Surface water balance and future water demands under environmental flow requirements, Nam Xong Watershed, Laos

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ABBREVIATIONS

DMH	Department of Meteorology and Hydrology
DONRE	District Office of Natural Resources and Environment
DWR	Department of Water Resources of Lao PDR
EDL-GEN	Electricity du Laos – Generation Public Company
FAO	Food and Agriculture Organisation
GDP	Gross Domestic Product
GOL	Government of Laos
Ha	Hectare
HH	Household
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resources Management
Km^2	Square kilometre
l/p/d	Litre per person per day
Lao PDR	Lao People's Democratic Republic (Laos)
LMB	Lower Mekong Basin
mm	Millimetre
m^3	Cubic metre
m^3/s	Cubic metre per second
m^3/mth	Cubic metre per month
m^3/y	Cubic metre per year
m^3/ha/y	Cubic metre per hectare per year

m^3/p/y	Cubic metre per person per year
%	Percent
MABIA	Method for daily simulation of evapotranspiration and soil water capacity
MAF	Ministry of Agriculture and Forestry of Lao PDR
MEM	Ministry of Energy and Mines of Lao PDR
MIC	Ministry of Industry and Commerce of Lao PDR
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
MONRE	Ministry of Natural Resources and Environment of Lao PDR
MPI	Ministry of Planning and Investment of Lao PDR
MRC	Mekong River Commission
m.a.s.l	Metre above sea level
NNRB	Nam Ngum River Basin
NSE	Nash-Sutcliffe Efficiency
NSEDP	National Socio-Economic Development Plan
NXD	Nam Xong Dam
NXW	Nam Xong Watershed
PAFO	Provincial Department of Agriculture and Forestry
PEST	Parameter Estimation Tool
PMO	Prime Minister's Office
PONRE	Provincial Department of Natural Resources and Environment
RBC	River Basin Committee
RMSE	Root Mean Square Error

TWG	Technical Working Group
SEI	Stockholm Environment Institute
WEAP	Water Evaluation and Planning Model
WEPA	Water Environment Partnership in Asia

SUMMARY

The abundant water resources in the Nam Xong Watershed of Laos is readily available for the multiple uses of both socio-economic development and the environment. The competitive demands, land use, and climate change constraints are key challenges to sustainability of the water resources and its associated functions in the watershed. Therefore, this research paper aimed at studying the surface water balance and projection of the future demands as well as minimum environmental flow requirement for effective water governance. To achieve this aim, the rainfall runoff method in the Water Evaluation and Assessment Planning (WEAP) model package was employed in this study. Three predicted scenarios were constructed for the future water demands projection, namely increases of the irrigated agriculture, population (domestic use), and industrial production units. The current account year was set in 1997, and the future projection period was from 1998 until 2040. The paper then presented and discussed the results of the model simulation and analysis to enable understanding of the watershed water resources conceptualisation.

The surface water resource in the Nam Xong Watershed is relatively abundant in terms of its total water inflows into the watershed system every year. The total water availability amounts to approximately 25.5 billion m^3 per annum, while the total current water demand is approximately 135.88 million m^3/y. Of the primary users, the agriculture sector shows the highest water demand of approximately 129.84 million m^3/y, and 4.94 million m^3/y and 1.09 million m^3/y for the domestic and industry sectors, respectively. However, by the year 2040, the average annual water demands are expected to have dramatically increased, especially in the agriculture and industry sectors. The agricultural water demand is anticipated to increase from the current use of about 129.84 million m^3/y to about 159.73 million m^3/y, or an increase of 1.2 times from present levels. Notably, according to the study scenarios, the industry water demand will also significantly increase from 1.09 million m^3/y to approximately 146.86 million m^3/y, or an increase of 135 times. Furthermore, the domestic water demand would also increase from 4.94 million m^3/y to about 125.06 million m^3/y or equivalent to an increase of 25 times over the present extraction rate. However, although the total water availability is enough to supply the growing needs of water users, inadequacies might potentially occur in some areas during the dry season, for instance February and March. In addition, the minimum environmental flow requirement was also defined for the study area. The potential minimum flow requirement for the Nam Xong mainstream is approximately 9.6 m^3/s. This was determined by analysing the observed

mean minimum and maximum flow at the Nam Xong dam station (upstream station), which considered as the most natural flow station at the most downstream of the watershed. Therefore, this minimum requirement is very important for the downstream livelihood of Lao communities, freshwater ecosystems, and environmental functions of the river.

Although the available water resource in the watershed is relatively abundant and sufficient to meet the current and future water demands of Laos, including the environmental requirement, there are challenges and uncertainties of the increasing demands, land use changes, and climatic condition changes, which may pose some significant impacts on the watershed. Consequently, integrated water resource management and sustainable allocation is crucial, as is recognising the importance of capacity building and climate change adaptation, for the future of the watershed and equitable use of the water resources. Therefore, further research is needed to contribute to a better understanding of the water resource assets in the Nam Xong Watershed.

DECLARATION

I certify that this thesis does not incorporate without acknowledgment 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.

Signed Phousavanh Fongkhamdeng

Date 29 November 2019

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1. INTRODUCTION

1.1 Background and rationale

Water resources are crucial for agriculture, industry, and domestic use, and serves as a catalyst that plays an important role in socio-economic development and environmental functions (Zhou et al. 2015). Water is a unique resource that supports direct and indirect human well-being by securing the productivity of many different sectors in the community (Kumar, Kanga & Sudhanshu 2018). Conversely, inadequacies in the water resource can adversely impact other systems, such as natural, social, and economic systems, and including domestic demand and supply, agriculture, industry, hydropower, tourism, and biodiversity. Although water covers about two thirds of the planet’s surface, only 2.5% is fresh, non-saline water (Oki & Kanae 2006).

Furthermore, less than 1% of water is accessible and suitable for human consumption, because much of the freshwater is locked up in glaciers, snow, and polar ice. Consequently, freshwater is recognised as a scarce resource in many places that is also irregularly distributed in space and time over the planet and is under increasing pressure from human activities. As shown in Figure 1.1, Oki and Kanae (2006, p. 1069) have illustrated the global water budget review and water cycle, which provides a better understanding of the relationships between surface and groundwater, atmospheric water, precipitation and evaporation, and freshwater infiltration to land. This diagram demonstrates the interconnectedness and interdependency of the terrestrial water balance with the hydrological system and explains why the water resource is one of the most important elements on earth, which needs to be managed sustainably for the future.

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Figure 1.1. Global water budget diagram (Oki & Kanae 2006, p. 1069).

However, Vorosmarty et al. (2000) and Liu et al. (2018) have argued that the availability of the water resource in the future is difficult to determine and quantify due to the rapid pace of human development and corresponding increasing demand, the uncertainties of climate change that is affecting the planet's hydrological system, and the diversification of water use complexity. As a result, the assessment of water availability and predicting future demands on the resource has become a key area of important research. According to Liu et al. (2018), water availability assessment is a fundamental process of the water resource allocation and management. Of these processes, the stream water flow is a key factor and variable for assessing the surface water resource availability condition through the hydrological analysis process (Mishra & Singh 2010; Tsakiris & Vangelis 2004). River basins or watersheds are diverse in terms of water quantity, water quality, and human activities according to differing upstream and downstream circumstances. Thus, integrated water resource management (IWRM) is vital for modern-world water governance. One of the major authorities on IWRM, GWP (2000, pp. 13-4), has set a direction for water resource management and defined the freshwater resource as:

1. Freshwater is a finite and vulnerable resource, essential to sustain life, development, and environment.

2. Water development and management should be based on participatory approach, involving users, planners, and policy-makers at all levels.

3. Women play a central part in the provision, management, and safeguarding of water.

4. Water has economic value in all its competing uses and should be recognized as an economic goods based on the equitable standard and affordability by the poor.

In recent years, the IWRM principles have been widely promoted and progressively incorporated into the policies of many nations. At the same time, the IWRM strategies have evolved to a more systematic watershed-based management in many countries aiming to address the complex internal and transboundary water-related issues and competition for the water resource in the watershed geography, rather than according to the administrative boundary. A watershed is defined hydrologically as a land area or region where all the water run-off flows to a common location, but in a more holistic sense also incorporates aspects of socio-economic and environmental significance, such as considerations for the human population and the ecology of the area (GWP 2000).

The Lao People's Democratic Republic (Lao PDR, or Laos) is a developing nation classified as one of the least developed countries with a population of approximately 6.5 million (MPI 2016). Of the total, 77% of the population live in the rural and remote areas (Lao Statistics Bureau 2012), where most of the population rely on agricultural and natural resource use for their livelihood. More than 90% of the country area is geographically located in the Lower Mekong Basin (LMB), accounting for approximately 35% of the total water runoff to the LMB system, which is considered as the highest contributing proportion in the region. The typical discharge of the rivers in Laos occurs at about 80% during the rainy season and the remainder of 20% in the dry season (DWR 2008b). The national average annual rainfall is over 1,900 mm with average surface water 332.5 km^3 and is equivalent to more than 55,000 m^3 per capita per annum. This surface water figure has been considered as the highest amount per capita in the Asian region (DWR 2008b, 2014). Additionally, the internal groundwater resource shows about 38 km^3/year (FAO 2011). This water source is the main rural and remote area water supply; however, there is very limited monitoring of the variations in the quality and quantity of the groundwater throughout the country. As can be seen from Figure 1.2 (DWR 2019b), Laos has classified 62 river basins or watersheds, each being designated for management under the principles of IWRM. These basin plans support the national socio-economic development growth, such as agriculture, industry, livelihood of communities, and sustainable development. For example, the agriculture sector aims to achieve 19% in the national development growth structure, which will contribute to poverty eradication (Lao Statistics Bureau 2012; MAF 2015). Therefore, scientific and collaborative study of the water resource and its management is needed to enable effective management of the basins and watersheds.

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Figure 1.2. River basins atlas in Laos (DWR 2019b).

Although water scarcity is becoming widespread in other parts of the world, Laos has an abundant water resource in the LMB region, with utilisation of its water resource still observably low at approximately 2.8% of the annual surface water resource (DWR 2008b). Although, the water scarcity in some parts of the country has also occurred in the recent years. While the existing groundwater supply and accessibility is plentiful, the exact figure is unknown due to limited information. Nonetheless, the utilisation of all water sources for socio-economic development in the country continues to increase, particularly as irrigation, industry, and hydropower usage is growing rapidly. This is likely to result in water use competition in some areas and may generate adverse impacts in the future on the river flow morphology, water quality, human health, and environmental sustainability.

More significantly, the frequency and extent of natural disasters, such as flood and drought, are likely to increase because of climate change and local land use changes, especially in areas where forested land has been replaced by agriculture and urban environments (Sayasane 2013). In particular, climate change has been shown to cause major effects on the environment and human activity, for instance lower agriculture yields due to increased intensity of drought and flood events (Olesen & Bindi 2002). The changing climate may also affect the hydrological cycle in terms of water availability as well as the variability of the river flow, that pose challenges in both the short and long-term (Olmstead 2014). Meanwhile, Laos is rapidly developing across sectors that use quite a large amount of natural resources in the watershed areas, such as land and water. The water resource use has been rapidly increasing, while there is yet a lack of comprehensive water resource and watershed management system in place. Therefore, integrated watershed management is obviously important in the context of Laos.

Nam Xong Watershed (NXW) is one the most significant priority sub-watersheds located in the central part of the Nam Ngum River basin, central part of Laos (Figure 1.3). The watershed area is approximately 1,800 km^2. The total length of the Nam Xong mainstream is approximately 107 km. The annual precipitation varies between 766 mm – 3,400 mm (DWR 2013). The Nam Xong watershed is the third largest sub-watershed among the 18 sub-watersheds in the Nam Ngum River basin (Figure 1.3). The watershed is situated in the central part of northern Laos, about 83 km north of Vientiane Capital City. Vientiane Province covers about 97.3% of the total watershed area and presents 100% of the population proportion, while other provinces contribute only a small proportion of land cover with no village or population present inside the watershed. The largest urban centre in the watershed is named Vangvieng District. The district is well-known as a tourist attraction with natural features enjoyed by visitors.

Geographically, the watershed consists of a mixture of limestone karsts and sandstone landscapes. In the northern mountainous area, the geology is dominated by limestone karst. The northern region of the watershed is high topography with slopes exceeding more than 30% in some areas. The northern part of the watershed consists of mountainous areas where agriculture is mainly limited to high-land shifting cultivation of rice, which has been recognised as a significant problem resulting in erosion and land degradation (DWR 2013). In addition, the watershed is divided by the Nam Xong Diversion Dam located in the southern part of the watershed (Figure 1.3). The dam is developed on the Nam Xong River estuary at a distance of approximately 27 km (DWR 2013).

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Figure 1.3. Nam Xong watershed administration map.

The watershed is vital for lowland agriculture activity, fisheries that make up about 56.6%, tourism, mining, and other important economic activities (DWR 2013). Nevertheless, the watershed has experienced issues of altered forest cover and soil degradation from slash-and-burn agriculture, water quantity and quality degradation, poverty, and land-use conflicts among the local people (DWR 2008a). The watershed presents important water and natural resources, which are exploited and serve to support the local socio-economic development and livelihood of local communities. Significantly, the watershed, the river, and the natural beauty of the environment are also a national tourist asset that creates employment and income.

Currently, the watershed has been facing the rapid urbanisation, population growth, overexploitation of water resources, tourism industry boom, and irrigation expansion. Furthermore, the Nam Xong Diversion Dam (NXDD) in the downstream part is a massive land use change and hydropower development (DWR 2013; Sayasane 2013). The Nam Xong Diversion Dam is a small hydropower dam operated by Electricity du Laos – Generation Public Company (EDL-GEN). This dam comprises of the weir, diversion canals, and hydropower plant. The dam generates 6 MW and diverts the water to the Nam Ngum reservoir with a canal length of 2.5 km. The rest of the water is released to the Nam Xong downstream and then flows to Nam Lik River (which is a tributary of the Nam Ngum). The gross water storage capacity is about 13.5 million m^3. The average diversion discharge is 65.1 m^3/s and minimum downstream discharge at the diversion canal is 2 m^3/s (MEM 2019). However, there is no clear indication of the returned minimum environmental flow contribution needed for the downstream areas of Nam Xong or Nam Ngum Rivers. These major factors influence the watershed and create challenging pressures on the water resources, water use tensions, and sustainability of the resource.

The typical challenges for water resource management and planning in the Nam Xong watershed relate to the public and government concerns that need to be collectively sought out and addressed. According to DWR (2013), the main challenges include lack of comprehensive policy, lack of strategy and plans of actions, and limited scientific knowledge and capacity. Moreover, there is also lack of community awareness, and inadequate financial support and investment in the water management sector. In terms of institutional arrangement, there is some overlapping and unclear water related sector responsibilities that result in ineffective coordination and collaboration among stakeholders in the watershed. Nevertheless, some policy and legislation frameworks are in place, although the implementation and reinforcement of those legislative frameworks has been somehow weakened. One reason for this weakness is that there has been no comprehensive scientific water resource assessment and allocation plan in the watershed. Consequently, the pressures on the water resource are being pushed up via the rapid population growth, increased water demands, and rapid water related infrastructure development, such as Nam Xong Diversion Dam and irrigation expansion. These increased demands have resulted in the water infrastructure being developed in the watershed, despite that development would predictably alter the downstream water flow environment, water quality degradation, loss of fisheries, and impacts on local livelihood (DWR 2013).

In order to address those challenges, the Government of Laos (GOL) has developed and approved the water and water resources law in 2017 and the 8th Edition of the National Socio-Economic Development Plan (NSEDP). More specifically, the government approved the Natural Resources and Environment Action Plan 2016-2020, Strategy 2025, and Vision 2030 for safeguarding water resource management issues. In this document, 10 priority river basins have been officially identified to be comprehensively managed, including Nam Ngum, Nam Ou, Sebangfai, Sebanghieng, Sekong, Sedon, Nam Theun-Kading, Nam Ngiep, Nam Tha, and Nam Xam (MONRE 2015). Of these priority river basins, the Nam Xong watershed is in the Nam Ngum River Basin, which is prioritised as part of the national agenda. Hence, improving water management of Nam Xong watershed is considered a nationally high priority. At the Nam Xong watershed level, although the GOL has developed and implemented the Nam Xong watershed profile and management plans, there is still a lack of comprehensive scientific information and reliable researches on the surface and groundwater balance and long-term allocation plans (DWR 2013). This shortcoming leads to create questioning and conflicting issues among the stakeholders. The water resource allocation should be conducted based on the principles of equality, resource efficiency, and sustainability (Hu et al. 2016). Hence, holistically scientific water resource assessment is needed to implement and support the future water allocation through promotion of cross-sectoral collaboration and information sharing. In order to fulfil that aim, the integrated water resource management needs stakeholder cooperation and collective solutions at all levels. As asserted by Biswas and Tortajada (2010), good water governance needs transparency, multi-stakeholder participation, increased accountability, and power decentralisation. Moreover, effective water governance requires effective water resource allocation and management to overcome the collective problems (Biswas & Tortajada 2010).

To achieve the goals of sustainable management of the Nam Xong watershed, study of the surface water balance condition and demands on the resource is a priority of the government in addressing the complex water related issues and allocation needs (DWR 2014; MONRE 2015). Hence, more scientific assessment and study of the water resource is of primary importance for national and local water resource planning and management at the watershed scale. To do that, an understanding of history of the hydrological changes over a certain period in the watershed is required, as well as other influencing factors that might affect the natural water resource system. Therefore, understanding of water balance and future demand projection as well as the required minimum environmental flow will be substantive as a gateway for model setting and scenario development to evaluate and investigate the water resource condition. Therefore, this study is critically important in assessing the surface water availability condition in the watershed and to strategically predict water demands for the diverse water users both upstream and downstream towards the year 2040 in a more sustainable and scientific manner.

1.2 Objectives

- To study and project surface water balance and future water demands in the Nam Xong watershed.
- To study and identify the minimum environmental flow requirement for the Nam Xong watershed.

1.3 Expected results

- The surface water balance and future water demands in the Nam Xong watershed assessed and projected.
- The minimum environmental flow requirement for the Nam Xong watershed assessed and defined.

1.4 Research questions

- What is the surface water balance projection for sustaining the increased use and development in the Nam Xong watershed by the year 2040?
- How does the increased water demands affect and influence surface water condition in the watershed towards the year 2040?

- What is the minimum environmental flow requirement for the Nam Xong watershed for its downstream environment and community needs?
- What are the appropriate and sustainable water governance options and recommendations?

1.5 Scope of the study

The scope of this study focused on the surface water balance and future water demands prediction in the Nam Xong watershed in the central part of Laos. In addition to the main scope of study, the minimum environmental flow study was a significant part of this analysis. The study area covered the whole watershed and so called "the study area" (Figure 1.3). The study applied the Water Evaluation and Planning Model Package or WEAP Version 19.2.0.0 developed by the Stockholm Environment Institute (SEI). As baseline data inputs, the study used daily hydrological and meteorological and water use datasets available in the area from 1997-2018 (22 years) and then set up the future projection till 2040 as the scenario. These datasets included river flow, precipitation, potential evaporation, and three main water uses: domestic, agriculture, and industry. In this study, only the surface water quantity was included, while the water quality and groundwater were not included due to the data limitation and time constraints.

1.6 Structure of the thesis

This thesis paper covers five main chapters that include:

Chapter 1: Introduction

Chapter 1 focuses on the general water resource importance, its main problems, and management requirements from the global perspective downscale to the national and local watershed levels. The chapter also defines the main objectives, anticipated outputs, research questions, scope of the study, and the thesis structure.

Chapter 2: Literature Review

This chapter outlines and critically analyses the relevant existing literature on six main topics. These include water balance study, theory and prospects around the world; environmental flow study and requirement for the watershed management and function, water demands and allocation; climate change impact on the water resource system; water resources policy and institutional framework; and last is a discussion of the application of both advantages and limitations of the WEAP model package.

Chapter 3: Materials and Methodology

This section presents the study area selection and detailed description, data preparation and analysis for input into the WEAP model package. In addition, this part shows methods on how to input, simulate, and calibrate the model results at each step.

Chapter 4: Result and Discussion

This chapter illustrates the key results and discussions of the WEAP model simulations and data analysis. The findings and results are used to critically discuss the cause and effect, possible problem occurrence and consequences, and some possible solutions.

Chapter 5: Conclusion and Recommendation

This last chapter synthesises all the works done in all of the previous chapters. This section summarises and reiterates the importance of the research topic, main findings and results, as well as identifying some research limitations and providing recommendations for future research.

2. LITERATURE REVIEW

2.1 Water balance study

Water balance is an important approach and tool for water availability assessment and evaluation for water allocation, demand projection, and watershed level management, which is normally applied at the watershed or catchment scale (Ladson 2008). The water balance is a significant tool for evaluating and assessing the water availability or deficit in the watershed system (Bilibio et al. 2017; Soldevilla-Martinez et al. 2014). Also, the water balance plays a critical role in quantifying and computing the water availability and predicting the future demand (Kumar, Kanga & Sudhanshu 2018). The water balance is an important tool to understand water accounting in a specific water system, catchment, or watershed with a specific time frame (Ladson 2008). In other terms, the water balance represents the study of water supply and demand management, which depends on the size and rate of extraction by the human population, agriculture, industry, and other internal water users, and very much depends on the seasonal fluctuations and climate condition in each area (Shaw et al. 2011).

The water balance is influenced by many factors that may have impact on the water use for different development sectors. For example, large-scale land use change might affect the river flow regime and land-moisture variation over time (Kabat et al. 2004). This water balance approach assists to quantify the implication and relationship of the watershed precipitation/rainfall, evaporation, evapotranspiration, and surface and groundwater runoff (Kumar, Kanga & Sudhanshu 2018). The water balance concept has been applied and studied widely in the literature and provides a technical and scientific framework for future water use and governance, including the effective water budget projection, allocation, and sustainable water resource management. According to Kumar, Kanga and Sudhanshu (2018), the general scientific water balance concept and equation has been used and applied widely in the body of published academic work on water resource management. The basic equation is the summing up of the total mass of water inflow to the watershed system minus the total mass of the water flowing out of the system. In the text book on hydrology, Ladson (2008) presents the specific equation of the water balance as:

Mass of water inflow – Mass of water outflow = Change in Storage (Equation **1**)

The author explains further that the water inflow includes precipitation, surface water inflow (some diversion from other watersheds into the system), and subsurface or groundwater inflow (where the subsurface watershed might not coincide with the surface watershed). Furthermore, the total mass of water outflow counts the evaporation, evapotranspiration, subsurface or groundwater outflow, stream flow, and diverted water from the watershed system. Figure 2.1 illustrates some aspects of this water balance concept (Ghandhari & Moghaddam 2011). In addition, the application of the water balance approach needs to consider the watershed or water system boundary; water users, such as water supply, irrigation, industry; and water storage in different locations, such as lakes, storm water tanks, reservoirs, farm dams, and vegetation (Ladson 2008).

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Figure 2.1. Diagram of the water balance in the watershed (Ghandhari & Moghaddam 2011).

The water balance study has been scholarly applied in a wide-range of water resources research fields. Studies have been discussed widely among researchers and other interest groups on the usefulness and shortfalls of the water balance approach. Most studies focused on estimating the total water budget. The general approach is accounting of water flowing into the watershed from different sources of inflows, while total water outflows are also quantified at the watershed outlet.

2.2 Environmental flow

Environmental flow is the substantive requirement for the basic environmental and social sustainability of the river system. The environmental flow is the water flow requirement to maintain and sustain the river ecosystem and people well-being accounting for both quantity and quality of the resource (Brisbane Declaration 2007; Sun, Xu & Yang 2012). However, the environmental flow requirement is relatively difficult to quantify, yet the recognition of its importance would benefit both society and the environment, including pollution management and aquatic ecosystem enhancement (GWP 2012). The environmental flow is a variable component of the natural river flow that includes the aspects of the flow frequency, timing, magnitude, duration, and change of the flow event (King, Tonkin & Mahoney 2009). Therefore, environmental flow is required for multiple water use purposes, especially the environment.

