauged area of the corridor of the Old River and Middle River in the California delta, United States of America (USA).

The monthly water balance model was first created in the 1940s and since then it has been modified and widely applied in many countries and river basins in terms of hydrological modelling (Xu & Singh 1998). Bock, Farmer and Hay (2018) gathered hydrological data from

1,575 flow gauges and 109,951 hydrologic response units across the USA to estimate river runoff and quantify uncertainty in a monthly water balance model. Alley (1985) simulated three different models of monthly water balance to forecast one-month-ahead streamflow in New Jersey, USA. Another study was conducted by Vandewiele and Ni-Lar-Win (1998) who used two types of monthly water balance models (P and PE models) applied in 55 river basins of 10 countries. Precipitation and evapotranspiration data are the main requirements for the PE model while the P model uses only precipitation data (Vandewiele & Ni-Lar-Win 1998).

It is notable that water balance models are very useful for integrated water management; however, some models need to be adapted for site conditions. These models are simulating tools to assist in quantifying water regime components, such as precipitation, runoff, evapotranspiration, and aquifer infiltration and discharge (Goyal et al. 2018; Saha & Setegn 2015). However, the study by Vandewiele and Ni-Lar-Win (1998) demonstrated that there is no universal model that can be applied to all river basins. A specific method needs to be modified according to the scale of study areas and real conditions. Goyal et al. (2018) state that the concept of the water balance is an attempt to sustainably manage water resources in the long-term.

2.2. Water allocation

Water allocated for human and environmental activities needs to be considered. Water allocation can be defined as a process which systematically divides the amount of available water in the system to different regions and competing users (Speed et al. 2013), such as agricultural, domestic, industrial, and environmental components. Precipitation minus evapotranspiration accumulates in a catchment and flows to streams and recharges to aquifers. Human activities and the ecosystem have used this water to thrive and survive (Oki & Kanae 2006). However, increases in demand and, at the same time, limited water supply require equitable allocation of the resource.

Situations of water scarcity and high water demand can cause water conflict and pose a huge challenge when allocating water for all in an equitable and fair manner. As the world population is growing, the need for natural resources, especially water, is also increasing (Dinar, Rosegrant & Meinzen-Dick 1997; OECD 2015). The OECD (2015, p. 21) projected that global water demand will increase from 2000 to 2050 by 55%, even though water is now already over-used and over-allocated in many areas. Moreover, the effects of climate change are beginning to negatively impact water quantity and quality in many regions (Hellegers & Leflaive 2015; OECD 2015). When water is limited, the users compete to satisfy their needs, and this acts as a catalyst for water conflict (Bangash et al. 2012; Hu et al. 2016; Roozbahani, Schreider & Abbasi 2015). The conflicts of water use have occurred in many regions around the world, for example, the riparian countries of the Areal Sea Basin (Bernauer & Siegfried 2012), the Sefidrud Basin in northern Iran (Roozbahani, Schreider & Abbasi 2015), Nile, Mekong, Euphrates, Amu Darya, Syr Darya, and Ganges Rivers (Carius, Dabelko & Wolf 2004), and Murray-Darling Basin in Australia (Connell 2007).

However, Carius, Dabelko and Wolf (2004) argued that in most cases water conflict has occurred because of poor water governance and management, rather than limited water resources. This might include 'lack of adequate water institutions, inadequate administrative capacity, lack of transparency, ambiguous jurisdictions, overlapping functions, fragmented institutional structures, and lack of necessary infrastructure' (Carius, Dabelko & Wolf 2004, p. 61). Thus, strong institutions and reliable data are fundamental for equitable water allocation and sustainable water management (Carius, Dabelko & Wolf 2004).

As water is a complex resource, efficiently allocating water requires many different elements at the system and user levels (Young 2013, cited in OECD 2015). The mechanisms at the system level include the elements of legal status of water ownership, institutional arrangements, identification of available and limitation of water resources, definition of permitted uses and exceptional circumstances, prioritisation, requirements of water entitlements, monitoring and enforcement, and appropriate infrastructures (OECD 2015, p. 47). At the user level, the elements of a water allocation regime consist of water entitlements, abstraction charges, obligations on flow and discharge returns, duration of water entitlements, and trading water entitlements (OECD 2015, p. 48). In addition, OECD (2015, p. 120) has developed a checklist to assess the performance of water allocation regimes as follows.

System level elements:

1. Are there responsible organisations and water allocation plans at a river basin scale?
2. Is the legal status for each water resource type clear?
3. Is water availability well-understood?
4. Is there preservation for environmental flow and sustainable use?
5. Is there an approach to minimise the risk of water shortage?
6. Is there an effective emergency plan?
7. Is there a mechanism to deal with an increase in water entitlements over limited resources?
8. Are there effective monitoring systems and clear sanctions in place?

9. Are there effective water supply infrastructures?
10. Are the water-related policies across sectors coherent?

User level elements:

11. Is the definition of water entitlements legally clear?
12. Are there appropriate abstraction charges for all users?
13. Are there obligations and enforcement on returned flow and discharges?
14. Is there a mechanism for water users to trade water entitlements?

In a river basin (or a specific area), it is crucial to study the water budget and water demand for water allocation planning. For examples, Roozbahani, Schreider and Abbasi (2015) applied a water allocation model in the Sefidrud River Basin in Iran where there has been a severe water conflict. They found that up to 83% of available water in the river basin could be allocated to different users without compromising the environmental flow (Roozbahani, Schreider & Abbasi 2015). Furthermore, Chang and Wang (2013) conducted a study of the Shihmen Reservoir River Basin in Taiwan as a case study for water allocation in drought conditions. They assessed the drought condition and produced evaluation diagrams to indicate the drought threshold before simulating water allocation scenarios, and finally determined a suitable water discount rate for water supply to agriculture in order to mitigate drought disasters (Chang & Wang 2013). Another water allocation study was conducted by Vasto-Terrientes et al. (2016) in the Tarragona city located in the Mediterranean area of Spain. Vasto-Terrientes et al. (2016) designed many different scenarios according to environmental and economic criteria, and then proposed water allocation strategies including finding alternative water sources, diverting water from inter-basins, and managing water use efficiency of industrial, agricultural, and domestic sectors. These studies are very useful for effective water allocation planning against climate change impacts.

In addition, Lacombe et al. (2011) conducted a study on water availability and water use in the lower NNRB in Laos. This study aimed to determine whether the water from the Nam Ngum River would be adequate to supply the agricultural area in the Vientiane Plain during the dry season. They assessed the current water use based on the capacity of the pumping stations along the river, the area of agriculture obtained from the Department of Irrigation, and the irrigation area delineated from satellite images. Water availability was estimated from the water released from the Nam Ngum 1 hydropower dam, using streamflow data from the downstream gauge stations (Thalat, Pakkayoung, and Thangon stations from 1966-2006). The findings of this study revealed that the available water in the Nam Ngum River was much greater than the irrigation water demand and could satisfactorily supply the agricultural sector even during the dry season of an extreme drought year (Lacombe et al. 2011). However, this study considered only irrigation as a water user, while the domestic and industrial sectors were not considered. Moreover, water demand and supply in the rainy season was not considered in this water balance study.

2.3. Climate change

In the 21st century, climate change has emerged as one of the most critical global issues faced by humanity and the planet. Climate change can be defined as ‘a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods’ (UN 1992, p. 7). According to climate observations, IPCC (2014) confirmed that global warming is unequivocal, global temperature has increased, sea level has risen, and the glaciers have shrunk. From 1880 to 2012, there was an increase in the land and ocean surface mean temperature of 0.85°C (Figure 1a) (IPCC 2014, p. 2). The average sea level rose by 0.19 m from 1901 to 2010 (Figure 1b) and the extent of Arctic sea-ice declined by 3.5% to 4.1% per decade from 1979 to 2012 (IPCC 2014, p. 4).

The main causes of climate change have been from human activities (IPCC 2014). Population growth combined with rapid industrialisation has acted as a catalyst for global warming (Han & Chatterjee 1997; IPCC 2014; Vörösmarty et al. 2000). As the global population increased, economic productivity also grew to meet the demand. Consequently, there are more development activities for humans that cause adverse impact on climate. Over two decades ago, Bongaarts (1992, p. 301) argued that ‘Human activities such as the burning of fossil fuels, deforestation, rice cultivation, use of fertilizer in agriculture, and production of chlorofluorocarbons (CFCs) lead to the emission of a number of greenhouse gases’. These anthropogenic greenhouse gases (GHG), which have been emitted since the pre-industrial era, have led to an increase in concentration of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) in the atmosphere (Figure 1c) (IPCC 2014). Figure 1d shows the global anthropogenic CO_2 emission; the cumulative CO_2 emissions from 1750 to 2011 were 2,040 $GtCO_2$ (IPCC 2014). The observed data in Figure 1 indicate a change of climate.

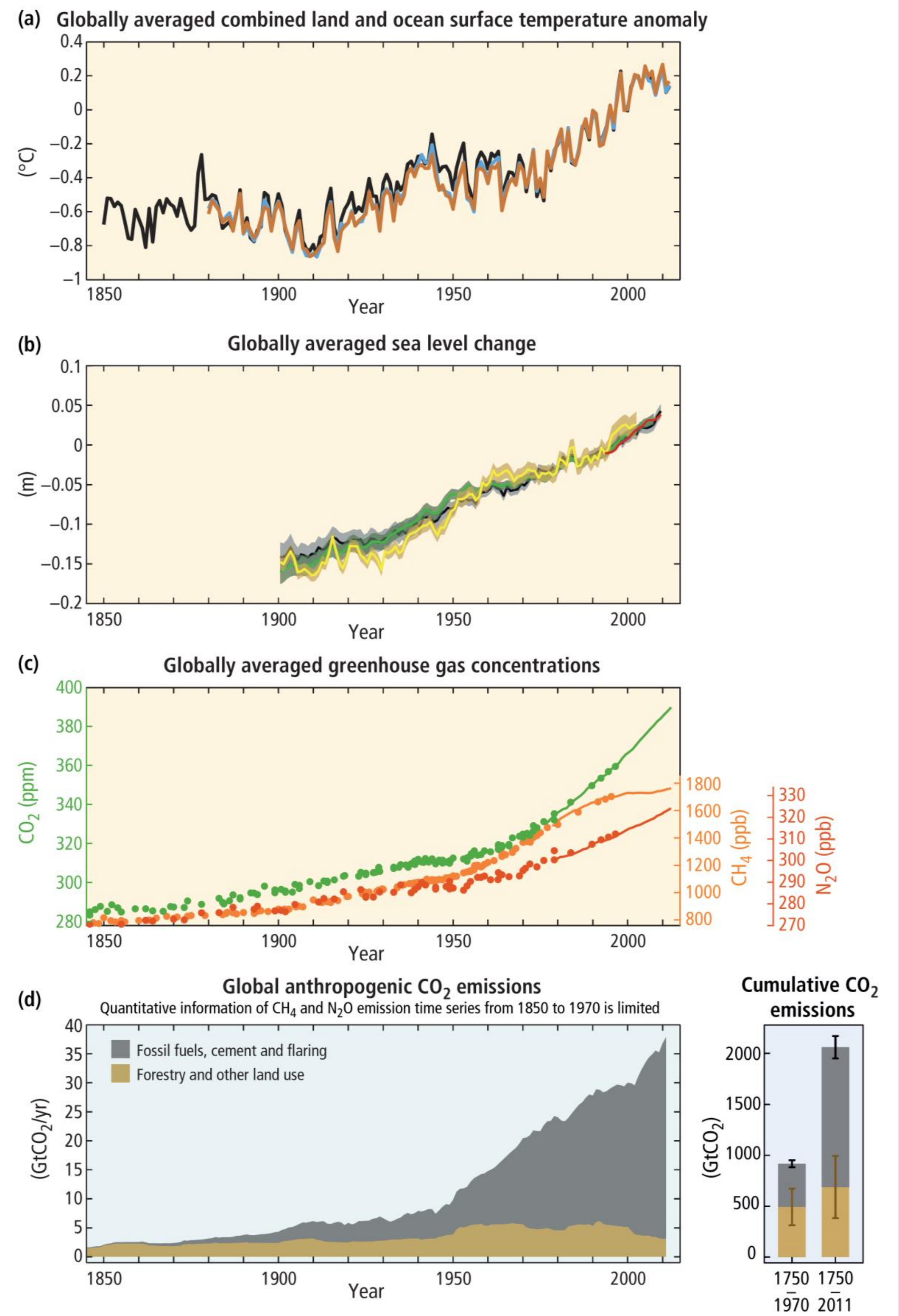


Figure 1: Observed change of the global climate system (different line colours in (a) and (b) represent different datasets) (IPCC 2014, p. 3).

In addition to temperature and atmospheric effects, water resources have also been affected by climate change (Hagemann et al. 2013). Global warming is altering hydrological regimes and affecting both quantity and quality of water (Cornea, Dima & Roca 2011; IPCC 2014). When the average global temperature increases, it leads to an increase in evaporation of surface water and change in rainfall patterns resulting in vulnerability to reduction in water availability (Arnell 1999). Global precipitation has been projected to increase; however, it may not be distributed equally over every region (Arnell 1999, p. S32; IPCC 2014). For example, Figure 2b shows that the high latitudes, equatorial Pacific, and mid-latitude wet regions will experience heavier rainfall while mid-latitude and subtropical dry regions will likely have less precipitation (IPCC 2014, p. 11). Hagemann et al. (2013, p. 140) projected that more than 10% of water availability will decrease in the regions of Central, Eastern and Southern Europe, some catchments in Middle East, Mississippi Basin, Zhu Jiang Basin in China, Murray Basin in Australia, and Okavango and Limpopo basins in Southern Africa. In addition, an intensification of hydrological cycle due to global warming will result in dryer dry seasons and wetter rainy seasons, which will cause more severe floods and droughts with greater frequency in these events (Cornea, Dima & Roca 2011). Flooding causes higher sediment, nutrient, and pollutant loads in surface water, whilst droughts increase the concentration of contaminants in water (IPCC 2014, p. 69). This will alter the physical, chemical, and biological properties of water, which poses threats to freshwater species, the ecosystem, and water quality (IPCC 2007, p. 49).

Many scenarios have been introduced to project climate change situations in the future. Most well-known and widely used scenarios were developed by IPCC (2000) as Special Report on Emissions Scenarios (SRES). These scenarios represent a wide range in economic and technological variables as well as GHG emissions. There are in total 40 different scenarios, which can be categorised into four families as follows (IPCC 2000).

- **The A1 family** assumes a homogeneous world with rapid economic development and more innovative technologies while the global population reaches the peak in 2050 and then declines. The A1 family consists of three groups representing alternative energy options namely fossil intensive (A1FI) with six scenarios, non-fossil energy sources (A1T) with three scenarios, and a balance across all sources (A1B) with eight scenarios.

- **The A2 family** represents a very heterogeneous world with continuous global population growth reaching 13.3 billion in 2050 and 15.1 billion in 2100. However, economic and technological development is regionally oriented and slower than the other scenarios. The family consists of six scenarios.

- **The B1 family** characterises a more integrated and environmentally friendly world. The global population has been assumed to grow as A1 reaching the peak at 8.7 billion in the mid-century and declines thereafter. Economies rapidly develop towards a service and information system with ecologically sound technologies focusing on the global economic, social, and environmental solutions. This family consists of nine scenarios.

- **The B2 family** assumes a world with continuous population growth but at a slower rate than A2, reaching 9.3 billion and 10.4 billion in 2050 and 2100 respectively. It is focused on local solutions to economic, social, and environmental sustainability towards environmental protection with economic development at moderate levels and fragmented technological change. This family consists of eight scenarios.

In the IPCC fifth assessment report, IPCC (2014) projected future climate change until 2100 showing that mean temperature, precipitation, and sea level will generally increase (Figure 2). They used four scenarios under the Representative Concentration Pathways (RCPs) which are mainly driven by GHG emissions, air pollution concentrations, and climate policy (IPCC 2014). The four scenarios are RCP2.6 (very low emissions), RCP4.5 and RCP6.0 (intermediate scenarios), and RPC8.5 (high GHG emissions) (IPCC (2014). According to these scenarios, IPCC (2014) projected that the average global temperature will increase by 0.3°C to 1.7 °C under RCP2.6 and 2.6°C to 4.8°C under RCP8.5 in 2081-2100, compared to the average in 1986-2005 (Figure 2a). Precipitation has been projected to increase, especially in the areas of high latitudes, equatorial Pacific, and mid-latitude wet regions; however, it will decrease in mid-latitude and subtropical dry regions (Figure 2b) (IPCC 2014). The mean sea level has been projected to rise under all scenarios of RCPs. The observed rate in 1971-2010 was around 2 mm/y, yet it is likely to rise at 8 to 16 mm/y during 2081-2100 under the RCP8.5 scenario (Figure 2c) (IPCC 2014). These projections illustrate that the global climate is continously changing and posing threats to the environment and humans.

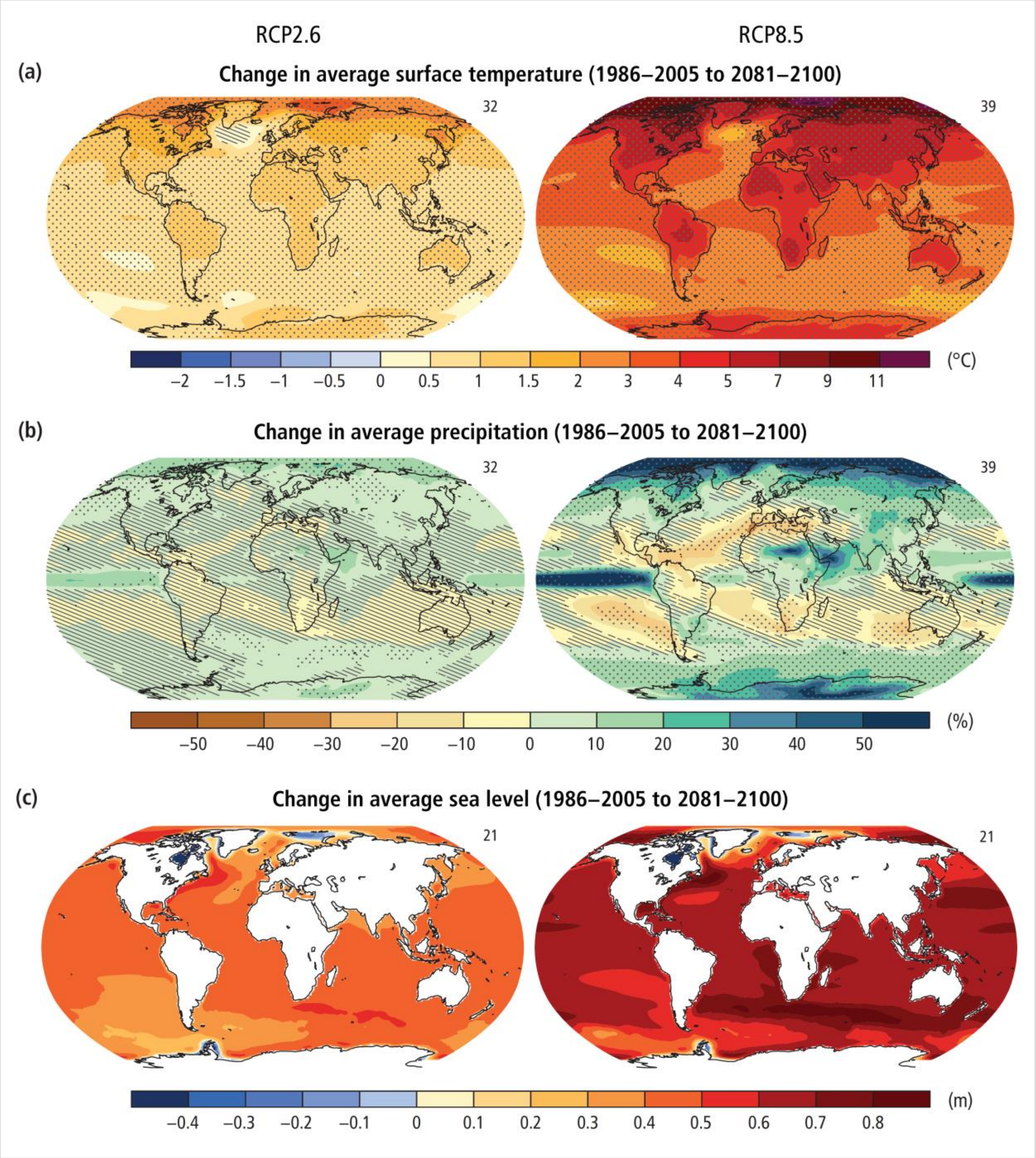


Figure 2: Projected change of the average global temperature, precipitation, and sea level based on the RCP2.6 scenario (left) and the RCP8.5 scenario (right) (IPCC 2014, p. 61).

2.4. Lao water institutional and policy frameworks

Lao People’s Democratic Republic (Lao PDR or Laos) has moved to a new era of water resources management. In the early 1990s, the Government of Laos (GoL) adopted the Integrated Water Resources Management (IWRM) approach and began to draft the national water policy and strategy as well as to establish water institutions (Jusi 2012). The first water resources law was established in 1996 and was recently revised in 2017. Even though the national water strategy has not been officially adopted as an individual document, the concept of IWRM and strategic plans have been incorporated in the National Socio-Economic

Development Plan (NSEDP) (MPI 2016), the Natural Resources and Environment Strategy (MoNRE 2015b), and the 5 year action plan of the Natural Resources and Environment Sector (MoNRE 2015a).

2.4.1. Water institutional arrangements

Water institutions in Laos have been transformed and updated from time to time in order to deal with the current issues. In the past, water management was very fragmented and around 10 agencies were directly involved in the management and development of water resources (ADB 2002, Manivong 2005, and Nonthaxay et al. 2004, cited in Jusi 2009; Jusi 2012). In 1998, the Water Resources Coordination Committee (WRCC) was established as the first national water apex body to coordinate water issues with different agencies at the national and local levels (GWP 2004). Later, this organisation was transformed into the Department of Water Resources (DWR) under the Water Resources and Environment Agency (WREA) established in 2007 (DFAT 2010, p. 4). In 2011, WREA combined with the land, forest conservation, and mineral conservation sectors to form the Ministry of Natural Resources and Environment (MoNRE) (MoNRE 2015b).

Under the new reformation of MoNRE, DWR has been retrained as an organisational entity. According to the mandate of DWR issued by MoNRE (2017), DWR’s role is to manage and coordinate water resources throughout the country. This includes river basin planning, water data and information management, minimum flow identifications, water licencing and entitlements, and groundwater management (MoNRE 2017). The management of water resources in Laos is generally based on administrative boundaries rather than hydrological boundaries (Jusi 2009). DWR acts as the national coordinating body, operating at the national level and it has vertical line offices or branches in every province and district. The Water Resources Section is operating at the provincial level while the Water Resources Unit looks after at the district level, as indicated in Figure 3.

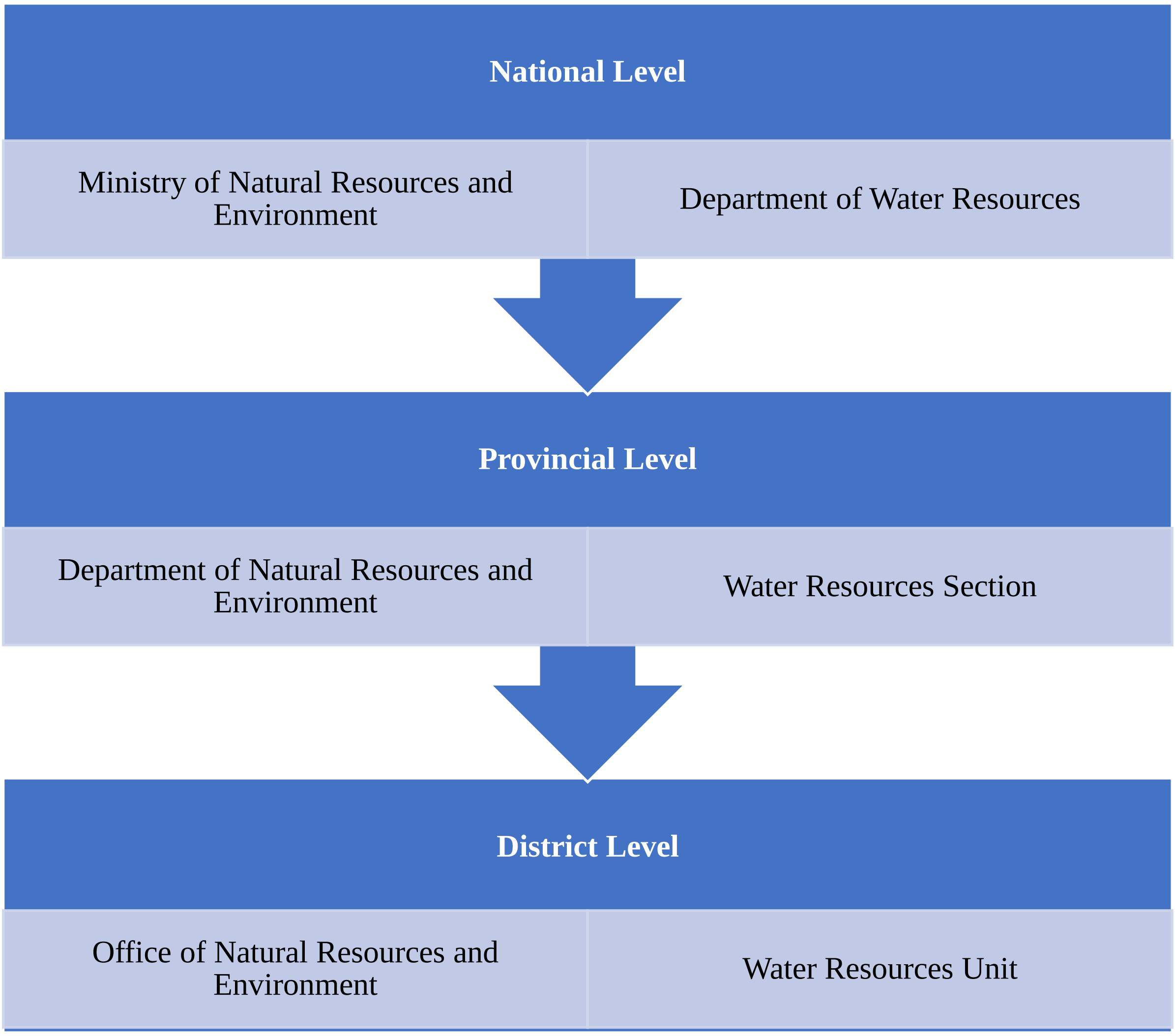


Figure 3: Administrative water management structure in Laos.

