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Impacts of Climate Change on Water Resources and Corresponding Adaptation Strategies of the Nam Ngum River Basin, Laos

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IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES AND CORRESPONDING ADAPTATION STRATEGIES OF THE NAM NGUM RIVER BASIN, LAOS

by

Dumindu Lasitha Jayasekera

A dissertation submitted in partial fulfillment
of the requirements for the degree

of

DOCTOR OF PHILOSOPHY

in

Civil and Environmental Engineering

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2013

ABSTRACT

Impacts of Climate Change on Water Resources and Corresponding Adaptation Strategies of the Nam Ngum River Basin, Laos

by

Dumindu L. Jayasekera, Doctor of Philosophy

Utah State University, 2013

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This dissertation evaluates the climate change impacts on both hydrologic regimes and water resources of the Nam Ngum River Basin (NNRB) in Laos. The NNRB is expected to undergo rapid changes due to the future development of reservoirs and dams for hydropower generation. Water demands are expected to increase and water availability conditions will worsen with any changes to the hydrologic cycle due to climate change. The future development of hydropower in the presence of water allocation challenges due to population growth, land use changes, and climate change is needed to assess. For this purpose, a reliable methodology is used to estimate the climatic variables and a suitable basin scale integrated water resources management modeling framework is required. An assessment of climate change impacts and adaptation measures is required to minimize the watershed scale impacts and to maintain sustainability in the 21st century under competing demands for water.

This dissertation consists of three parts. The first part is focused on improving an appropriate downscaling methodology using General Circulation Models (GCMs) to estimate precipitation for representative weather stations of the NNRB at watershed scale for monthly temporal scale. Accurate reproduction of historical climatic conditions (from 1961 to 2000) was performed using a conditional generation method. Bias-correction was applied to GCMs in order to quantify the climatic variables under the climate change at selected weather stations for the baseline period. The estimated change factors at weather stations are used to estimate the future climatic variables. The first part of the study uses the outcomes of CGCM3.1 T63 and ECHAM5 for two future time periods, from 2011 to 2050 and from 2051 to 2090. The second part of the research is aimed at evaluating the changes in hydrological regimes and the long-term water resources impacts and system performance at the watershed scale under the status-quo condition for worst case scenario (A2 emission scenario) using CGCM3.1 T63. The third part evaluates the system adaptation measures at watershed scale and how the water resources system needs to be managed to minimize water shortage conditions and to improve system performance.

The major findings of this study suggest that (1) climate will be wetter and warmer, especially in the latter part of the century, indicating less water availability for water users mainly for agricultural purposes due to higher potential evapotranspiration rates compared to precipitation rates; (2) equitable water allocation is challenged due to the water resources system’s ability to satisfy the changing demands that will inevitably be placed without significant system degradation for agriculture and domestic water users under the status-quo condition; and (3) adaptation measures improving the water productivity, water use efficiency and forestry sector at watershed scale enhance the hydropower generation, sustainability in agricultural and domestic water user sectors.

(186 pages)

PUBLIC ABSTRACT

Impacts of Climate Change on Water Resources and Corresponding Adaptation Strategies of the Nam Ngum River Basin, Laos

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Dumindu L. Jayasekera, Doctor of Philosophy

The Nam Ngum River Basin (NNRB) in Laos has received attention of foreign investors due to high hydropower development potential and low per capita electricity consumption. The NNRB is rapidly developing due to its hydropower generation potentials while water demands will increase for agricultural and domestic purposes due to population increase and land-use changes. Water availability conditions will be affected with the increasing water demand and climate change may worsen the water availability conditions. Climate is often defined as the weather averaged over time whereas weather describes atmospheric conditions at a particular place and time in terms of air temperature, pressure, humidity, wind speed and rainfall. On regional scale, climate change impact assessment is crucial for water resource planning, management and decision making. First part of this study, reliable estimation of climatic variables is performed under climate change. Second part assess the changes in water resources regimes and sustainability conditions of agricultural and domestic water user sectors under climate change for “do nothing” option that are critical for strategic planning and to minimize the negative impacts. Third part assesses the long-term climate change trends, water allocation challenges and appropriate adaptation measures to minimize watershed impacts to achieve sustainability and long-term management goals. The major findings of this study shows (1) wetter and warmer climates especially in the latter part of the century indicating less water availability, (2) sustainability in meeting the water demands for agriculture and domestic use is affected under "do nothing" option, and (3) watershed scale adaptation measures improve the (1) hydropower generation, (2) sustainability conditions in agricultural and domestic water user sectors, and (3) flow regimes.