In recent times, the body of published research on water resources has documented greatly increased rates of land-use change and degradation, rising levels of river exploitation and other forms of natural water resource overuse, and increasing effects of climate change throughout much of the world (Arthington 2012). These global trends have been shown to alter the natural flow regime of many rivers, especially the river estuaries and downstream sections of the watersheds, and these changes are likely to cause serious ecological consequences (Arthington 2012). In addition, Kennish (2002), Sierra et al. (2004), and Sun et al. (2009) also assert that the downstream and estuary areas are particularly fragile and easily threatened by the upstream water exploitation and water related infrastructure development. In some cases, the natural environmental flow requirement has been shown to not be sufficient in order to sustain and conserve the riverine ecosystems due to the current seasonal discharge changes and complex fluctuations (Shinozaki, Fujiwara & Shirakawa 2018) and, therefore, there is uncertainty about the survival of these systems in many locations.

A wide range of methods is described in the literature to assess the environmental flow requirement, depending on the objective-based approach. The methods include the study and assessment of the hydrological and hydraulic regime, ecological habitats, socio-economic assessments, and holistic approaches (Tharme 2003). The environmental flow assessment approach is not an easy river flow estimation formula and is not a fixed number of cubic meters per second. Rather, determination of the river flow requirement must consider specific geomorphological and ecological aspects of the river, such as fisheries, downstream water supply needs, tourism, and river channel maintenance (Meynell 2012). Hence, the environmental flow assessment is primarily useful in that it can be conducted in different environmental contexts, different scales, and with various biophysical system backgrounds, as well as in different political and socio-economic development settings (Arthington 2012).

In the context of Laos, the concept of a minimum environmental flow is relatively new and not yet well-implemented in management policy. Although the minimum flow requirement has been clearly stated in Article 21 of the national law on water and water resource (National Assembly 2017), yet the clear scope on what is the flow requirement for each river and watershed is not defined. The main objective is to preserve and maintain the water for basic people's livelihood and sustainable environment and ecosystem value in the watershed. However, the national legal framework and the detailed action plan for concrete implementation of the law remains a major challenge due to lack of relevant technical capacity, experience, tools, and resources. Therefore, a baseline study is required for future comprehensive research and application countrywide.

2.3 Water demand and allocation

Water demand is the sum of water volume or amount needed to meet various user requirements of users in the watershed system or an area (GWP 2012). Water demand management is a fundamental factor for the watershed water resource planning and governance. Without proper water demand management through the stakeholder partnership modality and cooperative management structure, the effective water demand management is unlikely to succeed (Hering & Ingold 2012). Consequently, this may be increased water use tensions and conflicts among internal and external water users or stakeholders. The demand for water may not have direct relationship with the minimum requirement (Gleick 2003). Therefore, the water demand management requires comprehensive and holistic approaches, strategies and instruments to support implementation, such as mandatory water conservation, water pricing, public-private partnership, and society engagement (Tortajada & Joshi 2013).

The effective water demand assessment and projection is one of the possible options aiming at understanding the real need for securing water for all. The water demand projection is one of the important tools for water use planning, supply designs, and operations in order to meet the increased demands in the long-term (Herrera et al. 2010). Moreover, the authors claimed that the long-term water demand projection is useful for the water resource planning and design purpose. However, Bougadis, Adamowski and Diduch (2005), and Jain and Ormsbee (2002) argued that the short-term water demand assessment is also a vital process to assist the water managers in making better management decisions for balancing both water supply and water demand. In their research, the authors employed a calibrated mathematical model to predict the short-term water demand. Hence, the short and longer-term water demand assessment and prediction is also an active field of study that involves various datasets and indicators.

The population growth and requirement for the environment are arguably the key indicators for water demand projection and management. These factors are increasingly dependent on adequate water for proper, acceptable quality, and sufficient volume for their subsistence and functions. Thus, the people-oriented approach is crucial for future projection and addressing the water demand challenge with lower cost and impact on the environmental (Browne 2015). Furthermore, Browne (2015) also argued that the practice-oriented approach is a set of highlighted mechanisms for the water demand and supply studies. Therefore, both people and practice-oriented approaches are needed for water demand assessment and future projection. In addition, given the significance of the water demand management and allocation, the multi-stakeholder dialogues, joint citizen actions, and other deliberative forms of engagement with the community are potentially effective approaches that may lead to more equitable water demand allocation and management in the watershed (Dore & Lebel 2010). Therefore, the water demand study is an important field for effective water resource planning, allocation, and governance in avoiding water use insufficiency and inequity.

2.4 Climate change

Climate change is a wide scholarly topic of discussion in the literature and is now generally recognised in both the academic world and broader society as the most significant global environmental problem affecting the whole of the human population and future generations and the natural environment going into the new millennium (Shaw et al. 2011). According to the International Panel on Climate Change (IPCC), in the last 100 years, the mean temperature has increased by 0.3°C – 0.5°C globally (IPCC 1990). The accelerating trend of the global mean temperature rise reached 0.87°C during the short period between the year 2006 to 2015. The projecting trend of the current global warming is at 0.2°C per decade (IPCC 1990, 2018). It is further reported by the IPCC that the global warming will increase at or exceed 1.5°C by the year 2100, which will result in dramatic effects on the earth's ecosystems and will affect water resources. Consequently, the effects of climate change will potentially increase the average global rainfall, river flow or runoff, and potential evaporation that might then increase the intensity of the overall water related extreme events (Mishra & Singh 2010; Tsakiris & Vangelis 2004).

A number of scholarly writings have discussed the severity of likely impacts of climate change on water resources, especially river flow regime. For example, Arnell (1999), Kang, Khan and Ma (2009), and Magadza (2000) have reported that climate change has the potential to significantly exacerbate the stress on water resources in many parts of the earth's land areas. In addition, it appears from literature that, although the global average rainfall will increase due to climatic changes, large land surface areas will experience a reduction of rainfall instead. More specifically, the effect of the higher temperature and greater evaporation may result in the increase of the river runoff at the global scale. This phenomenon of runoff increases in tropical zones, such as in the Southeast Asia region, will include effects on Laos. Above all, researchers agree that water is a vulnerable resource and there are potentially many challenges ahead under the changing global climate patterns, especially in the arid and semiarid regions that depend on precipitation (Misra 2014).

At the country level context, Laos is geographically landlocked and a tropical monsoon country with an abundance of natural resources that include the forest, water, minerals, fertile soil, vast wilderness areas, and aquatic ecosystems. However, the country is entering a new era of rapid socio-economic development, human population growth, and poverty reduction, creating some challenges and obstacles to accommodate this growth and increasing prosperity. There are implications arising from climate change, such as more frequent flooding, drought, storms, and typhoon events that are occurring due to variability in precipitation and temperature (MONRE 2010; Pongmala 2017). World Bank (2011) has identified the need for Laos to take urgent steps to prepare for climate changes, and has published recommendations for the water sector, such as surveying and mapping and improving knowledge and skills of water engineers.

Economically, climate change has brought some impacts on the Lao economic growth that has led to a decrease of the Gross Domestic Product (GDP) of about 3% or approximately 80 million US Dollars (Kyophilavong & Takamatsu 2011). In addition, the average temperature has increased at a range between 0.1-0.3°C per decade during the period 1951 to 2000, and this figure is further projected to increase by about 1.4-4.3°C by the year 2100 (World Bank 2011). Therefore, the climate change is well-recognised as expected to have a real impact on the environment and Lao people's well-being in the coming era. It can therefore be concluded that the issue of climate is likely to have significant impact on the water resource system in Laos that needs to be further researched to help create deeper understandings of how this impact or change will affect water and the environment for future water resource planning and management.

2.5 Water resources policy and institutional framework

2.5.1 Policy, strategy and action plans

A water resources policy framework is an important regulatory setting that plays a crucial role for the national and local water resources management direction and guidance for all sectors. The sustainable and integrated water resource management is being implemented and discussed across water-use sectors in the country involving agriculture, hydropower, industry, energy and mining, and natural resource. People are using and extracting more and more water for their daily subsistence, and social-economic development. Therefore, sustainable water resources management is crucial for the future country development. According to Loucks (2000) "sustainable water resource management is a concept that emphasises the need to consider the long-term future as well as the present". Consequently, integrated water resource management is designed to satisfy the needs of local people and the environment in accommodating the increased water demands of diverse development aspects at the watershed level. Therefore, the government of Laos formulated and reinforced the national policy, strategy and action plans towards the year 2030.

At the national level, the government has developed and implemented the 8th Edition of the National Socio-Economic Development Plan (NSEDP) 2016-2020, Strategy 2025 and Vision 2030, which integrated all the development sectors policies to support the national and local implementation (MPI 2016). Based on the plan, the government targets to ensure the green, clean and sustainable development through the planning and management of natural resources in more practical, fair, effective and sustainable manner. Particularly, the water resource planning and management has been identified as the government priority. The detailed plan of the government is to manage at least ten priority river basins namely Nam Ngum, Nam Ou, Nam Theun-Kading, Nam Ngiep, Nam Sam, Nam Ma, Sebangfai, Sebanghieng, Sedone, and Sekong (MPI 2016). Of these, Nam Xong watershed is located within Nam Ngum River basin, which is of national priority and significance. In addition to that, the government planned to develop and implement the IWRM demonstration park at Nam Por sub-watershed which is a tributary of the Nam Xong watershed. This plan is to promote and set up the first national IWRM Demonstration Park for future water and related issue education, research and study, training and knowledge hub on-site, and broad-based public awareness. Hence, the water resource management in the Nam Xong watershed is an important recognition of the government's long-term plan aiming to secure water for all communities and sectoral development in the area.

At the sectoral level, the government also developed and approved the 1st Natural Resources and Environment Sector Plan towards the year 2020, strategy 2025 and long-term vision 2030 in alignment with the national plan. This sectoral plan and strategy emphasised the significance and real need for the integrated natural resource and cross-cutting issue management (MONRE 2015). More importantly, the sector disseminated the national plan by indicating the need for better collaboration and active involvement of all natural resource and related sectors such as land, water, forest, mineral and geology, climate change, environmental quality and promoting research as well as national, regional and international cooperation (MONRE 2015). In this regard, the related action plans are to promulgate and implement the amended law on water and water resources, develop and implement the IWRM plans and managerial committees for at least in the ten national prioritised river basins. Furthermore, the government promotes study and research on the streamflow in the river basins for effective water use planning and management, as well as water quality monitoring for at least 200 monitoring points throughout the country. Thus, these aspects reveal that the water resource sector is a real priority of the government aimed for effective management through more scientific study and collective collaboration across sectors.

In addition, the government has also formulated and approved the strategy on climate change in March 2010. The strategy stated seven important impact areas, such as agriculture and food security, water resource management, forestry and land use change, public health, energy and transport, industry, and urban development (MONRE 2010). Of these, the adaptation and mitigation measures for the water resource sector are also identified for implementation, for instance the urgent need for climate change scenario development for the watershed management, such as application of the hydrological and streamflow simulation models for longer-term prediction. However, the key obstacles to implement these actions are lack of the local capacity and public awareness. Significantly, there are limited facilities or advanced applied-technology, and inadequate real-time water resource data. Therefore, these are necessary to improve and implement all related climate change preparation actions on the ground.

Although the policy, strategy and action plans are in place, the robust reinforcement, and implementation remain as challenges. These include the lack of local capacity, scientific water resource studies, and financial support as well as inadequate technical tools and facilities are also concerns (MAF 2015). There is also a lack of other policies of integration between water use and water management sectors, as well as lack of regular monitoring and evaluation of the implementation. In order to overcome those obstacles and challenges, it is important to implement and reinforce the policy framework by increasing more responsibility and accountability of the government at all levels, and by promoting more stakeholder collaboration. Moreover, stronger partnerships with the private sector and international communities is a must for sustainable use of natural resources (World Bank 2011). In addition, the government needs to create climate and disaster relief funds and capacity development (Pongmala 2017). In summary, the policy and strategic and action plans are vital enabling tools for the sustainable and holistic watershed management.

2.5.2 Water and water resources law and regulations

Water and water resources law of the year 1996 can be traced as the beginning and entry point of the water resource and watershed management in Laos. Since then, this water and water resources law has been improved and amended in 2017. This is due to the changes of the policy, environmental condition, national socio-economic development, and water management needs in the new development atmosphere in the country. This amended law provided the new regulatory framework of the water resource legislation profile that will be implemented and enforced further. More specifically, this law promulgated a wide-range of water and watershed management. According to the current Law on Water and Water Resources (Article No. 36), the clearly defined purposes of water use for basic human needs and use for other development purposes (National Assembly 2017, p. 16) includes:

1. *Drinking and consumption by people;*
2. *Irrigation, forestry and agricultural production, husbandry and fishing;*
3. *Electrical power production and mining;*
4. *Industry production;*
5. *Communication and transport;*
6. *Medicine, health protection and hygiene;*
7. *Recreation, sports and tourism;*
8. *Other targets.*

More relevant to the watershed management, the amended law states the necessity of the watershed management and planning system, which represents the mechanism for integrated water resource management. The watershed planning system provides the broad technical framework for better environmental objective setting and sustainable water resource management in the watershed. In this national law, there is an emphasis and definition in the articles No. 10, 11, and 12 on the importance and establishment of the water use management plan and strategy at the watershed level. This aims to promote the sustainable water use allocation in securing water for all communities and development sectors, especially the water allocation for basic local people's need and the environment (National Assembly 2017).

Apart from the national law and regulatory framework, the local water resource regulation was also established aiming to facilitate and implement those umbrella legislations at the Nam Xong watershed scale. The regulation on water quality monitoring and management was developed and issued by the three district governors in 2013 (Lao-Thai-German Trilateral Cooperation 2014). Additionally, this part of the regulation also introduced the simple technical guidelines on the water quality monitoring and management to be further applied and implemented by the local authorities. Regardless, the local legislation only laid out the water quality issue, while the overall watershed and water use allocation plan is yet to be put in place. Therefore, there is some gap for watershed management and future water use management in the watershed area. However, this would be a part and baseline of the water use management process by contributing to the water availability condition study for future water use allocation plan and regulation formulations.

2.5.3 Institution and coordination

Generally, the national administrative system is divided into four main levels and hierarchy as central, province, district, and village levels. The general policy framework is formed and decentralised the implementation to the province, district, and village respectively. Most of the policy and strategy frameworks are discussed and designed based on the local priorities and needs. The government has been implementing and monitoring the 3-build decentralisation policy framework related to the water resource sector (MAF 2015; MONRE 2015) to delegate more power to the local administrative units. For better river basin or watershed coordination, the government issued the Prime Minister's Decree on Establishment and Activities of River Basin Committee (RBC) in 2010. This legislation aimed to coordinate the water resource and its related sector in the watershed in the country based on an integrated approach (PMO 2010). Hence, the legislative development is an important platform and back up for the integrated and holistic watershed management.

Water resource stakeholder coordination is among most important coordination mechanisms in the country, especially in the NXW. Although there are quite diverse water stakeholders in the watershed, the effective coordination is still a far reaching commitment by the users for smoother cooperation (DWR 2013). This also revealed the lack of effective data sharing among agencies in the watershed for water study and planning processes. In addition, a cross-sectoral working group at the technical level, named the Nam Xong watershed technical working group (TWG) has been set up (Lao-Thai-German Trilateral Cooperation 2014). The working group consisted of three main districts of Kasy, Vangvieng and Hinheup of Vientiane province (Figure 2.2). The working group was formed to better coordinate and collaborate between upstream and downstream districts as well as promotion for regional, national, and local collaboration. The working group aimed to enhance better coordination of the stakeholders in the districts. While in the past, each district managed their own water resources in their area. As a result, the promotion of the coordination and collaboration among diverse stakeholders is crucial for effective Nam Xong watershed management.

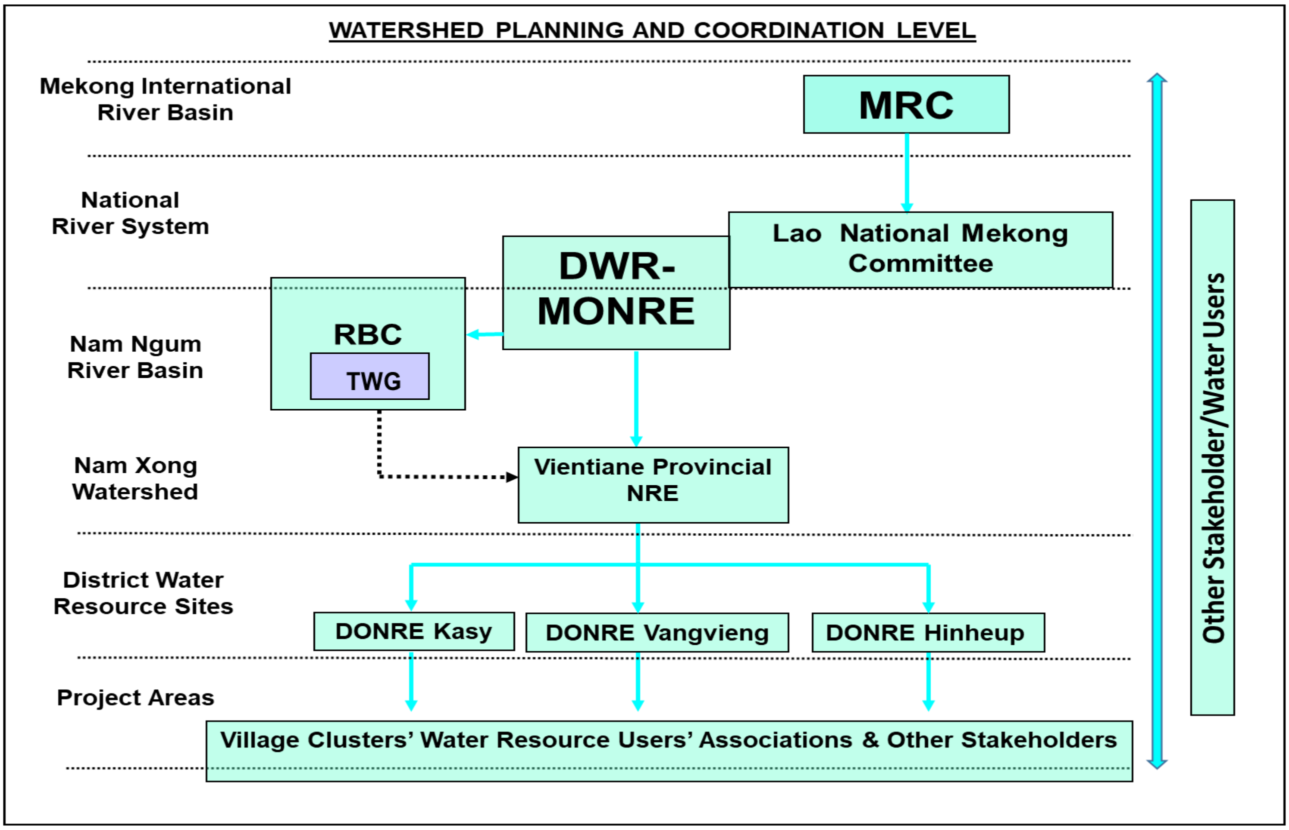

Figure 2.2. Diagram of the watershed planning and stakeholder coordination, adapted from Pasicolan (2012, p. 19).

2.6 WEAP model application

Water Evaluation and Planning System (WEAP) is a tool for rapid assessing and examining the water resource in a catchment or watershed system for the main purpose of water resource planning, predicting of water demands and long-term management and development strategies (Loon & Droogers 2006; Sieber & Purkey 2015). The WEAP model was developed by the Stockholm Environment Institute (SEI) in 1988. The WEAP model package is a state-of-the-art and comprehensive computerized water resource planning model that assists water resource planners with a powerful and straightforward resolution tool (Azlinda & Mohd 2012; Loon & Droogers 2006; Metobwa, Mourad & Ribbe 2018; SEI 2012; Sieber & Purkey 2015; Sithiengtham 2019). The WEAP model is very useful for water resource assessment and evaluation of broad-based strategic environmental assessments (Gao, Christensen & Li 2017). Based on the SEI (2012), WEAP is applicable in a single and even complex watershed system addressing wide range of water related issues such as sectoral water demand allocation and water use rights, river flow and ecological requirement and conservation, streamflow and groundwater interaction and simulation, water pollution tracing and control, hydropower and reservoir operations, and water project cost-benefit analysis. The WEAP model is structured five different "Views" or called "Views Bar" showing the schematic, data, results, scenario explorer, and note views (SEI 2012).

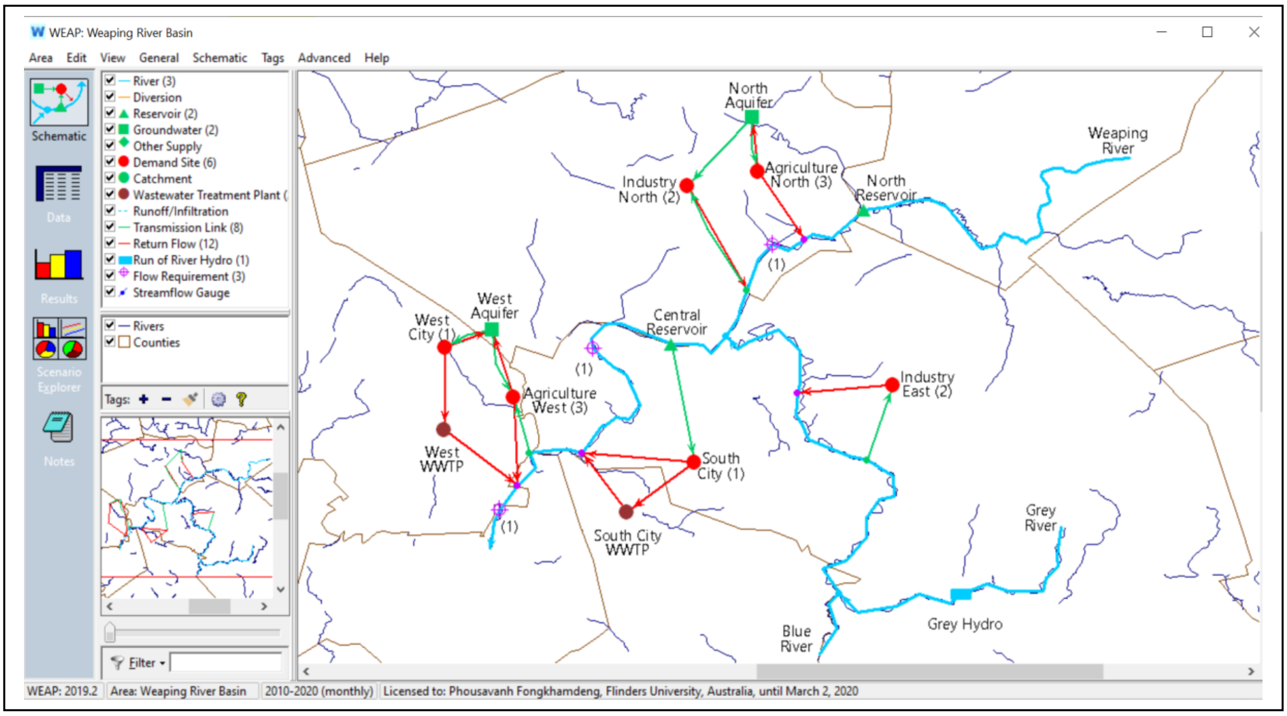

Figure 2.3. General WEAP model feature and schematic package snapshot.

Generally, there are five main methods in the WEAP model package. These methods include the Rainfall Runoff, Irrigation Demands Only (simplified coefficient approach), the Soil Moisture Approach, the MABIA Method, and the Plant Growth Model Method (Sieber & Purkey 2015). The selection and application of a method is based on the objective and purpose of the research and users' needs. Apart from these methods, the WEAP model package allows linking to other scientific water modelling packages that requires adequate and accurate input data, while WEAP input data require monthly or yearly data time series. In this study, the simplified rainfall runoff or simplified coefficient method will be applied in the case of the Nam Xong Watershed in Laos. In general, this method is the simplest among five main WEAP methods that calculate and simulate the river flow and balance by mainly employing the discharge, potential evaporation, and rainfall datasets (Sieber & Purkey 2015).