2.4.2. 8th National Socio-Economic Development Plan

The 8th National Socio-Economic Develop Plan (NSEDP) (hereinafter, the 8th Plan) has been developed as a five-year strategy for all sectors in Laos. The 8th Plan covers the period of 2016-2020 and it is notable that water plans have been synthesised into this plan (MPI 2016). This indicates that the GoL has been more aware of the importance of water management. The 8th Plan sets the targets for water resources management by selecting 10 out of 64 river basins as a priority to be managed based on the IWRM principles, developing a national IWRM demonstration park, developing wetland management plans, and identifying 200 water quality monitoring points across the country (MPI 2016). Within the 10 priority river basins, the NNRB is one of the top priorities for its water resources to be managed and allocated systematically.

2.4.3. Natural Resources and Environment Strategy 2025

The Natural Resources and Environment (NRE) Strategy 2025 is the first 10-year strategic plan of MoNRE that covers all issues of its sector. The strategic document summarises the achievement of the NRE sector in the last 15 years (2001-2015), states the vision for 2030, and indicates the strategic plans for 2025 (MoNRE 2015b). This strategic plan covers the main areas of water, land, forest, geology, climate change, disasters, and the environmental quality. The water strategic plan has also been incorporated into this strategy, stating that the strategy will ‘Implement IWRM and IRBM plans to secure the balance of water use between socio-economic development, livelihoods, and ecosystem protection’ (MoNRE 2015b, p. 33). Even though this strategy remains very general, it is a very important direction for the NRE sector, especially the water sector in Laos, to implement water resources management in a more sustainable way.

2.4.4. Natural Resources and Environment Action Plan 2016-2020

The NRE action plan is the 5-year plan of the NRE sector modified from the NRE strategy. This plan identifies the overall direction, specific goals, major activities, and priority projects. The water management plan has been more elaborated in this action plan. The highlights of the plan are as follows (MoNRE 2015a).

- Update and disseminate the water resources law.
- Establish river basin committees for the 10 priority river basins namely Nam Ngum, Nam Ou, Nam Tha, Nam Xam, Nam Theun-Kaking, Nam Ngiep, Xebungfai, Xebunghieng, Sekong, and Sedone River basins.
- Develop and implement IWRM plans for the 10 priority river basins and integrate the areas of water quality, groundwater, wetland, flood and drought, data and information, and awareness raising and capacity building in IWRM.
- Study the streamflow in the main rivers to ensure that water extracted for agriculture does not affect the minimum flow for the ecosystem.
- Set up at least 200 water quality sampling points in the 10 priority river basins.

It can be seen from the list of actions that water allocation for irrigation is one of the national priorities in terms of securing the minimum requirement of flow in rivers. In addition, NNRB is also one of the priorities that the government has been focusing on in its application of IWRM concepts to manage water resources in the river basin.

2.4.5. Water and Water Resources Law 2017

The law on water and water resources was initially approved in 1996 (National Assembly 1996) and then it was revised in 2017 (National Assembly 2017). Because the conditions of water development and management changed, the law needed to be updated to deal with the emerging issues. The new version of the law provides the legal principles, regulations, and measures regarding the management, governance, protection, development, and extraction of water resources (National Assembly 2017, p. 1). This includes integrated river basin planning, water allocation (water use permits and minimum flow identifications), and restrictions that may affect water quality and quantity. This law is an important legal tool for Laos to protect, manage, and develop water resources sustainably. However, technical guidelines and other sub-legislations are urgently needed to support the effective implementation and enforcement of the law.

2.5. Water Evaluation and Planning (WEAP)

2.5.1. WEAP descriptions

As water resources have been threatened and these threats have increased management challenges in many regions over the past decades, many tools and models have been developed to support decision making in water management planning. However, conventional models are not adequate for a complex simulation of water scenarios because there are many issues of concern, such as limited water to be allocated among competing users, climate change, ecological considerations, and policies for sustainable use (Sieber & Purkey 2015). For this reason, an integrated approach has emerged in water resources management and development in order to deal with the issues of water quality, equitable allocation, and ecosystem preservation.

The Water Evaluation and Planning system (WEAP) is a software tool that applies an integrated approach in sustainable water resources management planning. The WEAP software was first developed in 1988 and since then has been continuously supported and developed by the Stockholm Environment Institute (SEI) (SEI 2019a). As a microcomputer program simulating straightforward water balance models, WEAP provides comprehensive, flexible, and user-friendly support to planners in the analysis of policy frameworks and water allocation (SEI 2016). WEAP can be used as a database where it can store and compare a dataset of water demand and supply for analysis in the short and long term. As a forecasting tool, it is able to simulate streamflow, groundwater storage, water availability, water demand, evapotranspiration, pollution loads, and other environmental aspects. In addition, WEAP, as a policy analysis tool, can simulate a full range of scenarios in water development and management in order to answer various ‘what if…?’ questions (Sieber & Purkey 2015), as indicated by the following examples:

- What if the population growth rate changes?
- What if agriculture is intensified?
- What if the number of industrial units increases?
- What if rainfall patterns change?
- What if mean temperature increases?
- What if hydropower dams are built?
- What if water use efficiency is introduced?
- What if water treatment plants are built and operated?

As a water balance model, WEAP can be applied to single river basins or sub-basins, complex drainage systems, urban water use, and agricultural areas. It can support a wide range of issues for decision making, such as ‘sectoral demand analyses, water conservation, water rights and allocation priorities, groundwater and streamflow simulations, reservoir operations, hydropower generation and energy demands, pollution tracking, ecosystem requirements, and project benefit-cost analyses’ (Sieber & Purkey 2015, p. 1).

According to the WEAP user guide (Sieber & Purkey 2015), the steps of WEAP applications can be defined as follows.

1). Study definition: set up a schematic diagram or system components (Figure 4), boundary, time frame, units, and problem configuration.
2). Current account: input baseline or current data to provide a snapshot of actual water availability, demand, quality, and regime for the system calibration.
3). Scenario construction: create logical assumptions based on historical data, policies, costs, development plans, hydrological and technological trends, and other related factors.
4). Evaluation: evaluate the results of scenarios regarding the sufficiency of water, benefits and costs, environmental flow, and uncertainties.

To accomplish these functions, WEAP has a number of main components presented as schematic nodes. There are a total of 14 components: river, diversion, reservoir, groundwater, other supply, demand sites, catchment, wastewater treatment plant, runoff/infiltration, transmission link, return flow, runoff river hydro, flow requirement, and streamflow gauge (SEI 2019b).

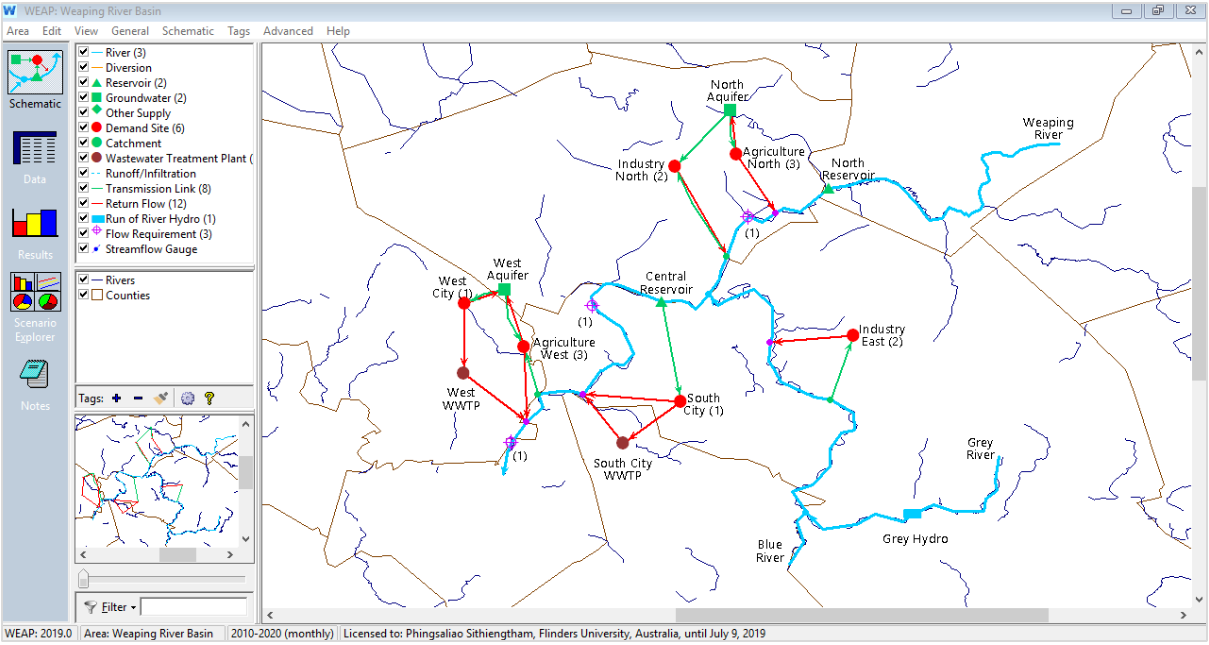


Figure 4: An example of a WEAP schematic diagram (SEI 2019b).

2.5.2. WEAP limitations

Even though WEAP is a powerful tool in integrated water resources planning, there are some limitations associated with this software (WEAP version 2019.0). For example, WEAP does not consider the shape and slope of rivers. The drainage system is assumed to be a flat surface, which is not realistic and this can lead to inaccuracy in streamflow calculation. In addition, WEAP does not model water quality in reservoirs and groundwater (Sieber & Purkey 2015). Hence, there is a need to combine with other models, such as MODFLOW, MODPATH, and QUAL2K, to simulate groundwater flow and water quality.

2.5.3. Examples of WEAP

Over the years, WEAP has become a popular software model that has been used widely in many river basins and sub-basins around the world (SEI 2019a). There are many studies that have employed WEAP to simulate the water balance and estimate future water availability and demand against climate change effects (McCartney et al. 2009 and Rayej 2012, cited in Berredjem & Hani 2017). One of the studies was conducted by Berredjem and Hani (2017) in the Lower Seybouse sub-basin located in the northern part of Algeria. They assessed the current water use and used WEAP to estimate water demand in three different sectors, namely household, industrial, and agricultural sectors. The findings showed that the water demand in the sub-basin will increase significantly, leading to insufficient water supply issues (Berredjem & Hani 2017). The researchers also modelled climate change impacts with the scenarios of extended drought. These scenarios projected higher unmet water demand (Berredjem & Hani 2017). This study indicates that sustainable water policy and technology are urgently needed for the Lower Seybouse sub-basin.

Another study using WEAP was conducted in the Mae Klong River Basin located in the west of Thailand by Khalil, Rittima and Phankamolsil (2018). The current surface water availability and water extraction were assessed and then the A2 and B2 scenarios of SRES was incorporated with six different simulations based on the current policies to forecast the future change of water status. Khalil, Rittima and Phankamolsil (2018) gathered data on water use, eight-station rainfall, six-gauge streamflow, evapotranspiration, and land use. Spatial data were analysed in ArcGIS and then put into WEAP model. They divided the river basin into six sub-catchments and employed the rainfall-runoff (simplified coefficient method) for the catchment method in WEAP. The model was calibrated and validated using the measured streamflow. The results revealed that unmet demand occurred in dry years and water shortages occurred in all scenarios (Khalil, Rittima & Phankamolsil 2018). This requires revision of the policy for sustainable water management in the river basin. In this study, however, groundwater which could be a major source of water supply was not considered in the model due to limited data availability (Khalil, Rittima & Phankamolsil 2018).

In addition, Jayasekera and Kaluarachchi (2013) conducted a study of water availability and water allocation under climate change for the whole NNRB in Laos. They divided the river basin into seven sub-catchments for the soil moisture method in WEAP model. The baseline data were consolidated in the period of 1991-1998 and they projected the future change for 2011-2090 using the A2 emission scenario (Jayasekera & Kaluarachchi 2013). The model was calibrated with observed streamflow data from 1991 to 1996 and validated with data from 1997 to 1998. The streamflow gauges used for the calibration were Naluang and Hinheup stations located in the upper and middle zones respectively (Jayasekera 2013, p. 50), while the lower gauge at the Pakkayoung station was not considered.

Jayasekera and Kaluarachchi (2013) simulated the model with different water allocation priorities. The water user sectors considered in this study were agriculture, domestic, and hydropower. Industrial factories were not separated as a water demand site and groundwater was not included as a supply source. The results showed that both rainfall and potential evapotranspiration in the NNRB will generally increase until the end of this century (Jayasekera

& Kaluarachchi 2013). With the climate change challenges, Jayasekera and Kaluarachchi (2013) concluded that the agricultural sector will face higher unmet water demand compared to domestic water use in the near future. The study suggested that effective climate change adaptation measures are required for sustainable water resources management and allocation planning in the NNRB.

CHAPTER 3: DATA AND METHODOLOGY

3.1. Study area

This study was conducted for the Nam Ngum downstream area between the Vernkham and Pakkayoung stream gauging stations. The Vernkham gauge, latitude 18°10'37" North and longitude 102°36'53" East, is located in Vernkham Village, Xaythany District, Vientiane Capital, Laos. The Pakkayoung gauge is positioned at around 76 kilometres upstream from the Vernkham gauge, at the latitude of 18°25'50" North and the longitude of 102°32'20" East. This upstream gauge is located in Pakkayoung Village, Viengkham District, Vientiane Province, Laos. These two locations along the Nam Ngum River were used to delineate the study area, as shown in Figure 6.

The boundary delineation was processed in a Geographic Information Systems (GIS) program called ArcMap version 10.6 (ESRI 2018). ArcHydro tools were used in conjunction with ArcMap to recondition a Digital Terrain Model (DTM) to characterise the stream cross-section (Merwade 2012). The 50 m cell resolution DTM was obtained from the Mekong River Commission Secretariat (MRCs). The derivation of this DTM is described in Section 3.2.10. After reconditioning, sinks in DTM were filled to eliminate small imperfections and adjust elevations to make streams connected (Mitchell 2012). The flow directions raster was generated from the filled DTM and then this raster was used to derive the flow accumulation. To determine conditional elevations, the Con command in ArcMap was applied to the flow direction and flow accumulation rasters. After that, the Stream Order function was used to generate the streamlines. The streamline raster was then reclassified to remove very small stream orders before conversion to line features. When the drainage system was established, the two locations of the stream gauges at Vernkham and Pakkayoung villages were used as pour points for 100 m snapping and delineating the catchment boundary for the study area. The process of delineating the study area is shown in Figure 5.

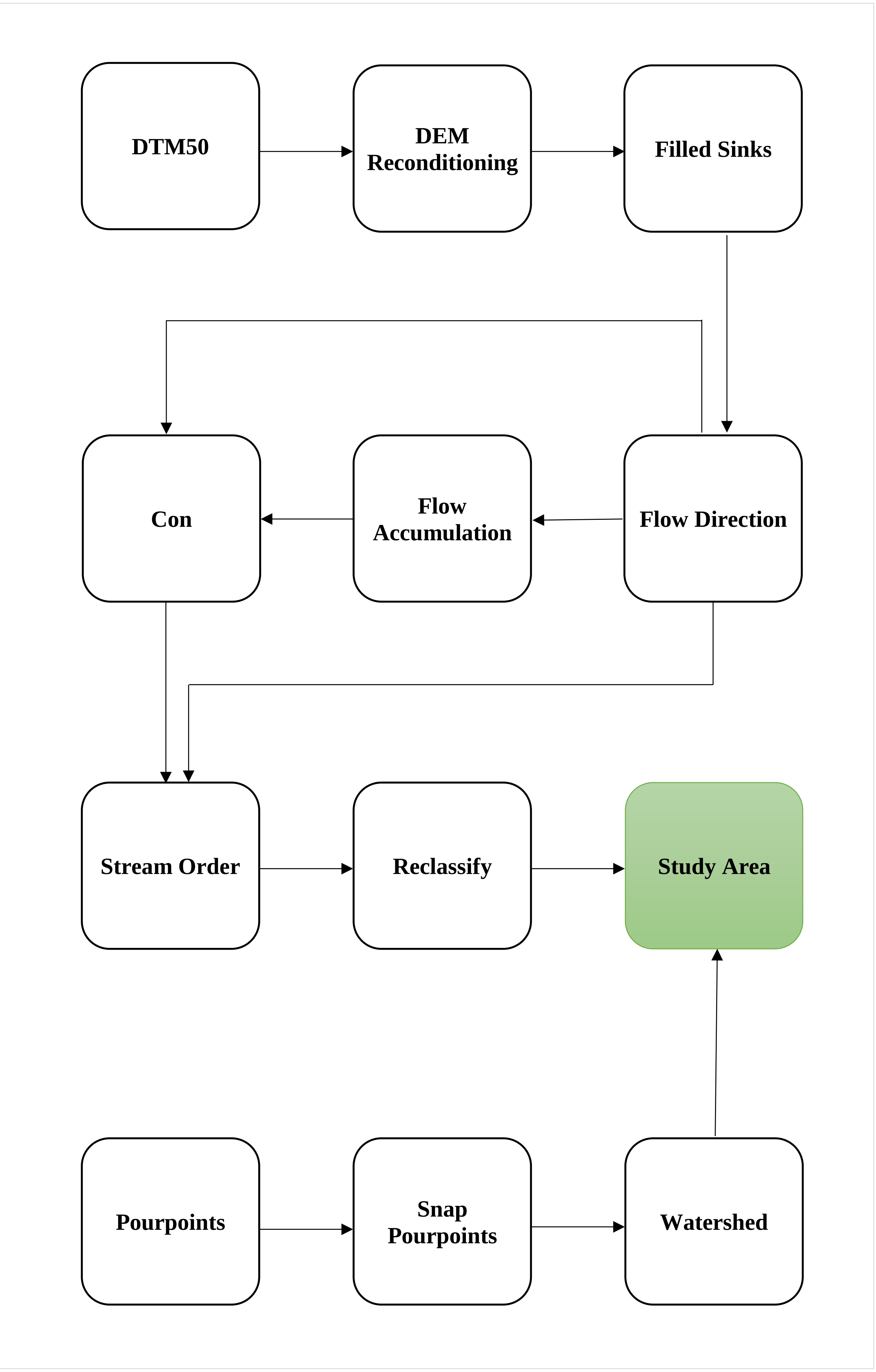


Figure 5: Flow chart of the key processes used to delineate the study area.

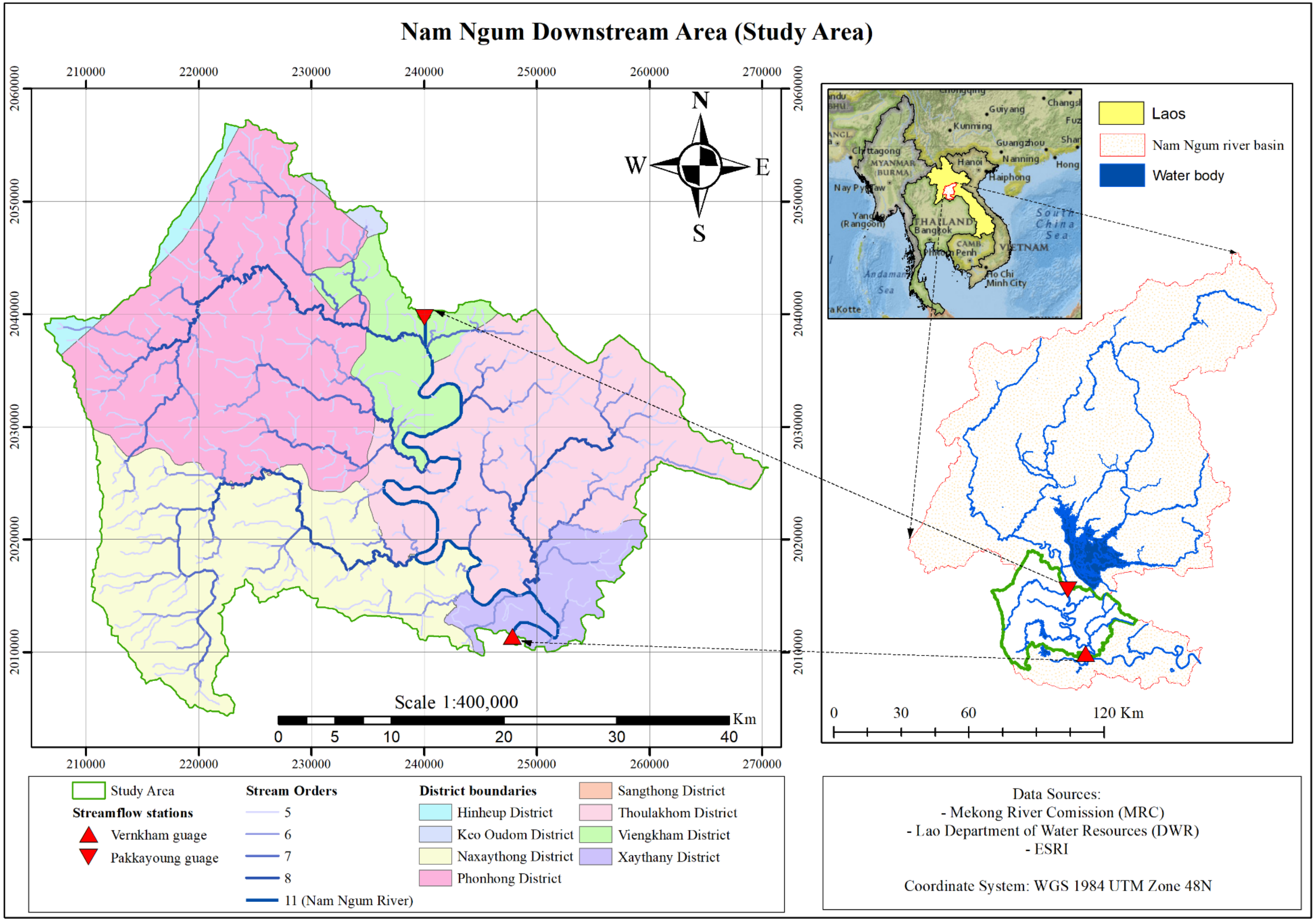


Figure 6: Map of the Nam Ngum downstream area (study area), showing the streamflow gauge locations, districts, and stream networks.

The study area covers two provinces and has an area of 167,192 ha. The northern part is located in Vientiane Province, covering mainly three districts namely Phonehong, Viengkham, and Thoulakhom. The southern part is in the Vientiane capital, covering two main districts: Naxaythong and Xaythany. Around 94% of the study area overlaps with the Nam Cheng-Nam Souang sub-basin. The Nam Cheng-Nam Souang sub-river basin is one of eighteen sub-basins in the NNRB and its boundary has been delineated by DWR (Nam Cheng-Nam Souang Taskforce 2015). In this study area, there are many rivers flowing to the Nam Ngum River particularly Nam Cheng, Nam Souang, Nam Phanai, Nam Kham, and Nam Bout Rivers (Figure 7) (Nam Cheng-Nam Souang Taskforce 2015). The study area has been divided into five sub-catchments and one floodplain area for WEAP schematisation as the model requires catchment nodes for water balance simulation. The sub-catchments divisions are shown in the following map.

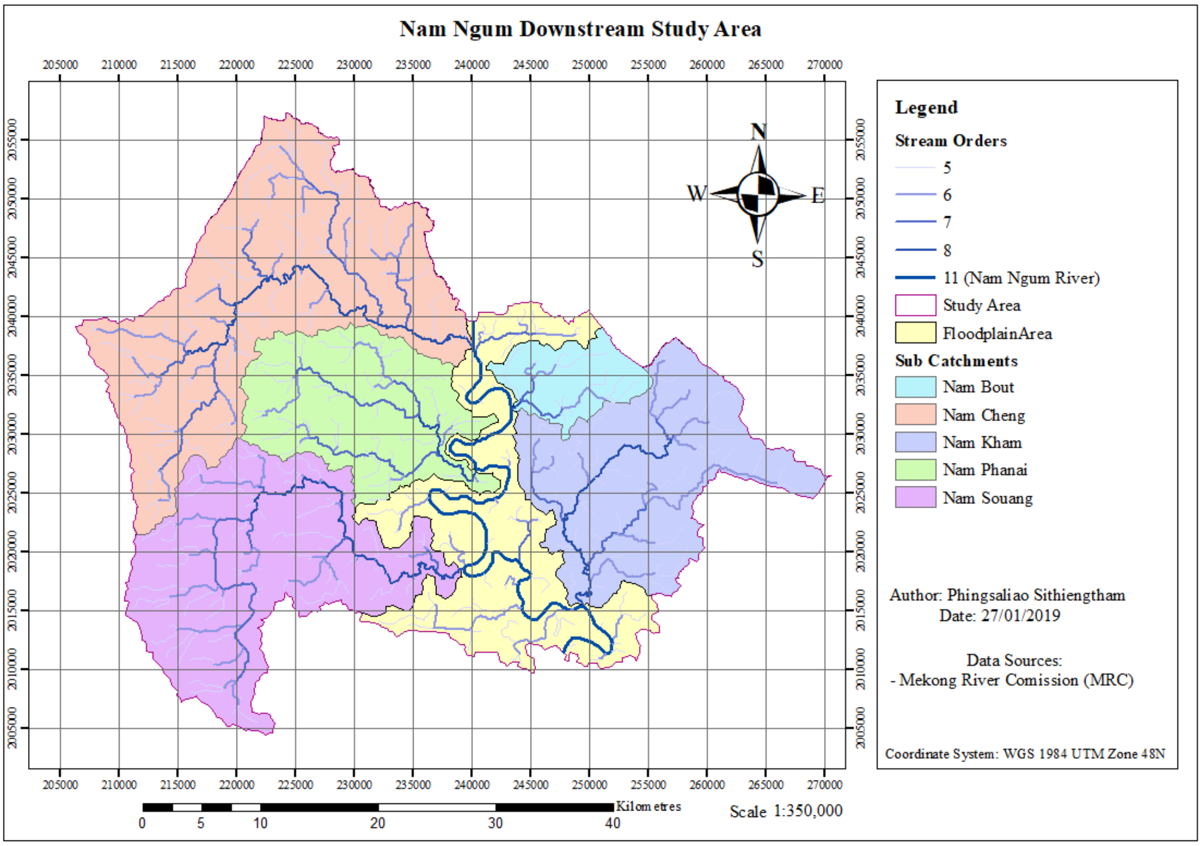


Figure 7: Sub-catchments in the study area.