(Dumindu L. Jayasekera)

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CHAPTER 1

INTRODUCTION

Water is a precious natural resource required for the survival of all living beings. Since the available amount of water is limited, scarce and not spatially distributed in relation to the population needs, proper management of water resources is necessary to satisfy the current demands as well as sustainability. Water resources planning and management in the 21st century is becoming a challenge due to the conflicting demands from various stakeholder groups, population increase, rapid urbanization, land-use change for agricultural activities, climate change producing shifted hydrologic cycles and the increasing incidences of natural disasters. Among these challenges, climate change impacts due to global warming by anthropogenically increasing greenhouse gases on water resources are emerging concerns for decision-makers. Any change to the climate in a region drives the changes in hydrologic regime (typically, precipitation-runoff relationship) and thus produces an unexpected fluctuation in magnitude and timing of streamflow.

Climate change is a global concern. The Intergovernmental Panel on Climate Change [*IPCC*, 2007a] refers to climate change as any change in climate over time, whether due to natural variability or as a result of human activity. Future climate change will have various impacts all over the world. But, climate change is assumed to have a negative impact on developing countries [*Stern*, 2007; *IPCC*, 2007b] because availability of water is an essential component in socio-economic development and poverty reduction. It is expected that climate change will aggravate problems related to rapid population growth, existing poverty and a heavy reliance on agriculture and the environment. The majority of developing countries are in tropical and sub-tropical regions, areas predicted to be seriously affected due to changes in precipitation and temperature. The main concern is developing countries have limited capacity to cope with the problems caused by climate change.

South-East Asia (SEA) is considered one of the world's most vulnerable regions to the impacts of climate change [*Zuang et al.,* 2010]. It has about 563 million population with an average annual population growth about 2% compared with the 1.4% global average. It also has an annual average urban population growth about 3.5% compared to 2.6% and 2.1% in the developing Asia and the World, respectively [*World Bank*, 2008]. A report published by Asian Development Bank [*ADB*, 2009] confirms that SEA is already impacted due to increasing trend in mean surface air temperature and decreasing trend in mean annual precipitation from 1951 to 2000. Climate change is also exacerbating water shortages in many areas, constraining agricultural production and threatening food security, causing forest fires and degradation, damaging coastal and marine resources, and increasing the risk of outbreaks of infectious diseases [*ADB,* 2009].

The Mekong region in SEA is one such region comprised mainly by developing countries, and its rapids development over the last 20 years has contributed for Asian economic growth [*ADB-GMS,* 2010]. Recently published reports [e.g., *Eastham et al.,* 2008; *ADB,* 2009; *TKK and SEA START RC,* 2009] show growing international concern about the potential impacts of climate change mainly due to the changes in precipitation and temperature in this region, which is highly dependent on agriculture and fisheries for food security and income generation. Because, any change to precipitation and temperature will result to change the magnitude and timing of water availability for water users. Moreover, a good review of research studies carried out for modeling of hydrology and water resources of the Mekong River Basin (MRB) is provided by *Takeuchi* [2008] and *Costa-Cabral et al.,* [2008] simulated the hydrologic response of hypothetical scenarios of land cover and use of future climate of the MRB.