In the past years, there were quite a number of scholars who applied the WEAP model package for water resource planning around the world. In this regard, three cases of the studies that applied this model were selected for further review and exploration for an opportunity to better understand the context, advantages, gaps, and immediate recommendations. These studies are: 1) “Projecting water demand and availability under climate change through the application of WEAP at the Nam Ngum downstream area, Laos” (SEI 2019; Sithiengtham 2019), 2) “Water demand simulation using WEAP 21: A case study of the Mara River Basin, Kenya” (Metobwa, Mourad & Ribbe 2018), and 3) “Assessment of water demand in Langat catchment using Water Evaluation and Planning (WEAP)” (Azlinda & Mohd 2012).

The first study concerns the projection of water demand and assessing of water availability in the downstream area of Nam Ngum River basin in Laos (SEI 2019; Sithiengtham 2019). This study was a major master thesis at the College of Science and Engineering, Flinders University, Australia published online on the official WEAP webpage in 2019 (SEI 2019). The author aimed to evaluate and assess the water balance and then projected the future water use demand up to the year 2050. The main methodology applied the WEAP model package by using different data sets such as hydrological (river discharge), climate (rainfall, temperature, wind, humidity), land use, population growth and main sectoral water use (domestic, agriculture and industry) data analysis. The main result of this study revealed that the water demand of this area is likely to increase by the year 2050, but there was not a major concern for the local water use due to adequate water availability in the study area (Sithiengtham 2019). However, under the climate and land use change, there might be an alteration for the water flow regime and water availability in the area. Hence, the appropriate water restoration projects, water related infrastructure and management measures need to be developed and implemented in the area.

The second paper is a simulation of water use demand applying the WEAP model in Mara River Basin, Kenya (Metobwa, Mourad & Ribbe 2018). This article was published in the journal publication of the *International Journal on Natural Resource Ecology and Management* that appeared in 2018. The study objective was to simulate and evaluate the different sectoral water demand, contributing to the local water resource allocation policy implementation. The research employed the WEAP model for the simulation and future water demand scenario development and analysis. The main water use data was incorporated into the model for simulation such as domestic, agriculture, industry, tourism, livestock, and wildlife demand. This typical study set the current account year to 2010 and the future scenario simulation until the year 2045. The main findings showed that total water demand by different sectors increased under the three scenarios development such as water policies, water pricing and demand management strategy (Metobwa, Mourad & Ribbe 2018). Hence, the management strategies recommended by the article included needs for more integrated river basin management, upscaling the water restoration facilities, implementation of specific water demand strategies such as storm-water restoration, wastewater reuse, wetland protection as well as related policy intervention.

The third paper was the assessment of water demand in Langat catchment in Selangor, Malaysia applying the Water Evaluation and Planning (Azlinda & Mohd 2012). The key objective of this paper was to investigate and assess water availability and projection demand and supply based on the current account year 2000 and future scenario setting towards the year 2010. The main data source was collected and analysed before input into the model simulation namely water and land use, river and climate data such as four streamflow stations, two reservoirs, nine rainfall stations and four evaporation measurement stations. The WEAP model computerised and simulated the results based on three main scenario settings that included high population growth (7%), scenarios of normal, dry and wet years, and extended dry climate sequence. The interesting results illustrated that the trend of the water resource tends to be leading to scarcity under the pressure of population growth and climate variation in the catchment (Azlinda & Mohd 2012). Thus, the authors suggested and recommended that the use of the WEAP model is important in projecting the future water demand and supply strategy at the watershed level. Therefore, the intention of all stakeholders' cooperation is highly required in avoiding the future water resource problem.

From the review of the three articles and papers, it can be reflected that there is some similarity in terms of the WEAP model set up and simulation processes; however, there are differences in terms of data requirements, study objectives, and future assumption options or scenario development. Significantly, these reviewed papers are very useful and relevant to the current research in Nam Xong watershed in preparing the data and need, WEAP model simulation and calibration techniques as well as the effective scenario development and result interpretation. In addition, the reviews revealed that the WEAP model package is an important and comprehensive tool for integrated water resource management and long-term planning support, which is depending on the purpose of the study and condition of the study area (Sieber & Purkey 2015). However, there is wide application of the WEAP model around the world, and the applied model still has some challenges and limitations in its application. For example, the limitation of the application of the WEAP model might depend on the quantity and quality of the data inputs. The model might have some limited performance for the direct water quality assessment and groundwater investigation for which it would still need to link with QUAL2K and MODFLOW models, respectively (Sieber & Purkey 2015; Sithiengtham 2019). Therefore, the WEAP model application might be more useful on studies where the clear objective-based aim is set, and efficient and accurate data analysis can be acquired.

3. MATERIALS AND METHODOLOGY

3.1 Study area

The location for this research was the Nam Xong Watershed (NXW) area at the central part of the Nam Ngum River Basin in Laos and was then referred to as “the study area”. The total area of the watershed is approximately 180,423 ha or equivalent 1,800 km^2. The watershed lies within the latitude 18°38’58” N - 19°17’10” N and the longitude 102°13’37” E - 102°37’57” E. The watershed is classified as a small-scale watershed in Laos. Geographically, the watershed boundary covers three provinces of Vientiane, Luang Prabang, and Saysomboun. These three provinces occupy six districts, which are Phoukhoun (Luang Prabang province), Longcheng (Saysomboun province), Kay, Vangvieng, Hinheup and Feuang Districts (Vientiane province). All villages in the watershed are located in three districts of the Vientiane province (Kasy, Vangvieng and Hinheup), while Feuang district and the other two districts in the remaining two provinces occupy only land coverage without villages or population. Therefore, this study mainly focused on these three districts, discussed throughout the paper.

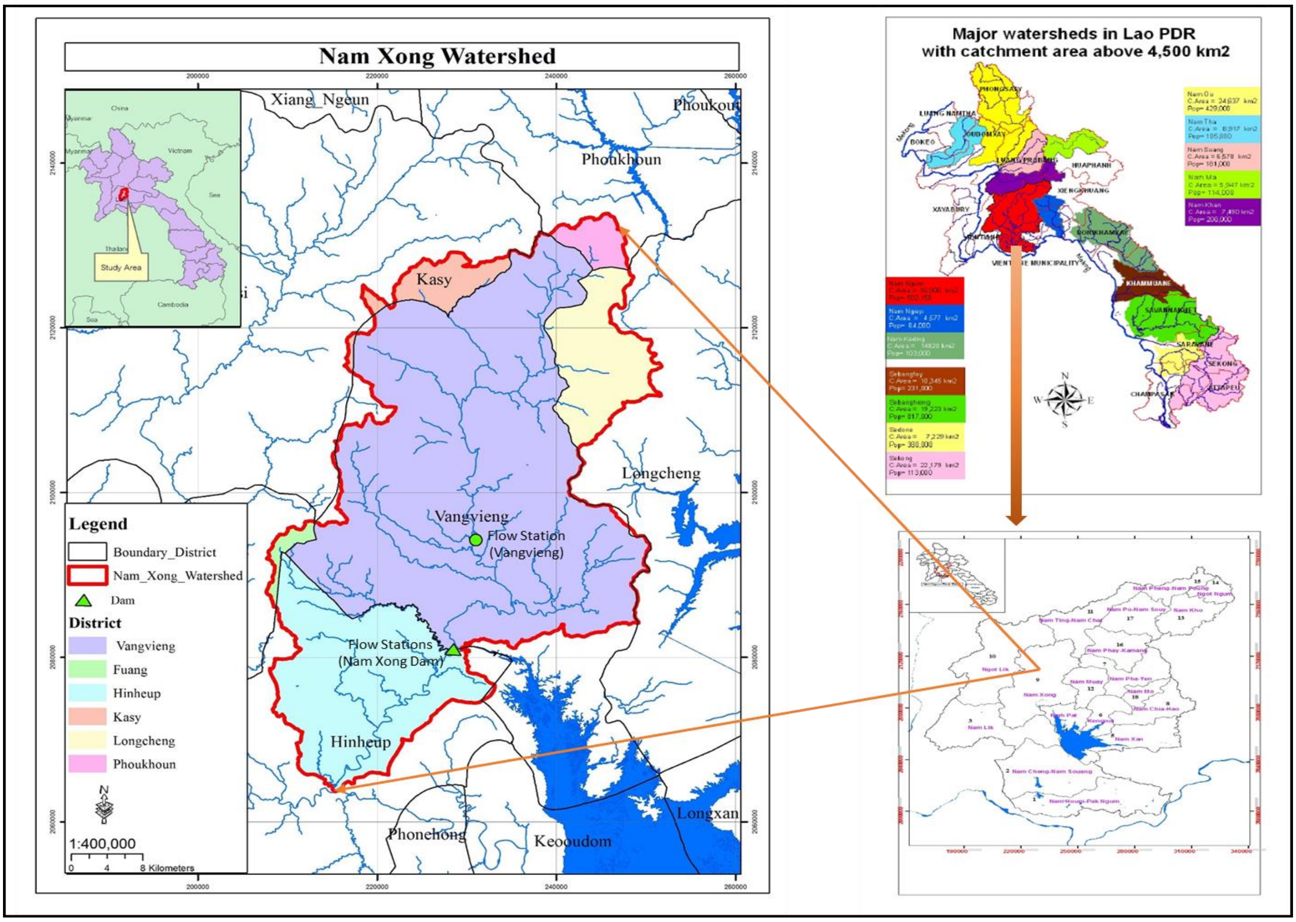

Figure 3.1. Location of the study area.

3.2 Data preparation and analysis

There are two main data sets for this study that include hydro-climatic data, and land and water use data.

The first dataset, three meteorological stations in Kasy, Vangvieng, and Hinheup districts are selected and used in this study. Of these, only Vangvieng station is located in the NXW, while Kasy and Hinheup stations are located outside or nearby the NXW boundary. The climatic data included the daily precipitation (mm), and potential evaporation (mm). In addition to those observed data, three hydrological stations are also selected for observed river flow at Vangvieng (one station) and Nam Xong dam (two stations, upstream and downstream of the dam, Hinheup district) with daily discharge measurements (m^3/s). There were no hydrological stations present at Nam Xong River or its tributaries in Kasy district. The hydro-climatic data has been checked and derived from the Department of Meteorology and Hydrology (DMH), Nam Xong Dam and three main districts. The data period is from 1997-2018 (22 years) with no missing data. In addition, the groundwater recharge rate was derived from the WetSpass-M model calculation in the Lower Nam Ngum River basin (downstream of NXW) (Douangsavanh 2019). The annual rainfall was used to estimate the natural recharge. The groundwater recharge rate was estimated to be about 26% of the total annual rainfall and this estimated rate was used in this study.

The second set of the data concerns land use, population, and water use. The land-use data for the year 2010 was selected and derived from the Department of Water Resources (DWR) and Mekong River Commission (MRC). In addition, three types of main water use data were also collected, which were agriculture, domestic, and industry. These were considered as the main water users in the NXW. The population data was also obtained for the WEAP model simulation and scenario development. Therefore, the data used in this study are described in detail and analysed in the below sections.

3.2.1 Precipitation

There are three meteorological stations in the NXW at Kasy, Vangvieng and Hinheup districts, or referred to in this study as “meteorological stations”. Daily precipitation data series from 1997 to-2018 (22 years) were collected from the Department of Meteorology and Hydrology (DMH) and three District Office of Natural Resources and Environment (DONRE). The precipitation data set was analysed and converted to a monthly time scale. Figure 3.2 shows that the annual rainfall in the Vangvieng district has the highest proportion of the NXW area. The maximum average monthly rainfall was about 850 mm for July in the Vangvieng district. While the temporal rainfall pattern in the other two districts of Kasy and Hinheup was relatively similar to each other, they showed significantly less rainfall than Vangvieng in the wet season.

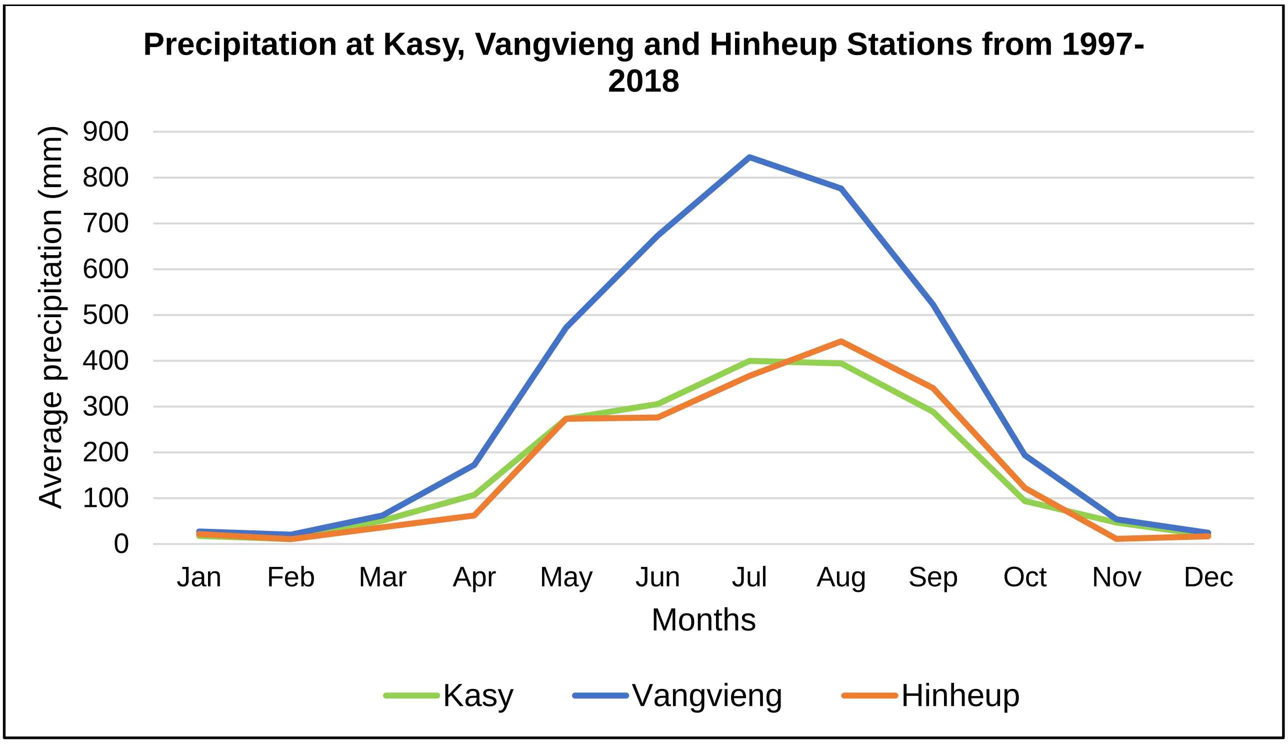

Figure 3.2. Average monthly precipitation at Kasy, Vangvieng and Hinheup stations.

3.2.2 River flow

In the study area, there are three river flow gauges or discharge measurement stations that are located at Nam Xong mainstream. Of these, upstream station located in Ban Huaysangao village, Vangvieng district and the two downstream stations sited at Nam Xong Dam (upstream and downstream of the dam), called "Vangvieng Station" and "Nam Xong Dam Station" respectively. The daily discharge was collected for the period of 1997-2018. This dataset was obtained from the DMH, the Vangvieng district DONRE and Nam Xong Dam. The mean river flow of the Nam Xong mainstream at Vangvieng station ranged between 20-140 m^3/s throughout the year (Figure 3.3), while the observed mean river flow at the Nam Xong dam (upstream and downstream) stations ranged between 14-290 m^3/s, and 3.7-156.5 m^3/s, respectively. The mean annual river flow at Vangvieng and Nam Xong Dam (upstream and downstream of the dam) stations are 59 m^3/y, 99 m^3/y, and 37.7 m^3/y respectively. Notably, the river flow at the Nam Xong dam station (upstream section) was higher than at the Vangvieng station during the beginning and the rainy season, but lower during the dry season than in the Vangvieng station.

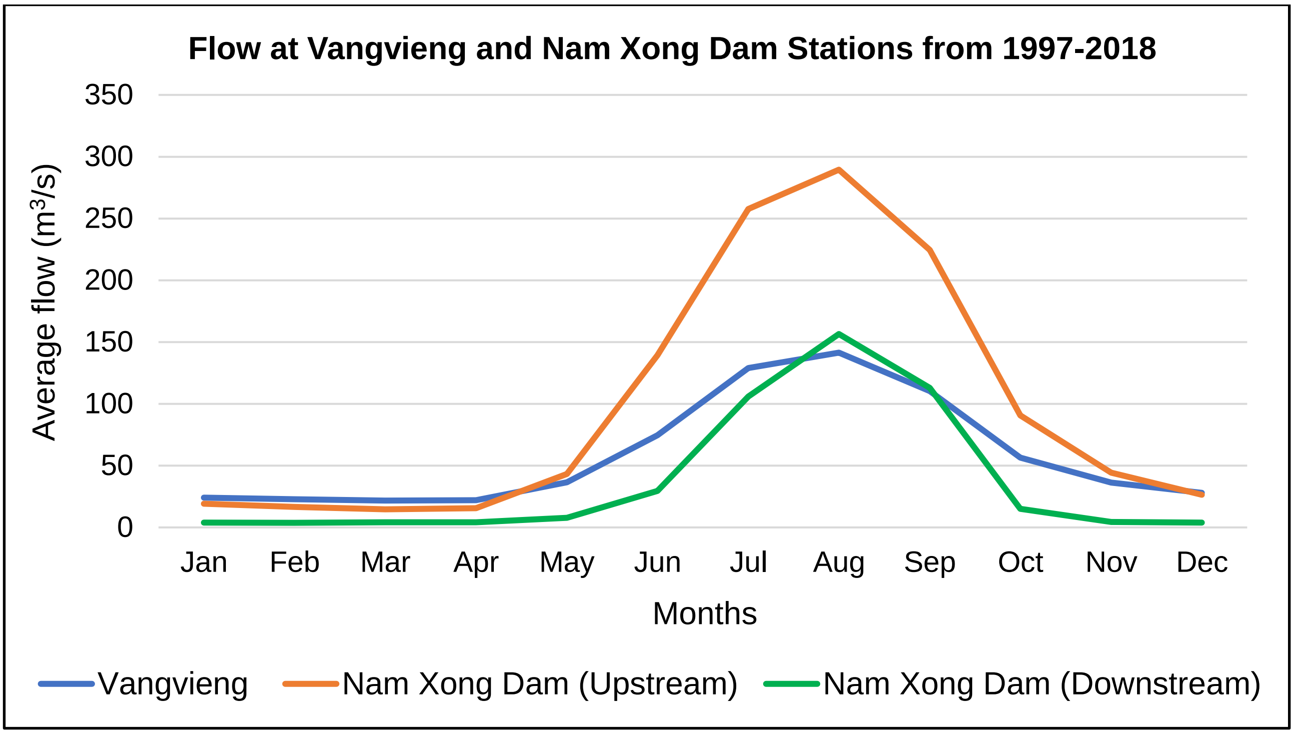

Figure 3.3. Annual mean river flow at the Vangvieng and Nam Xong Dam stations.

3.2.3 Evaporation

Evaporation data from 1997-2018 were collected for this study. The Vangvieng station was the only station in the NXW that measured the potential evaporation and is hence used in this study. The highest potential evaporation rate occurred during the dry season (November-April) when the sun light and radiation rate is high. The maximum evaporation is approximately 173 mm per month for March (Figure 3.4), while the lowest evaporation rate in the watershed is about 25 mm per month for July and August. The mean annual evaporation rate is 65 mm per month.

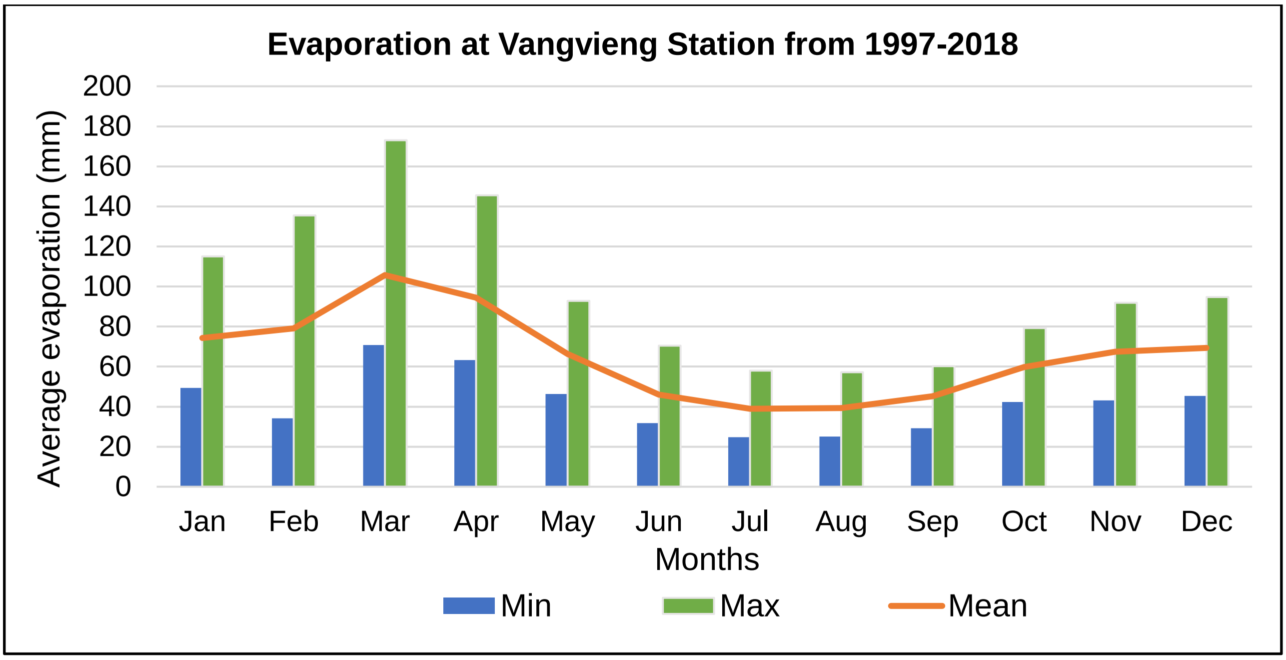

Figure 3.4. Average monthly potential evaporation (piche) at the Vangvieng station.

3.2.4 Nam Xong Dam

Nam Xong dam is a concrete gravity overspill dam type designed for electricity generation and water diversion operation of the Nam Ngum 1 dam reservoir or called the Nam Xong dam (Figure 3.5). The elevation of the dam is approximately 245 m.a.s.l. The dam generates 6 MW with three turbines from a discharge of 43.33 m^3/s/unit or 130 m^3/s for the three turbines together. Most of the discharge is diverted to the Nam Ngum 1 dam reservoir through a diversion canal length of 2.5 km. The remaining water is discharged to the Nam Xong downstream and then flows to Nam Lik river (Nam Ngum's tributary). The gross water storage capacity of the dam is about 13.5 million m^3. The average diversion discharge is 65.1 m^3/s and the minimum diversion discharge is 2 m^3/s (MEM 2019). Although, the minimum discharge to the Nam Xong main stream is not clearly set. The summary of the dam characteristics is presented in Table 3.1.

Table 3.1. General characteristics of Nam Xong Dam.