There is rapid development in this study area, especially agriculture and urbanisation. According to DOI and JICA (2009, cited in Lacombe et al. 2011, p. 7), 75% of the agricultural area in the NNRB is concentrated in the downstream part or the Vientiane Plain, and this plain contains one-third of the irrigated area of the country. As this study area is close to the Vientiane prefecture, urbanisation is rapidly extending to surrounding areas especially Naxaythong and

Xaythany districts. In addition, other development sectors that use water are appearing such as industrial factories, water-based tourism, navigation, fishing, and infrastructure development (Nam Cheng-Nam Souang Taskforce 2015).

3.2. Data description and analysis

This water balance study requires various hydrological, hydrogeological, physical, and climate input data for the WEAP model. The key data required are described in the following sections.

3.2.1. Precipitation

Precipitation is the key input data for hydrological modelling. Precipitation can be in the form of rainfall, snow, sleet, or hail (URI n.d). In this study area, only rainfall was taken into account. The daily rainfall data from 2010 to 2016 were obtained from the Lao Department of Meteorology and Hydrology (DMH), which was measured at the Vernkham station (see the location in Figure 6). The average annual rainfall at this station was 1935 mm, which is about the average annual rainfall in the whole of the country (DWR 2008, p. 47). The wet season is from May to October. On average, the wettest month was September with 421 mm while the average driest month was February with 9.16 mm (Figure 8).

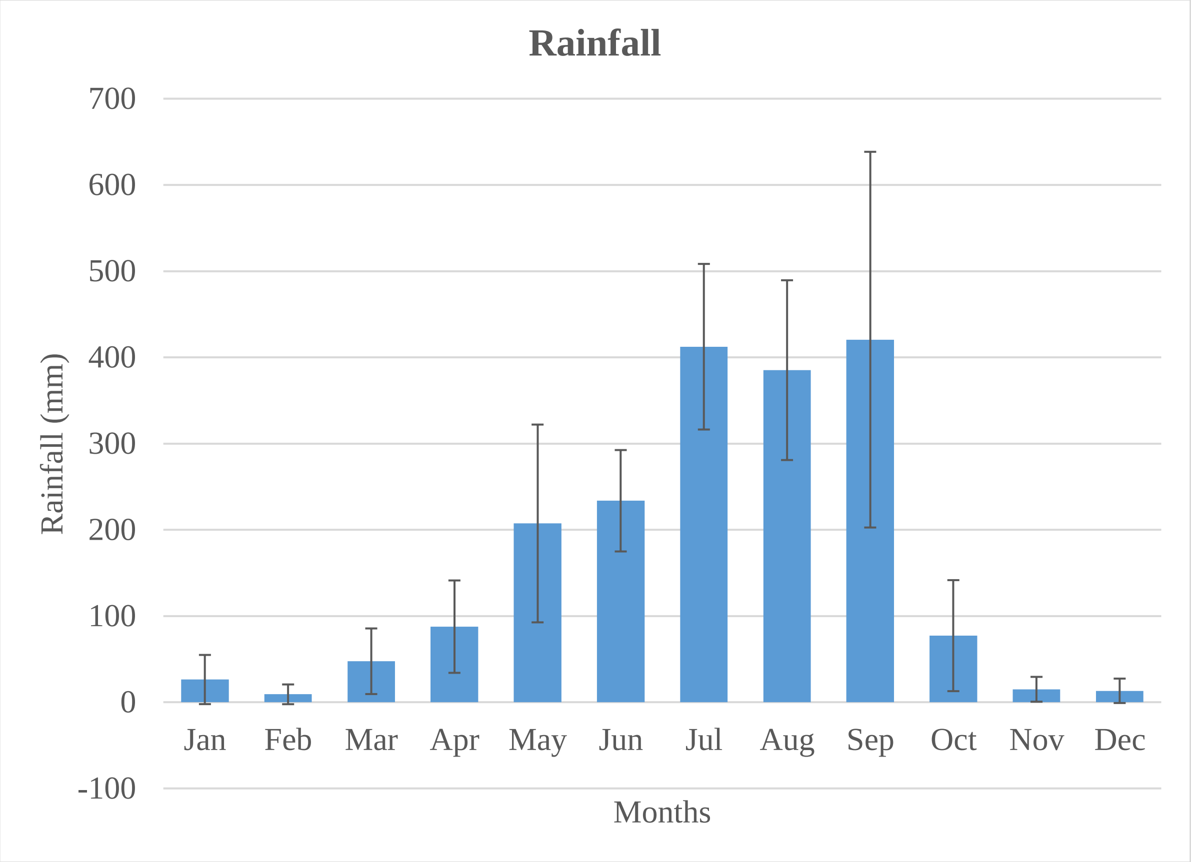


Figure 8: Average monthly rainfall from 2010 to 2016 at the Vernkham station with one standard deviation error bars (Data source: DMH).

3.2.2. Temperature

Weighted mean temperature is one of the required data for the soil moisture method in the WEAP model. The temperature data used in this study were obtained from DMH, which are the daily minimum and maximum temperature measured at the Vernkham station from 2010 to 2016 as shown in Figure 9. The mean daily minimum temperature ranged from 16.4°C to 25.0°C, while the mean maximum temperature ranged between 29.7°C and 36.8°C. January was the coldest month while the warmest month occurred in April. The average between the maximum and minimum temperature was used as an input into the WEAP model.

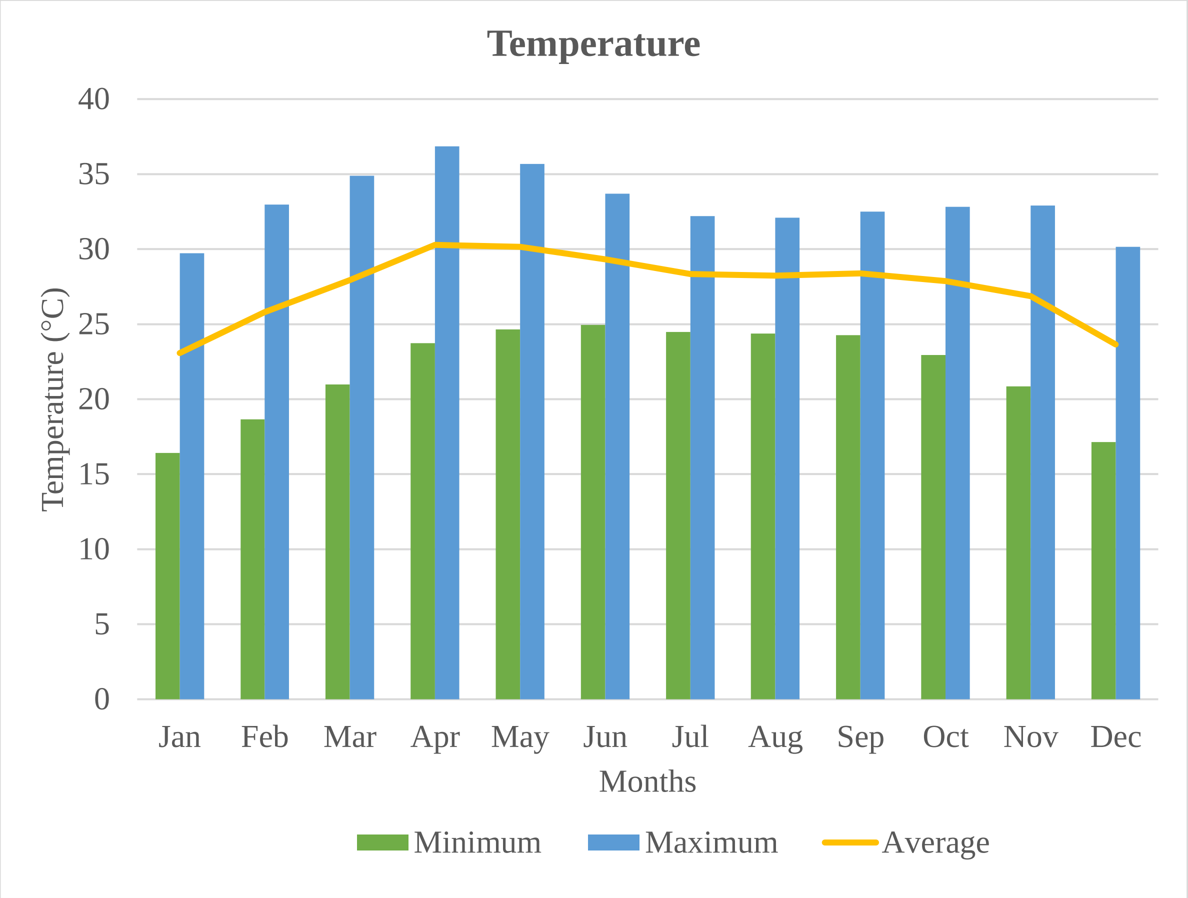


Figure 9: Average temperature from 2010 to 2016 at the Vernkham station (Data source: DMH).

3.2.3. Wind speed

Wind speed is also required for the soil moisture method in WEAP. The daily maximum wind velocity used in this study was measured from 2010 to 2016 at the Vernkham station by DMH. Figure 10 illustrates the average monthly wind speed and this shows the velocity range from 2 m/s (October) to 2.83 m/s (February).

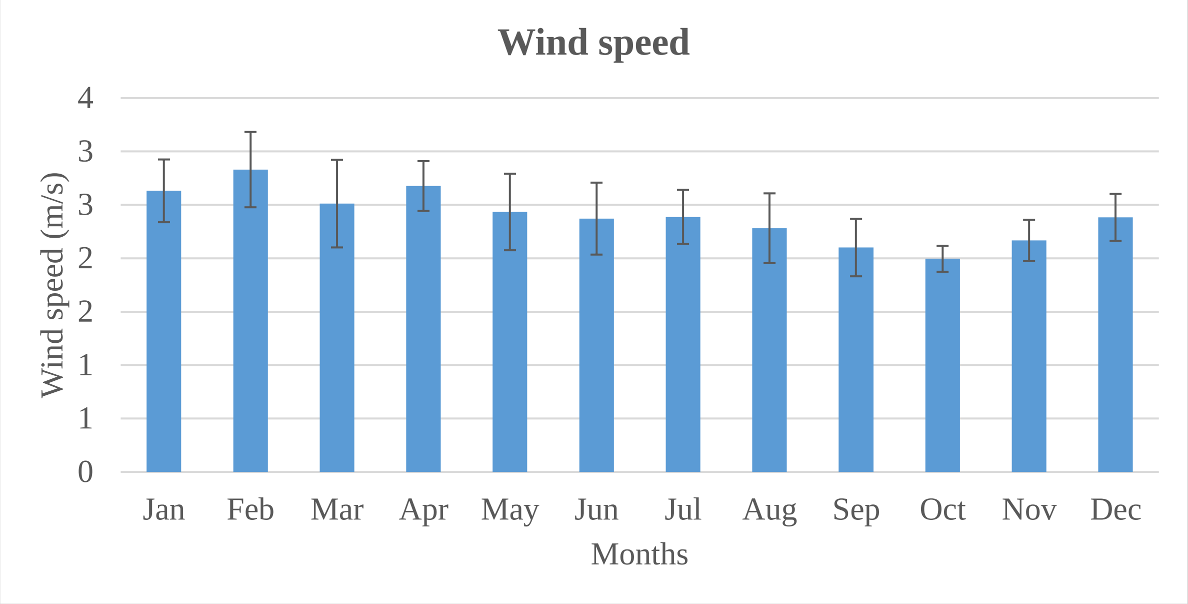


Figure 10: Average wind speed from 2010 to 2016 at the Vernkham station with one standard deviation error bars (Data source: DMH).

3.2.4. Humidity

Humidity is an important parameter in the soil moisture calculation for the WEAP catchments. Daily minimum and maximum humidity data at the Vernkham station were obtained from DMH. Figure 11 presents the average humidity from 2010 to 2016, illustrating that mean maximum humidity ranged from 91.0% to 97.7%, while the mean minimum humidity ranged from 42.9% (February) to 71.2% (August). The average daily humidity, estimated using the mean maximum and mean minimum humidity, was an input into the WEAP model of this study.

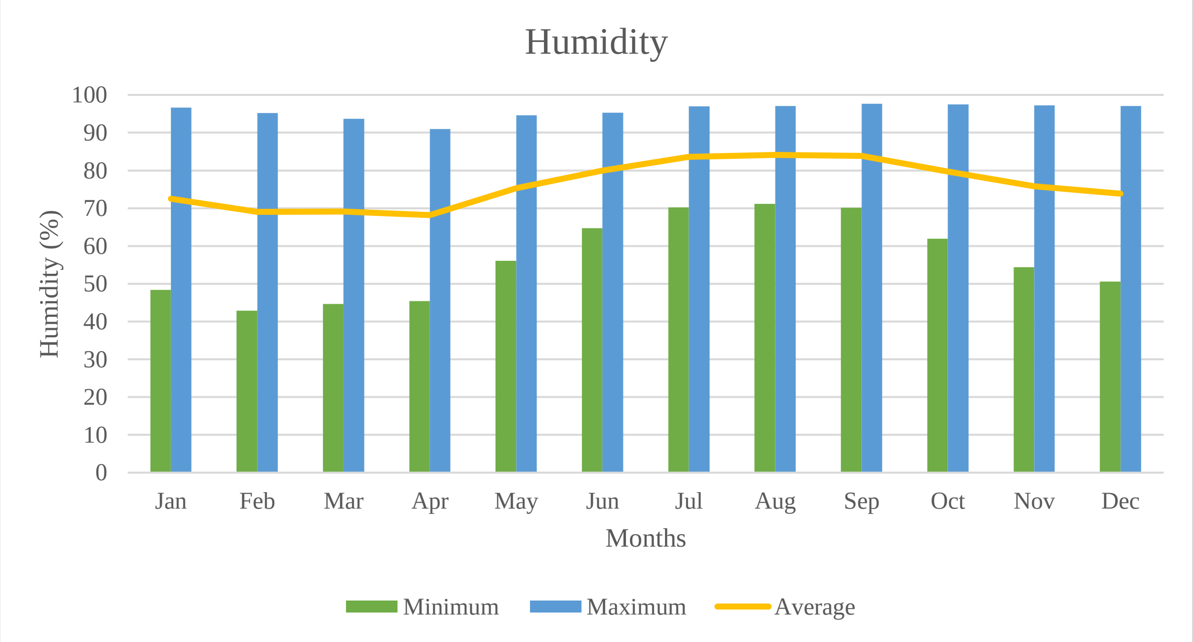


Figure 11: Average humidity from 2010 to 2016 at the Vernkham station (Data source: DMH).

3.2.5. Sunshine and cloudiness fraction

Sunshine duration is a key indicator to determine cloudiness fraction (Allen et al. 1998). Daily sunshine duration in hours was observed at the Vernkham station by DMH from 2010 to 2016. According to the observed data, more sunshine hours occurred during the dry season between October and May. On average of the monthly basis, the highest value was at 8.18 hours per day occurred in February, while July had the least number of sunshine hours (4.21 hours per day) (Figure 13).

Cloudiness fraction refers to the fraction of daytime hours with sunshine, ranging from 0 to 1, where 0 is completely overcast and 1 is no clouds (Sieber & Purkey 2015). WEAP requires cloudiness fraction to simulate soil moisture in the catchment model. According to Allen et al. (1998, p. 42), the cloudiness fraction is expressed by the following equation.

$$\textbf{Cloudiness fraction} = n/N \qquad \textbf{Equation 2}$$

Where n is the actual duration of sunshine (observed)

N is the maximum possible duration of sunshine or daylight.

N is dependent on the sun positions or latitude as indicated in the following figure.

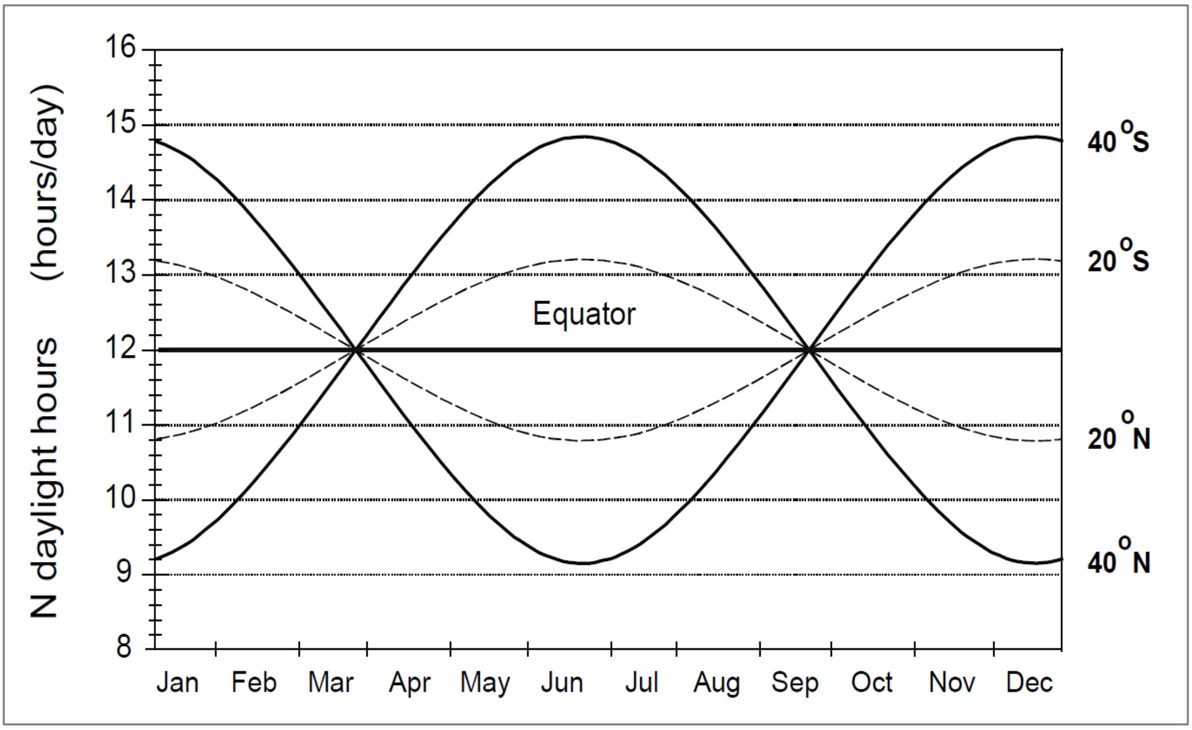


Figure 12: Annual variation of the daylight hours (N) for different latitude (Allen et al. 1998, p. 42).

As the study area is located at the latitude of approximately 18°20’North, the cloudiness fraction was estimated using Equation 2 (Figure 13).

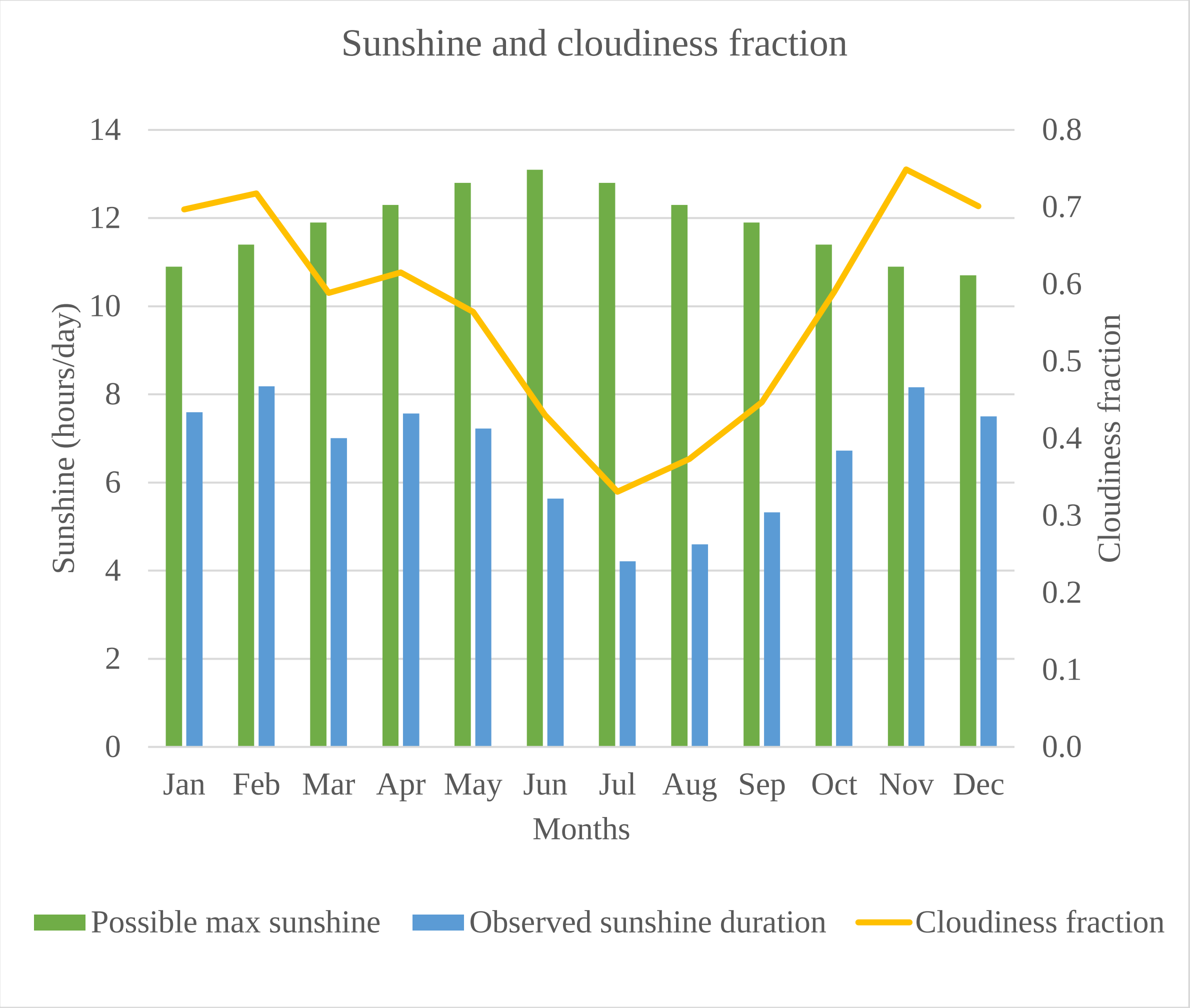


Figure 13: Average sunshine and cloudiness fraction from 2010 to 2016 at the Vernkham station (Data source: DMH and Allen et al. (1998, p. 42)).

3.2.6. River flows

There are two surface flow discharge gauges in the study area along the Nam Ngum River. The first gauge is located at the upstream in the study area and is called the Pakkayoung gauge. The second gauge is located at the downstream in the area and called the Vernkham gauge as shown in Figure 6. The daily streamflow data at both gauges during 2010-2016 were obtained from DMH. Figure 14 illustrates the average monthly streamflow at the Pakkayoung and Vernkham gauges. It can be seen from the figure that the flows were generally high from June to October and the flow at the lower gauge was around 25% higher than the flow at the upper gauge. The discharge at the Pakkayoung gauge represented the head flow of the Nam Ngum River in the model, while the observed discharge at the Vernkham gauge was used for model calibration and validation.