The main challenges of the region are 1) population increase, 2) urbanization and resource depletion, and 3) rapidly developing economies of riparian countries. Due to these challenges and competing demands, the region is more vulnerable to the additional challenges such as water availability posed by climate change [*IPCC,* 2001]. Furthermore, disparities are growing, particularly between urban and rural areas, and water and related resources are under increasing pressure. Some countries like Laos have high potential for hydropower development and place a high priority on reducing poverty and hunger. Capitalizing on hydropower potentials by investing on hydropower generation has become a key concern in the region. This is important because the demand for electricity has risen in recent decades due to rapid economic development in the riparian countries of the MRB and other parts of SEA. Compared to other countries in the region, Laos has relatively low per capita electricity consumption and therefore the lowest domestic electricity demand [*MRC,* 2010]. Due to this reason, Laos has the potential for power exports to neighboring countries. The rivers in Laos contribute around 35% of the Mekong River flow and have an estimated 18,000 MW of exploitable hydropower production potential of which less than 3% have been developed [*International Rivers,* 2008]. Nevertheless, existing hydropower projects have created uncompensated losses and unmitigated impacts. Poor planning and implementation have exacerbated poverty amongst affected villagers [*International Rivers,* 2008]. Therefore, it is questionable whether this lack of planning is unlikely to maximize electricity production or revenue under climate change conditions.

Main livelihoods of the people are subsistence farming relying on precipitation, fisheries and non-timber forest products and the people are dependent on their rivers for all aspects of their lives including fresh water, fish, irrigation and fertilization of crops, transportation and recreation. Approximately 75% of the MRB population is directly dependent on agriculture and fisheries. Moreover, in 2006 agriculture contributed 42.6% of Laos' GDP, 20.3% of Vietnam's GDP, and 31.9% of Cambodia's GDP [*UNEP*, 2006]. Farmers in the MRB have used the river and its tributaries for irrigation for years and the basin's massive rice production is important for the region's social values as well for its economy. These sectors are highly vulnerable to the changes in river ecosystems caused by large dams and long-term changes in flow regimes due to climate change.

Deforestation is among other issues that affect the environment of the MRB and it is largely caused by population growth and economic development. The forest cover in the Mekong Basin in 1970 was estimated to be 50% of the total land but by 1985 only 30% of the basin area was classified as forest. Furthermore, the percentage of forest cover continues to decrease [*Hori,* 2000]. As the region's population grows there is greater demand for land for residential, commercial, and agricultural purposes. In addition, “slash-and-burn” the local agricultural cultivation technique intensifies the erosion caused by bared land. Also, erosion from lands produces a drastic reduction in water quality which negatively impacts fish populations. Moreover, erosion reduces hydropower generation potential because of the more rapid accumulation of sediment in dams. Consequently, although deforestation does not directly affect dam building in the Mekong Basin but its effects cannot be ignored.

Impacts of climate change on agriculture and food production will be largely due to water availability, and most countries in the region have identified water resources as a priority sector under National Adaptation Plans of Action (NAPA) [*MOE*, 2005; *MONRE*, 2008; *WREA*, 2008]. The region's water resources are already undergoing rapid change as a result of other pressures such as population growth and economic development, and all countries have ambitious plans for water resources development in the next 10-20 years. There are limited research studies found in the recent literature for the Mekong region to assess the effective climate change adaptation strategies to minimize negative impacts due to water shortages for major water users at watershed scale and their relative advantages and benefits under competing demand for water.

There is a growing need for an integrated analysis that can quantify the impacts and trends of climate change on various aspects of water resources such as precipitation, hydrologic regimes, drought, hydropower generation, etc. The integrated analysis, however, requires reliable data, methodologies and integrated water resources modeling framework that can properly characterize the study area where hydrologic information has not been carefully monitored.

Therefore, the overall goal of this dissertation is to assess the future variability of hydrologic regimes and water resources of the Nam Ngum River Basin under both climate change and water resources operations and to assess the potential impacts and adaptation strategies of the study area. The specific objectives and tasks to achieve this goal can be summarized as follows:

1. Development and application of a methodology for estimation of precipitation using General Circulation Models (GCMs) and demonstrate the applicability of bias-correction methodology at a regional-scale.
    - Develop a stochastic framework for precipitation generation to simulate long-term precipitation occurrence and non-occurrence at individual location using discrete time/space Markov chain based conditional probabilities.
    - Apply bias-correction methodology to transform the precipitation distribution from coarse GCM scale to regional (observed) scale.
    - Perform statistical downscaling using a perturbation approach to estimate the precipitation under climate change at a given weather station.
2. Development of hydrologic and water allocation model for assessing the water resources impacts and water allocation challenges
    - Develop a hydrologic and water allocation model for assessing the current water management and allocations conditions for historical and future climatic conditions.
    - Simulate integrated water allocation and priority management options to govern the allocation of water between competing demands, consumptive demand for agricultural and domestic water use or non-consumptive demand for hydropower generation or ecosystem protection.
    - Assess the water resources impacts and sustainability issues at watershed scale under historical and future climatic conditions for status-quo using water resources system performance indicators.

3. Identify the water resources impacts under climate change and identification of appropriate adaptation strategies to improve the overall system performance indicators
    - Analysis of long-term trends of watershed impacts and assessment of adaptation strategies for identified impacts.
    - Evaluation of adaptation strategies by means of water resources system performance indicators.
    - Compare the overall benefits of adaptation strategies with no adaptation (status-quo) condition.

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CHAPTER 2

ESTIMATING MONTHLY PRECIPITATION IN RURAL RIVER BASINS UNDER CLIMATE CHANGE: AN IMPROVED BIAS-CORRECTING STATISTICAL DOWNSCALING APPROACH [1]

Abstract

This study extended the work of *Kim et al.*, [2008] to generate future precipitation under climate change using a discrete-time/space Markov chain based on historical conditional probabilities. A bias-correction method is proposed by fitting suitable statistical distributions to transform precipitation from the general circulation model (GCM) scale to watershed scale. The demonstration example used the Nam Ngum River Basin (NNRB) in Laos which is a rural river basin with high potential for hydropower generation and significant rain-fed agriculture supporting rural livelihoods. This work generated weekly precipitation for a 100-year period using historical precipitation data from 1961 to 2000 for ten selected weather stations. The bias-correction method showed the ability to reduce bias of the mean values of GCMs when compared to the observed mean amount at each station. The simulated precipitation series is perturbed using the delta change estimated at each station to project future precipitation for the Special Report on Emission Scenarios (SRES) A2. GCMs consisting of third generation coupled general circulation model (CGCM3.1 T63) and European center Hamburg model (ECHAM5) projected an increasing trend of mean annual precipitation in the NNRB. Seasonal precipitation percent changes showed an increase in the wet and dry seasons

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[1] Coauthored by Dumindu Jayasekera and Jagath J. Kaluarachchi

the Providing REgional Climates for Impacts Studies (PRECIS) regional climate model with the highest increase in the dry season mean precipitation of about 31% from 2051 to 2090. While the GCM projections showed good results with appropriate bias corrections, significantly underestimated historical behavior and produced higher mean absolute errors compared to the corresponding GCM predictions.

2.1 Introduction

A key challenge in water resources planning and management is to estimate the water availability and to adopt management strategies in the presence of climate change. [*Intergovernmental Panel on Climate Change (IPCC) fourth assessment report –AR4,* 2007a] defined climate change as “a change in the state of the climate that can be identified by changes using statistical tests in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. The change refers to any change in climate over time, whether due to natural variability or as a result of human activity”. Southeast Asia is one such a region vulnerable to climate change and its variability, including rise in sea level, shifts of climatic zones, and the occurrence of extreme events such as droughts and floods [*UNFCCC*, 2007].