Name	Gross Storage Capacity (mil. m^3)	Max. diversion discharge (m^3/s)	Ave. diversion discharge (m^3/s)	Min. downstream discharge (m^3/s)	Ave. turbine discharge ($m^3/s/unit$)
Nam Xong Dam	13.5	210	65.1	2	43.33

Source: (MEM 2019)

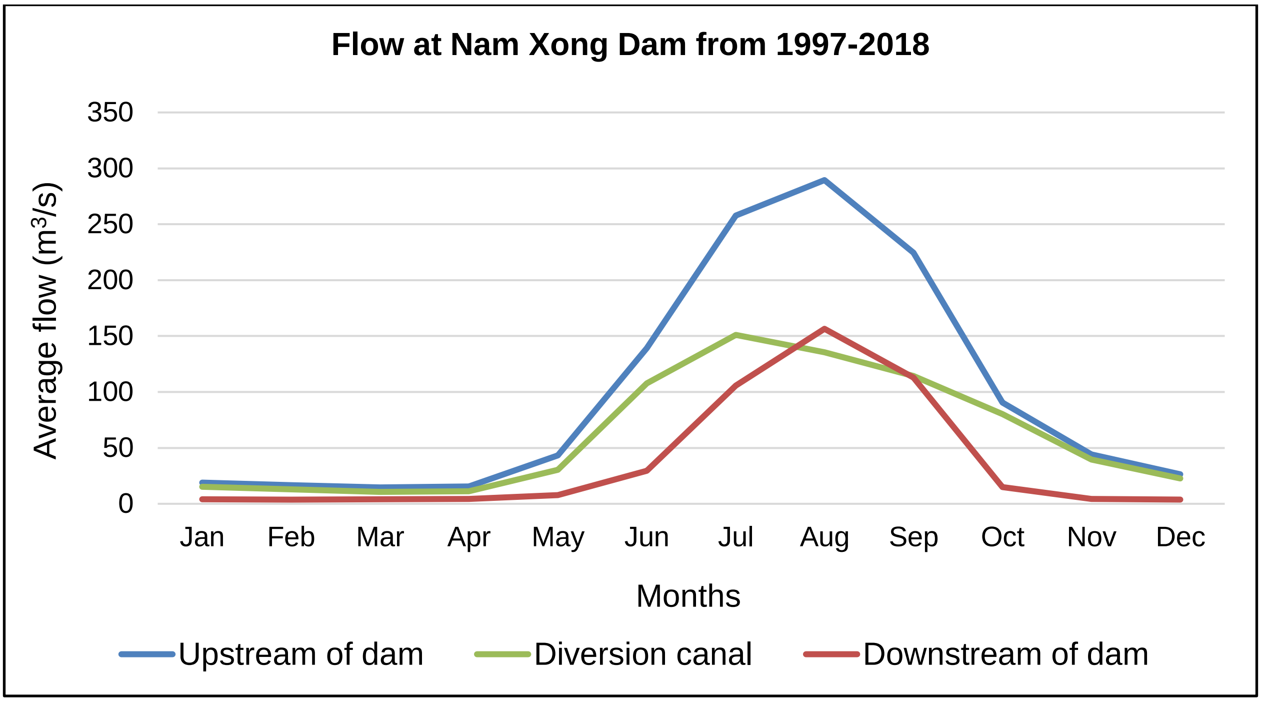

Figure 3.5. Average monthly river flow at Nam Xong Dam (at upstream, diversion canal and downstream dam stations).

3.2.5 Population

The population in the Nam Xong Watershed is approximately 44,886 people. Of these, there are 22,141 female or about 49.4 % of the total population (Lao Statistics Bureau 2010). There are a total of 68 villages and 7,699 households in the watershed. Vientiane province presented 100% of the population in the NXW. Other provinces only contributed a small proportion of land and forest area with no villages and population. Vangvieng district showed highest population concentration in the watershed of about 80%. Hinheup and Kasy districts have respectively about 18% and 2% of the population in the watershed. The population growth rate is about 1.5% per annum, and the average population density is approximately 27 persons per square kilometre (Lao Statistics Bureau 2015; Vientiane Provincial Governor 2015).

Table 3.2. Population distribution in Nam Xong Watershed 2010.

No.	Name of Districts	No. of Village	No. of Household (HH)	Total Population (person)	Percentage (%)
1.	Kasy	3	176	957	2.14
2.	Vangvieng	49	6,004	35,578	79.44
3.	Hinheup	16	1,519	8,351	18.42
	Total:	**68**	**7,699**	**44,886**	**100**

Source: Lao Statistics Bureau (2010)

3.2.6 Land use

Land use data is important for analysing the change that might affect the water resource in the watershed area. The dataset derived from the Department of Water Resources and the Mekong River Commission. In the NXW, there are 12 major land use types (Table 3.3). Of these, the broadleaved deciduous forest covers a major part of the watershed, about 84,590 ha or approximately 47% of the total watershed. The shrub land and broadleaved evergreen forest occupy 45,323 ha (25%) and 19,433 ha (11%) respectively. The agricultural land area is summed up by three land use types, which are paddy rice, shifting cultivation, and other annual crop areas for each district (Table 3.4). This total agriculture land area was simulated in the WEAP model as an "Agriculture" demand site.

Table 3.3. Land use types in the Nam Xong Watershed in 2010.

No.	Land use type	Area (ha)	Percentage (%)
1	Shrub land	45,323	25.12
2	Urban Area	954	0.53
3	Bare Soil	3,493	1.94
4	Broadleaved Deciduous Forest	84,590	46.88
5	Broadleaved Evergreen Forest	19,433	10.77
6	Bamboo Forest	10,311	5.71
7	Marshes/Swamp area	147	0.08

8	Water Body	479	0.27
9	Paddy Rice	8,840	4.90
10	Shifting Cultivation	5,314	2.95
11	Annual Crop	197	0.11
12	Grassland	1,341	0.74
	Total:	**180,423**	**100**

Source: DWR (2019a)

Table 3.4. Agricultural land areas in the Nam Xong Watershed in 2010.

No.	Districts	Paddy rice (ha)	Other crops (ha)	Total areas (ha)	Percentage (%)
1	Kasy	10	65	75	0.53
2	Vangvieng	7,685	3,148	10,833	76.28
3	Hinheup	1,046	2,248	3,294	23.19
	Total:	**8,741**	**5,461**	**14,202**	**100**

Source: DWR (2019a)

3.2.7 Industry

The industry sector is important in contributing to local social and economic development. In the study area, the industrial units were collected from the Lao Ministry of Industry and Commerce. The primary data was obtained and then classified in three industrial units of small (combination of the micro and small units), medium, and large units. The industrial units were analysed by overlaying and matching with the village locations in each district in the study area. The industrial size category was based on the size of the total number of employees in a factory or industrial unit. Based on the government regulation on small and medium industry size categorisation in 2017, the micro industrial unit has employees from 1-5 persons, the small unit comprises of employees from 6-50 persons, while the medium and the large units present total employees of 51-99 persons and >100 persons respectively (GOL 2017). In this study, the micro and small units were merged as “small”. Hence, the total classified industry is 291 units in the watershed. The detailed classification of the three industrial units in each district is presented in the Table 3.5. These units are used as water demand sites in the WEAP model and water use rate calculation for the industrial sector.

Table 3.5. Industrial production units in the Nam Xong Watershed.

No.	Districts	No. of Villages	Industry (unit)			Total industry (unit)	Percentage (%)
			Small	Medium	Large		
1	Kasy	3	0	0	0	0	0
2	Vangvieng	49	248	0	3	251	86.25
3	Hinheup	16	39	1	0	40	13.75
	Total:	**68**	**287**	**1**	**3**	**291**	**100**

Source: MIC (2015)

3.3 Method

There are five major methods in WEAP model. These methods include the rainfall runoff, irrigation demands only versions of the simplified coefficient approach, the soil moisture, the MABIA, and the plant growth model. In this study, the rainfall runoff method was selected for simulation. This is a reasonably simple method compared to the other methods that helps to understand the fundamental surface and groundwater condition of the watershed. The method presents various options for the streamflow and water balance calculation (Krittasudthacheewa et al. 2012). The rainfall runoff method uses the hydro-climatic, land and water use and population data. This method considers the evapotranspiration for both rain-fed and irrigated crops applying a crop coefficient. WEAP calculates the remaining amount of the water consumed by the crops as the runoff to the watershed system including to river, reservoir, groundwater recharge through infiltration, and surface runoff (Sieber & Purkey 2015). This study was focused only on the surface water condition, while the groundwater was not fully included due to limited data and time constraint. The schematic view of the rainfall runoff method of the WEAP model is shown in the Figure 3.6.

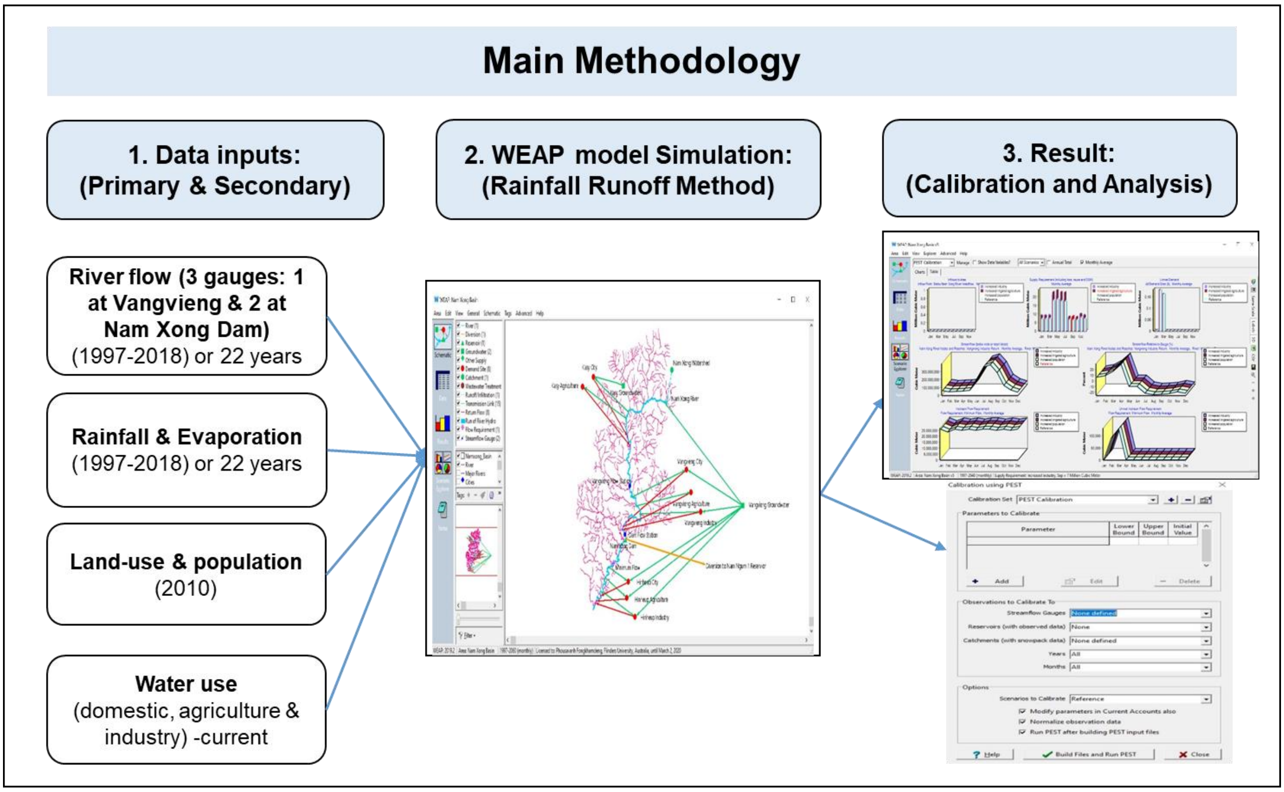

Figure 3.6. Diagram of the main methodology of the study.

3.3.1 Water head flow

The water head flow is the water amount flowing into the river and entire watershed system (Sieber & Purkey 2015). In the watershed, there are diverse tributaries of the Nam Xong mainstream and these river systems contributed to the river flow in the mainstream in addition to the precipitation and groundwater recharge. In this study, the water head flow is measured at the Nam Xong mainstream. The Vangvieng gauging station represented the water head flow of the watershed that collected the daily river flow during the period between 1997-2018.

3.3.2 Reservoir

A reservoir is one of the water infrastructures that stores and holds the storm water runoff for various purposes. There are four purposes for reservoir storage zones, which are flood control, conservation, inactive, and buffer zones (Figure 3.7). These classified zones are used and designed in the WEAP model under the reservoir tree. In the WEAP model, the reservoir water is freely discharged or released to the downstream area in order to meet the downstream water demand. At the flood control zone, the WEAP model assures the flood control zone is preserved and does not allow the water in the reservoir to exceed the top of the conservation zone (Sieber & Purkey 2015, p. 86).

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Figure 3.7. Water reservoir zone classification and operation (Sieber & Purkey 2015, p. 86).

In the Nam Xong Watershed, there is a dam reservoir located in the downstream part of the watershed. The reservoir type "runoff" that is comprised of the weir, dam, and diversion canal. The reservoir capacity is approximately 13.5 million m^3 (MEM 2019). The main purpose of the reservoir is to store water for electricity generation of about 6 MW and typically supply and divert the water to the Nam Ngum 1 reservoir by the 2.5 km diversional canal (refer to Section 3.2.4).

3.3.3 Water demand sites

There are three main water demand sites or categories in this study area. These include domestic water use (city), agriculture and industry. According to WEPA (2012) the national water usage in Laos predominantly consist of agriculture (82%), industry (10%) and domestic water use (8%). Hence, the three main water users in the NXW are described below:

- **Domestic (city)**

The demand of the domestic water use are calculated based on the population occupying each district area (Section 3.2.5) and the assumed domestic water use rate (Section 3.3.4.1). The annual population growth rate for Vientiane province of approximately 1.5% was applied in the process (Lao Statistics Bureau 2015; Vientiane Provincial Governor

2015), while the assumption for the domestic water consumption is approximately 90% without return to the watershed system.

- **Agriculture**

The agriculture water demands are quantified by multiplying the assumed water use rate (Section 3.3.4.2) with the total land use areas of the paddy rice and other crops (Section 3.2.6). By the year 2030, the estimated water use for irrigation is about 14% (PAFO 2017). The assumption of the water consumption for the agricultural sector is approximately 90% and about 10% was assumed to be lost to the system in this study area.

- **Industry**

The industrial water demands are also multiplied by the assumed water use rate for each industrial unit (Section 3.3.4.3) with the total industrial productions (Section 3.2.7). The annual industrial sector growth rate is approximately 10.7% in Vientiane province (Vientiane Provincial Governor 2015). The water consumption for this sector is assumed at approximately 90% and about 10% returning to the watershed system.

3.3.4 Water use rates

3.3.4.1 Domestic water use rate

In this study, the water use rate is potentially assumed based on the population in the watershed area. The population was estimated for each district by overlay of a population map with the village map in each district. Then, the estimated daily water supply system in Laos was used to classify each district (WASA, cited in Sayasane et al. 2016).

Table 3.6. Category of daily water supply system in Laos.

No.	Category	Population served (person)	Domestic water use rate (l/p/d)
I.	Big city	> 100,000	200-250
II.	large town	50,000 - 100,000	120-200
III.	medium town	20,000 - 100,000	100-120
IV.	small town (high potential)	5,000 - 20,000	80-100
V.	small town (low potential)	2,000 - 5,000	60-80
VI.	community	< 2,000	40-60

Source: WASA, cited in Sayasane et al. (2016)

Based on the water use supply category, the average domestic water use rate for Kasy, Vangvieng, and Hinheup districts met the category VI, III, and IV respectively. In this regard, Kasy district water use category is assumed to be 40 l/p/d, while Vangvieng and Hinheup districts water use are assumed to be about 100 l/p/d and 80 l/p/d respectively. Therefore, the estimated water use rate has been quantified as shown in Table 3.7. The average water use rate is 8.73 m^3/p/y, 129.86 m^3/p/y, and 38.10 m^3/p/y for Kasy, Vangvieng, and Hinheup districts respectively. This rate is used in the WEAP model for the water demand of city or domestic water use sites.

Table 3.7. Domestic water use rate in the Nam Xong Watershed.

No.	Districts	Population served (person)	Water use rate by category (l/p/d)	Water use rate (m^3/p/y)
1.	Kasy	957	40	8.73
2.	Vangvieng	35,578	100	129.86
3.	Hinheup	8,351	80	38.10

3.3.4.2 Agriculture water use rate

Agriculture is one of the important sectors for food security. In the NXW, the agriculture water use presented about 97%. In order to calculate and estimate the annual water use rate for the agricultural sector, the agricultural areas were extracted from the land use map 2010 (DWR 2019a). The agricultural areas were classified and quantified by summing areas of rice paddy fields, shifting cultivation area, and other crop area (refer to Section 3.2.6). The estimated water use rates for each agricultural types were derived from the regulation of the irrigation operation and management (MAF 1993). Based on that, the estimated water use rate for the paddy rice averaged about 13,000 m^3/ha/y, while for other crops the rate was about 3,000 m^3/ha/y. Hence, these rates were applied in the WEAP model for this study.

3.3.4.3 Industry water use rate

The industrial water use rate has been assumed and quantified based on the water use report of the Vientiane Water Supply State Enterprise from the year 2014-2017. There are classified water supply meters with the size range between 13-300 mm. In this regard, these have been classified in three different meter sizes or water use groups. The meter sizes between 13-50 mm were assumed to represent the “small industry unit”, the meter sizes between 80-100 mm were assumed as “medium industry unit” and the sizes from 150-300 were assumed as “large industry unit” in this study. The annual water use rate for each category was derived from the enterprise report under the water use for factory. The average of each category is presented in Table 3.8. Thus, the average water use per unit per annum for small, medium and large industry is 2,870.15 m^3/y, 18,217.25 m^3/y, and 100,832.21 m^3/y respectively. This average and the assumed rates were used in the WEAP model.

Table 3.8. Industry water use rates.

Year	Meter size	Average water use (m^3/y)
2014	Small	2,569.60
	Medium	17,129.50
	Large	166,141.00
2015	Small	3,106.40
	Medium	17,569.00
	Large	82,997.50
2016	Small	3,261.20
	Medium	19,396.00
	Large	76,058.00
2017	Small	2,543.40
	Medium	18,774.50
	Large	78,132.33
Average	**Small**	**2,870.15**
	Medium	**18,217.25**
	Large	**100,832.21**

Source: Modified from Vientiane Water Supply State Enteprise (2015a, 2015b, 2016, 2017)

3.3.5 Flow requirement

Flow requirement is the minimum instream flow rate for the basic environment maintenance and human needs along the river (Sieber & Purkey 2015). This defines the minimum monthly instream flow for the benefit of local people and water environment, such as water quality aspect, aquatic and terrestrial resource, navigation, tourism and recreation, downstream water demand requirement, and others (Sieber & Purkey 2015). In the WEAP model package, the minimum flow requirement node was created below the Nam Xong Dam gauging station. This was assumed to be representative of the lowest downstream point of the mainstream or the watershed section. Initially, the flow requirement node was set up in the WEAP model as 1st priority as equal to all other three districts and dam demand sites. In parallel with the WEAP model simulation, the simple flow plot was produced and defined the preliminary minimum flow requirement in the dry season period (November-April) at the Nam Xong Dam station.

3.3.6 Calibration

The historical or observed river flow of the Vangvieng and the Nam Xong Dam (upstream) stations were compared using a linear relationship between the two stations. The acquired equation is used to quantify and simulate the observed river flow from the year 2005-2018. The applicable equation is presented below:

$$y = 0.428x + 16.474 \qquad \text{(Equation } \mathbf{2}\text{)}$$

Where "y" is flow rate at Vangvieng station

"x" is flow rate at Nam Xong Dam (upstream) station.

The relationship of this linear process is quite reliable based on R^2 value showed at 0.96 ($R^2 = 0.96$).

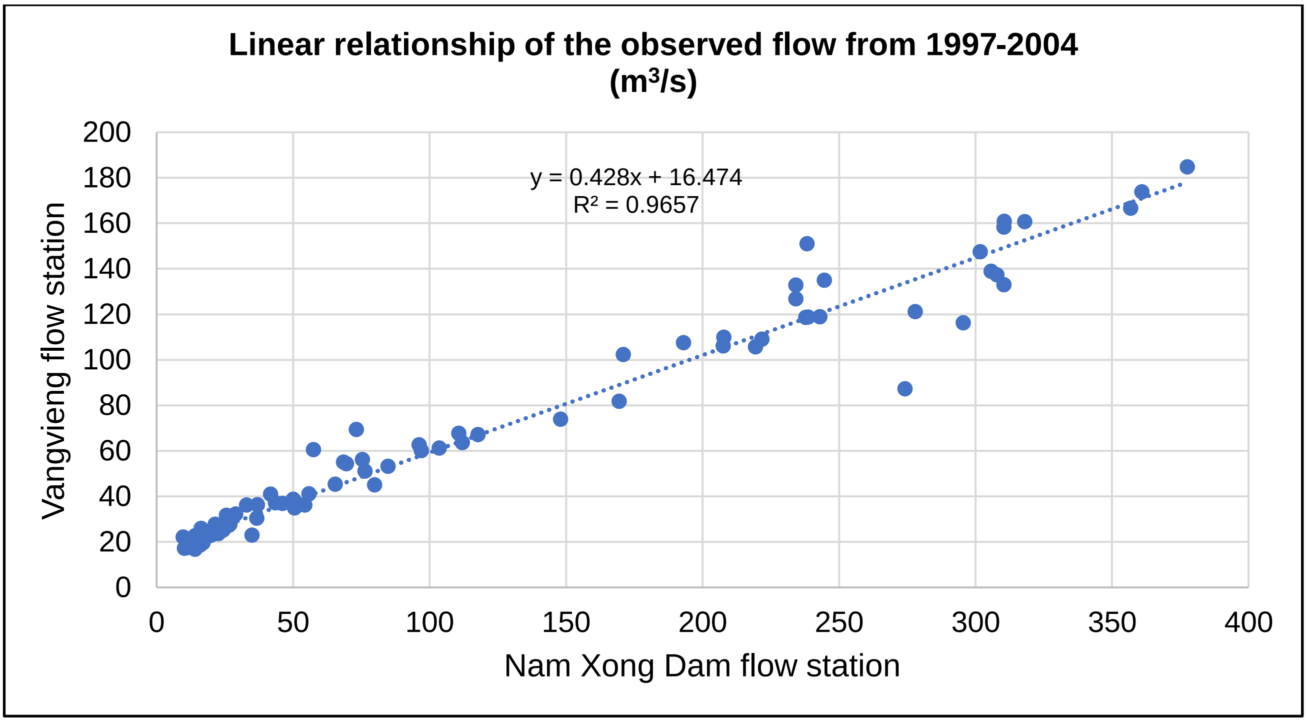


Figure 3.8. Linear relationship of the observed river flow at the Vangvieng and Nam Xong Dam stations from 1997-2004.

The model calibration process was also conducted to match the observed river flow with the WEAP model simulated flow. The process aimed to quantify and analyse the accuracy and reliability of the observed river flow and the performance assessment of the WEAP model simulation for this study. The WEAP model calibration was conducted manually and automatically. The 22 years of the observed river flow at the Nam Xong Dam station were chosen for the calibrated parameter adjustment. The model calibration was also conducted by applying the function of the Parameter Estimation Tool (PEST) in the WEAP model package for the automatic adjustment method. This is an automatic process that assists quantifying and comparing the simulated WEAP model outputs (Sieber & Purkey 2015). Moreover, this function required the monthly data time step to quantify the accuracy of the model outputs with one or more parameters. In this calibration process, the river flow parameter was only performance parameter adjustment. In order to evaluate and confirm the calibrated performance rating, the Nash–Sutcliffe model efficiency coefficient (NSE) was applied for the assessment of this hydrological model performance rating. In addition, the root mean square error (RMSE) was also applied to quantify the error of the streamflow calculated by the WEAP model. The quantification equations 3, and 4 (Nash & Sutcliffe 1970; Ritter & Muñoz-Carpena 2013) and model performance rating is shown in Table 3.9 below:

$$\mathbf{NSE} = \mathbf{1} - \frac{\sum_{t=1}^{T}(Q_m^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - Q_o)^2} \qquad \text{(Equation 3)}$$

Where, Q_o is the mean observed river flow or discharge.

Q_m is simulated model river flow or discharge.

Q_o^t is the observed river flow of discharge at time.