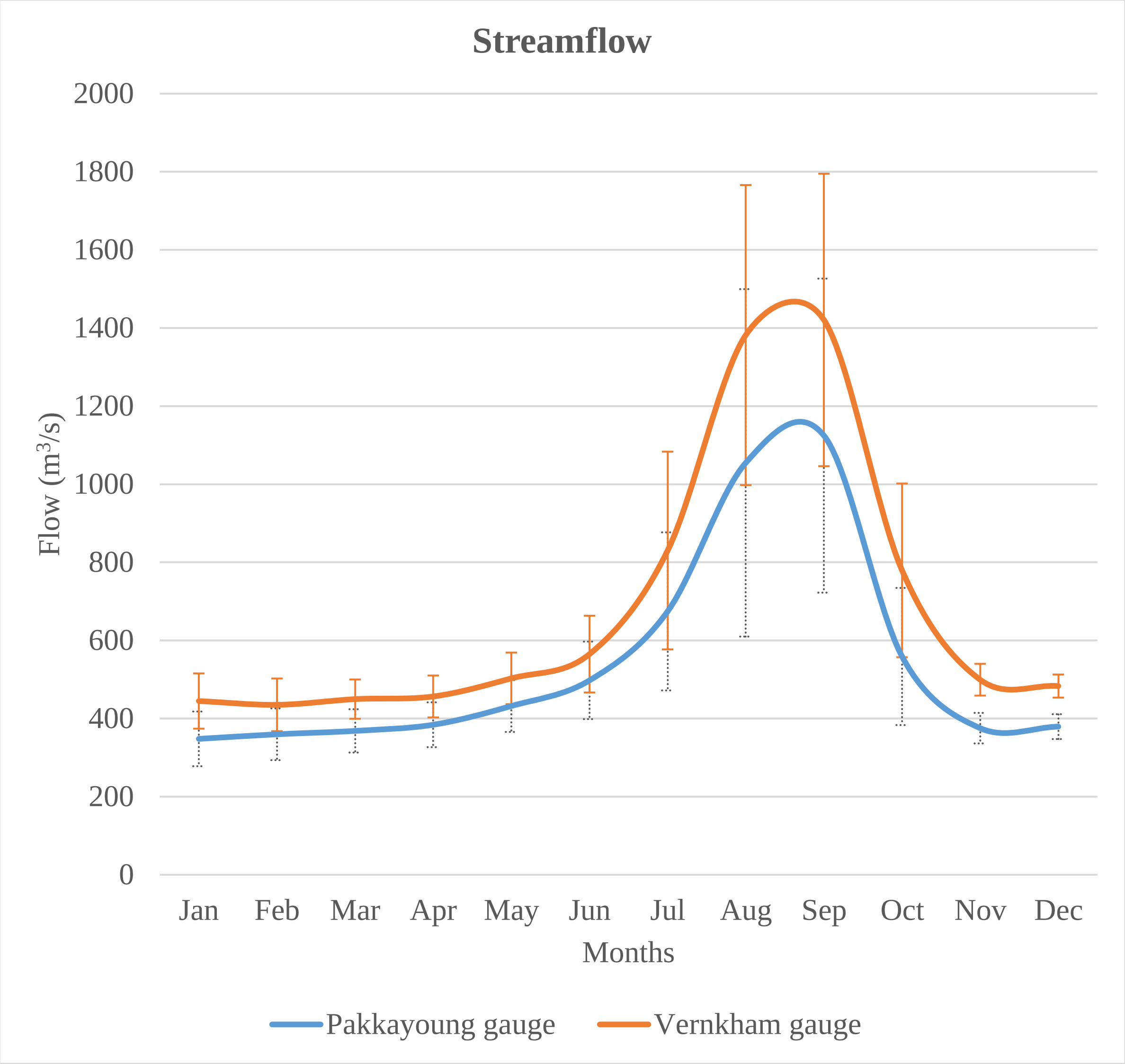


Figure 14: Average the Nam Ngum River flow from 2010 to 2016 at the Pakkayoung and Vernkham stations with one standard deviation error bars (Data source: DMH).

3.2.7. Land use

The data of land use types in the study was derived from a land use map. The map was updated in 2010 by the Mekong River Commission Secretariat (MRCs). This map was obtained as a raster file and was processed in ArcMap version 10.6 (ESRI 2018) to identify the area of each land cover type for each sub-catchment in the model. The land use types were consolidated into six groups, namely forest, irrigated area (paddy rice and vegetable), shrubland, urban area, water body, and bare soil as shown in Table 1. Figure 15 illustrates that shrubland covered the largest area, covering 42% of the total area. The second and third largest land use types were forest and paddy rice, which occupied 27% and 22% respectively. The forest includes broadleaved deciduous, broadleaved evergreen, coniferous, and bamboo forests. The areas of water body, urban area, and shifting cultivation covered around 3% each of the total areas, while bare soil presented only 0.1%.

Table 1: Land use 2010 in the study area (Data source: MRCs).

No.	Land cover	Sub-catchment Areas (ha)						Total (ha)
		Nam Cheng	Nam Souang	Nam Phanai	Nam Kham	Nam Bout	Floodplain Area	
1	Shrubland	22,058	10,426	9,495	12,628	2,766	12,523	69,897
2	Forest	11,730	19,379	4,413	7,346	1,543	1,258	45,669
3	Paddy rice	8,024	1,833	6,048	7,796	2,342	10,727	36,770
4	Water body	702	1,661	542	414	145	2,260	5,723
5	Urban area	1,244	377	715	470	83	1,884	4,773
6	Shifting cultivation (Vegetables)	2,533	1,377	148	68	-	-	4,125
7	Bare soil	1	24	55	80	23	53	235
8	Total (ha)	46,292	35,077	21,416	28,802	6,900	28,705	167,192

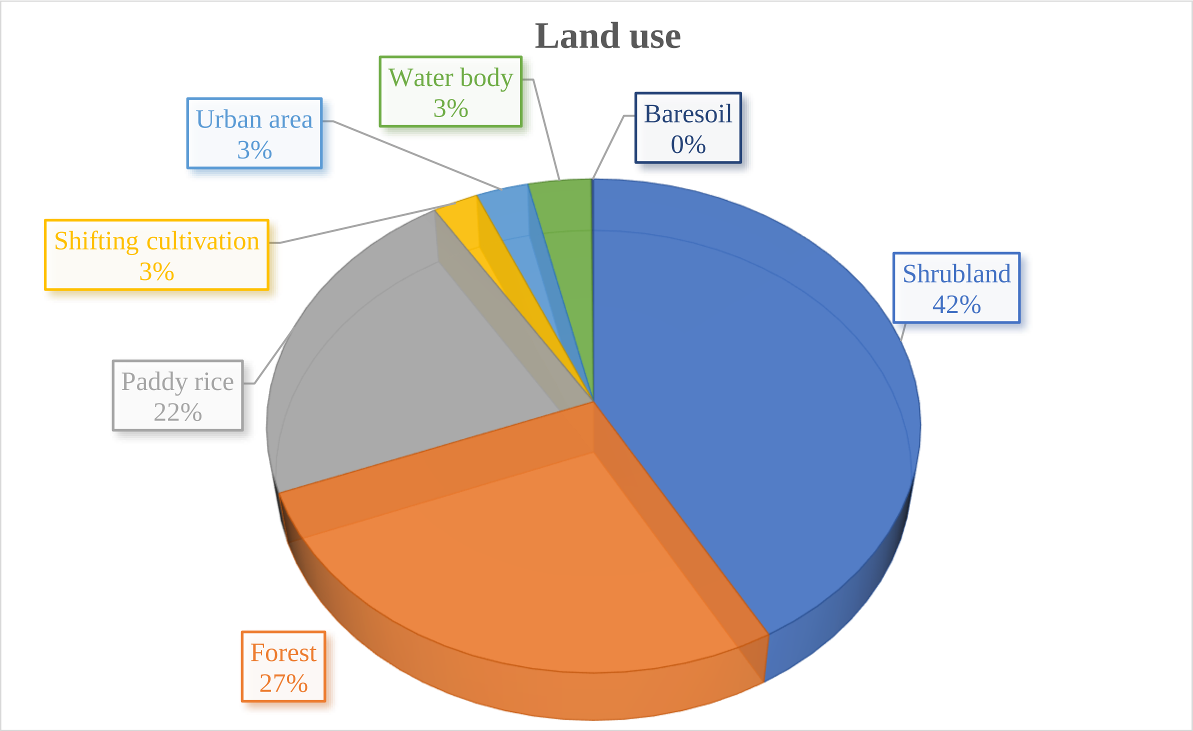


Figure 15: Proportion of land use 2010 in the study area (Data source: MRCs).

3.2.8. Population

Population is a key indicator of domestic water use. The number of residents in the study area was obtained from the Lao Statistics Bureau (LSB) in the form of a Shapefile updated in 2010. There were 31,457 households with a total population of 160,974 people, of which 81,715 are female (Table 2). Approximately 22% of the total population lived in the Vientiane capital with half in Xaythany District and the other half in Naxaythong District. Around 78% resided in Vientiane Province including Phonhong District 37%, Thoulakhom District 31%, Viengkham 9%, and Keooudom 1% (Figure 16).

As the population data was updated in 2010, the number of residents was put into the WEAP model with 2010 as the base year. For years after 2010, the annual growth rate of the Lao population was applied, which is 1.45% on average for 2005-2015 (Lao Statistics Bureau 2015, p. 22).

Table 2: Population 2010 in the study area (Data source: LSB).

No.	Districts	Provinces	Household	Population	Female
1	Naxaythong	Vientiane Capital	3,222	17,393	8,833
2	Xaythany	Vientiane Capital	2,967	17,518	8,750
3	Phonhong	Vientiane Province	11,129	60,089	29,859
4	Thoulakhom	Vientiane Province	10,951	49,343	25,097
5	Keooudom	Vientiane Province	242	1,220	630
6	Viengkham	Vientiane Province	2,946	15,411	8,546
Total			**31,457**	**160,974**	**81,715**

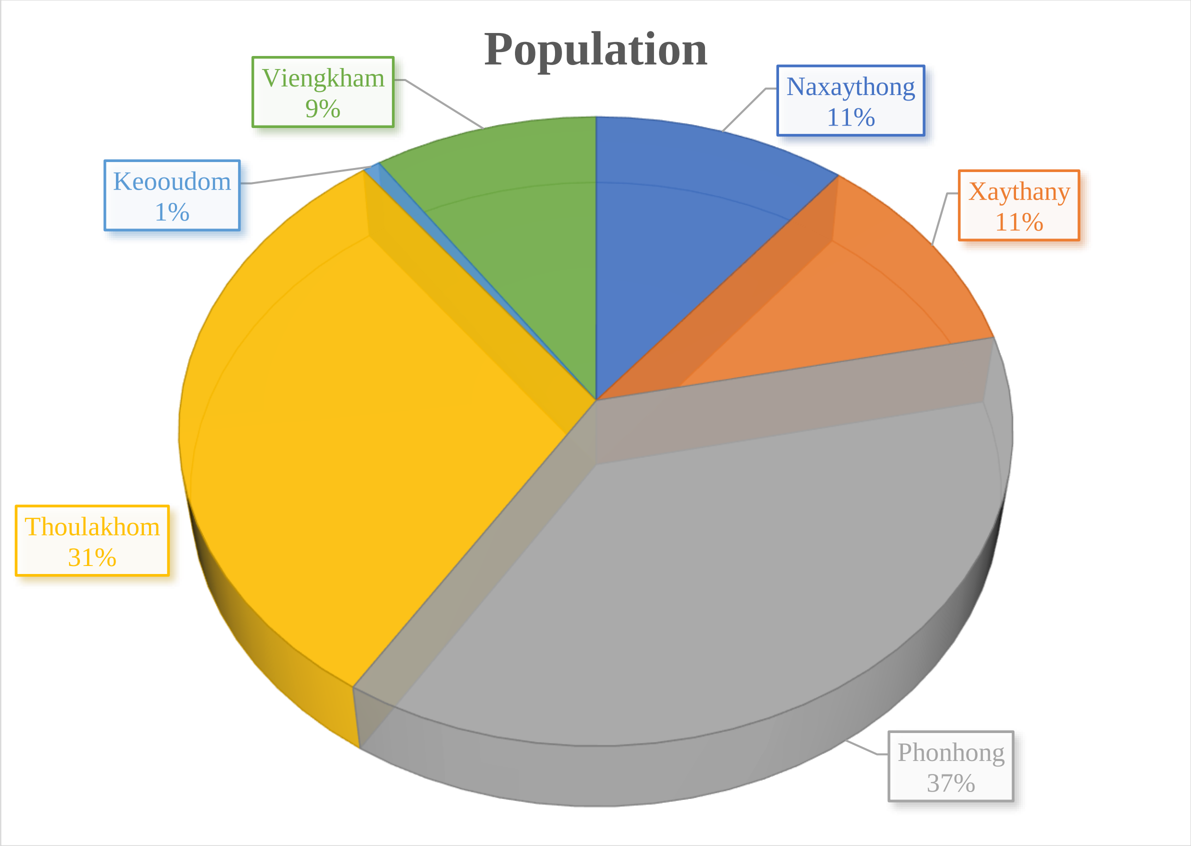


Figure 16: Proportion of the population 2010 classified by the districts in the study area (Data source: LSB).

3.2.9. Industrial units

The data of industrial units were received from the Lao Ministry of Industry and Commerce (MoIC). According to DIH and UNIDO (2018a, p. 16) and (DIH & UNIDO 2018b, p. 5), the factory establishments in Laos have been classified into four sizes according to the number of employees as follows:

- Micro factory: Less than 10 employees.
- Small factory: 11-50 employees.
- Medium factory: 51-200 employees.
- Large factory: More than 200 employees.

The statistics obtained are the industrial establishments in the Vientiane capital and Vientiane Province. The Vientiane capital's data was updated in 2017 while the Vientiane Province's statistics were from 2015. The data lists received present the names of villages and districts of the locations of each industrial factory. The names of villages and districts were matched to the population map which also shows the names of villages and districts in order to find out how many factories are located in the study area. Micro and small factories were merged into one group as small factories, so there were three sizes of industrial water demand in this study.

According to the data obtained, there were in total 422 industrial factories in the study area (Table 3). Of the total, 399 units were small factories, while 14 and 9 units were medium and large factories respectively. There were 290 units located in Vientiane Province and 132 units in the Vientiane capital. According to the five year socio-economic development of Vientiane Province, 13% annual growth in the industrial units is predicted (Vientiane Governor 2015, p. 82). This growth rate was applied to the WEAP model for future years.

Table 3: Industrial units in the study area (Data source: MoIC).

No.	Size	Vientiane Province (2015)	Vientiane Capital (2017)	Total
1	Large	2	7	9
2	Medium	4	10	14
3	Small	284	115	399
Total		**290**	**132**	**422**

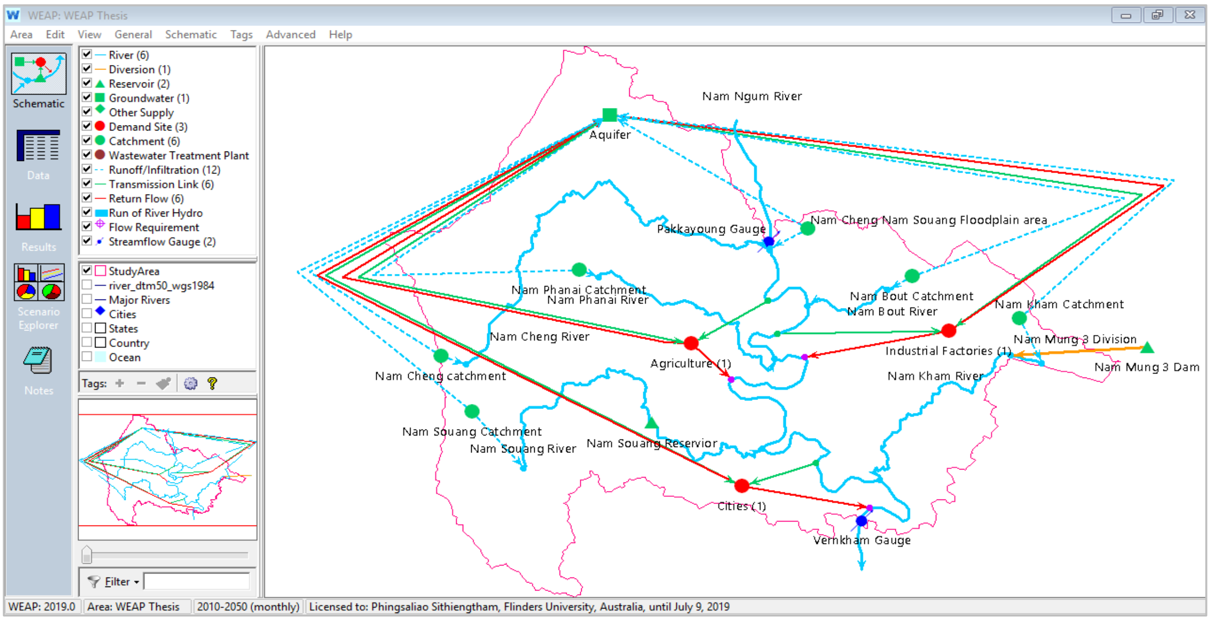
3.2.10. Digital Terrain Model

The Digital Terrain Model (DTM) is the input data to derive the study area or catchment boundaries, elevations, and slope for the WEAP model. The DTM was produced by MRCs in 2003 for the Lower Mekong Basin (LMB) covering the whole of Laos, Cambodia, and part of Thailand and Vietnam with the resolution of 50 metre cell size. This DTM was derived from four data sets as follows (MRCs 2003).

- Original DTM50: 1:50,000 American topographic maps and partially 1:100,000 Russian topographic maps, generated by Centre for Development and Environment, University of Bern and MRCs.
- Digital Elevation Models (DEM) with 20 metre cell size of the Mun River Basin produced from 1:10,000 topographic map 1982 by the Royal Irrigation Department of Thailand.
- DEM100 for Mekong floodplain from Phnom Penh to the Mekong Delta generated by the MRCs.
- DEM50 of the Tonle Sap region generated by MRCs.

3.3. Methodology

After data collection and analysis, the WEAP model was employed as a key tool in this water balance study. Firstly, the schematic diagram of the study area (Figure 17), as applied in WEAP, was established and the time frame was set up from 2010 to 2050. This means that 2010 was selected as the current account year or the initial conditions, and the model was simulated from 2011 to 2050 as reference scenarios. However, most of the observed data are between 2010 and 2016. The key features of the WEAP model in this study are elaborated in the following section.



☑ River (6)
☑ Diversion (1)
☑ Reservoir (2)
☑ Groundwater (1)
☑ Other Supply
☑ Demand Site (3)
☑ Catchment (6)
☑ Wastewater Treatment Plant
☑ Runoff/Infiltration (12)
☑ Transmission Link (6)
☑ Return Flow (6)
☑ Run of River Hydro
☑ Flow Requirement
☑ Streamflow Gauge (2)

☑ StudyArea
☐ river_dtm50_wgs1984
☐ Major Rivers
☐ Cities
☐ States
☐ Country
☐ Ocean

WEAP: 2019.0 | Area: WEAP Thesis | 2010-2050 (monthly) | Licensed to: Phingsaliao Sithiengtham, Flinders University, Australia, until July 9, 2019

Figure 17: The WEAP schematic diagram with node components of the study area.

3.3.1. Head flow

A river head flow is the amount of water flowing through the first node of that particular river (Sieber & Purkey 2015). In this study, six key rivers have been identified namely Nam Ngum, Nam Cheng, Nam Phanai, Nam Souang, Nam Kham, and Nam Bout (Figure 7). The head flow for the Nam Ngum River is represented by the observed discharge at the Pakkayoung gauge. This was put as daily data from 2010 to 2016. The head flows of the other rivers are derived from their particular catchment nodes. This means that the Nam Cheng, Nam Phanai, Nam Souang, Nam Kham, and Nam Bout river discharges are generated from available precipitation and application of the soil moisture catchment method (this method is described in the next section).

3.3.2. Catchment method

There are five different methods for catchment water simulation in WEAP. They are the Rainfall-Runoff (Simplified coefficient method), the Irrigation Demand only (Simplified coefficient method), the Rainfall-Runoff (Soil moisture method), the MABIA method (FAO56), and the Plant Growth method (SEI 2019b). In this study, the soil moisture method was selected to simulate the rainfall runoff relationship in the study area. This method divides the soil into two layers (Figure 18). The upper soil layer, or Bucket 1, is for simulating the runoff, shallow interflow, evapotranspiration, and soil moisture while the lower soil layer, or Bucket 2, is for simulating percolation and baseflow, which can be transmitted to the aquifer or routed to a river (Sieber & Purkey 2015). Figure 18 illustrates how the soil moisture method functions.

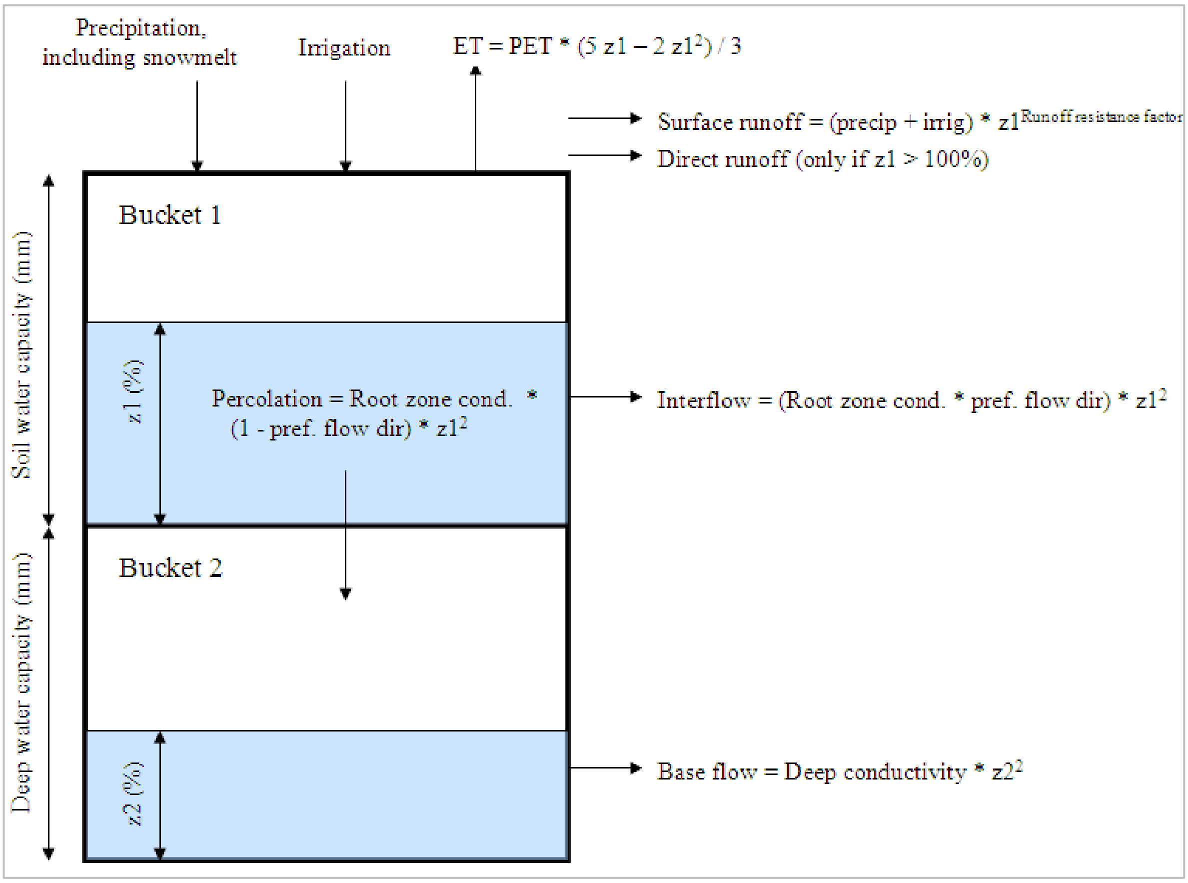


Figure 18: The conceptual diagram and equations of the soil moisture catchment method (Sieber & Purkey 2015).

Root zone conductivity: This conductivity determines the ability of water to be transmitted as interflow and percolation. The initial values for this hydraulic conductivity were obtained from Liu and De Smedt (2004, p. 49) and then they were calibrated with the parameter estimation (PEST) calibration in WEAP for each different land use type.

Deep conductivity: This represents the ability of water transmitted as baseflow. This value does not vary for different land cover type. It was calibrated in the WEAP model considering an initial value from Liu and De Smedt (2004, p. 49).

Runoff resistance factor (RRF): This kind of factor directly affects the amount of river discharge, which ranges from 0-1,000 where high value of RRF reduces runoff (Sieber & Purkey 2015). Runoff coefficient from Liu and De Smedt (2004, p. 53) were considered as initial concepts for RRF value calibration.

Preferred flow direction: This parameter determines the proportion of water whether it percolates to a deep aquifer or flows at shallow sub-surface. The initial concept for this value was considered based on the slope in the study area before calibrating.

Crop coefficient (Kc): Kc is one of the important parameters to calculate evapotranspiration. Initial Kc values were obtained from the crop evapotranspiration study of the Food and Agriculture Organisation (FAO) by Allen et al. (1998), and then they were calibrated.

Soil water capacity: This refers to the capacity of the topsoil layer that can hold water. This value was calibrated for each land use type.

Deep water capacity: This refers to an aquifer, so it was ignored since a groundwater node was created and linked to the catchment nodes in the model.

Z1 and Z2: These are the relative storages of the upper and lower soil layers respectively. The initial values for these storages were manually calibrated.

The calibration for the abovementioned parameters is described in Section 3.3.7.1.

3.3.3. Reservoir

The WEAP system divides a reservoir into four zones for operations: an inactive zone, a buffer zone, a conservation zone, and a flood control zone (Figure 19). The water in the reservoir will be automatically released when it exceeds the top of the conservation zone. At the conservation zone, water will be freely released to supply downstream water demand or requirements. When it reaches the buffer zone, WEAP will start to restrict the release based on a buffer coefficient in order to conserve the reservoir storage for supplying water demand. The buffer coefficient ranges from 0 to 1. When it is close to 1, the reservoir will try to release water to fully meet downstream requirements. If close to 0, WEAP will give higher priority to the reservoir storage than downstream water demand; however, it still releases some water for downstream users (Sieber & Purkey 2015). When water dwindles to the inactive zone, the reservoir will not function to release any water from the storage.

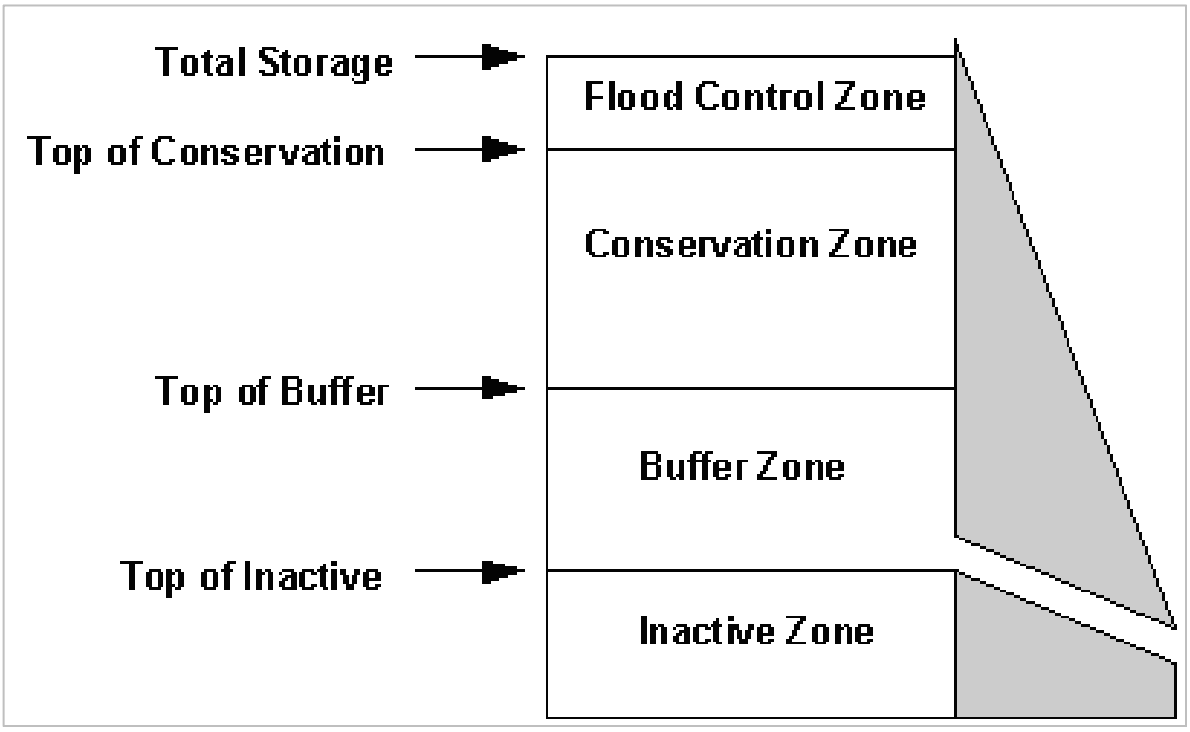


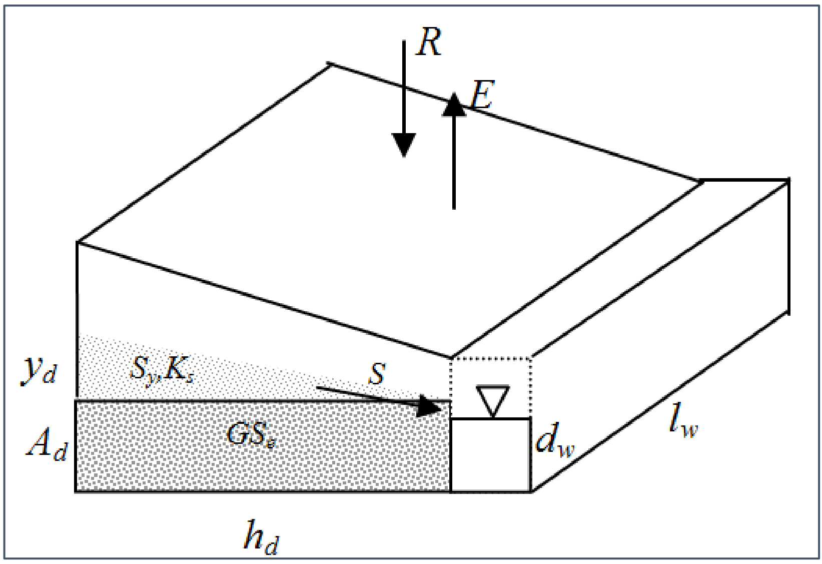
Figure 19: Reservoir operation zones in WEAP (Sieber & Purkey 2015).

There is one major reservoir in the study area called the Nam Souang reservoir. The data for this reservoir was obtained from the Department of Agriculture and Forestry of the Vientiane capital (PAFO VTE 2010). The total storage capacity of this reservoir is currently 127 million m^3, and its inactive zone can contain 34.2 million m^3 of water (PAFO VTE 2010). The operational rule of this reservoir in the model was to store water during the rainy season and release water during the dry season for agricultural demands. According to PAFO VTE (2010), the reservoir can supply water to 9,000 ha in the rainy season and 7,000 ha in the dry season.

3.3.4. Groundwater

In general, groundwater and surface water are hydrologically connected as a single resource (Winter et al. 1999). In this WEAP model, a groundwater node was established and connected to catchments, rivers, and demand sites. It has been assumed that groundwater sources in this study area are connected as a single aquifer.

Groundwater and surface water interactions were modelled by two methods namely the soil moisture catchment method and the ‘wedge’ method. The soil moisture catchment method was used to simulate groundwater recharge as Percolation = Root zone conductivity * (1 – Preferred flow direction) * $(z1)^2$. This is described in Section 3.3.2 and Figure 18. For the wedge method, groundwater is symmetrically stylised as a wedge, with only one side of the river being simulated because of the assumption of symmetry (Sieber & Purkey 2015). This means it is assumed that what happens on one side, such as recharge and extraction, will also occur on the other side. The following Figure 20 presents the groundwater wedge connected to a river.



- **GS_e**: Groundwater storage at equilibrium.
- **A_d**: Aquifer depth at equilibrium
- **h_d**: Horizontal distance
- **y_d**: Height above the river
- **S_y**: Specific yield
- **K_s**: Hydraulic conductivity
- **d_w**: River depth
- **l_w**: River length
- **S**: Seepage
- **R**: Recharge
- **E**: Extraction

Figure 20: A schematic diagram of the wedge method of groundwater and surface water interactions (Sieber & Purkey 2015).

Groundwater storage (GS_e): With an assumption that the groundwater table is in equilibrium with the river, the groundwater storage has been calculated based on the following equation (Sieber & Purkey 2015).

$$GS_e = (h_d)*(L_w)*(A_d)*(S_y)$$

Equation 3

Where:

- h_d is the horizontal distance from the edge to the river. The distance from the edge of the study area to the Nam Ngum River was measured in ArcGIS, and this value was used to calculate the groundwater storage at the equilibrium (GS_e).
- L_w is the length of rivers. This was measured in ArcGIS from the upstream boundary at the Vernkham gauge straight to the downstream boundary at the Vernkham gauge for the Nam Ngum River.
- A_d is the aquifer depth. According to the report of ACIAR by Pavelic et al. (2016), the alluvium depth in this study area ranges from 2 m to 40 m. The average depth of the alluvium depth was assumed as the mean aquifer depth, which is approximately 20 m.
- S_y is the specific yield of the aquifer. This value was estimated by Pavelic et al. (2016, p. 29) in the Nam Phanai sub-catchment (in this study area) using a water budget method. S_y was estimated to be 19%.

Seepage (S): This represents the rate of water exchange across the stream bed whether it discharges to a river or recharges from the river to the aquifer. Seepage is calculated in WEAP according to time-steps for both sides of the river on the basis of the following equation (Sieber & Purkey 2015).

$$\boldsymbol{S = 2\left(K_s * \frac{y_d}{h_d}\right) * l_w * d_w} \qquad \textbf{Equation 4}$$

Where:

- K_s is hydraulic conductivity. This value was calibrated in the soil moisture catchment method. (refer to Section 3.3.2).
- D_w is the wetted depth. The depth of the Nam Ngum River measured by DMH from 2010-2016 at the Pakkayoung gauge was used. The average value was 4.84 m.
- y_d is the height of the groundwater table above the river level. This determines whether the river is gaining or losing. y_d is calculated in WEAP according to the change in storage as with the following equation (Sieber & Purkey 2015).

$$\boldsymbol{y_d = \frac{GS-GSe}{(h_d)(l_w)(S_y)}} \qquad \textbf{Equation 5}$$

Where: GS is the groundwater storage varying over time according to the recharge and extraction. The initial storage was assumed to be 30% higher than the storage at equilibrium.

3.3.5. Water use rates

Water use in the study area has been classified into three main categories, namely agricultural use, domestic use, and industrial use. The water use rate for agriculture was obtained from a scientific study in the area while the water use rates for industry and household were derived from water supply reports.

The agricultural water use rate was derived by the use of CROPWAT, a crop water balance model for irrigation planning and management. Clement et al. (2018) employed the model to study water-use efficiency of irrigation in the Vientiane Plain. The study found that paddy rice requires 930 mm or 9,300 m^3/ha, while vegetable crops require 356 mm or 3,560 m^3/ha for total gross water supply (Clement et al. 2018, p. 25). These water-use rates were used as annual water demand for agriculture in the WEAP model.

The domestic and industrial water use rates were derived from the statistics of water supply in the Vientiane capital of Laos. Water use in the Vientiane capital has been supplied by the Vientiane Capital Water Supply State Enterprise (Nampapa Nakhonluang), extracting water sources from groundwater and the Nam Ngum River (Nampapa Nakhonluang 2017). Their customers include the two districts in the study area, which are Naxaythong and Xaythany districts.

The state enterprise has divided their customers into three user groups namely 1) household use, 2) bureau, state organisation, and diplomat use, and 3) business, commerce, and industry use (Nampapa Nakhonluang 2014, 2015, 2016, 2017). In this study, Group 1 and 2 were merged as domestic use. Based on the four years of statistics of Nampapa Nakhonluang (2014, 2015, 2016, 2017), the volume of annual water supplied was divided by the population served to derive the domestic water use rate (Table 4). The average for 2014-2017, 87 cubic metres per capita or 273 litres per day per person, was used as the domestic water demand rate for the WEAP model.

Table 4 Water supply statistic for industry in the Vientiane capital (Modified from Nampapa Nakhonluang 2014, 2015, 2016, 2017)

Year	Population served (persons)	Water supplied (m^3)	Water use rate (m^3/person/y)
2014	540,327	46,540,680	86.13
2015	569,627	44,945,366	78.90
2016	541,312	51,017,197	94.25
2017	570,793	49,703,828	87.08
Average	**555,515**	**48,051,768**	**87**

The industrial water use rate has been classified into three sub-categories according to the size of water meters installed. The Vientiane Capital Water Supply State Enterprise provides water for industrial customers with different sizes of water meters ranging from 13 mm to 300 mm (Nampapa Nakhonluang 2014, 2017). The meters with the sizes of 13, 15, 20, 25, 40, and 50 mm were assumed to have been installed for small industrial units, while the sizes of 80 and 100 mm water meters were for medium industrial units, and the meters with the sizes of 150, 200, and 300 mm were assumed for large industrial factories. The water use rates for the three different sizes of industry were derived by dividing the volume of water supplied by the number of water meters of each sub-category. One industrial or business unit was assumed to have installed only one water meter.

Table 5 presents water use rates for the different sizes of industrial factories. The average of the four years of statistics (2014-2017) was used in the WEAP model. The rate of 1,583.91 m^3/y was for a small industrial unit, 17,340.37 m^3/y was for a medium size, and 108,285.81 m^3/y was for a large one.

Table 5: Water supply statistic for industries in the Vientiane capital (Modified from Nampapa Nakhonluang 2014, 2015, 2016, 2017).

Year	Size	Number of meter (unit)	Water supplied (m^3)	Water use rate (m^3/unit/y)
2014	Small	3,352	5,202,623	1,552.10
	Medium	98	1,586,036	16,184.04
	Large	7	1,281,855	183,122.14
2015	Small	3,456	6,056,076	1,752.34
	Medium	95	1,599,672	16,838.65
	Large	8	663,980	82,997.50
2016	Small	3,544	6,521,506	1,840.15
	Medium	96	1,757,982	18,312.31
	Large	10	743,477	74,347.70
2017	Small	7,446	8,868,688	1,191.07
	Medium	106	1,910,806	18,026.47
	Large	9	834,083	92,675.89
Average	Small	4,449.5	6,662,223.3	1,583.91
	Medium	98.75	1,713,624	17,340.37
	Large	8.5	880,848.75	108,285.81

3.3.6. Demand sites

There were three key demand sites consolidated in this study. They were the city (domestic), industrial, and agricultural categories. WEAP assesses water demand according to annual activity levels and water use rates.

- Domestic water use: This was calculated by multiplying the population (Section 3.2.8) by the domestic water use rate (Section 3.3.5). The annual population growth rate of 1.4% was applied (Lao Statistics Bureau 2015, p. 22). In addition, water consumption was assumed to be 85% which is not returned to the system.
- Industrial water use: The number of industrial factories was multiplied by the industrial water use rate (Section 3.2.9 and Section 3.3.5). A 13% annual industrial growth rate was also applied according to the Vientiane Governor (2015, p. 82). In addition, water consumption was assumed to be 85%, which is not returned to the system.
- Agricultural water use: The agricultural area derived from the land use map including paddy rice and vegetables (Table 1) was multiplied by the agricultural water use rate (Section 3.3.5). In addition, product-embodied water or water loss from the system was assumed at 65% of total water use for agriculture (Zygmunt 2007, p. 6).

3.3.7. Model calibration and validation

The WEAP model was calibrated and validated according to observed stream flow data. The Nam Ngum River discharge has been measured at the Vernkham gauge located at the outlet of the study area (Refer to Section 3.2.6 and Figure 14). The data were collected by DMH daily from 2010 to 2016. Data from 2010 to 2013 were used for calibration, while data from 2014-2016 were used for validation.

3.3.7.1. Calibration

The calibration was done with the Parameter Estimation (PEST) in WEAP based on monthly time-steps. Sieber and Purkey (2015, p. 337) describe PEST as ‘a free software package for Model-Independent Parameter Estimation and Uncertainty Analysis’. It helps to improve the accuracy of simulations by comparing simulated streamflow to historically observed streamflow and automatically modifying some parameters (Sieber & Purkey 2015). The four years of observed discharge data, from 2010 to 2013, at the Vernkham gauge were selected for the model parameters adjustment. Automatic and manual adjustments were operated. The calibration was mainly for the parameters of catchments such as soil water capacity (SWC), runoff resistance factor (RRF), root zone conductivity (RZC), deep conductivity (DC), preferred flow direction (PFD), crop coefficient (Kc), initial topsoil layer storage (Z1), initial bottom soil layer storage (Z2), and albedo. According to World Bank (2017, pp. 23-4), four key parameters, namely SWC, RZC, RRF, and PFD, are sensitive, so these parameters were the initial focus before adjusting the other parameters.

After the calibration, the quality of the model was evaluated according to the study by Moriasi et al. (2007). Moriasi et al. (2007) recommend three quantitative approaches to quantify how well the model fits the observed data in watershed simulations. They are Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR). The calculations of these approaches are presented as Equation 6, 7, and 8 (Moriasi et al. 2007, pp. 887-8). The satisfaction of the outputs of the model has been classified into 4 levels ranging from 'Unsatisfactory' to 'Very good' as shown in Table 6.

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right]$$

Equation 6

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)*(100)}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)}\right]$$

Equation 7

$$RSR = \frac{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}\right]}{\left[\sqrt{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{mean}\right)^2}\right]}$$

Equation 8

Where Y_i^{obs} is observed values.
Y_i^{sim} is simulated values.
Y_i^{mean} is the mean of observed data.
n is the total number of observations.

Table 6: Performance ratings of NSE, RSR, and PBIAS for a hydrological monthly time-step model (Moriasi et al. 2007).

No.	Rating	RSR	PBIAS (%)	NSE
1	Very good	RSR < 0.50	PBIAS < ±10	0.75-1.00
2	Good	0.50 - 0.60	±10 - ±30	0.65 - 0.75
3	Satisfactory	0.60 - 0.70	±30 - ±50	0.50 - 0.65
4	Unsatisfactory	RSR > 0.70	PBIAS ≥ ±50	NSE ≤ 0.5

3.3.7.2. Validation

The validation was carried out after the calibration. The streamflow observed at the Vernkham gauge from 2014 to 2016 was the reference data for the validation. NSE, RSR, and PBIAS were also used to quantify the accuracy of the model in the validation process.

3.3.8. Scenarios simulations

The model simulation was up to 2050. The year 2010 was set for initial conditions, 2010 to 2013 was used for calibration, and 2014 to 2016 was used for validation. The future simulation was set for 2017 to 2050.

The main river inflow to the area was derived from the observed discharge at the Pakkayoung gauge. The monthly average of the discharge from 2010 to 2016 was used as the head flow of the Nam Ngum River in the study area. The water year method was applied, which defines very dry, dry, normal, wet, and very wet years. The average discharge was for normal years, while the minimum flow was for very dry years and the maximum flow was for very wet years. Dry and wet years were intermediate of very dry to normal years and very wet to normal years, respectively. These proportions were also used for the future rainfall. The proportions of the water year method are presented in Table 7. The list of years that were tested or assumed to be very dry, dry, normal, wet, and very wet is presented in Table 8.

Table 7: The monthly fractions of the river inflow derived from the historical flow record for very dry, dry, normal, wet, and very wet hydrological years.

Months	Very dry	Dry	Normal	Wet	Very wet
January	0.62	0.81	1	1.19	1.38
February	0.66	0.83	1	1.16	1.32
March	0.65	0.83	1	1.12	1.24
April	0.73	0.87	1	1.18	1.36
May	0.66	0.83	1	1.16	1.32
June	0.62	0.81	1	2.98	4.96
July	0.49	0.74	1	1.84	2.69
August	0.46	0.73	1	2.05	3.09
September	0.44	0.72	1	1.9	2.81
October	0.61	0.8	1	2.17	3.34
November	0.71	0.86	1	1.17	1.34
December	0.7	0.85	1	1.13	1.27

Table 8: Assumptions on future climate conditions for the water year method.

Years	Status	Years	Status	Years	Status
2017	Normal	2029	Normal	2040	Dry
2018	Normal	2030	Wet	2041	Wet
2019	Normal	2031	Wet	2042	Normal
2020	Dry	2032	Wet	2043	Very dry
2021	Dry	2033	Very wet	2044	Very Wet
2022	Dry	2034	Very wet	2045	Normal
2023	Very dry	2035	Very wet	2046	Normal
2024	Very dry	2036	Normal	2047	Normal
2025	Very dry	2037	Normal	2048	Normal
2026	Normal	2038	Normal	2049	Very wet
2027	Normal	2039	Normal	2050	Very dry
2028	Normal				

The model requires climate data for future simulation. Precipitation, temperature, and wind speed data for 2017 to 2050 were extracted from SEA START RC (n.d). These data were projected by a general circulation model named ECHAM 4 based on the A2 emission scenario (SEA START RC n.d). According to IPCC (2000, p. 10), the A2 scenario represents a continuously increasing population and regionally oriented economic development. This scenario was selected because it is likely to be worse than the others and if this case can be managed, the other scenarios will be also manageable (Jayasekera 2013, p. 74). In addition, for humidity and cloudiness fraction, the monthly averages of the measured data at the Vernkham station from 2010 to 2016 were used in this model.

In addition, development scenarios were established in the model to explore future water demand and availability. The scenarios include three possibilities: what if water demand increases, what if climate changes, and what if water inflow declines. The increased demand scenario is according to the government plans for example, agriculture is planned to be intensified by 5.5% annually, industrial units are planned to increase by 13% annually (Vientiane Governor 2015), and the population growth rate of 1.45% is according to Lao Statistics Bureau (2015). Future water availability was also modelled or experimented based on climate conditions as given in Table 7 and Table 8. Lastly, a scenario of halved water inflow from the Nam Ngum River to the study area was also modelled to determine whether the water is enough if the Nam Ngum 1 dam and the Nam Lik dams release 50% less water.

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Model calibration and validation

The calibrated model presented the simulated streamflow that were closely comparable to the observed data. Nine parameters were calibrated and their final values are presented in Table 9. Based on these values, the simulated streamflow is similar to the observed streamflow at the Vernkham gauge (Figure 21). It can be seen that for the first two years, 2010-2011, the simulated streamflow and the observed streamflow match well. For the other years of both calibration and simulation, however, the simulated streamflow is generally lower than the observed data. In the calibration period (2010-2013), the average observed discharge at the Vernkham gauge is 718.0 m^3/s while the simulated discharge is 647.6 m^3/s. For the validation period (2014-2016), the average observed and simulated discharge values are 653.7 m^3/s and 581.1 m^3/s, respectively (Table 10).

Table 9: Calibrated values for the WEAP model.

No.	Para-meters	Calibrated values							Unit
		Forest	Shrub-land	Paddy rice	Shifting cultivation	Urban area	Water body	Bare soil	
1	SWC	2,680	1,420	1,180	890	530	2,390	570	mm
2	RZC	2,160	1,720	3,120	1,960	1,180	4,280	1,390	mm/month
3	RRF	30	19	16	13	25	3	7	No unit
4	PFD	0.81	0.86	0.93	0.77	0.95	0.92	0.88	No unit
5	Kc	0.58	0.48	0.95	0.83	0.71	0.97	0.18	No unit
6	Initial Z1	45	40	85	68	15	100	35	%
7	Initial Z2				30				%
8	DC				357				mm/month
9	Albedo				0.35				No unit

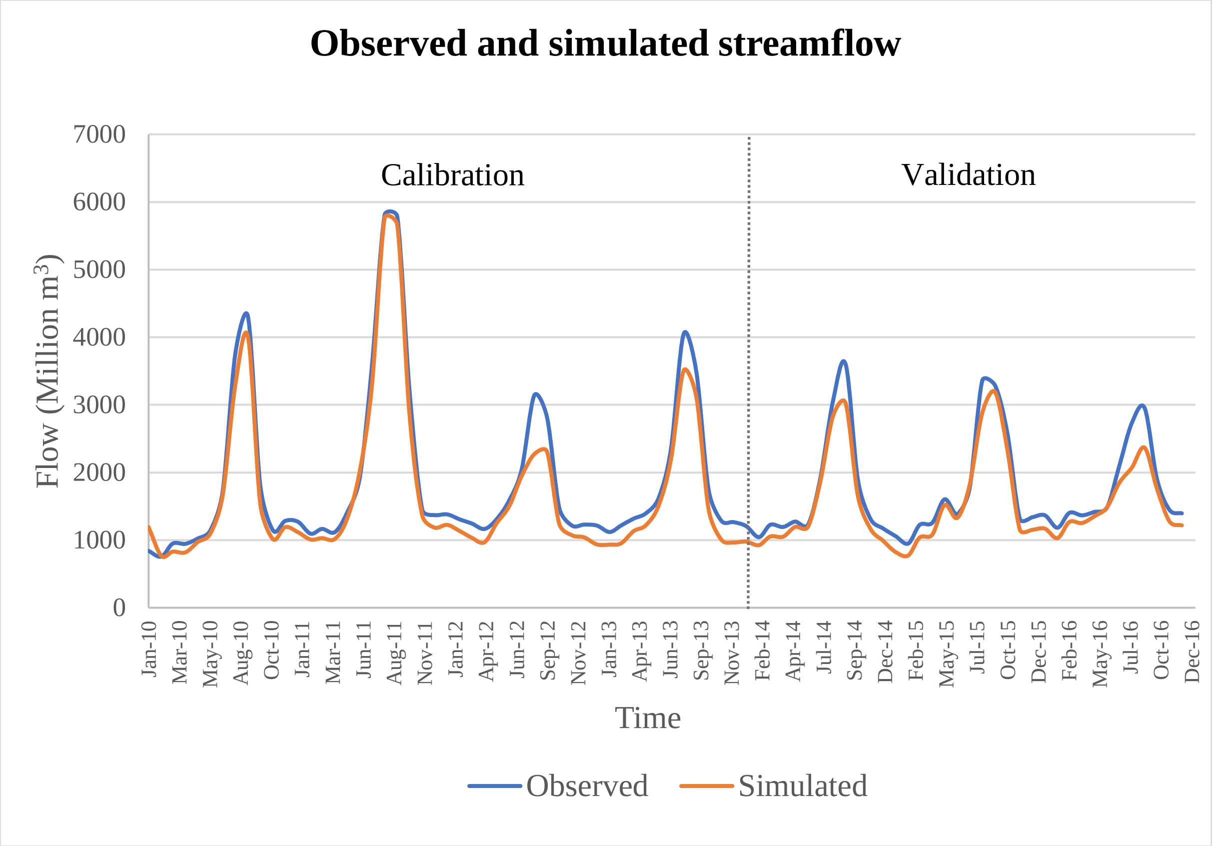


Figure 21: Simulated and observed streamflow at the Vernkham gauge from 2010-2013 for calibration and from 2014-2016 for validation.

There are three possibilities that could cause the simulated streamflow to be lower than the observed flows. Firstly, there may be some external groundwater that flows into the Nam Ngum downstream area and seepages to the Nam Ngum River between the Vernkham gauge and the Pakkayoung gauge. This area is located close to the Nam Ngum 1 reservoir and the elevation of the reservoir is around 40 m higher than the elevation of the Nam Ngum River in the study area. Therefore, there may be a possibility that the water from the upstream reservoir might percolate to the lower area. However, external groundwater inflow is not included in this study. Secondly, there might be some inaccuracy in the measured data. Lacombe et al. (2011, pp. 14-5) presented a graph of observed historical flow at the Nam Ngum River showing unrealistic streamflow peaks which they argued were due to errors in flow measurements. Finally, the rainfall data at the Vernkham station used in this model might not be 100% representative of the whole study area. Due to data constraints, the climate data from nearby stations were not interpolated. These three possibilities could explain why there are differences between the simulation and observation discharges.

However, the calibrated model does produce reasonable values of NSE, PBIAS, and RSR (Table 10). The NSE for the calibration and validation periods are 0.95 and 0.89 respectively. The PBIAS are 9.82% for the calibration period and 11.09 for the validation period. The RSR values are 0.21 and 0.34 for the calibration and validation periods, respectively. According to the rating classified by Moriasi et al. (2007) as shown in Table 6, the NSE, PBIAS, and RSR of the calibrated model as well as the NSE and RSR of the validation period are classified as 'Very good', while only the PBIAS for the validation period is categorised as 'Good'. This demonstrates that the model is capable of simulating the water balance in the Nam Ngum downstream area, and can simulate scenarios of future changes, such as climate change, agricultural intensification, infrastructure development, and population growth.

Table 10: Quantitative accuracy of the model through calibration and validation.