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(O_i - P_i)^2}{N}} \qquad \text{(Equation 4)}$$

Where, $\boldsymbol{O_i}$ is observed river flow.

P_i is simulated river flow.

N is sample size.

Table 3.9. General hydrological model assessment and performance rating

Performance rating	NSE value	RMSE value
Very good	0.75 < NSE < 1.00	The RMSE values range from 0 to ∞. Where the RMSE value = 0 indicates a perfect fit.
Good	0.65 < NSE < 0.75	
Satisfactory	0.50 < NSE < 0.65	
Unsatisfactory	NSE < 0.50	

Sources: Moriasi et al. (2007), and Ritter & Muñoz-Carpena (2013)

3.3.7 Scenario development

In this study, the WEAP model simulation is predicted up to the year 2040. Meanwhile, the year 1997 is set as the current account year or the initial year. Therefore, the future model simulation is commenced from the year 1998-2040 or 43 years. There are three main scenarios set up such as increase irrigated agriculture, increase population, and increase industry unit. The importance of these scenarios was related the local development agenda as top priority of the government, and the real situation of the population growth and rapid socio-economic development needs. Hence, the three scenarios were described below:

- **Scenario 1: Increased irrigated agriculture area**

Agriculture is one of the main water users in Laos. Irrigation is the main agricultural water user, it extracts water from diverse sources. Based on Vientiane Province Plan until the year 2030, estimated irrigated agricultural area is expected to increase by approximately 14% compared to the total current irrigated land (PAFO 2017). In this study, it is assumed that the future irrigated agricultural area would increase by an equivalent 30% of the total agriculture land toward the year 2040 or about 1.2% growth per annum. In this regard, the scenario is set to question that what if this irrigated agriculture area increased, then what are the potential impacts on the water demands in the watershed.

- **Scenario 2: Increased population**

In the Nam Xong Watershed area, there is a relatively small population compared to the greater watershed area. However, the population has been growing rapidly. Based on the government reports, the population growth rate is approximately 1.5% per annum (Lao

Statistics Bureau 2015; Vientiane Provincial Governor 2015). In regard to the WEAP model scenario, this growth rate is used as the potential scenario for the domestic water demands projection for the entire watershed until the year 2040.

- **Scenario 3: Increased industry units**

The industry sector is one of the main water users in the watershed area. However, in the watershed there presented quite a small amount of total water consumption compared to the existing industrial production units; therefore, the prediction of increased water use for this sector would be very interesting. Thus, the scenario for the increase of industrial units was set for the future water demand prediction. Based on the current report, the industrial sector development increases by about 10.7% per annum (Vientiane Provincial Governor 2015). This average growth rate was employed in the WEAP model calculation for this scenario prediction until the year 2040.

4. RESULTS AND DISCUSSIONS

4.1 Calibration process

4.1.1 Observed river flow

The analysis of the observed river flow data was examined and implemented before used as input into the WEAP model. The Vangvieng flow gauging station was selected for quality checking for 1997-2014 (Section 3.3.4). The comparison between the Vangvieng and the Nam Xong Dam stations (upstream dam station) was visualised in Figure 4.1. As a result, it was revealed that the observed river flow curve between two gauging stations was consistent. However, the river flow in the dry season (November-April) at the Nam Xong Dam station was typically lower than the Vangvieng station throughout the 22 years of data series. Lacombe et al. (2011) argued that the river flow at the lower measurement station is generally accumulated due to receiving more runoff from tributaries during the wet season and water table discharge in the dry season. Thus, explanation of this anomalous phenomenon needs analysis of both up and downstream stations.

In relation to this, there are three potential assumptions that are important. First, there might have been a change at the river flow gauging station or relocation of the station. Second, there might have been storm events that may cause the river-bed to change, impacting the water level. Last, there might be some uncertainties related to on-site water level measurements and recording (Sithiengtham 2019) that could likely result in inaccurate stage discharge relationships. In addition, the decreasing low flow might be due to water loss to the groundwater in the dry season and there might be more extraction of water before the Nam Xong Dam's river flow station. However, further data uncertainty analysis is not included in this study.

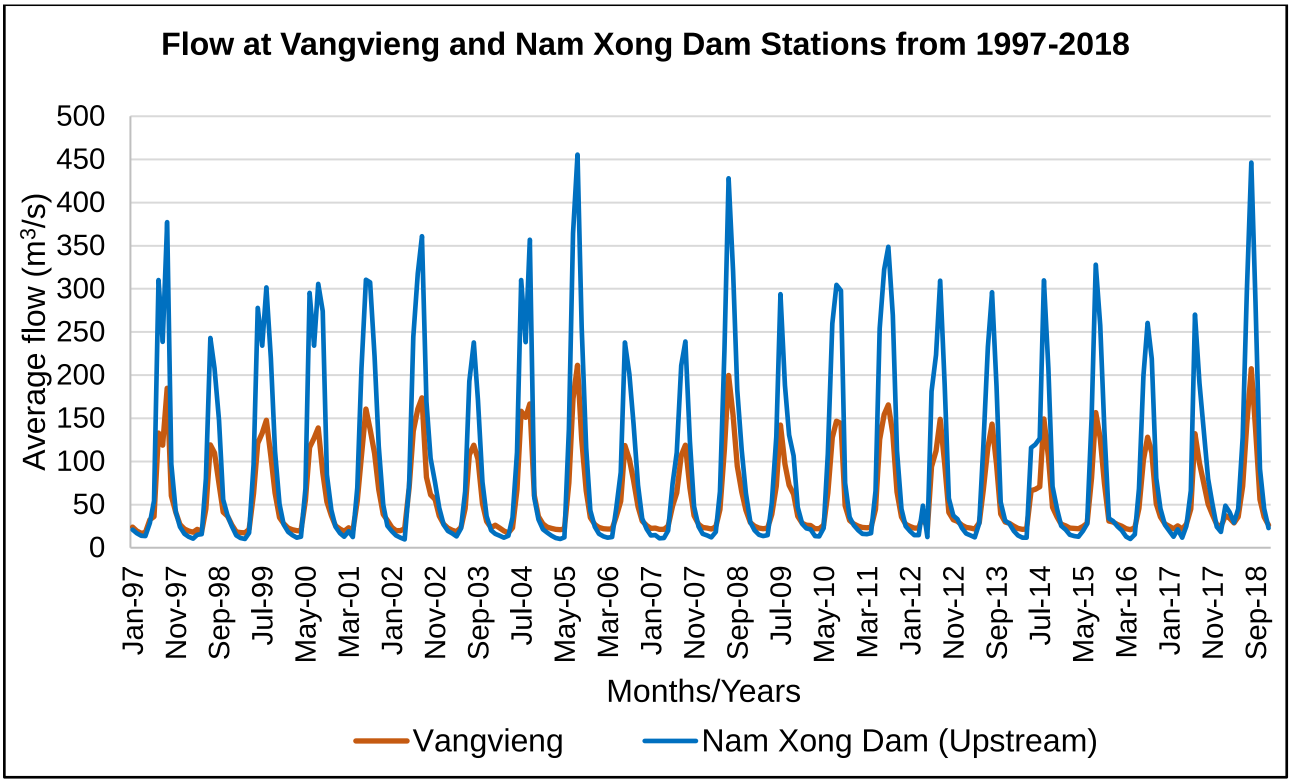


Figure 4.1. Comparison of the observed river flow at the Vangvieng and Nam Xong Dam stations.

4.1.2 WEAP model calibration

The model calibration process is an important step for parameter estimation (Oliva 2003). The WEAP model calibration was manually and automatically conducted. The observed river flow at the Nam Xong Dam station (upstream station) was elected as a parameter for the calibration process and comparison between the observed and simulated flow by the WEAP model. The calibration period was from 1997-2018 using monthly time step of the river flow parameter. There were two main tested methods employed in this section. Firstly, the Nash–Sutcliffe model efficiency coefficient (NSE) used to assess the predictive hydrological model. Moriasi et al. (2007) and Ritter and Muñoz-Carpena (2013) reported and recommended that the NSE value is an important coefficient of model efficiency. They suggested and confirmed that the NSE value between ≥ 0.5 – 1 shows a range of satisfactory, good and very good model simulation efficiency and accuracy. The WEAP calibrated simulated flow compares well with the observed flow (Figure 4.2). The NSE for the model calibration period is 0.99, which is interpreted as a "very good" performance (Table 4.1). Secondly, the root mean square error (RMSE) method was also used to test the model result performance by using the observed and simulated flow at the

Nam Xong Dam (upstream) station. The RMSE value for this model calibration is 0.1, that indicated as a “very good” model performance (see also in Table 4.1).

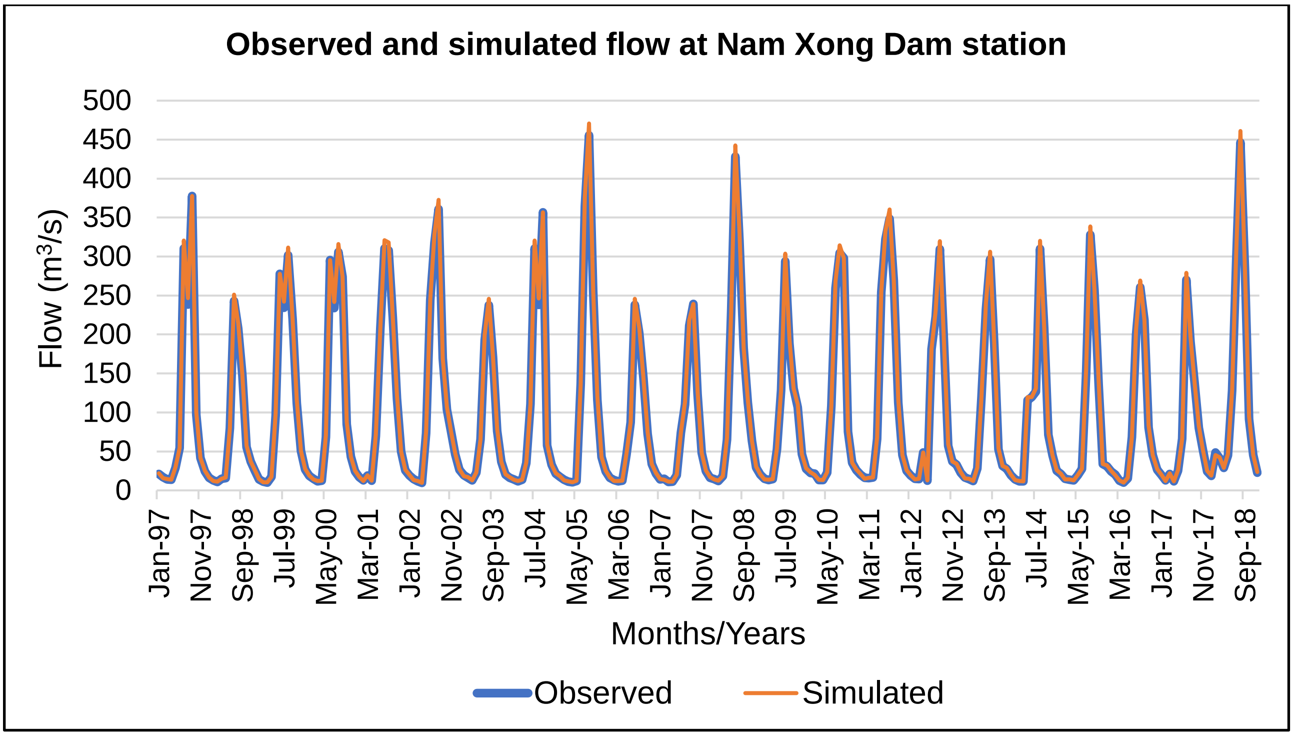


Figure 4.2. Comparison of the observed and simulated flow at the Nam Xong Dam station from 1997-2018.

In addition, the mean monthly observed river flow at the Nam Xong Dam station at the same period was also tested for the model assessment (Table 4.1). Through this further analysis, the mean observed river flow is 98.46 m^3/s, while the mean simulated river flow at this station by the WEAP model is approximately 100.43 m^3/s or about a 2% mean over-prediction. Therefore, the calibrated model assessment was successfully conducted showing the high reliability and a low bias (Lacombe et al. 2011).

Table 4.1. Quantitative assessment and performance rating of the model simulation.

Simulation	NSE value	RMSE value	Q_{Obs} (m^3/s)	Q_{sim} (m^3/s)	Performance rating (NSE and RMSE)
Calibration (1997-2018)	0.99	0.1	98.46	100.43	Very good

Remark: Q_{Obs} represents the mean observed river flow or discharge
Q_{sim} represents the mean simulated river flow or discharge

4.2 Current water availability

Water resource availability in the watershed system is basically to supply, supplement, and maintain the diverse water use demands and environmental requirement. Once the WEAP model was successfully run and simulated, it showed that the total water availability is quite rich in terms of the total amount flowing into the Nam Xong watershed system. The total water inflows or watershed runoff is approximately 25.5 billion m^3 flowing into the watershed system each year. The model simulated the inflows and outflows, which showed a reasonable balance in terms of the total inflows and outflows of approximately 25.5 billion m^3/y (Figure 4.3). The average monthly water inflows in the watershed area is approximately 2.12 billion m^3/mth. Meanwhile, the water outflows also showed the same rate as the inflows. The total water availability in the study area is quite variable and seasonally fluctuating based on the availability of the rainfall each year. As the result of the model calculation, the average inflows and outflows by the seasons have been quantified. The average inflows in the rainy and dry seasons were about 19.7 billion m^3 in the rainy season or equivalent 77.2% of the total inflows, and about 5.8 billion m^3 in the dry season period or equivalent 22.8% of the total inflows proportion to the study area. In this regard, the higher proportion of the water inflows in the rainy season depends very much on the intensive rainfall and pattern every year. This is because the study area is one of the highest rainfall areas in the country (DWR 2013).

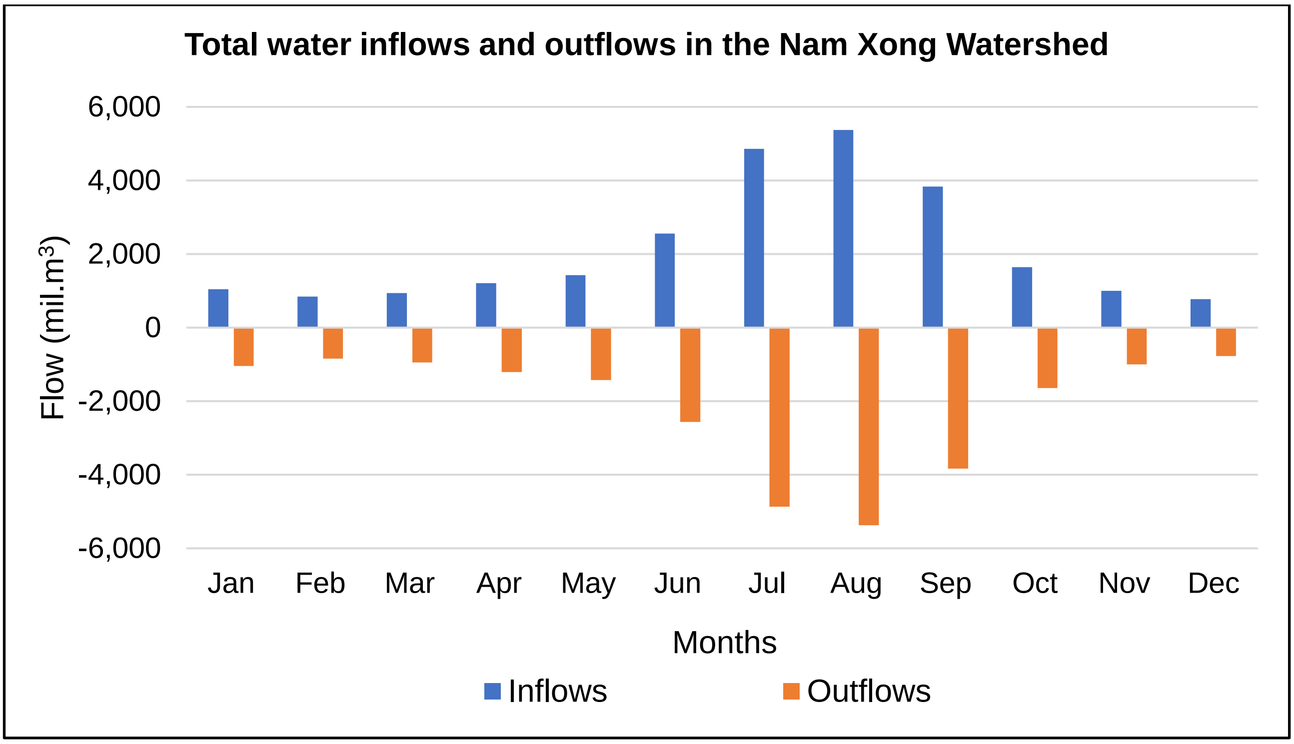


Figure 4.3. Total water inflows and outflows in the Nam Xong Watershed.

4.2.1 Water inflows

Based on the model result, the main water inflows in the watershed are derived from diverse sources of water. These included the precipitation and groundwater recharge. The water inflows to the area are seasonally dependent and variable in each period. This can be observed in that the water inflows in the watershed are of a significantly higher amount in the rainy season and then a lower amount in the dry season period. The total water inflows potentially showed at 25.5 billion m^3/y. Of these figures, the water derived from the rainfall and the Nam Xong river runoff is about 23.4 billion m^3/y or equivalent 91.8% which showed as the main water source (Figure 4.4), while only about 2.1 billion m^3/y or equivalent 8.2% of the total water inflow is from the groundwater recharge. In addition to that, the water inflows were derived from different sources, but showed high inflow amount in the rainy season which was approximately 19.7 billion m^3/y during the month of May to October of the year. On the other hand, the dry season period contributed water inflows of only 5.8 billion m^3/y, primarily during November to April.

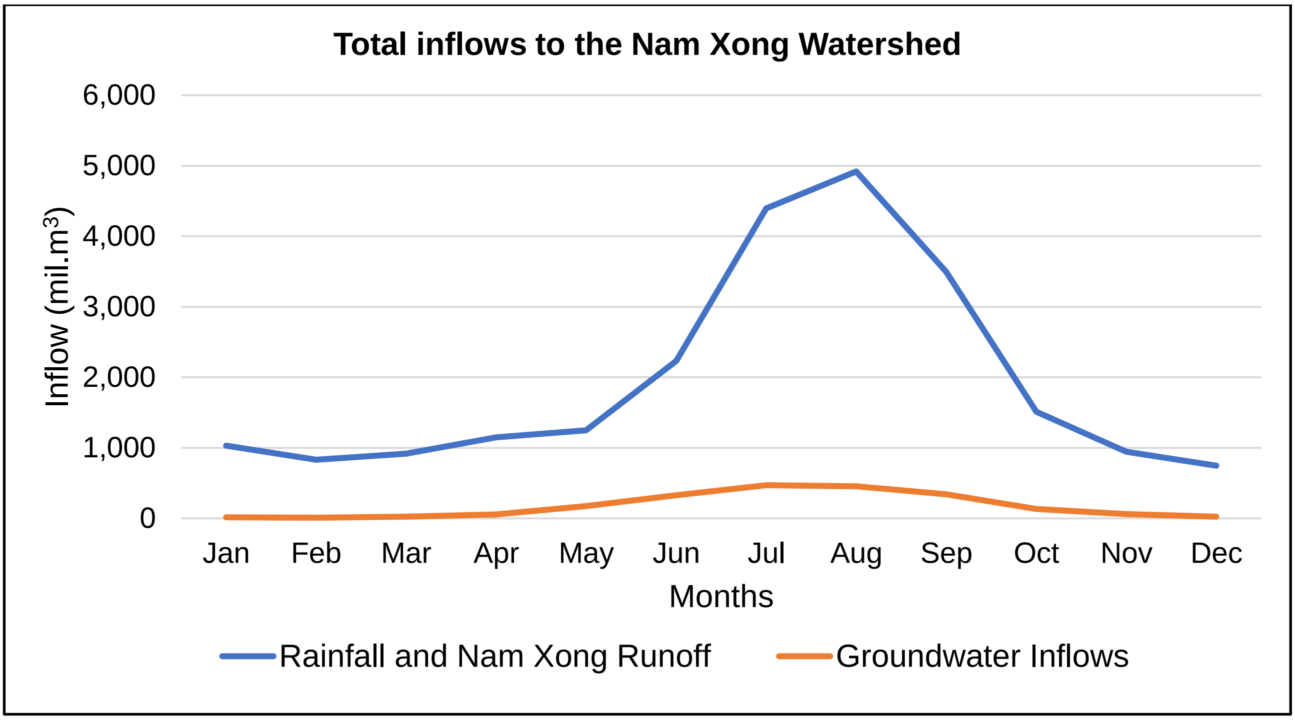


Figure 4.4. Average water inflows in the Nam Xong Watershed.

4.2.2 Water outflows

The water outflows from the watershed area showed at about 25.5 billion m^3 every year. There are three main water outflows from the systems, which are evaporation, Nam Xong river runoff including the diversion to the Nam Ngum 1 reservoir, and outflows to the groundwater source. The water outflows to the Nam Xong river runoff showed highest proportion in the watershed (Figure 4.5). This main outflow is about 23.4 billion m^3/y or equivalent 91.8% of the total water outflows. Other sources of the water outflows are evaporation and loss to the groundwater system, which are about 1.52 billion m^3/y and 0.58 billion m^3/y, or equivalent 5.98% and 2.23% of the total outflows, respectively. Observably, the water outflows are higher during the rainy season from May to October. The average monthly outflow to the Nam Xong River was approximately 1.95 billion m^3/mth, while the average monthly outflows through evaporation and to the groundwater were approximately 0.13 and 0.04 billion m^3/mth, respectively. In addition to that, the amount of the water outflows that were partly diverted from the Nam Xong Dam reservoir to the Nam Ngum 1 Dam reservoir were part of the Nam Xong River runoff which were not specifically separated. This revealed that the main source of water diversion was from the main stem of the Nam Xong river (MEM 2019). Hence, the total outflows showed equal proportion when compared with the total inflows.

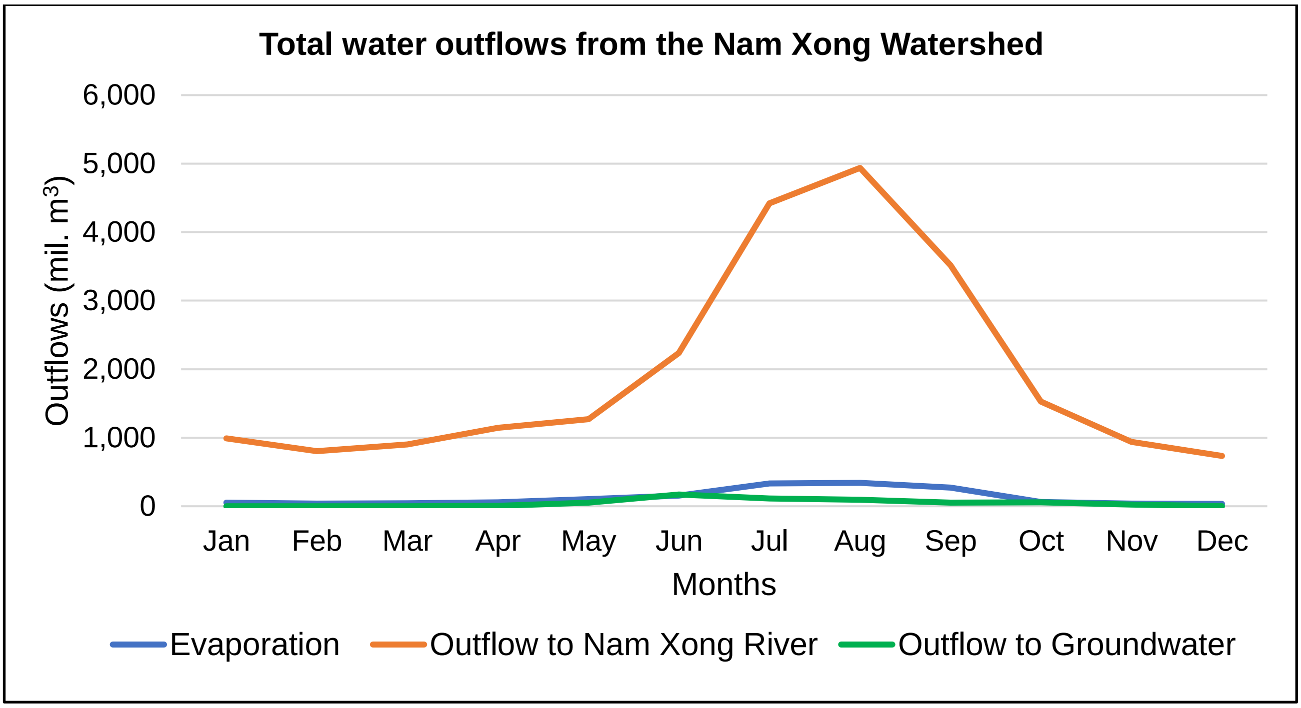


Figure 4.5. Average water outflows from the Nam Xong Watershed.