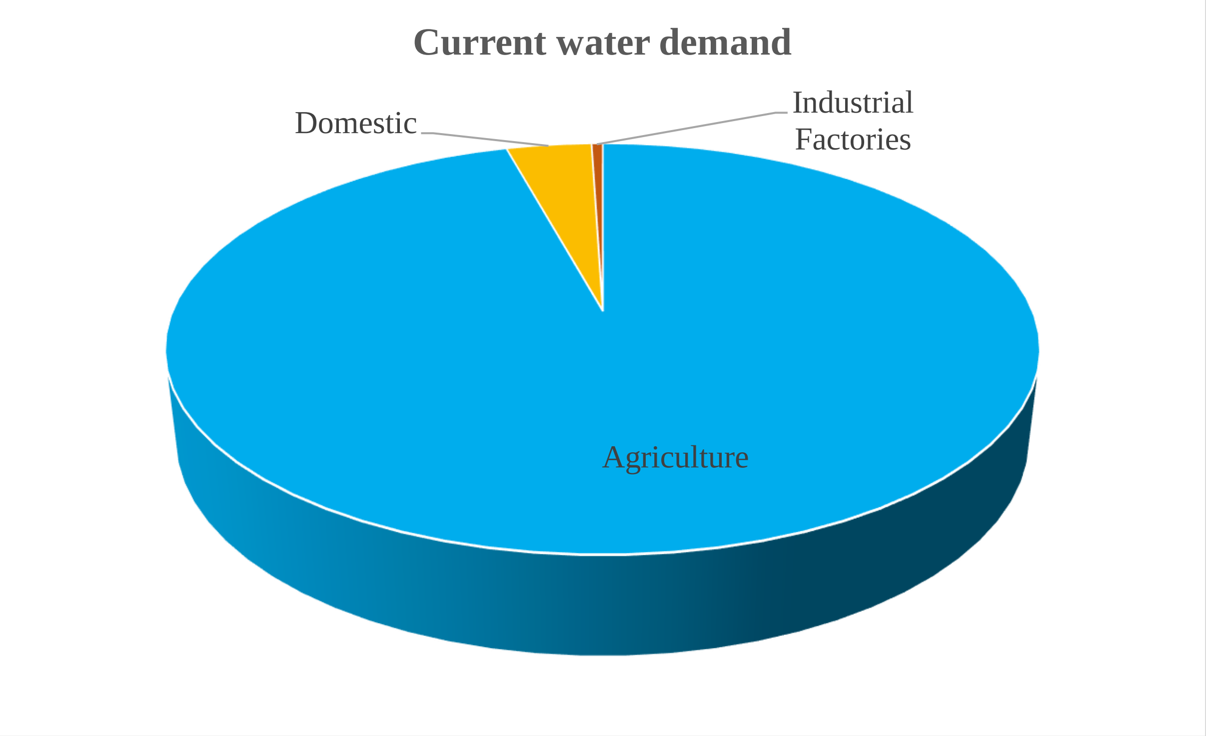
No.	**Simulations**	**NSE**	**PBIAS** (%)	**RSR**	$Q_{\bar{obs}}$ (m^3/s)	$Q_{\bar{sim}}$ (m^3/s)
1	Calibration (2010-2013)	0.95	9.82	0.21	718.0	647.60
2	Validation (2014-2016)	0.89	11.09	0.34	653.7	581.1

Remarks: $Q_{\bar{obs}}$ is the average observed discharge.

$Q_{\bar{sim}}$ is the average simulated discharge.

4.2. Current water demand

The quantity of water use by various sectors is quite different. Figure 22 presents the current amounts used by the sectors of agriculture, industry, and domestic or municipality. The current water demand in the Nam Ngum downstream study area is 372.5 million m^3/y (2010). The agricultural sector acts as the major water user, which extracts 356.6 million m^3/y or 95.74 % of total water extraction. The second biggest user is the domestic sector, which consumes 14 million m^3/y equivalent 3.76 %. The smallest water user is the industrial sector, which uses only 0.5% of the total water extracted in the study area, or an equivalent of 1.85 million m^3/y.



Water users	Annual water use (m^3)	Proportion (%)
Agriculture	356,646,000	95.74
Domestic	14,004,738	3.76
Industrial Factories	1,849,318	0.50
Total	372,500,056	100

Figure 22: Current amounts of water use by sectors in the Nam Ngum downstream area.

4.2.1. Agricultural water use

From Figure 22, it can be seen that irrigation requires much more water than the other users. This is because the study area includes some parts of the Vientiane Plain, which are suitable for planting crops such as paddy rice and vegetables. According to DOI and JICA (2009, cited in Lacombe et al. 2011, p. 7), one-third of the whole country's irrigated area is in the Vientiane Plain and 75% of the agricultural area in the NNRB is concentrated in the downstream part.

In addition, agriculture is the most inefficient water user (UN-Water and FAO 2007, cited in Mogelgaard 2011), so it requires a great deal of water to satisfy its requirements. According to Clement et al. (2018, p. 25), only around 17% of the total irrigation water supply was used for paddy rice in the Vientiane Plain. This means the other 83% of the water for agriculture has been lost to the system through percolation, evaporation, and runoff.

Furthermore, water extraction is generally free for agriculture in this area. The Lao Presidential Decree on natural resources fees does not legally enforce the payment of fees for water used by agricultural operators (President of Laos 2015). Although no direct fees are involved, some farmers who pump water from rivers and groundwater must pay for the electricity cost and irrigation maintenance in these cases. However, as the water is free, many users often take water for granted and do not effectively manage and regulate the amount of water used. These circumstances help to explain why the water use for agriculture is inefficient and leads to high volumes of water extraction for planting in the Nam Ngum downstream area.

Rice is the major crop in the Nam Ngum downstream area. Figure 23 shows that paddy rice requires water at around 342 million m^3/y covering 96% of the total agricultural water extraction. According to the Vientiane Governor (2015, p. 13), Vientiane Province harvested approximately 290,000 tons of rice during both the wet and dry seasons in 2014-2015. Only 4% of the irrigation water was supplied to vegetable land and other agricultural plants, which equals around 15 million m^3/y.

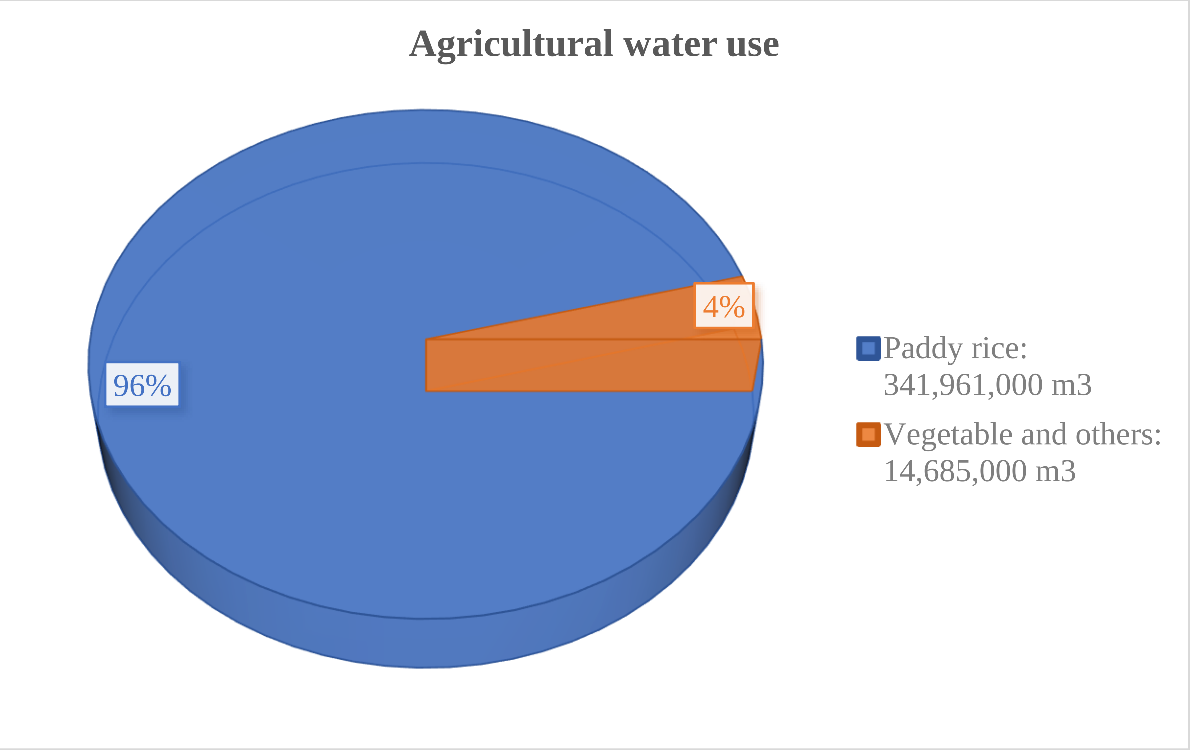


Figure 23: Current annual agricultural water use.

4.2.2. Domestic water use

Domestic water use is the second largest user after agriculture. Water use in this sector depends on the number of people living in the area. The total population in this study area is 160,974 persons (2010) and they consume around 14 million m^3/y of water. Figure 24 illustrates annual domestic water consumption by districts. Phonhong District uses more than the other districts, which extracts 5.23 million m^3/y or around 37% of the total domestic water.

This is because the study area covers almost the whole of the Phonhong District area. The second domestic water user is Thoulakhom District located on the eastern side of the Nam Ngum River. This district extracts around 4.3 million m^3/y equivalent to 31% of the total domestic water used in the study area. Xaythany and Naxaythong districts belong to the Vientiane capital and use 1.5 million m^3/y of water each or around 11%. Viengkham District consumes 9% or around 1.3 million m^3/y of water, while only 1% or 0.1 million m^3/y is used by Keooudom District.

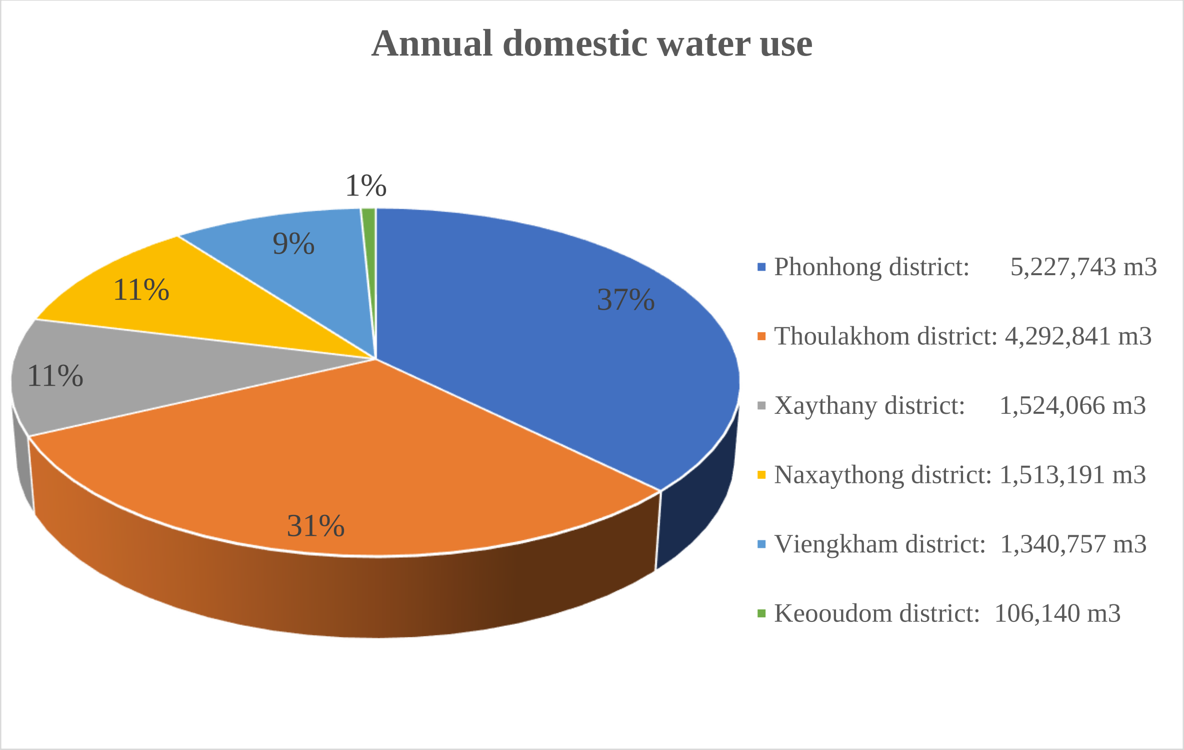


Figure 24: Current annual domestic water use classified by districts.

The water sources for the water supply in this area are from rivers and groundwater. According to Nampapa Nakhonluang (2017, p. 20), 99.6% of water supplied is extracted from surface water and only 0.4% is from groundwater. There are two main water supply companies in this study area. The Vientiane Capital Water Supply State Enterprise, or Nampapa Nakhonluang, provides water to Xaythany and Naxaythong districts. Another supplier is the Vientiane Province Water Supply State Enterprise, which supplies water to Phonhong, Viengkham, Thoulakhom, and Keo Oudom districts in Vientiane Province.

However, the water supply networks do not cover all households in the study area. Nampapa Nakhonluang supplied water to only 72% of their population in 2017. Thus, those who cannot access water supply infrastructure normally extract water from natural sources for household use, especially from groundwater by drilling wells. According to Heang (2015), groundwater could be a main source of rural water supply and averages 120 L/person/day.

4.2.3. Industrial water use

The industrial factories are the smallest sector that consumes water in the Nam Ngum downstream area. This sector requires approximately 1.85 million m^3/y. Figure 25 presents annual industrial water use organised into categories by the different sizes of factories. The number of large factories is relatively small; however, this category uses more water than the other groups. Large industrial factories in the Nam Ngum downstream area require 974,572m^3/y, equivalent to 53% of the total industrial water demand. The medium size factories need water for processing at around 242,765 m^3/y or around 13% of the total industrial water. This category requires less water than the others because the number of medium factories is still limited. For the small size of industry, its water use rate is the smallest in comparison to the others; however, there are many industrial units established as small or household businesses in the study area. This category extracts water at 631,980 m^3/y, equivalent to 34% of the total industrial water extraction.

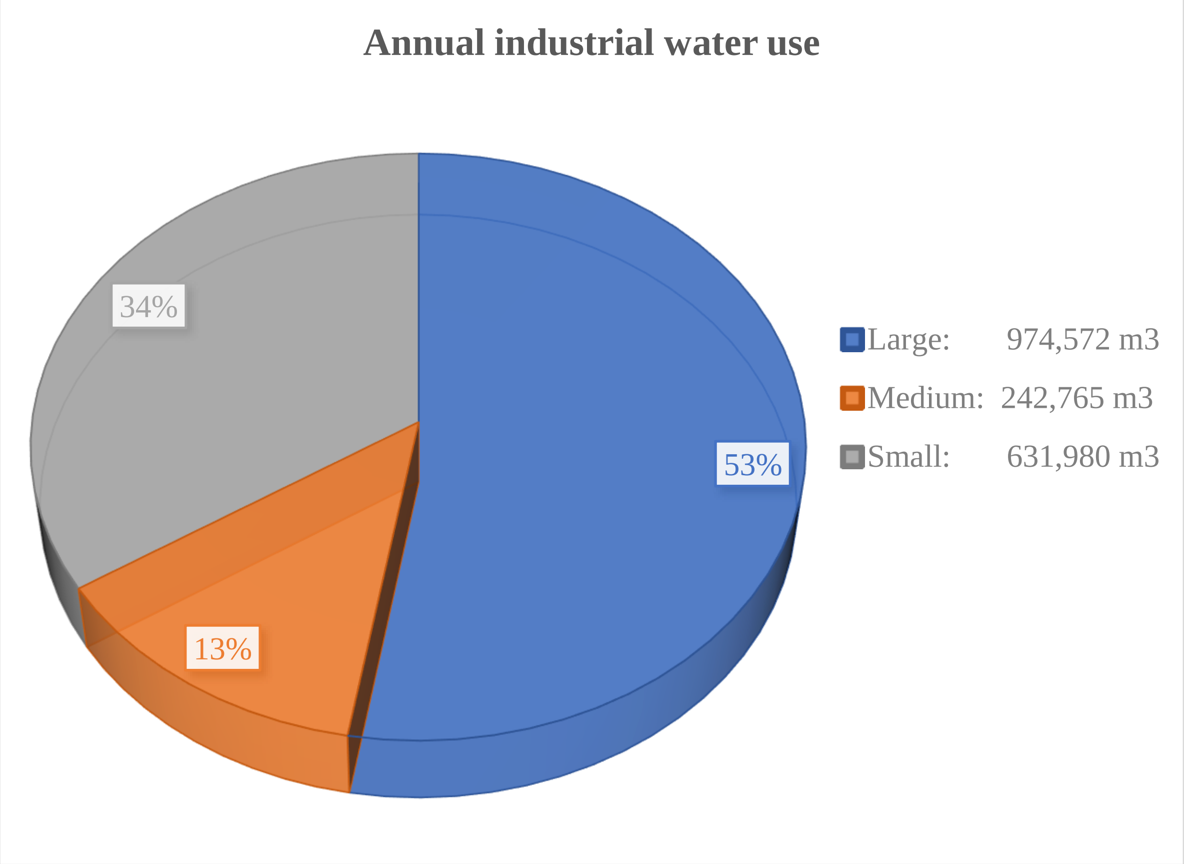


Figure 25: Current annual industrial water use classified by factory size.

Water sources for industrial use also come from both surface water and groundwater. Some factories also receive water from the water supply companies, Nampapa Nakhonelunag (Nampapa Nakhonluang 2017) and the Vientiane Province Water Supply State Enterprise. However, some factories also drill their own bores and pump water for use in manufacturing and other processes. This type of water extraction has occurred in many places because the users do not have to pay for water fees at present. Even though the Presidential Decree on natural resources fees was issued in 2015 (President of Laos 2015) and the water law was revised in 2017 (National Assembly 2017), the implementation and enforcement of this legislation in terms of water use licensing or water allocation still requires more technical guidelines for support. However, the groundwater use regulations recently established in early 2019 stipulate that extraction of groundwater of more than 20 m^3/day requires an application for a water license from the government (MoNRE 2019).

4.3. Current water availability

According to the analysis of water availability in the Nam Ngum downstream area, there is an ample quantity to meet demand remaining, even after the rates of extraction and epuration are considered. Due to groundwater data limitation, only surface water was studied in terms of the water availability in the area. The model shows that more than 17.8 billion m^3 runs off from the area through the Nam Ngum River discharge every year. Figure 26 shows the huge amount of water inflow and outflow to and from the Nam Ngum downstream area. The inflow and outflow are especially high in the rainy season, which averages 14.5 billion m^3/season and 13.79 billion m^3/season for the inflow and outflow respectively. The averages of the inflow and outflow of the dry season are 6.16 billion m^3/season and 6.68 billion m^3/season respectively. It can be seen that the outflow is generally higher than the inflow during the dry season, yet the outflow is lower during the rainy season. This is because some of the water input from rainfall during the rainy season is stores in soil, plants, and reservoirs before being released to rivers in the dry season.

Plenty of water is still available for extraction and the environmental flow requirement in the Nam Ngum downstream area. When the Nam Ngum River runoff (Table 12) and rainfall (Table 11) are compared to the total current water use (Figure 22), the water runoff and the rainfall are around 53 and 9 times higher than the water demand, respectively. Alternatively, the current water use is only 11.5% of the rainfall in the area and just 1.9% of the total water availability. The environmental flow requirement was recommended to be more than 1.5 billion m^3 during the dry season or around 96 m^3/s according to the observed mean dry season flow at the Thangon flow station, around 5 km downstream of the Vernkham station (Sanyu Consultants 2004, cited in Lacombe et al. 2011). Similar to Bartlett et al. (2012) who recommended 94 m^3/s based on the minimum observed value. In this case, the annual water extraction for agriculture, industries, and municipalities in the Nam Ngum downstream area could increase or be intensified up to around 46 times without compromising the environmental flow. Another consideration is that only the water from precipitation in the area could be extracted, while the water inflow from the other sources is left for flowing to the downstream. In this case, the water from rainfall, minus actual evapotranspiration (Figure 28), can supply up to 7 times more than the current water demand.

However, water availability is not equally distributed to the Nam Ngum downstream area. Most water is available in the Nam Ngum River, which flows through the centre of the study area. In other areas which are far from the Nam Ngum River, such as Phonhong District, the water availability might be limited compared to the other districts close to the river, especially Viengkham District and Xaythany District. In addition, the elevation of the Nam Ngum River is lower than demand sites, for example agricultural areas. Extracting the water from the Nam Ngum River requires pumping and channels or pipes for delivery. This means electricity and maintenance costs might be incurred and these would be borne by the water users.

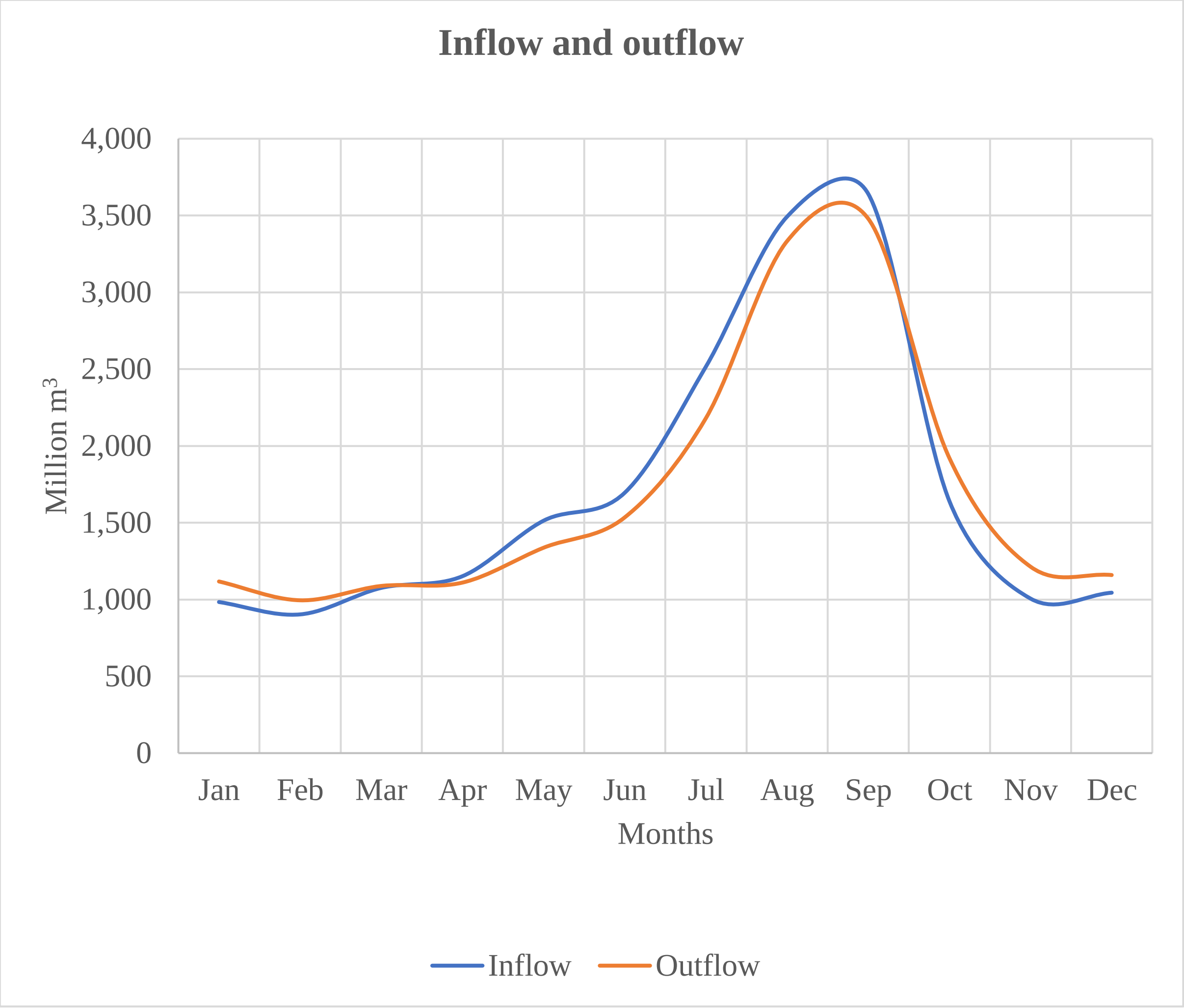


Figure 26: Average monthly water inflow to and outflow from the Nam Ngum downstream area.

4.3.1. Water inflow

There are three sources of the water input into the Nam Ngum downstream area. The first major inflow is from the combination of the release from Nam Ngum 1 dam and the inflow from the Nam Lik River. The Nam Lik River is one of the major tributaries of the Nam Ngum River. Its confluence is located at around four km downstream from the Nam Ngum 1 dam. As shown in Figure 27, the combination of these flows reaches 2.9 billion m^3/month in the peak of the rainy season. A total inflow from this source is 17.27 billion m^3/y (Table 11). Secondly, water input to the area is from precipitation. The average annual rainfall of 1,935 mm, providing around 3.24 billion m^3/y of water across the study area. Most of the rainfall occurs in the rainy season, which is from May to October. Lastly, the turbine flow of the Nam Mung 3 hydropower dam also contributes to the inflows. This dam has been operating since 2005 and diverting water from the Nam Mung River Basin into the NNRB. The water released from this dam is around 154.7 million m^3/y. Its peak release is in September at 23.55 million m^3 and the lowest release is in December at 6.32 million m^3 (Figure 27). However, there may be additional groundwater flowing into the study area, which is not considered in this current study.