4.3 Current water use

In the study area, the water use demand is diversified and competitive for local socio-economic development and people's well-being. There are three main water use sectors in this study, namely domestic, agriculture, and industry water use (Figure 4.6). The total current annual water use by these three sectors was quantified and accounted for 135.8 million m^3/y (Table 4.2). Of these, the agricultural water use accounted as the largest demand in the watershed with about 129.8 million m^3/y or equivalent to 95.56% of the total current water use proportion. Interestingly, the domestic water use placed as the second largest water extraction that was estimated at 4.9 million m^3/y or equivalent to 3.64% of the total proportion. While the industrial water use illustrated the smallest water use proportion in the study area with only about 1.09 million m^3/y or equivalent to 0.80%.

Table 4.2. Total current water uses by sectors in the Nam Xong Watershed.

No.	Water use type	Total annual water use (m^3/y)	Percentage (%)
1.	Domestic use	4,946,691	3.64
2.	Agriculture	129,843,490	95.56
3.	Industry	1,090,709	0.80
	Total:	**135,880,890**	**100**

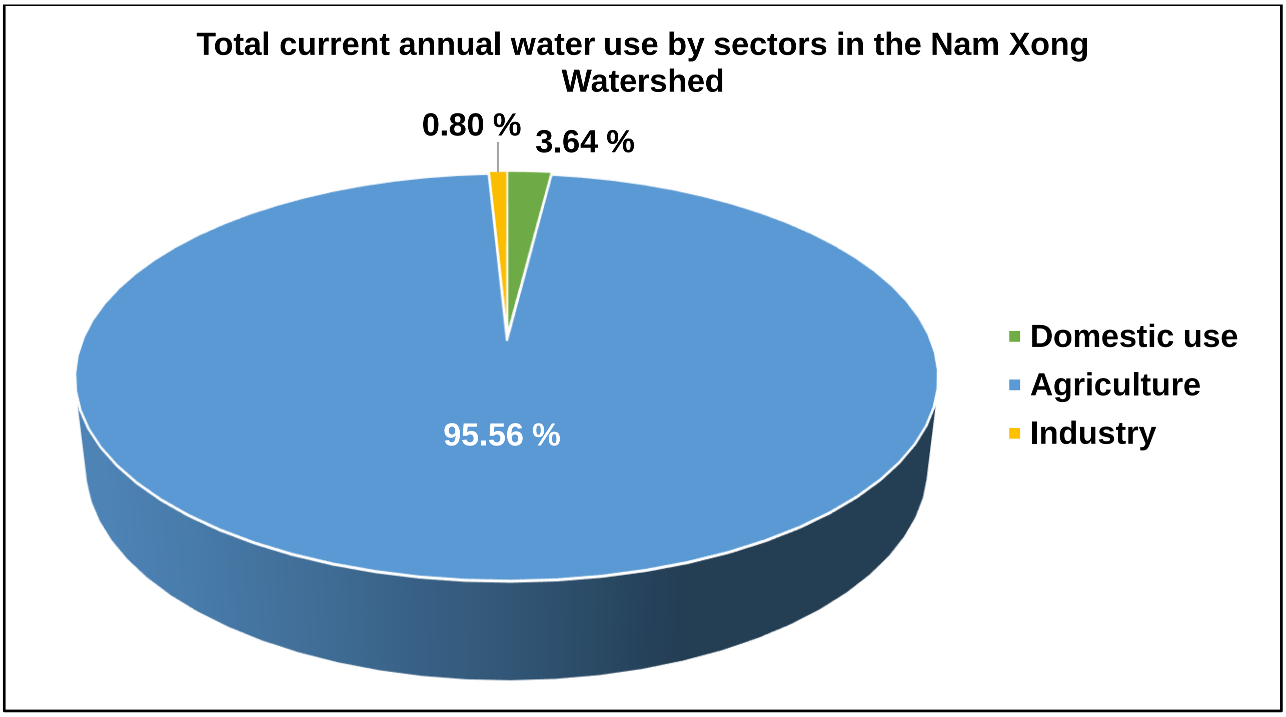


Figure 4.6. Current annual water uses by sectors in the Nam Xong Watershed.

4.3.1 Current domestic water use

Domestic water use is the primary important type of water extraction for the basic need of people. This current water use sector showed as the seconded largest water extraction in the watershed. In this study, the total water use for domestic purpose is 4,946,691 m^3/y (Table 4.3). The data covers the three districts of Vientiane province, which are Kasy, Vangvieng, and Hinheup (Figure 4.7). These three districts presented the villages and population size in the study area accounting for domestic water use activity. Based on the data collection and quantification, the greatest domestic water use is Vangvieng district with about 4,620,148 m^3/y or about 93.40% of the total domestic water use. The second and third largest use are Hinheup and Kasy districts with 318,185 m^3/y or equivalent 6.43%, and 8,357 m^3/y or equivalent 0.17% respectively. The main source of the domestic water use is from both surface and groundwater in which the pipe water supply system is not available. Pavelic, Xayviliya and Ongkeo (2014) argued that the groundwater is the primary domestic water source for the remote and small towns in the study area. Hence, further groundwater study is needed for water use allocation and watershed management.

Table 4.3. Current annual domestic water uses in the Nam Xong Watershed.

No.	Districts	Population served (person)	Water use rate (m^3/p/y)	Total water use (m^3/y)	Percentage (%)
1	Kasy	957	8.73	8,357	0.17
2	Vangvieng	35,578	129.86	4,620,148	93.40
3	Hinheup	8,351	38.10	318,185	6.43
	Total:	**44,886**	**176.69**	**4,946,691**	**100**

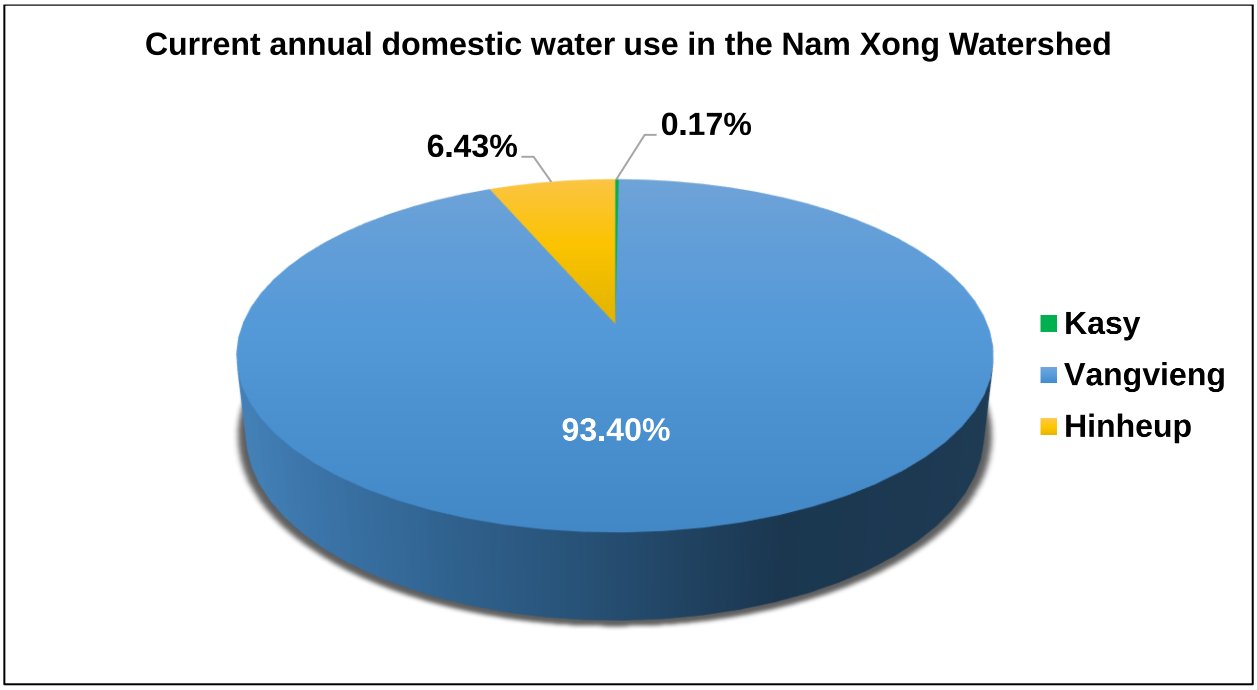


Figure 4.7. Current annual domestic water uses in the Nam Xong Watershed.

4.3.2 Current agriculture water use

Agriculture is the main sector which uses a high proportion of water in the watershed system and which also plays a role as the main driver of the economy in the area (Lacombe et al. 2014). In this study, the annual agricultural water use showed the highest proportion compared to the domestic and industrial sectors. In this regard, there are diversified distributions of the agricultural water use in three major districts based on their agricultural areas and sizes. Vangvieng district has the highest water use proportion for agriculture, 109,351,620 m^3/y or equivalent 84.22% (Figure 4.8). The Hinheup district is the second largest agricultural water user with a total amount of 20,336,830 m^3/y or equivalent 15.66% of the total water use proportion for the agriculture. At the other end of the scale, Kasy district showed very little agricultural water use, about 0.12% or about 155,040 m^3/y.

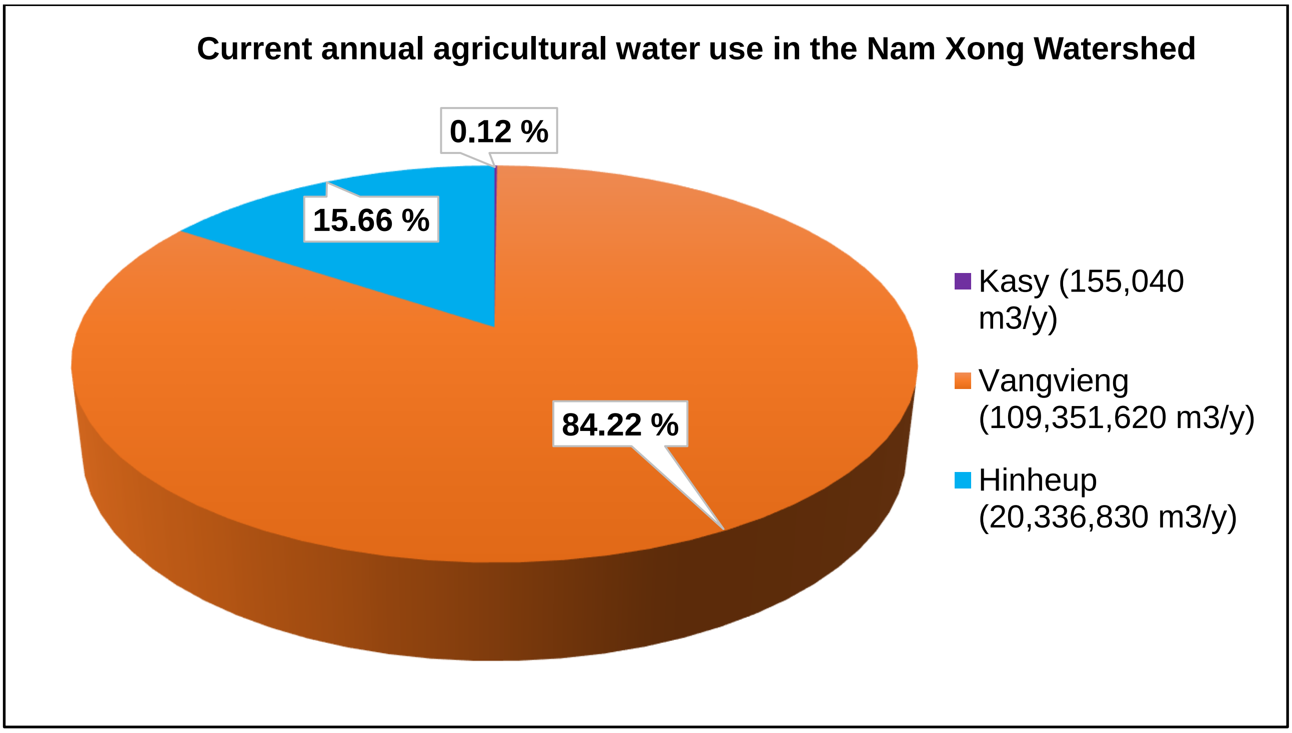


Figure 4.8. Current annual agriculture water use in the Nam Xong Watershed.

4.3.3 Current industry water use

Industry water use is another major water user in the watershed. In this study area, there are 291 industrial production units. However, the current annual industrial water use is quite small compared to the agricultural use. There are only two districts in the watershed that have industry water use or industrial activity, namely Vangvieng and Hinheup districts. Meanwhile, Kasy district has no industry in the study area. Vangvieng district covered most of the industrial water use, 89% or equivalent to 974,737 m^3/y (Figure 4.9). Hinheup district has a water use for industrial activity of 115,972 m^3/y or equivalent to 11% of the whole annual water use proportion for industry. The proportion of the industrial water use is relatively small compared to the domestic and agriculture water use reported in the Section 4.3.1 and 4.3.2. However, the industry has increased over the years, as the Lao government policy is to promote industrialisation and modernisation (Lao Statistics Bureau 2015; MPI 2016). Therefore, the industry sector is one of the priority sectors to study for more sustainable water demand management.

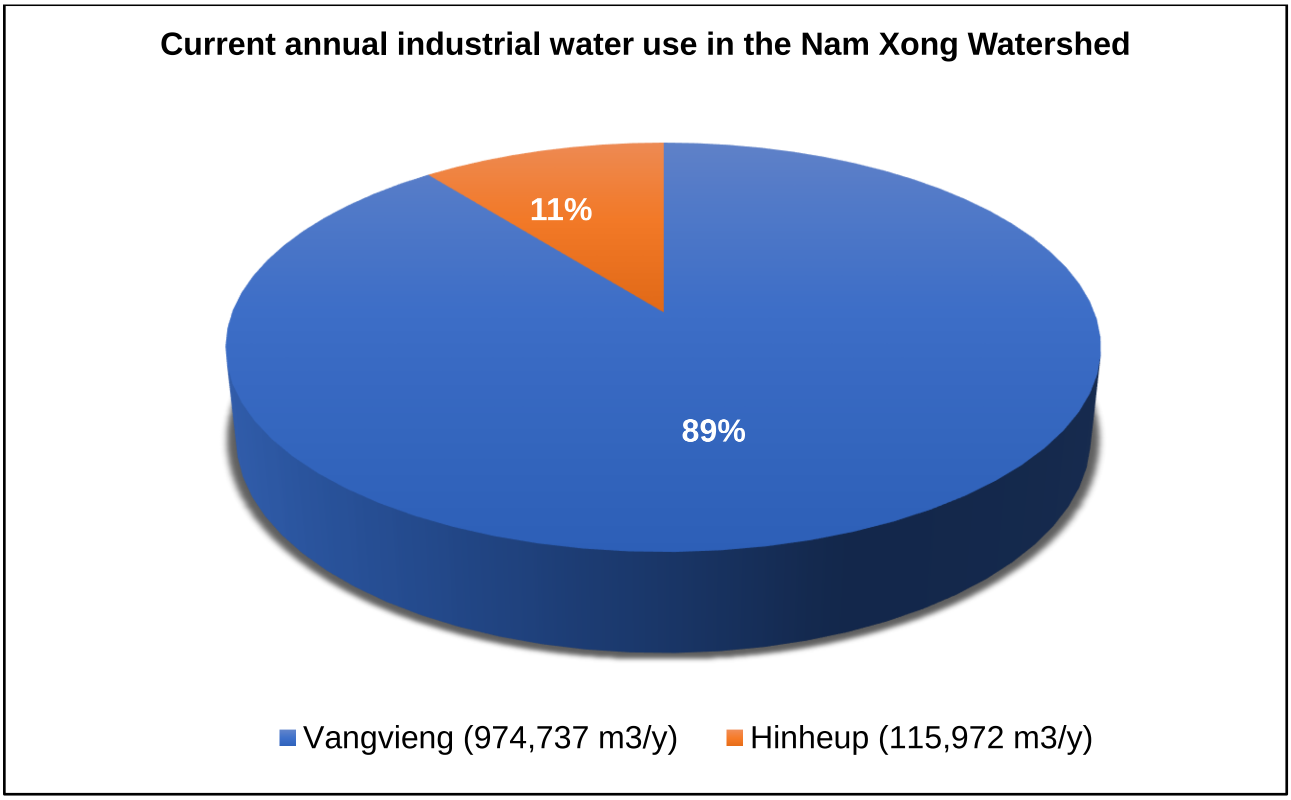
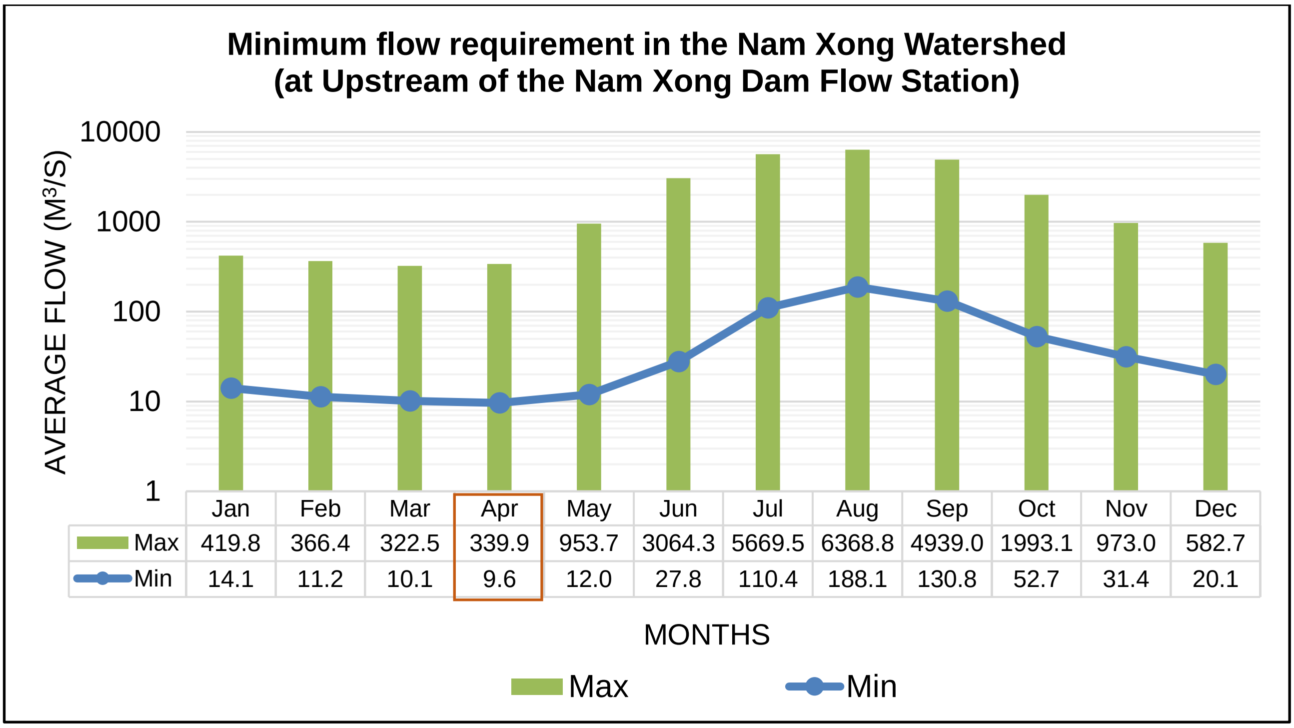


Figure 4.9. Current annual industrial water use in the Nam Xong Watershed.

4.4 Environmental flow requirement

Instream environmental flows play an important role in maintaining the riverine environment and people's basic well-being. The minimum environmental flow is required for different purposes, such as recreation, navigation, water quality maintaining, fish and wildlife, other water and environmental conservation objectives, and other downstream needs or obligations (Sieber & Purkey 2015). Therefore, there is a real need for the instream minimum environmental flow requirement to be met as an important means of maintaining the water asset for the downstream and surrounding environment. There are a wide range of methods used to quantify and define the minimum environmental flow. However, there is no fixed equation for quantifying the environmental flow requirement (Dubey et al. 2019; Shinozaki, Fujiwara & Shirakawa 2018). Other literature also supports that there is no specific equation for minimum flow requirement estimation. However, according to Dubey et al. (2019), the minimum environmental flow can be defined by using the flow duration curve analysis as one of the successful methods. This method was applied to represent the minimum environmental flow rate in the study area. Hence, the natural flow at the observed gauging station is important to allow a preliminary identification of the minimum flow requirement through the simple analysis of the observed mean minimum and maximum flow.

Based on the simple and manual analysis of the river flow of the study area, the upstream Nam Xong Dam flow station was selected as the flow station that is located at the most downstream section in the watershed. The observed river flow data were derived from the Nam Xong Dam site for the period of 1997-2018 or 22 years. Geographically, there is about a 27 km length of stream from the dam flow station toward the Nam Xong mainstream estuary or outlet (DWR 2013). Along this mainstream reach, there are 16 villages located within Hinheup district administrative boundary. This confirms that there is a real need for the environmental flow requirement for the downstream environmental functions and villages livelihoods. From the analysis of the mean monthly flow in the Figure 4.10, the minimum flow requirement for the Nam Xong mainstream is defined as 9.6 m^3/s for the downstream reach below the Nam Xong Dam. This figure presents the average minimum river flow of the low flow month of the dry season, which occurs in April. Therefore, this amount was assumed as the minimum environmental flow defined for the purpose of essential functions of the downstream environment and watershed health.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max	419.8	366.4	322.5	339.9	953.7	3064.3	5669.5	6368.8	4939.0	1993.1	973.0	582.7
Min	14.1	11.2	10.1	9.6	12.0	27.8	110.4	188.1	130.8	52.7	31.4	20.1

Figure 4.10. Mean minimum and maximum flow at the Nam Xong Dam flow station.

Apart from the simple observed flow analysis, the WEAP model showed some interesting outputs in relation to the environmental flow requirement. Once the WEAP model was simulated, the instream water requirement was also quantified based on the different available datasets inputted into the model. As a result, the total instream flow requirement for the downstream demand is approximately 302.95 million m^3/y or equivalent 1.19% of the total water inflows in the study area each year. The total instream flow requirements for the dry and rainy seasons are quite similar and are about 150 million m^3/y and 153 million m^3/y, respectively. The flow requirement for meeting the needs of diverse water uses vary depending on the months and seasons, but there is not a significant difference in terms of the water amount representation (Figure 4.11). The average monthly instream flow requirement ranges between 23-26 million m^3/mth. Of this amount, the month of February was revealed as having the lowest water requirement. This might be because there is quite a small amount of the water inflow availability during this month for the allocated supply to all water use, especially the basic livelihood and environmental flow.