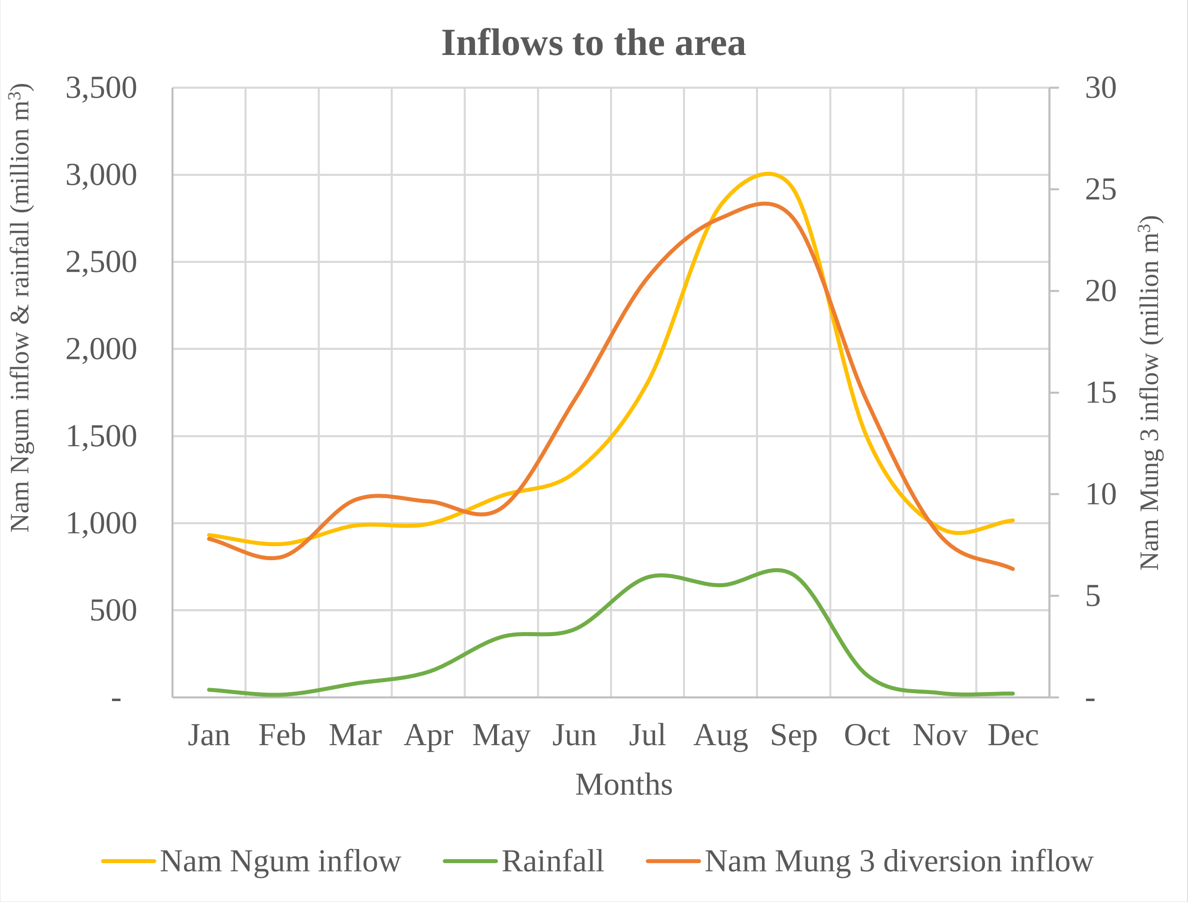


Figure 27: Average monthly inflow to the Nam Ngum downstream area by different sources.

Table 11: Total annual amount of water that inflows to the Nam Ngum downstream area.

Inflow sources	Amount of water (m^3/y)	Proportion (%)
Nam Ngum River inflow	17,273,225,143	83.59
Precipitation	3,235,673,208	15.66
Nam Mung 3 diversion inflow	154,690,539	0.75
Total	**20,663,588,889**	**100**

Water inflow to the Nam Ngum downstream area is variable. As the main inflow is from the Nam Ngum 1 dam, the release of water downstream is controlled by the dam operator. The dam is owned and operated by the Electricity du Lao (EDL), which is a state enterprise in Laos (JICA & MEM 2010). The operation of the dam is mainly for electricity generation, so the amount of water released can vary depending on electricity demand.

4.3.2. Water outflow

There are three mechanisms by which water is lost from the Nam Ngum downstream area (Figure 28). Table 12 presents the total annual amount of this water. The major outflow of water lost from the area is the Nam Ngum River runoff. Around 19.7 billion m^3 of the water flows to the downstream contributing to the Mekong River flow every year. The major river runoff occurs in the rainy season and is triple the amount of the river runoff in the dry season. The peak runoff is in August and September, which is nearly 3.5 billion m^3/month. The second mechanism of loss of the water from the area is evapotranspiration. According to the WEAP model simulation, the actual evapotranspiration is around 475 million m^3/y (Table 12). Another outflow is the water lost from the system due to extraction for human activities, which is approximately 293 million m^3/y. This water is extracted for agricultural, industrial, and domestic uses and mostly does not return to the system. It means this water is embodied in products and evaporated (Sieber & Purkey 2015). In addition, there might be some groundwater that flows out from the study area as baseflow to the downstream areas in the Vientiane capital. However, this type of flow has not been included in this current study. It can be concluded that a huge amount of water flows out from the Nam Ngum downstream area.

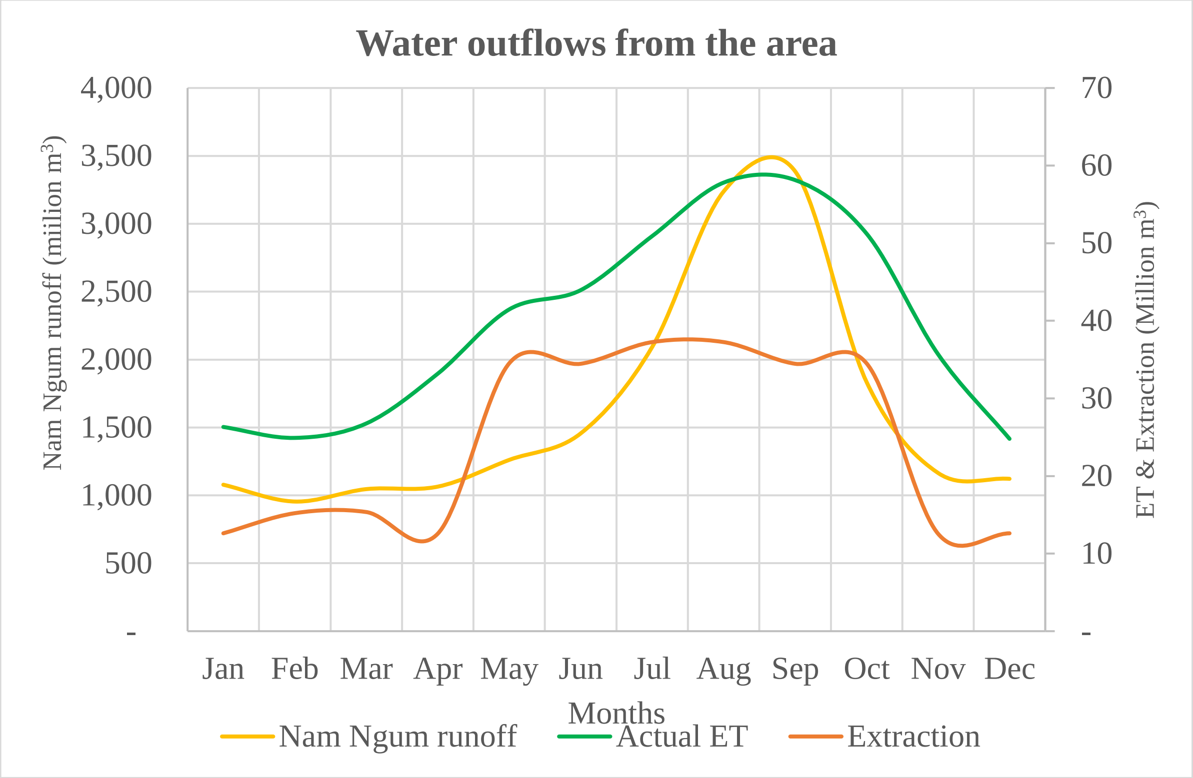


Figure 28: Average monthly outflow from the Nam Ngum downstream area by different sinks.

Table 12: Total annual amount of the water that outflows from the Nam Ngum downstream area.

Outflow Sinks	**Amount of water (m^3/y)**	**Proportion (%)**
Nam Ngum River runoff	19,701,328,765	96.25
Actual ET	475,166,667	2.32
Extraction	293,390,224	1.43
Total	20,469,885,656	100

4.4. Groundwater and surface water interactions

Groundwater and surface water are generally connected and can be considered a single resource (Winter et al. 1999). In most cases, over-pumping of groundwater triggers the reduction of the water level in rivers (Mukherjee, Bhanja & Wada 2018). At the same time, extraction of a large amount of surface water can also cause lowering of the groundwater table (Mukherjee, Bhanja & Wada 2018). In the Nam Ngum downstream area, groundwater also plays a significant role in being supplied to different water users. The WEAP model reveals that water infiltrates to the aquifer after raining and some groundwater discharges back to rivers.

4.4.1. Groundwater recharge

The recharge of groundwater in the Nam Ngum downstream area is mainly from rainfall. Figure 30 illustrates the amount of groundwater recharge in each period. According to the

WEAP simulation, the average groundwater recharge in this area is approximately 12 m^3/s or 235 mm/y. This value is in the range of the groundwater recharge in the alluvial sediments of Laos, studied by Viossanges et al. (2017), which provided values from 210 mm/y to 1,011 mm/y. The recharge mostly occurs in the rainy season, which is triple the recharge in the dry season. The average recharge in the rainy season from 2010-2016 is around 18.5 m^3/s, while the recharge in the dry season is approximately 6.4 m^3/s. When compared to the rainfall, the amount of the groundwater recharge accounts for around 12% of the annual rainfall in this area which averages 1935 mm.

Apart from rainfall, lithology also affects groundwater recharge and storage. According to Pavelic et al. (2016), the major geology in Nam Ngum downstream area can be classified into two types, which are hard rocks and alluvium (sand, gravels, and clays). The hard rocks are mainly located near the edges of the basin, which are the Phoukhaokhuay and Phouphanang mountains (Pavelic et al. 2016). In the middle of the area, there are deposits of alluvial sediments (Figure 29). These sediments have a fairly high dynamic in terms of groundwater recharge and discharge, so it is ideal for drilling wells for water use (Gunduz & Simsek 2011). Figure 29 presents the extent of alluvial deposits and their depths. The thickest deposits are around 40 m depth, and occur below the Nam Ngum River in Viengkham District. The thickness of this sediment reduces along the distance to the hills or edge of the basin. This influences groundwater yield. For example, the pumping rate at Phousan Village (Figure 29) is as low as 0.5 L/s while the yield at Ekxang Village can support the pumping rate at 5 L/s (Pavelic et al. 2016). This illustrates that even though groundwater recharge is high, the distribution of water availability in the area also depends on geological and lithological conditions.

Groundwater recharge is very important for maintaining the groundwater table and sustaining the subsurface ecosystem. According to the climate projection in the NNRB by SEA START RC (n.d) based on the A2 scenario, precipitation is projected to increase until 2050. As a consequence, the increased rainfall is likely to cause an increase in the groundwater recharge as a consequence. In addition, in wet or very wet years (e.g., 2030-2035, Figure 30), the recharge tends to rise. In contrast, during dry or very dry years (e.g., 2020-2025), the groundwater recharge seems to decrease as well. Even though in general the recharge is projected to increase, water demand is also expected to increase rapidly and this will affect the groundwater table as well as groundwater ecosystem if an effective program of sustainable management of water resources is not implemented.

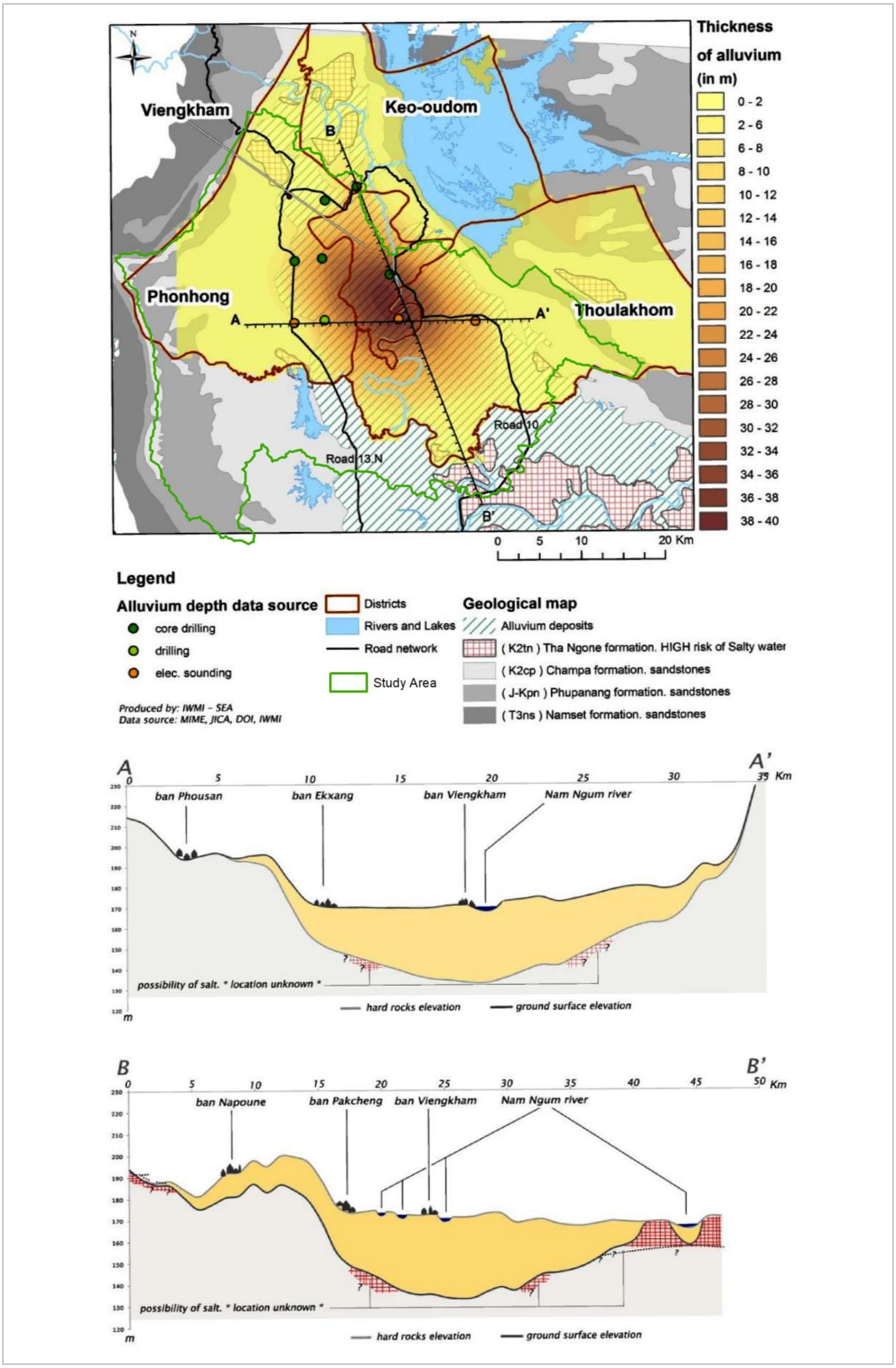


Figure 29: Extent and thickness of alluvium in the Nam Ngum downstream (Adapted from Pavelic et al. 2016).

4.4.2. Groundwater discharge

In the system of river networks, a river can be a gaining and/or losing river. According to the WEAP simulation, the Nam Ngum River is gaining water from the aquifer. This may be because the groundwater table in the Nam Ngum is generally higher than the river level. Figure 30 illustrates the amount of groundwater discharging to rivers. The average discharge flux is approximately 9 m^3/s (280 million m^3/y). It is notable that, unlike the groundwater recharge, aquifer seepage discharge to the river does not vary much over time and between seasons. Comparing this discharge to the recharge and rainfall, it equals 71.3% and 8.7% respectively. Therefore, it can be concluded that the seepage of water from the aquifer to rivers contributes to water availability in the Nam Ngum River.

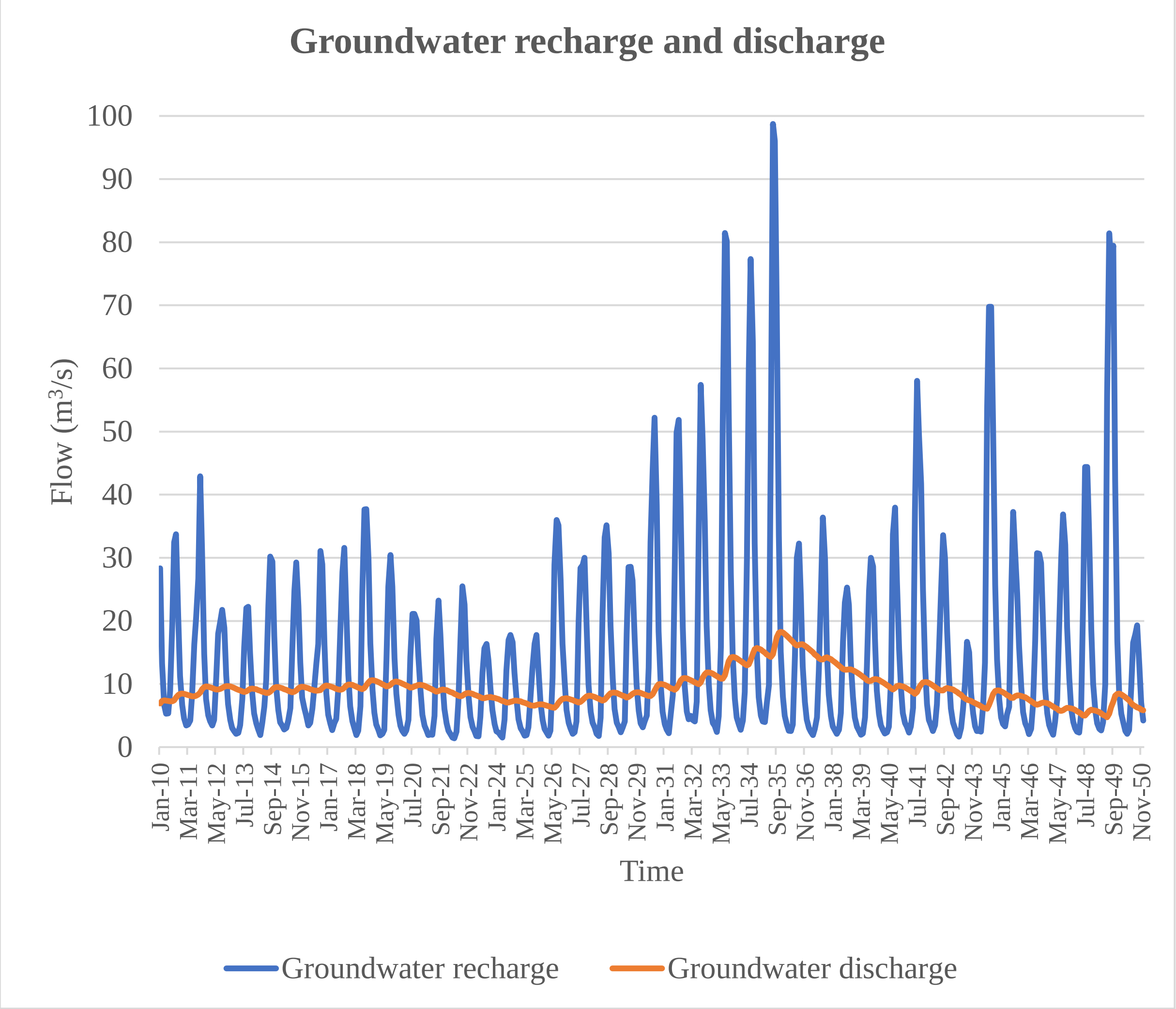


Figure 30: Groundwater recharge and groundwater discharge to rivers in the Nam Ngum downstream area.

4.5. Future water demand and availability

The future water demand and availability have been projected until 2050 according to different scenarios as follows.

4.5.1. Increased water demand scenarios

Water demand in the Nam Ngum downstream area is projected to rise until 2050. According to Vientiane Governor (2015), agricultural products and industrial units have been planned to increase annually by 5.5% and 13% respectively. At the same time, the population has been projected to increase by 1.45% annually (Lao Statistics Bureau 2015). Based on these projections, the total annual water demand would increase by 8.88 times from around 372 million m^3 at the current rate to approximately 3.3 billion m^3 in 2050 (Figure 31). It is interesting to note that the rapid increase in water demand can be attributed to rapid development in the area, such as industries and agriculture, while domestic water demand is projected to increase only slightly.

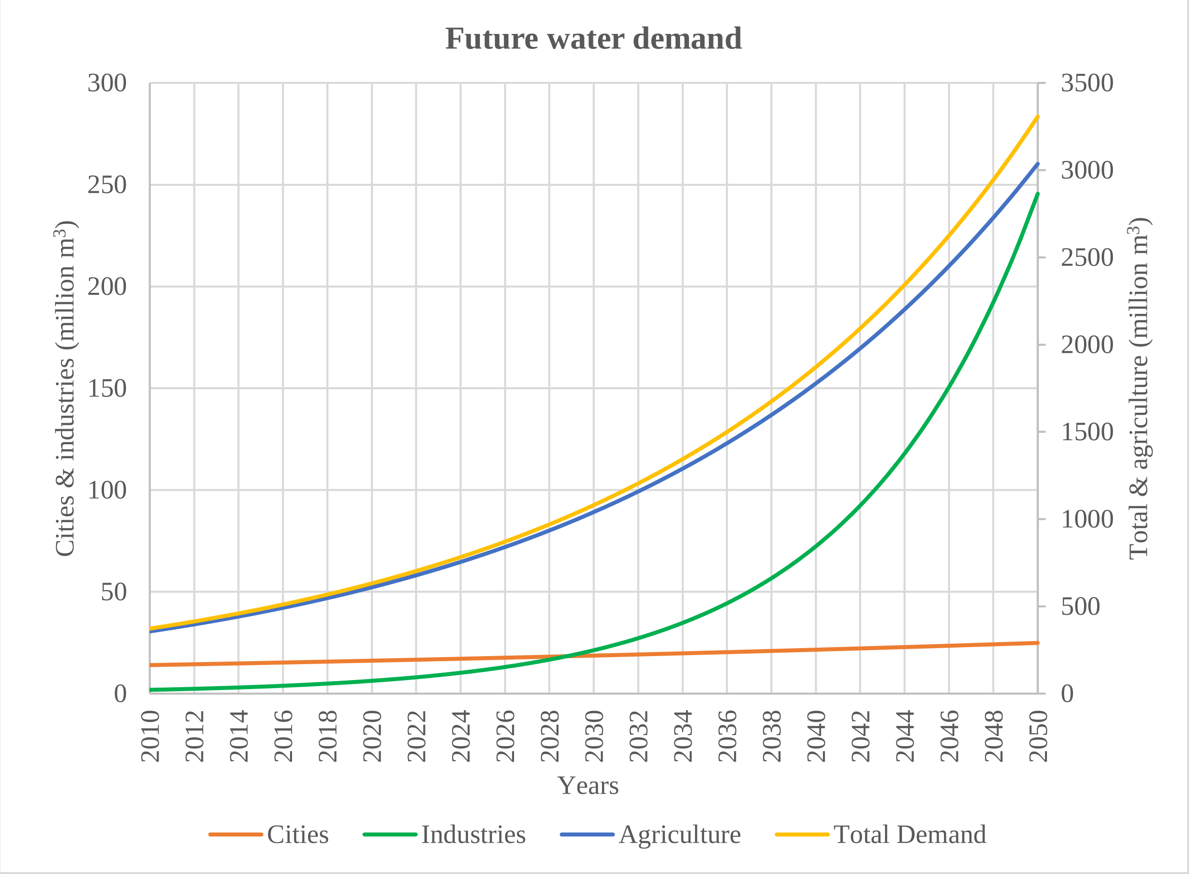


Figure 31: Projected water demand in the Nam Ngum downstream area by different sectors until 2050.

The agricultural sector will still be the largest water user in the Nam Ngum downstream area. By 2050, agriculture will require 8.5 times more water compared to the current demand, which is around 3 billion m^3/y (Figure 31). Therefore, the water demand of this sector will be much higher than the others such as industrial and domestic users.

Industry is the sector that uses the least water at the moment; however, the rate of increase is much higher than the other sectors. By 2050, water demand for industry is projected to be around 246 million m^3/y, increasing from the current demand of around 1.85 million m^3/y (Figure 31). This means the industrial water demand will increase by around 133 times from now to 2050. The water demand of this sector is projected to increase rapidly because Laos is attempting to advance from Least Developed Country (LDC) status. Therefore, the Lao Government has been focusing on industrial development as one the national priorities (MPI 2016). Even though the increasing rate of industrial water demand is high, the total amount of water that will be consumed by this sector is still low compared to the water used by the agricultural sector. Industry is projected to use approximately 12 times less water than the agricultural water demand in 2050.

Domestic water demand might not change markedly. At the current rate of demand, the cities in the Nam Ngum downstream area require approximately 14 million m^3/y. By 2050, the water demand in this sector may approach 25 million m^3/y, which is an increase of only around 1.8 times (Figure 31). This water demand might not increase as much as the other sectors because the growth rate of the Lao population is decreasing. The annual growth rates were 2.47% and 2.08% for 1985-1995 and 1995-2005, respectively (Lao Statistics Bureau 2015). According to the last population census in 2015, the annual population growth rate of Laos dropped to 1.45% (Lao Statistics Bureau 2015). This may be due to the dissemination and promotion of family planning by the public health and educational sectors, which has resulted in the people in Laos to have fewer children than in the past. As a consequence, the water demand for domestic use may not dramatically increase in comparison to the other demands. When compared to agricultural and industrial water demand in 2050, domestic water use will be 122 times and 10 times less respectively.

In general, the water demand in the Nam Ngum downstream area is projected to increase and meeting this demand requires more water supply. Therefore, sectors depending on water supply and the government need to prepare for this eventuality by implementing appropriate infrastructure development to store and distribute water to different users, create equitable water allocation planning, and secure the protection of both quantity and quality of water. However, even though water demand is increasing rapidly, according to the WEAP simulation, an unmet demand might not occur until 2050. This means that the water available in the Nam Ngum downstream area can still satisfy all water users until then, even during the dry season of the driest year. This result is consistent with the study on water availability for agriculture in the Vientiane Plain by Lacombe et al. (2011), which also concluded that there is more than enough water to supply agricultural demand in the dry season of extremely dry years. Thus, the increase in water demand at this level is not of high concern in the intermediate future if the amount of water inflow is not changing much.

4.5.2. Climate change scenarios

Climate change is one of the significant factors that affect water status, particularly water availability in the future. This scenario was created according to the climate data, especially rainfall and temperature, projected by SEA START RC (n.d) until 2050 in conjunction with an assumption of very dry, dry, normal, wet, and very wet years (Table 8). According to the projection by SEA START RC (n.d) based on the A2 scenario of SRES, rainfall and temperature in the Nam Ngum downstream area will tend to increase (Figure 32). The increase of rainfall would lead to increases in the water availability in the area and downstream runoff. At the same time, however, the temperature has also been projected to increase, which would raise the evaporation rate and change the rainfall pattern (Arnell 1999; Yilmaz & Yazicigil 2011). These climate changes may tend to act as a catalyst for increasing occurrences of floods and droughts in the Nam Ngum downstream area.

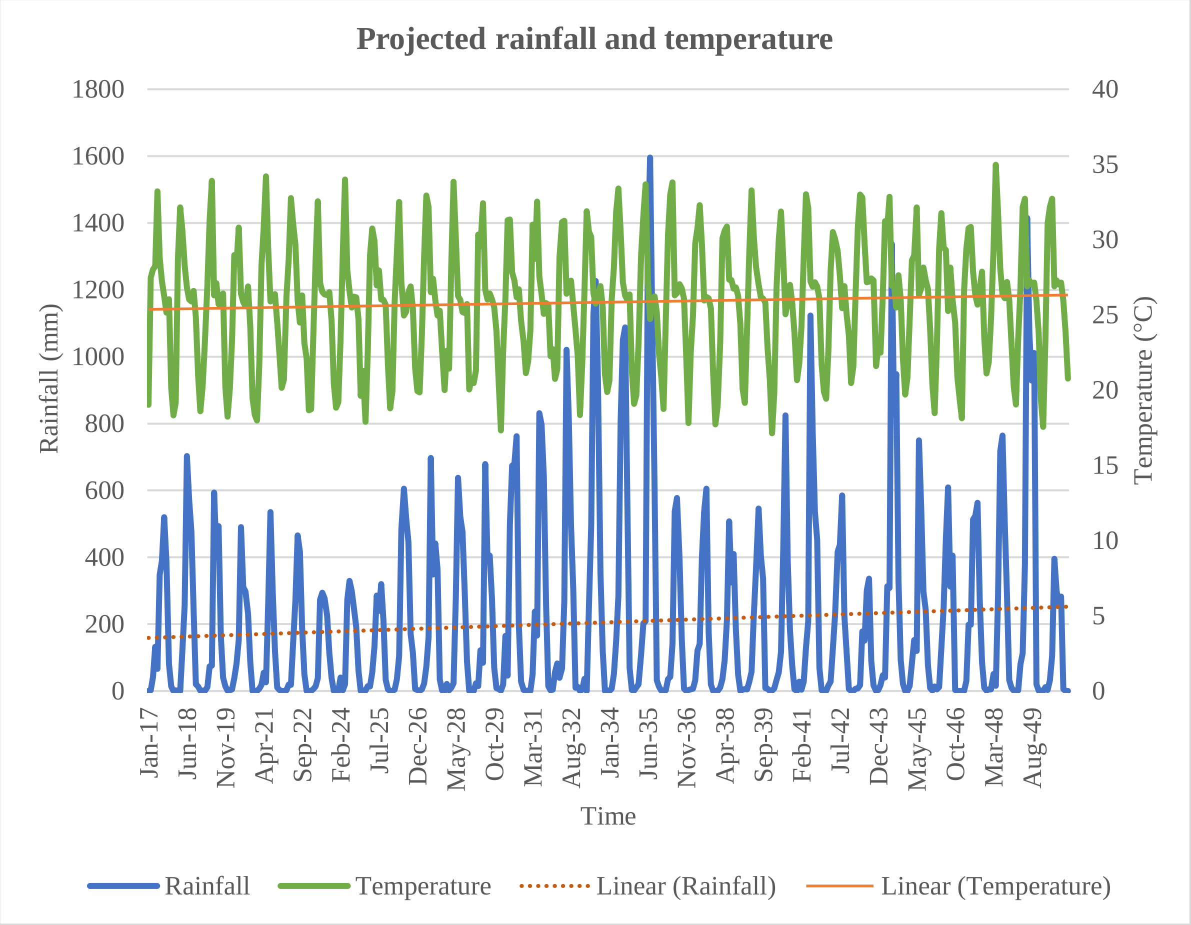


Figure 32: Projected rainfall and temperature in the Nam Ngum downstream area until 2050 (Adapted from SEA START RC (n.d)).

In very wet years, there is a very large amount of water that runs off from the Nam Ngum downstream area. For example, during 2032 and 2034, which are assumed as very wet years, the water runoff from the Nam Ngum River reaches around 3,800 m^3/s in the rainy season (Figure 33). Even though the impacts of floods are not included in this research, in periods of very intense rainfall, inundation of houses and farmland in the area and downstream is likely to occur. In very wet years, even in the dry season, water availability is still very high. The Nam Ngum River runoff at the Vernkham station has been projected to be around 490 m^3/s in the driest month of March (Figure 33). This amount of water is more than enough for the water extraction in that area. Overall, annual water runoff in the very wet years is around 48 billion m^3, which is around 129 times higher than the current water demand for agriculture, industries, and households.

In wet years (e.g., 2030-2032), plenty of water is still available. The Nam Ngum River runoff in the rainy season of the wet years is around 2,448 m^3/s (August), and in the dry season, the runoff is approximately 477 m^3/s (December) (Figure 33). Overall, total water runoff from the Nam Ngum River in the study area during the wet years is around 33.5 billion m^3/y, which is around 90 times higher than the current water demand in the Nam Ngum downstream area.

It is interesting to note that during dry and very dry years, the water in the Nam Ngum downstream area is still sufficient to satisfy water needs. For example, in the extremely dry years (2023-2025), the flow of the Nam Ngum River at the outlet of the study area is the lowest at around 250 m^3/s in the dry season (January) and highest at around 579 m^3/s in the rainy season (September). The total river runoff in a very dry year is around 11.4 billion m^3/y, which is around 30 times higher than the current water demand. Even in the dry season of the extremely dry years, water in the Nam Ngum River is still able to provide sufficient water supply for the different users in the area (Lacombe et al. 2011). This is because there are a number of reservoirs in the NNRB, located along the main river and its tributaries, especially the Nam Ngum 1 dam reservoir which is located around 10 km upstream of the study area. These reservoirs collect water during the rainy season and release more water in the dry season. Even though the main purpose or priority of the reservoirs is for electricity generation, the water released from hydropower dams has increased streamflow in the dry season (Kennard et al. 2018; Lacombe et al. 2014). Thus, water availability in the Nam Ngum downstream area will not constrain water extraction for agricultural, domestic, and industrial use even in the dry season of extremely dry years.

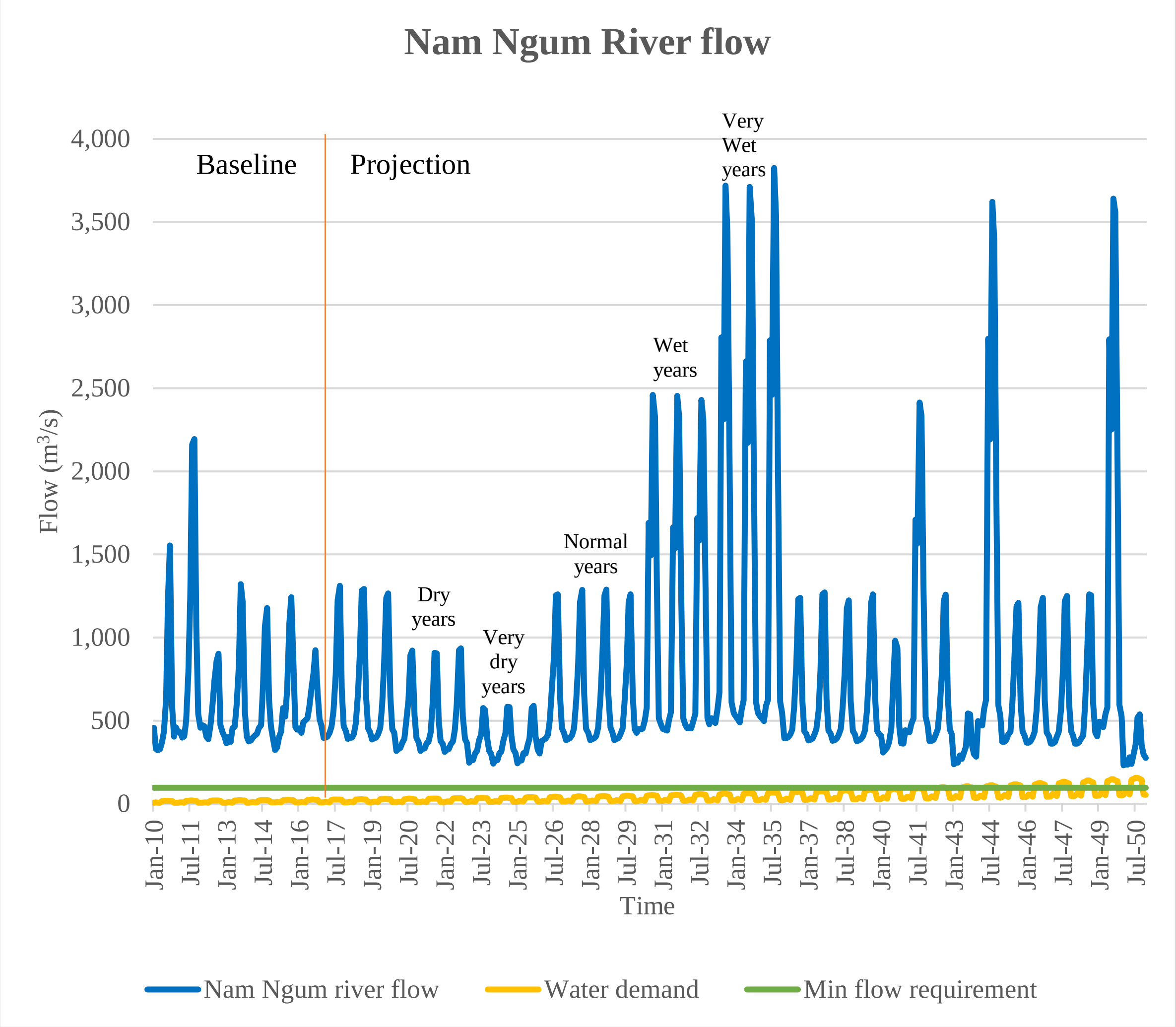


Figure 33: Simulated baseline and future Nam Ngum River flow at the Vernkham point (outlet of the study area) until 2050.

4.5.3. Halved water inflow scenario

The halved inflow scenario was modelled to investigate what might happen if the inflow from the upstream of the Nam Ngum River decreases by 50%. This means the amount of water released from the Nam Ngum 1 dam combined with the Nam Lik river inflow reduces by a half. This scenario was incorporated with the other scenarios such as increasing water demand and climate change with the water year method (Table 7 and Table 8). It is worth noting that even if the inflow to the area is halved, water availability is still able to satisfy water needs of all users. Even in the dry season of extremely dry years, unmet demand might not occur until 2050. For example, in 2050, the demand is expected to rise to around 3.3 billion m^3/y and this year is assumed to be a very dry year (Table 8); however, there is water in the Nam Ngum River in the study area more than the projected demand. With this scenario, in 2050 there might be 5.2 billion m^3 run off from the Nam Ngum River at the outlet of the study area after all extractions.

This is because there is rainfall in the study area itself, plus the contributions from Nam Souang reservoir and water diversion from the Nam Mung 3 dam. The average annual rainfall is around 1,935 mm for the area. According to PAFO VTE (2010), the Nam Souang reservoir has a capacity to store water up to 127 million m^3 and it can supply water to agriculture for 9,000 ha and 7,000 ha in wet and dry seasons respectively. In addition, the water released from Nam Mung 3 dam also has been used for irrigation in the eastern part of the study area, particularly Thoulakhom District. The average turbine flow from the Nam Mung 3 dam is approximately 5 m^3/s. Thus, even if the streamflow in the Nam Ngum River has decreased, the renewable water in the Nam Ngum downstream area is sufficient to substitute and maintain supply to the water users.

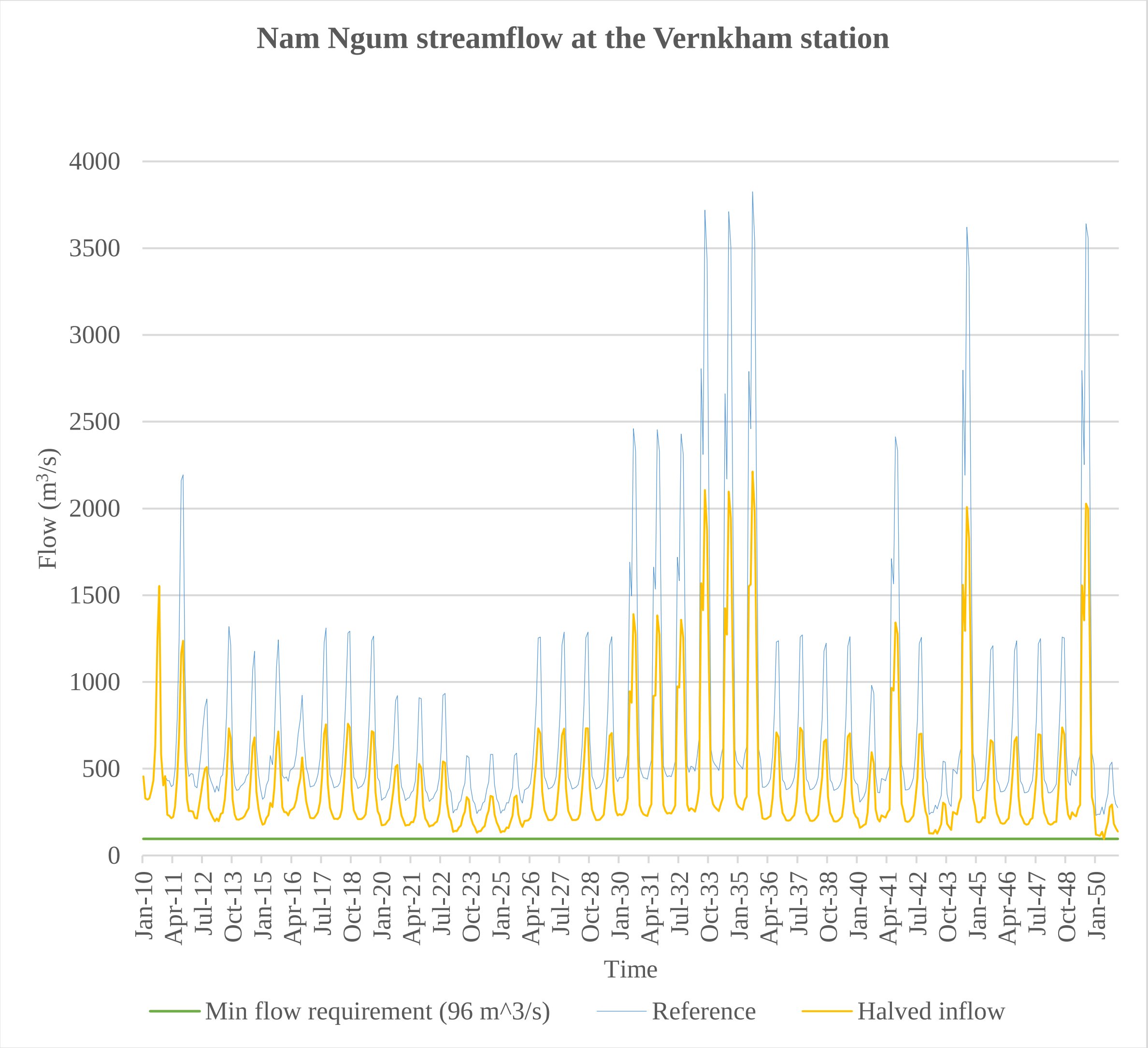


Figure 34: Comparison of the simulated Nam Ngum River flow at the Vernkham point to the minimum flow requirement of both reference and halved inflow scenarios until 2050.

However, if the Nam Ngum River inflow is halved, there may be an impact on the environmental flow and the amount of water available for downstream users. Figure 34 illustrates that the reference scenario meets the minimum flow requirement while the halved inflow could compromise the river runoff to the Mekong River in the future. At the current water demand, even in the dry season of very dry years, available water may be sufficient to supply to the users and the flow to the downstream area is more than the environmental flow requirement. However, when the water demand increases together with the impacts of climate change in the future, the streamflow in the Nam Ngum might be threatened. For example, in the extremely dry year of 2050, the streamflow of the Nam Ngum River at the Vernkham station is projected to flow at 94.96 m^3/s which is lower than the minimum flow requirement of 96 m^3/s recommended by Sanyu Consultants (2004, cited in Lacombe et al. 2011). In the future, beyond the period of this study's projection, if the water demand continues increasing and a dry climate period occurs, the streamflow of the Nam Ngum River may not meet the minimum flow requirement and, as a consequence, it would affect the environment and its contribution to the Mekong River flow.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

Water is an essential resource for all living things including humans who use water for consumption and development activities. Water demand has continuously been increasing because of population growth and development. In contrast, water availability tends to decrease in the areas where water scarcity has already occurred. Human development activities, in conjunction with climate change, which triggers more severe and frequent floods and droughts, lead to degradation of water quality and variable water quantity.

A water balance study in the Nam Ngum downstream area was conducted to assess current water demand and availability. This study used WEAP as the main tool to simulate the water balance. Apart from assessing the present water demand and availability, the study also ran the model to project future water demand according to population growth, industrial development, and agricultural intensification. In addition, water availability in the future was also simulated based on climate change conditions. The study found that there is much more water available than the current water demand.

The current water demand is approximately 372.5 million m^3/y in the Nam Ngum downstream area. The largest water user in the area is agriculture, which extracts around 95.7% of the total water demand. The second highest user is for domestic water users at around 3.8%, while the industrial sector currently requires the least water, accounting for only 0.5% of the total water demand.

The water demand at this level is not overly concerning because there is much more water available in the Nam Ngum downstream area. Each year, there is approximately 20.66 billion m^3 of inflow to the area. The sources are from the Nam Ngum River upstream, particularly the water released from the Nam Ngum 1 dam and Nam Lik River inflow (83.59%), precipitation (15.66%), and the Nam Mung 3 dam (0.75%). After part of the loss of water through evapotranspiration and extraction, around 19.7 billion m^3 is still left for run off in the Nam Ngum River each year. This runoff is 53 times higher than the current water demand. If this water is captured and used for the minimum flow requirement at 96 m^3/s, the water extraction in this area can be increased by around 46 times without compromising the environmental flow.

However, the water demand in the Nam Ngum downstream area is likely to increase rapidly. By 2050, the water demand is projected to increase by 8.88 times to around 3.3 billion m^3/y.

The agricultural sector will still be the largest water user, which requires approximately 3 billion m^3/y equivalent to 8.5 times higher than the current agricultural water demand. The most rapid increase in water demand will be from the industrial sector, because the Lao Government intends to promote economic and industry development, which have been selected as among the top national priorities (MPI 2016). The water use for the industry might increase by around 133 times reaching 246 million m^3/y in 2050. Lastly, the domestic water demand might increase very slightly compared to the other sectors. By 2050, domestic water users will require around 25 million m^3/y, which will increase only 1.8 times compared to the current demand. Generally, the need for water in the Nam Ngum downstream area is steadily increasing.

Under anticipated climate change scenarios, future water availability in the Nam Ngum downstream area will be very variable. In a very wet year, it is projected that there will be around 48 billion m^3 of water runoff from the Nam Ngum River, which is 129 times higher than the current water demand. The peak streamflow is projected to reach 3,800 m^3/s, which would be likely to cause flooding in the downstream area. In wet years, the runoff can be up to 33.5 billion m^3/y which is around 90 times higher than the current water demand. In dry and very dry years, the streamflow is projected to decline; however, it will still be adequate to supply the increased water demand and the environmental flow. Even in the dry season of very dry years, the minimum flow at the Nam Ngum River is projected to be 250 m^3/s which is more than enough for the ecosystem and human water use in the area by 2050. The total annual water flowing out from the Nam Ngum River at the Vernkham point in very dry years is projected to be around 11.4 billion m^3, which is 30 times higher than the current water demand. This is because there are many reservoirs in the NNRB that can store water and increase flow in the dry season. However, in the scenario with a reduction in the Nam Ngum River inflow, the Nam Ngum streamflow might not meet the minimum flow requirement in 2050 if that year is a very dry year.

Groundwater and surface water in this study area interact with each other. Groundwater recharge to the aquifer is on average about 235 mm/y equivalent to 12% of the total annual rainfall in the area. Some of the water, which percolates to the aquifer, flows back to rivers. It can be concluded that the Nam Ngum River is a gaining river. The discharge of groundwater to the river is roughly 9 m^3/s equivalent to 71.3% and 8.7% of the groundwater recharge and the rainfall, respectively.

Even though available water quantity is much more than water demand, water availability is not uniform over all zones in the Nam Ngum downstream area. The zones close to the rivers can access sufficient water easily, while some zones, especially those further from the rivers near the eastern and western edges of the study area, may suffer from water scarcity. Not only does the distance from the river limit water availability in these zones, groundwater availability is also limited because of the hard rock geology with limited productive aquifers. Thus, water infrastructures need to be developed to utilise the available water and distribute water for the benefit of all. In addition, as the water demand keeps increasing, there needs to be a focus on more effective water management and water allocation planning to protect the sustainability of water resources over the long-term and allocate water equitably for all users, which will enable Laos to achieve its Vision 2030 goals of the Natural Resources and Environment sector (MoNRE 2015b).

5.2. Limitations

Apart from the constraints of WEAP discussed in Section 2.5.2, due to time, distance, and data constraints, there are other important limitations associated with this research project as follows.

- The study area was limited to only a portion of the lower NNRB. The major inflow to the study area is from the Nam Ngum 1 dam and the Nam Lik inflow; however, the operations of the dams in the NNRB, such as the Nam Ngum 1 dam and the Nam Lik 1-2 dam were not included in this WEAP model. Hence, any change in operation of these dams might have strong influences on the inflow to the study area.
- Water quality, which can constrain water availability, was not considered in this study. Therefore, it is acknowledged that the amount of water in the Nam Ngum downstream area in terms of quantity might not be adequate for some uses (e.g., human consumption) if the water quality does not meet the quality standard.
- Specific flood and drought areas and their characteristics were not studied in this research project. Detailed knowledge about specific flood and drought locations might be essential for water allocation planning.
- Most of the observed data input to the WEAP model were only for a 7 year period from 2010 to 2016. It would reduce uncertainty if there were a longer period of historical data considered, particularly streamflow and rainfall, which mainly influence water availability in the study area.
- There are many methods to simulate the catchment water balance in WEAP, as discussed in Section 3.3.2; however, only the Rainfall Runoff (soil moisture) method was employed in this study. The other methods, such as simplified coefficient, MABIA, and plant growth methods, should be applied in order to compare the results.

- There was observation uncertainty and missing measured data required by the WEAP model that had to be calibrated such as soil water capacity, runoff resistance factor, conductivity, and crop coefficient (Table 9).
- There were some uncertainties associated with the simulation of groundwater and surface water interactions. The assumption of the wedge method that assumes symmetry on either side of the river might not be completely accurate. In addition, there was no measured seepage data for calibrating and validating the amount of water interaction between groundwater and the Nam Ngum River. Thus, all result values are subjected to approximation.

5.3. Recommendations

For water resources management:

1). Water infrastructures and technology should be developed to maximise the available water and distribute water to all users fairly in the Nam Ngum downstream area.

2). Water allocation planning is imperative in order to deal with increasing water demand and water conflict. In addition, water permits or licencing should be strictly implemented pursuant to the water law (National Assembly 2017) for both groundwater and surface water uses.

3). Regulations on water use should be specifically formulated for this area to protect water quality and the environmental flow. Existing related legislation should be strictly enforced and monitored.

4). Water extraction and water quality should be regularly monitored.

5). Water coordination mechanisms need to be improved and/or developed for coordinating among different water users particularly hydropower dam developers, water suppliers, fishermen, farmers, and business operators.

6). More encouragement of public participation and local awareness of water issues should be implemented. In particular, water data and information, including results of water monitoring, should be accessible for locals to increase their knowledge and involvement in more effective water management.

For further research:

1). The study area should be extended to cover a larger part especially hydropower dams because they strongly influence river flows in the downstream area.

2). Water quality should be included in the study. Even if there is ample water in terms of quantity, if the water quality is unacceptable, the water cannot be considered as available water for use.

3). As the findings of this current study show a significant amount of water flowing in the Nam Ngum River during the rainy season, especially during wet and very wet years (Figure 33), flood impacts and mitigation should be studied.

4). As water availability does not distribute to the area equally, some zones in the study area may experience water scarcity. Thus, specific drought locations should be studied.

5). The historical data used for the hydrological model should be gathered over a longer period in order to increase the accuracy of the model and capacity to project future scenarios. The main data types required are streamflow, rainfall, temperature, wind speed, humidity, and sunshine duration.

6). The other methods of the catchment node in WEAP as well as other hydrological models should be run to compare results.

7). Groundwater and surface water interactions should be simulated with other specific models, such as MODFLOW, and then linked to WEAP.

8). Groundwater inflow to and outflow from the area should also be studied to enhance the accuracy of water balance, particularly the seepage from the Nam Ngum 1 dam.

9). The length of future scenarios can be extended to a longer period of years, such as 2100 or 2200 in order to project the change in the more distant future and for long-term planning.

10). Scientific study of the environmental flow required in this area should be conducted to determine the amount of water available for extraction while still preserving sufficient streamflow for delivery to downstream ecosystems.

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