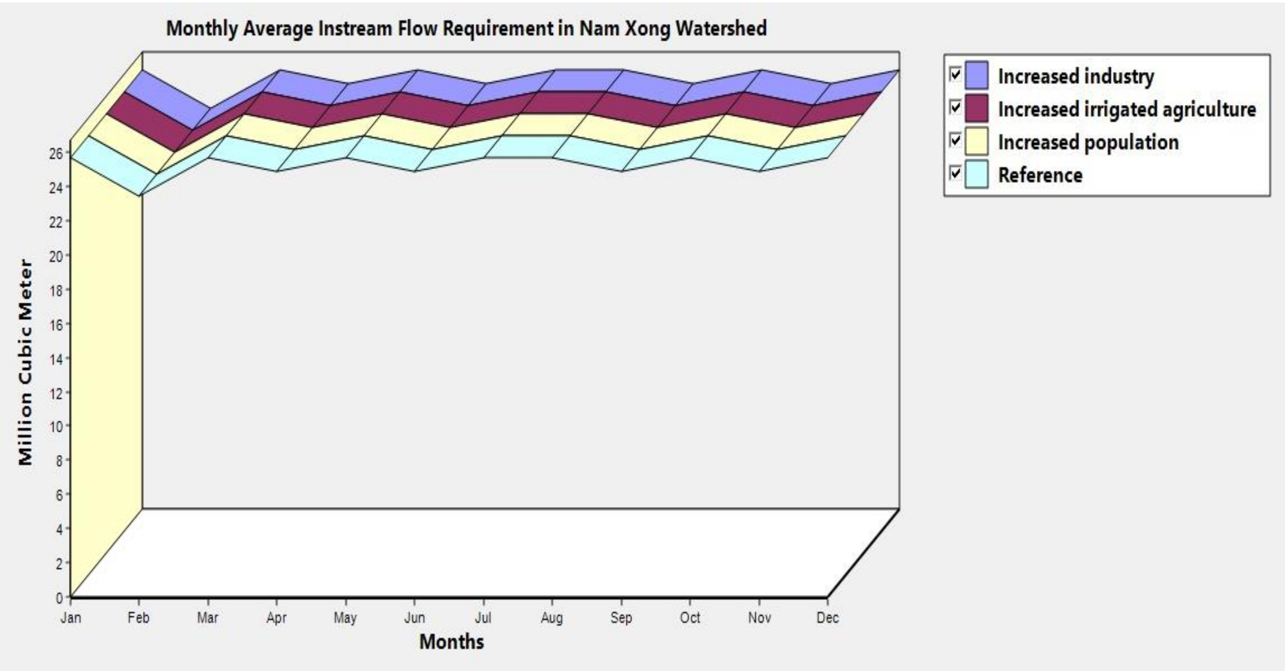


Figure 4.11. Instream flow requirement in the Nam Xong Watershed.

In addition to the total instream flow requirement, there is some unmet instream flow requirement for specific months and supply for the water use in the watershed. The WEAP model has quantified the unmet river flow requirement in comparison with the total instream flow required. The total unmet minimum flow is about 0.22 million m^3/y or equivalent 0.07% of the total instream flow requirement for this watershed area (Figure 4.12). Only the months of February and March showed unmet flow requirement to supply that might be inadequate for securing the water needed for diverse users during these two particular months. February and March are in the middle of the dry season. Hence, the unmet demand might have occurred because of the increased water use in the dry season and reduced discharge in the river system. Also, the groundwater source might be limited in some areas, particularly the areas that are a long distance from the river course. Other months of the year showed no unmet flow requirement, meaning that there was no significant impact on the flow requirement in the study area. The zero unmet flow requirement means there might be sufficient water for these remaining months or that demands were met within the requirement (Azlinda & Mohd 2012). However, there might be some change in terms of the future requirement in some specific aspects, such as river flow requirement for the downstream aquatic and terrestrial resources, especially in Hinheup district area or below the Nam Xong Dam area. In this connection, the dam may divert huge amounts of the available water from the watershed. Hence, the dam diversion may pose some problems for the river flow requirement for the downstream area. Felfelani et al. (2017), Pokhrel et al. (2012), and Pokhrel et al. (2018) discussed the issue of the water impoundment behind the hydropower dam and argued that this can alter the dynamics of the water environment, which can potentially affect the surface and groundwater systems as well as biodiversity.

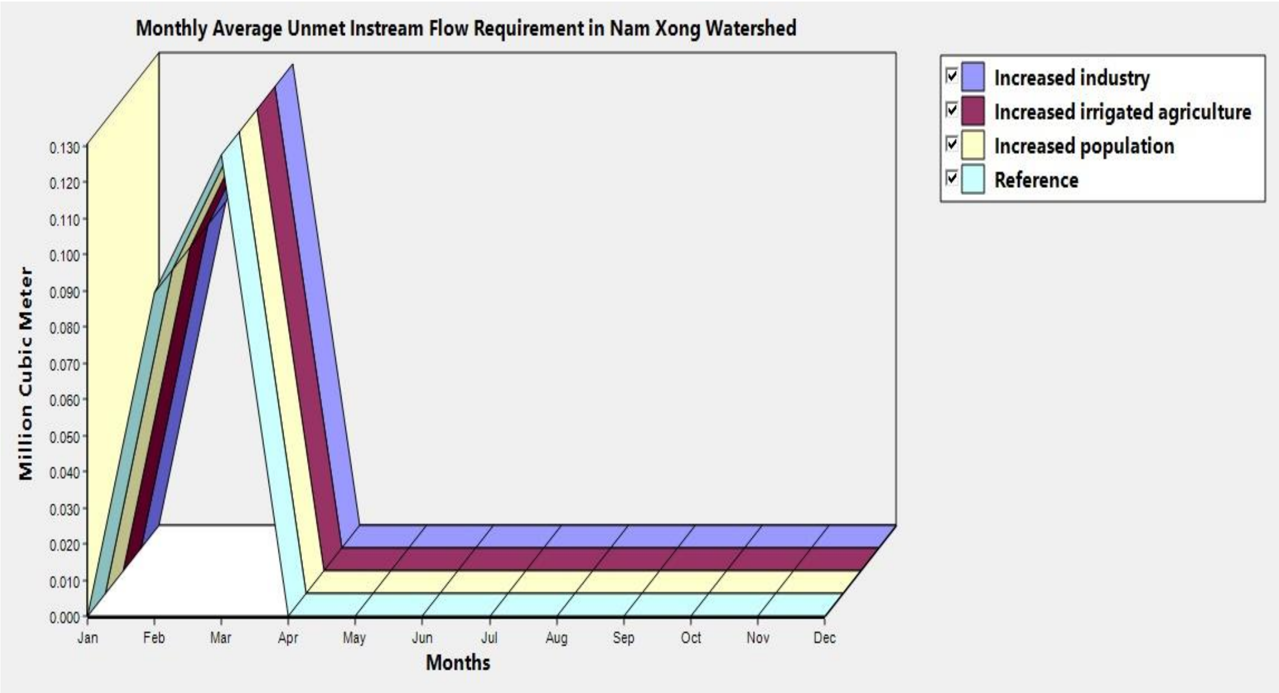


Figure 4.12. Monthly unmet instream flow requirement in the Nam Xong Watershed.

4.5 Projection of future water demands

Once the scenarios were set and input to the WEAP model, the water demands prediction under three different scenarios was computed and projected to compare with the reference or baseline water demands in the Nam Xong Watershed. Based on the results demonstrated in the Figure 4.13, it can be observed that there are potential increases of the water demands for supply to all three water use sectors, namely agriculture, domestic use that serves the population, and industry development. Interestingly, the agriculture and industry sectors showed significant high growth in water demand throughout the simulation period from 1998-2040 or 43 years, whereas the domestic water demand for the population remains relatively small and with little increase over the projection period. In addition to the WEAP model simulation result, the total water use demands will increase from the total current demands at approximately 5.2 billion m^3 to around 18.5 billion m^3 by the year 2040 by combining all the three water demands.

In addition to that, the total water demands presented some variation in terms of demands of each sector and each year. The annual predicted water demands reached about 431.65 million m^3/y, which increased to about 3.5 times of the reference year at the annual rate at 123.03 million m^3/y. Based on the Figure 4.13, it can be seen that the increase of the agricultural water demand is greater than the industry sector for most of the period until the latter part of the projection period when the industrial sector surpasses the agriculture sector. The water demands for the industry sector increases very rapidly during 2036-2040.Thus, these predicted total water demands may not have a potentially significant impact on the total water availability. However, this conclusion might only be valid for the areas that are near to the Nam Xong mainstream, and there may still be a water scarcity problem for these sectors in the remote areas away from the mainstream and its major tributaries (Sithiengtham 2019).

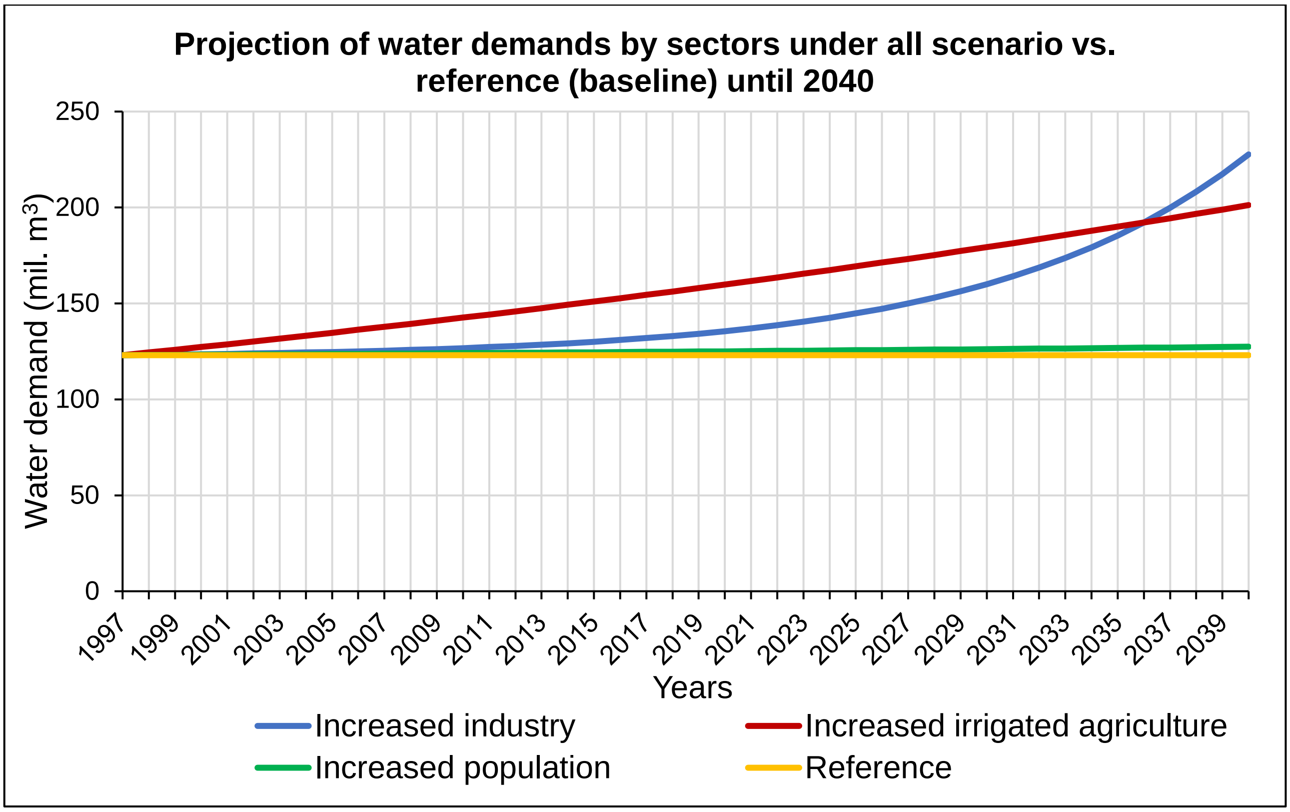


Figure 4.13. Projection of future water demand under three scenarios until 2040.

In addition, based on the WEAP model simulation, unmet water demands have been observed. These might potentially exist and be variable throughout the year depending on the seasonal water availability. The total average monthly unmet water demand for all three water use sectors showed to be about 0.34 million m^3/y or equivalent 0.25% of the total current water use or actual demands. The unmet water demands mainly happened with the agriculture water demand, especially in Vangvieng and Hinheup districts, accounting for about 0.31 million m^3/y and 0.01 million m^3/y, respectively. Nevertheless, these unmet demand figures showed only small amounts of water might be needed to support the agriculture sector. The highest unmet water demand phenomenon occurred during the dry season months, such as January-March, while the unmet demand in May, June, November and December was much less. During the months of April-May and July-October, which is the rainy or monsoon season in the area, the basic water demand and requirement was adequate.

In general, the water demands in the Nam Xong Watershed tend to increase for all three sectors by the year 2040 by about 3.5 times, compared with the current water demands or reference scenario. The increased water demands will substantially contribute and supplement the rapid local socio-economic development, which will meet the aims of the national economic growth of not less than 7.5% per annum (MPI 2016). The total water demand increase could inter-correlate with other factors, such as a need to increase more water supply, provide an adequate water storage infrastructure and facilities, effective water use planning and proper water allocation, as well as management of both quality and quantity of water in the entire watershed (Sithiengtham 2019). Given the rise in demand, there are indications of some unmet water demands for all three scenarios, especially in the dry season or months of February and March. According to Sayasane et al. (2016), the seasonal river flow during the dry season will be decreased in the Nam Xong Watershed, especially in March and April. This suggests that the future water demands might not be met during these months. Therefore, the detail of each water demand projection for agriculture, domestic use under population growth and industry sectors is discussed and analysed in the following Sections 4.5.1, 4.5.2, and 4.5.3 respectively.

4.5.1 Scenario 1: Increased irrigated agriculture areas

Agriculture is the main and largest water user that showed highest proportion of water extraction in the Nam Xong Watershed system. The reference or baseline account for the current water demands for the agriculture sector has been set in 1997 and the projection period is from 1998-2040 (or 43 years). The total area of irrigated agriculture is expected to increase by about 14% from now till the year 2030 or about 10 years increase (PAFO 2017). Hence, for the next 10 years, this sector is expected to grow up to about 30% compared to the reference year. Then, the future water demands for this huge water user was predicted by the WEAP model in order to demonstrate the future water needs towards the year 2040 based on the predicted growth rate. As the result presented in the Figure 4.14 illustrates, there are potentially increases in water demands for the agriculture development and expansion. When compared to the reference and projective scenarios result, the total current water demand in the reference scenario is approximately 5.2 billion m^3, while the water demand under the scenario of the increased irrigated agriculture is about 6.8 billion m^3. This is an increase by about 29.8% of the total reference water demands scenario. Lacombe et al. (2014) also reported that the irrigated agriculture would be increased by three times over the next two decades in the Nam Ngum River basin, which includes Nam Xong watershed. Hence, this rapid increase is expected to secure the agricultural production for local food security and some exports on the basis of modernised and industrialised agricultural promotion (MAF 2015).

However, some new agricultural technologies and techniques for the seasonal crop growing may be introduced to improve efficiency and productivity, especially for paddy rice which is the main crop in Laos (Bartlett et al. 2012). Moreover, paddy rice is considered as one of the most water consumptive crops and is the main local food source (Phengphaengsy & Okudaira 2008). Thus, expanding irrigated agriculture is needed in order to secure the local food security (MAF 2015), but also causes more water demand at the same time. Mekonnen and Hoekstra (2011) supported that the agriculture sector potentially consumes the largest amount of water compared to other sectors. In this relation, the irrigated agricultural expansion relies very much on the water requirement and availability in the watershed in order to satisfy the expansion needs. However, with the agricultural expansion and the added effects of climate change, there may be a significant effect on the entire watershed hydrological system (Krittasudthacheewa et al. 2012; Liu et al. 2018) due to rapidly increasing water demand each year. Meanwhile, the water availability assumes not to significantly increase, but rather may be decreased in some areas. Conversely, Ty, Sunada and Ichikawa (2011) have claimed that the surface water availability in some parts of Laos might increase due to increased rainfall intensification in the region and in the NXW. Therefore, it is vital that integrated water resource management and sustainable allocation of water, together with adaptation to climate change, are considered a high priority for the future of Laos (World Bank 2018).

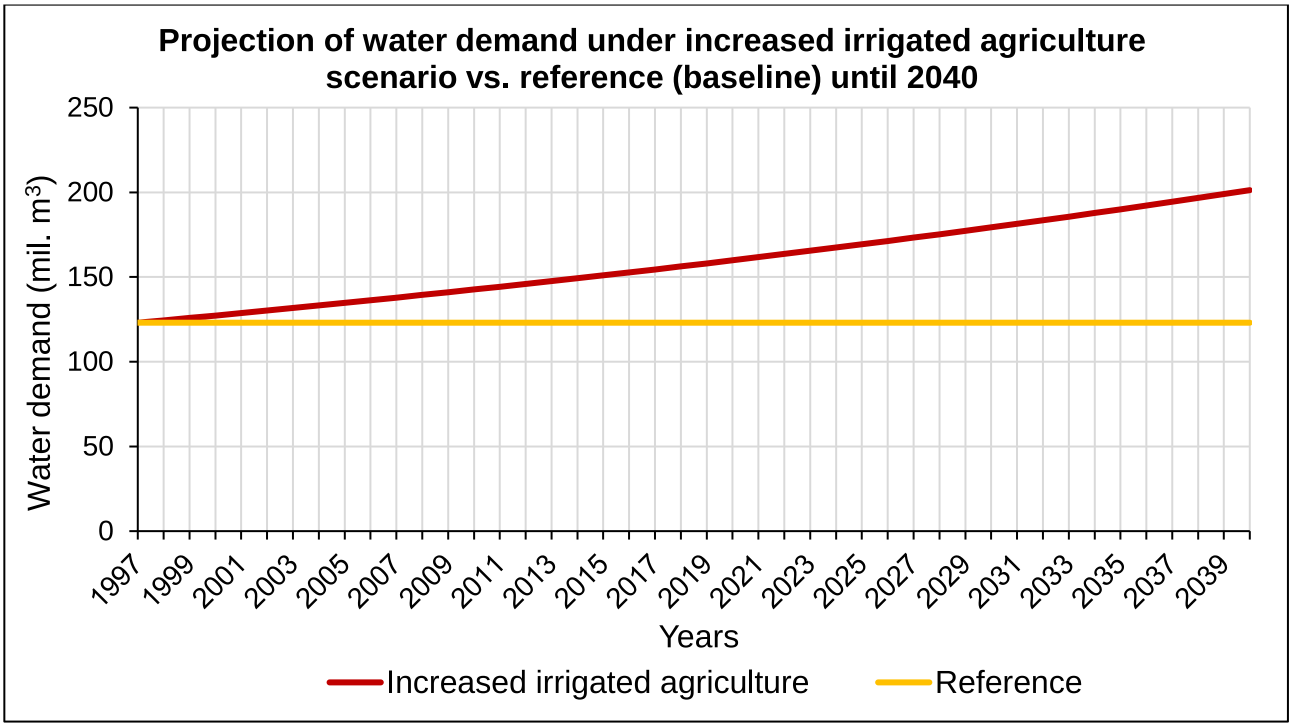


Figure 4.14. Projection of future water demand under increase irrigated agriculture until 2040.

Furthermore, in this study, the average monthly water demand has also been projected and observed from the year 1998-2040 or 43-years period. Based on the result in the Figure 4.15 the data indicates that there is a need for increased water availability for both dry and rainy seasons, but the research showed some variability for each month in water needs. It can be observed that the total annual average water demands increased from 123.03 million m^3/y to 159.73 million m^3/y or equivalent 29.8% compared to the reference scenario. In comparison, this demand might increase by about 1.2 times the current annual requirement. The highest period for the increased water demand from the agricultural sector occurred during the end of the dry season (April) and was dramatically lower in the mid-rainy season of July and August in particular. This result is because the agricultural planting season in Laos coincides with the period at the end of the dry season, especially for paddy rice growing when rice is planted, and fields are flooded with irrigation water.

Therefore, the water demand was assumed to increase at the onset of the rice planting season when there is little rainfall. Rice production is important to the national economy and a main food source, particularly for people in rural areas; however, other food crops are also grown in this dry period when there is inadequate rainfall. Consequently, the high demand for irrigation water at the end of the dry season is likely to remain constant due to the scarcity of rainfall. Furthermore, the uncertainty of rainfall reliability under future climate change circumstances may further exacerbate the water shortage problem because lack of consistent rainfall in the rice growing cycle will lead to significantly lower yield, create even higher water demand, and place economic hardship on rice growers (Olesen & Bindi 2002; Olmstead 2014).

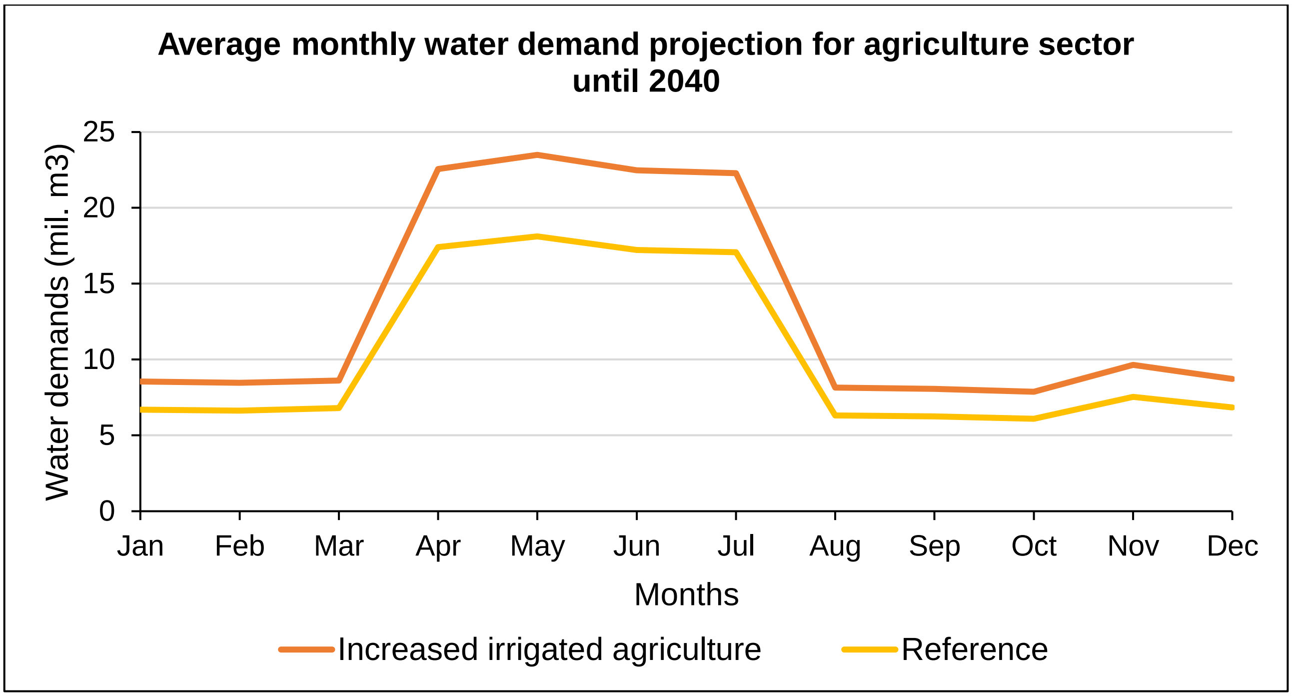


Figure 4.15. Average monthly water demand of agriculture sector until 2040.

4.5.2 Scenario 2: Increased population

The scenario of increased population was set based on the real projected population growth of Vientiane province, which is the location of the main watershed area. This scenario represented and aimed to project the future domestic or city water use of that population. The projected population growth rate in the study area is approximately 1.5% per annum (Lao Statistics Bureau 2015; Vientiane Provincial Governor 2015). After simulation by the WEAP model, the trend of the water demand by the domestic sector rose slightly with some small change in terms of total and average monthly water demands in the watershed. The total predicted water demands for all 43 years will reach approximately 5.3 billion m^3 or an increase of about 1.65% compared with the reference year at about 5.2 billion m^3. Annually, there will be variation in the water demands during each period. By the year 2040, the annual water demand will potentially rise to approximately 127.46 million m^3/y or equivalent to a 3.6% increase compared to the reference year (Figure 4.16). In comparison with the total current water use, the predicted water demand will increase by about 25 times higher than current use per annum. Although, this water demand for domestic use will gradually and constantly increase, the demand proportion is relatively small in scale compared to the agriculture and industry water demands projected during the same period.

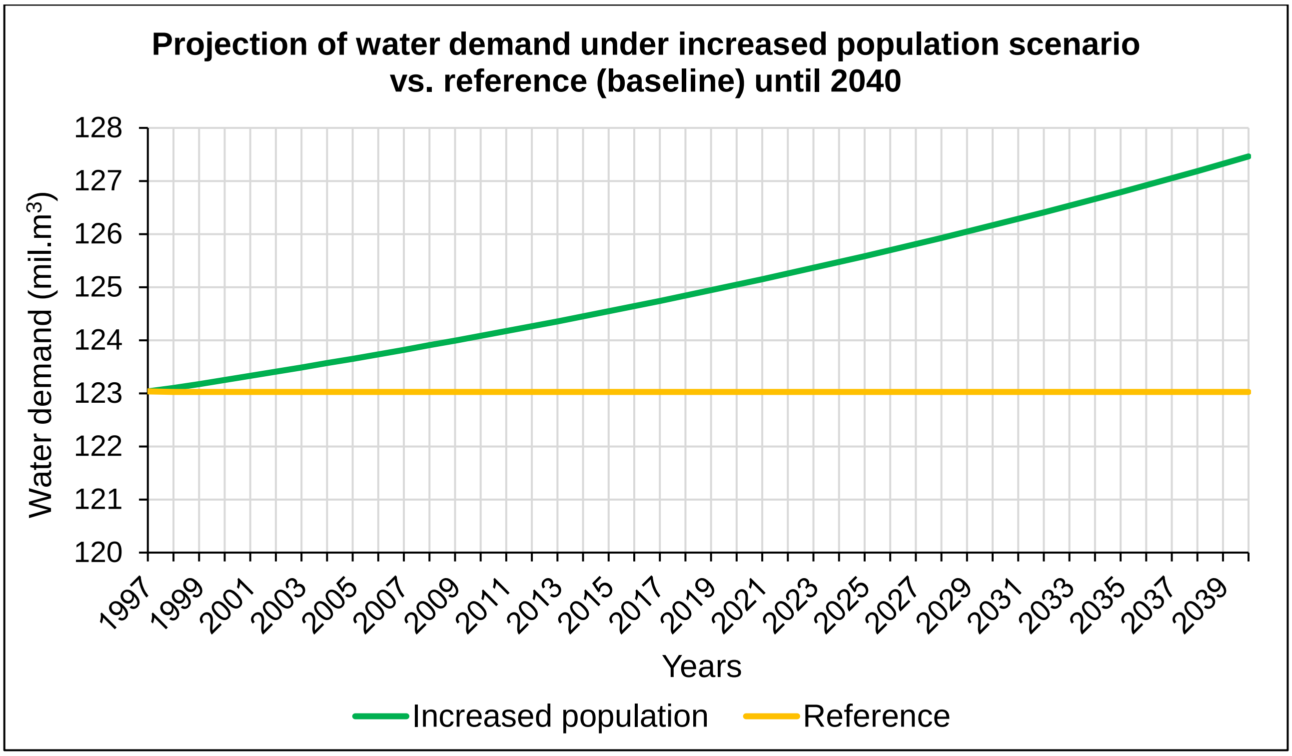


Figure 4.16. Projection of future water demand under increase population until 2040.

Similarly, the average monthly water demand for the domestic sector under this scenario also showed a similar pattern in comparison with the reference year (Figure 4.17). The average monthly demand reached about 10.42 million m^3/mth. The highest monthly water demand rate is about 18.32 million m^3/mth that observably occurs in May, while the month of lowest demand was in October, at a rate of approximately 6.20 million m^3/mth. In this regard, there may be some relevant factors influencing that difference between dry and wet season domestic demand. It could be assumed that the water use requirement for households during the dry season in some areas might be higher but might actually tend to be lower in the dry season. This may depend on differences in urban or rural settings and on whether domestic water is extracted from the river or from the groundwater, as is the case in rural areas distant from the main river and its tributaries. However, it can be seen from the figure that the scenario illustrates quite a small increase in demand associated with the small population size in the study area and the projected lack of significant growth. Unless the population growth assumption is beyond 1.5% per annum, the demand is unlikely to increase greatly; however, the quantity and quality of water for human consumption requires effective water management to secure the health and safety of the population

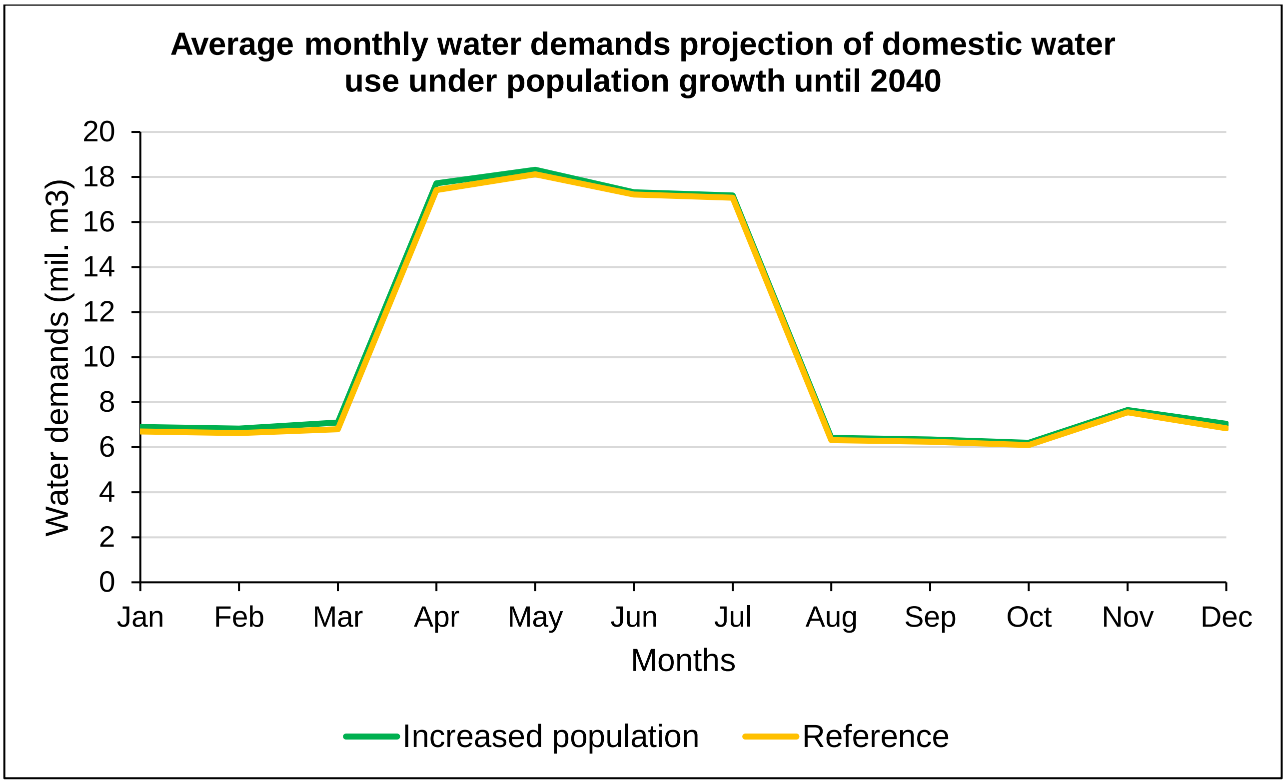


Figure 4.17. Average monthly water demand of domestic use until 2040.

4.5.3 Scenario 3: Increased industry units

The industry sector is one of the main economic drivers of development in Laos (MPI 2016). In this result section, the anticipated growth of the industry was about 10.7% per annum in the study area (Vientiane Provincial Governor 2015). Based on those fundamentals, the water supply for this sector is vital for future growth and sustainability of the Lao economy as one of the least developed nations in the South East Asian region. The WEAP model predicted and calculated the amount of water demand of the Lao industry sector towards the year 2040. The scenario of the increased industry production units in the watershed was set based on the long-term plan of the Vientiane province authority.

Once the model was simulated, it can be seen that there are dramatically increased water demands throughout the study period. The current water demand for the industry sector is about 1.09 million m^3/y. By the year 2040, the water requirement for this sector in the study area is expected to rise to approximately 227.66 million m^3/y or equivalent to an 85% increase compared to the reference scenario (Figure 4.18). On average during all 43 years, the water demand would be at about 146.86 million m^3/y or equivalent 135 times the current water use per year. Notably, the water demand has risen slowly in the first 10 years (from 1998-2008) and then began to rise increasingly from 2009-2010 onwards. The rapidly increasing water demand continued to proceed observably higher than the first 10 years at around 1.8 times. Furthermore, the demand rises sharply during the years 2037-2040. This significant increase in demand for water would be associated with the increase and expansion of the industry units, especially the growth in medium and large unit, the government's new industrial development policy (Vientiane Provincial Governor 2015), population growth and larger market expansion (Nozaki 2016), and the implementation of new advanced technological in the industry units throughout the watershed.

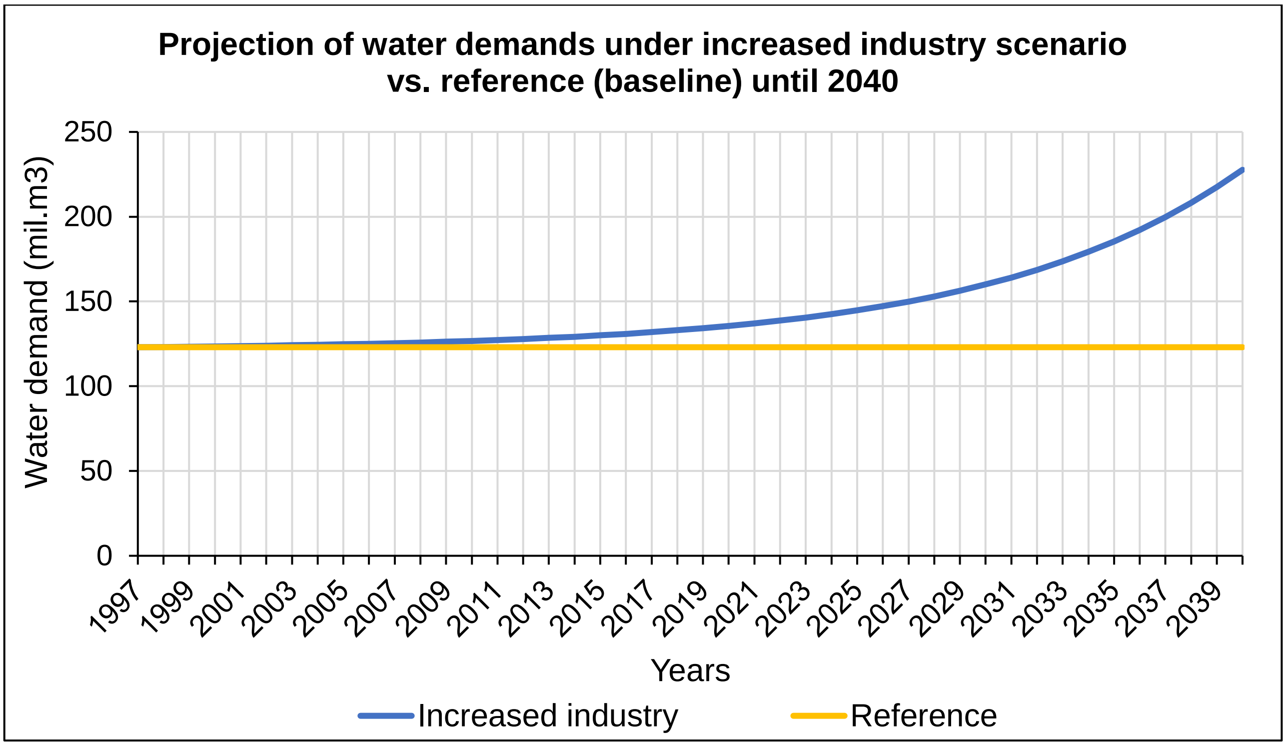


Figure 4.18. Projection of future water demand under increase industry units until 2040.

Aside from the total yearly prediction, the average monthly water demand for the industrial sector was also analysed in order to project the seasonal water demand trend throughout the study period. Based on Figure 4.19, it is clear that there is variability of the demands for each month and season, as was the case with the agriculture sector demand. The mean monthly water demand is approximately 12.19 million m^3/mth. The highest water demand occurred at the end of the dry season during the month of April with a rate of about 20.91 million m^3/mth. In contrast, the lowest water demand occurred at the end of the rainy season in the month of October with a projected rate of about 7.26 million m^3/mth. This increase in water demand in April is assumed to be for the water extraction from the river and some proportion from the groundwater sources. Hence, the need for more water in the dry months when rainfall is scarce is assumed to account for the high water amount taken out of the surface water system. In summary, though the water demand for the industry sector tends to increase over years to come, the quantity seems not to significantly impact the current water availability in the whole watershed. However, there will be some possible impacts if the water demand management is not comprehensively implemented, water quality degradation or if there are more rapid increases of industry units and other associated factors than has been projected.

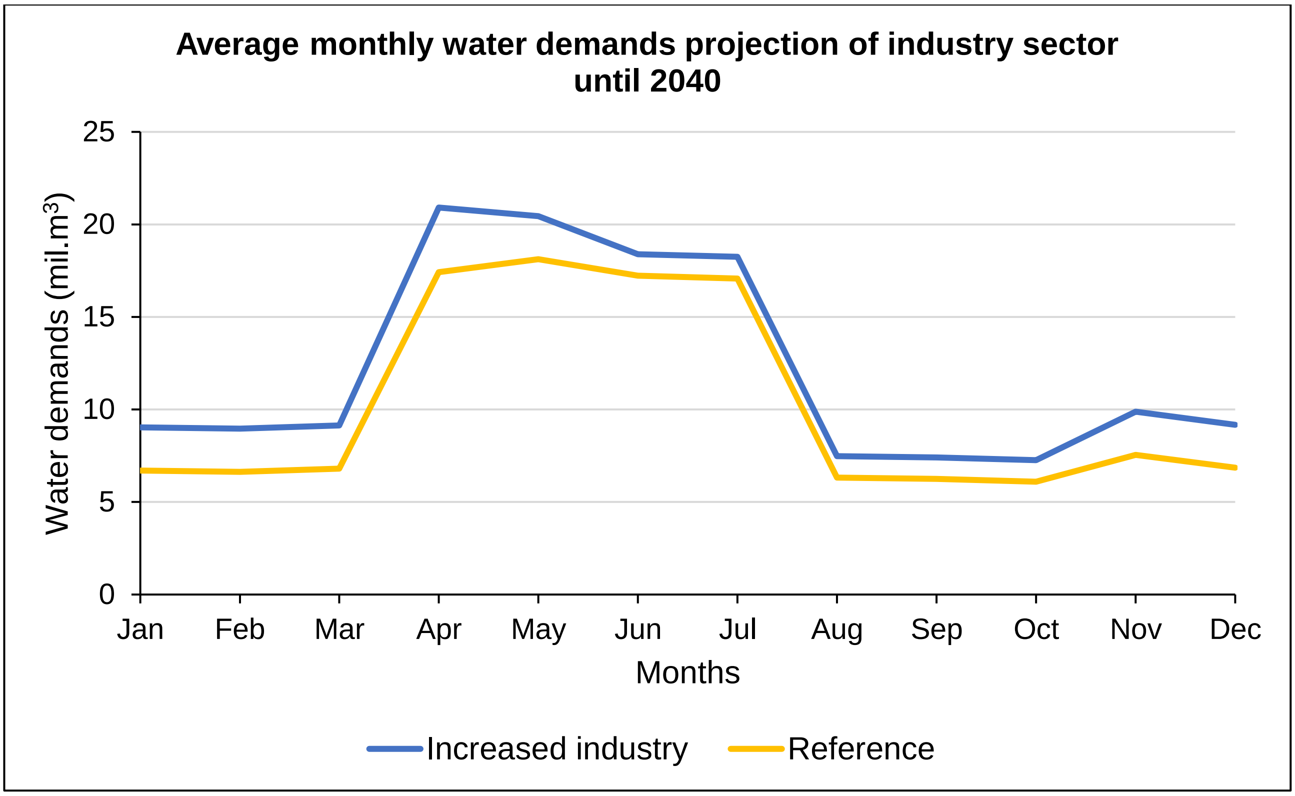


Figure 4.19. Average monthly water demand of industry sector until 2040.

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Water resources in Laos are vital for people's welfare and livelihood, socio-economic development, and environmental sustainability. Competing water resource use and increased water demand together with disturbances arising from the effects of climate change currently pose challenges for the country due to the variable water availability throughout the watershed system. Furthermore, human activities, such as deforestation and other land use changes, may lead to alterations in the water environment and its flow regimes that could create impacts on aquatic and terrestrial ecosystems, and on the human population and local communities in particular. Consequently, understanding the water balance, water demand projection, and environmental flow management is crucial for optimising the reliability of water quantity and quality, and addressing the challenges to meeting the country's demand for water in the longer term.

This study of water balance and future demand for water in the Nam Xong Watershed in Laos was selected for the purpose of demonstrating some of the options for future water resource management of the watershed and for application to similar resources elsewhere in Laos. The study employed the rainfall runoff method in the WEAP model package to simulate the current water balance and future demand prediction until the year 2040, over the 43-year period from the reference year of 1997. The hydrological, meteorological, social, and water use datasets were used for the model simulation, such as stream flows, rainfall, evaporation, groundwater recharge, water use, land use, and population. The model was set up and run successfully with some interesting results. The model calibration process was satisfactory implemented. Although the study was successfully conducted, there are some challenges and limitations due to the need to acquire data with spatial and time constraints. Therefore, the practical results of the study are revealed for further discussion.

The water availability in the study area is relatively abundant in terms of total amount and distribution. The main results showed that the total water availability in the study area is approximately 25.5 billion m^3 per annum. The main sources of the water inflows into the watershed systems are typically diverse. These include rainfall, surface water runoff or Nam Xong River system runoff, and groundwater recharge. The water outflows from the system include evapotranspiration, subsurface runoff, and river runoff to the downstream area, plus Nam Xong dam water diversion. The water inflows and outflows showed a balance figure in the watershed in terms of total water amounts. The current water demands for domestic, agriculture and industry sectors were studied and analysed. The total current water demand is approximately 135.88 million m^3/y. Of these, the agriculture possessed highest water demands of approximately 129.84 million m^3/y, and 4.94 million m^3/y and 1.09 million m^3/y for the domestic and industry sectors, respectively.

In the study, the future water demands for these three sectors have been projected until the year 2040 (from the period of 1998-2040 or 43 years) under three consecutive scenarios, which are increased irrigated agriculture, increased industrial units, and increased population. The total predicted water demands by the three sectors is approximately 18.5 billion m^3 in combination over all 43 years. Of these, the agriculture and industry sectors are about 6.86 billion m^3 and 6.31 billion m^3, respectively. While the predicted demand for the domestic use is only 5.37 billion m^3 which is the lowest in comparison to other sectors. In addition, the annual predicted water demand varied depending on the sectors, the seasons, and locations. By the year 2040, the average annual water demand will have rapidly increased, especially that of the agriculture and industry sectors. The agriculture water demand will increase from the current use of about 129.84 million m^3/y to about 159.73 million m^3/y or increase by 1.2 times. Interestingly, the industry demand will massively increase from 1.09 million m^3/y to approximately 146.86 million m^3/y or increase by 135 times. Lastly, the domestic water demand would also increase from 4.94 million m^3/y to about 125.06 million m^3/y or equivalent 25 times increase. Hence, it is clear that the water demands from the three sectors will rise significantly in the study area throughout the projected duration.

In addition, the minimum environmental flow requirement was also analysed and defined for the study area based on the current minimum stream flow and the model analysis. The potential and possible defined minimum flow requirement for this case study is about 9.6 m^3/s. This requirement is very important for the downstream livelihood of communities and sustainability of environmental functions, especially at the main river reach below the Nam Xong Dam or most of the downstream section where 16 villages are situated in Hinheup district. Although, this defining minimum flow requirement is very important for a small watershed like Nam Xong, further detailed study is needed to identify specific requirements for each riverine ecosystem and for aquatic species, such as fish.

In summary, it can be concluded that the water balance and demand management are important elements of effective integrated water resources management. In this study, the trend of the water demand was shown to increase for all sectors in the watershed towards the year 2040. However, this increase will not affect the capacity of the Nam Xong

Watershed to meet the increased demand in the foreseeable future. This was confirmed by Sayasane et al. (2016) research confirming that the increased water demand and use will not significantly alter the river flow systems and sufficient available water entering into the Nam Xong Watershed each year. However, their study did not consider the water demand from the industry sector. Therefore, some potential impact on the water use in the watershed could be expected in some areas if growth in industry water demand is included. Nevertheless, it is concluded that the water demands of the future can be met with low impact on the total water availability, provided that effective water governance both of quantity and quality is carried out in the watershed. Therefore, the comprehensive and integrated water resources management in the watershed is essential for better water demand management trade-off and sustainability of the resource.

5.2 Limitations

Based on the methods of the study, and under some constraints posed by distance data collection and time, there have been some challenges and limitations that include:

- The observed river flow datasets were deployed by only three available gauging stations at the Vangvieng district, Nam Xong Dam upstream and downstream flow stations. These are geographically located in the middle section of the watershed that might not represent the whole upstream and downstream water inflows and outflows from the river runoff.
- The study did not analyse aspects of the water quality. This might influence the domestic water availability and water demand for human consumption and household use that might not meet the national water quality standards in some areas.
- The groundwater recharge and discharge system were not studied for this paper, due to lack of previous academic study and data in the area. However, the estimated groundwater recharge rate that was input to the WEAP model was derived from other studies in the lower Nam Ngum River basin (downstream area of the NXW). Therefore, this rate may not be consistent with the context of the NXW because of the different geographical characteristics.
- The climate change impact on the current and future water availability and demand was not specifically studied in detail; however, climate change was referred to as likely to create uncertainty and unreliability of many factors relating to water resource management. Though unpredictable, climate change may affect the river flow and

hydrological characteristics in the study area due to the rainfall pattern change, extreme weather events, and temperature rise.

- This study only employed the simple rainfall runoff method in the WEAP model among other four methods. This method would not fully generate the comprehensive results of the water balance in the watershed. Other methods could potentially be applied for deeper understanding of the watershed water balance system, such as soil moisture, MABIA, and plant growth methods. These will help to better understand and conceptualise the complex watershed systems in a more comprehensive manner.
- The impact and operational rules of the Nam Xong dam on the water availability and demand were not studied in detail. This might be one of the key influencers on the total water availability and demands in the watershed, especially the downstream section below the dam.
- The environmental flow requirement was only analysed based on the observed river flow of the Nam Xong dam flow station (upstream station), which might not comprehensively represent the whole watershed. More studies and more comparison and analysis of observed flow stations would be useful for the whole watershed representation.

5.3 Recommendations

- The groundwater and water quality components should be studied in support of the assessment and projection of the current and future water demand and availability.
- A comprehensive study of climate change impact on the water availability in the entire NXW watershed should be carried out for better understanding of future conditions likely to affect the water resource.
- The minimum environmental flow requirement should be clearly defined and then implemented by the management authorities for maintaining the ecosystem functions. Moreover, improving dam operational rules are a regulatory necessity for securing the downstream flow requirement in the dry season in particular.
- The observed river flow gauging stations should be further developed in the upstream and downstream or at the nearest main river head flow and outlet for more effective data derivation and comparison.
- The integrated water resource management in the watershed should be implemented. This will enhance the effective management of water demand and supply.

- The water management and infrastructure should be environmentally designed and engineered for more effective water supply management.
- More comprehensive, empirical research is needed for further analysis and clarification of the water balance and future demand management in the watershed.

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