General Circulation Models (GCMs) are used to project future climates under different greenhouse gas emission scenarios [*IPCC*, 2007b]. The key limitation of GCM simulations is the coarse scale grid resolution that prevents the direct use of GCMs for impact assessment studies because GCM results cannot represent sub grid-scale features and dynamics at the watershed scale [*IPCC*, 2007b; *Vicuna et al.*, 2007]. GCMs supported by appropriate downscaling techniques, have long been used to simulate changes in regional climate systems over wide spatiotemporal scales and to allow information from coarser-scale atmospheric simulations to be used in watershed-scale hydrologic models [*Wilby and Wigley,* 1997; *Arnell et al.,* 2003]. There have been many studies and different downscaling techniques developed to transfer the coarse scale GCM output to regional scales. The most common downscaling techniques are (a) dynamical downscaling that uses regional climate models (RCMs) to simulate watershed-scale physical processes [*Giorgi et al.,* 2001; *Mearns et al.,* 2004; *Fowler et al.,* 2007]; and (b) statistical downscaling using statistical relationships between the regional climatic conditions and pre-identified large-scale atmospheric parameters [*Wilby et al.,* 2004; *Mehrotra and Sharma,* 2005; *Vrac and Naveau,* 2007]. Over the past years, a wide range of statistical downscaling techniques have been developed and most techniques fall into a category where response variables (mostly precipitation) are related to a discrete or continuous state, which is modeled as a function of the atmospheric and local-scale predictor variables [*Wilby and Wigley,* 1997; *Stehlík and Bárdossy,* 2002; *Mehrotra and Sharma,* 2005; *Vrac and Naveau,* 2007; *Mehrotra and Sharma,* 2010]. The limitations and assumptions of both techniques contribute to the uncertainty of results [*Fowler et al.,* 2007]. Studies by *IPCC* [2007b] and *Fowler et al.,* [2007] provided a good discussion of various downscaling techniques. In general, raw GCM precipitation amounts tend to underestimate year-to-year variability and poorly represent extreme events, when compared to the historical precipitation records [*Ines and Hansen,* 2006; *Knutti,* 2008] implying that the probability of sustained droughts/low flows or high flows are poorly predicted in future climate projections. This limitation will have a significant impact in water resource planning and management. There is a need to address this limitation and correct the bias of raw GCM outputs for appropriate use in hydrologic modeling.

A commonly used approach in recent studies is the use of change factors (CFs) [*Abbaspour et al.*, 2009; *van Roosmalen et al.*, 2009; *Sulis et al.*, 2011] often called the “perturbation method” [*Prudhomme et al.*, 2002] or “delta change” approach which assumes that the climate model represents relative change more accurately than the absolute climate values and the model bias is constant through time [*Fowler et al.*, 2007]. Generally, the CFs are applied to perturb the historical observed time series. A study by *Kim et al.*, [2008] investigated the long-term changes of precipitation by extending the historical precipitation series at multiple sites preserving the historical temporal and spatial correlation structures. The conventional approach is to use the mean of raw GCM grid values over space and few studies investigated the long-term changes of precipitation that persists for an extended period, typically decades or longer. *Kim et al.*, [2008] generated future monthly precipitation series and perturbed the series by the percent change of mean monthly precipitation at the grid nodes of GCMs spatially downscaled to weather stations. However, the question still remains whether the percent change at observed scale (i.e. at a given weather station) is similar to the percent change at the interpolated GCM scale given the different spatial scales. To compare the precipitation changes at a local weather station the coarse scale distribution from the GCM scale needs to be transformed to the observed scale of distribution by using its probability of occurrence. Another limitation of the previous study was its inability to reproduce the months with zero precipitation (or dry states), because monthly time scale is not adequate to include the precipitation non-occurrence (dry-state) condition.

The need and prior applications of bias-correction methods have been discussed in the recent literature. *Johnson and Sharma* [2012] developed a nested model for bias correction at multiple time scales. *Johnson and Sharma* [2011] discussed bias correction can be performed using parametric and nonparametric approaches. *Li et al.*, [2010] proposed an equidistant quintile matching technique of bias correction for monthly precipitation and temperature using IPCC AR4 models. *Fowler et al.,* [2005]; *Frei et al.,* [2006]; *Christensen et al.,* [2007]*;* and *Schmidli et al.,* [2007] assessed the ability of RCMs to reproduce credible climate change scenarios for extreme events and climate variability at a regional scale. *Fowler et al.*, [2007] suggested that at least for present-day climates, dynamical downscaling methods provide little advantage over the statistical techniques. *Kerr* [2013] stated that regional models should be tested to evaluate whether the model outputs are capable of regional scale modeling compared to the use of global models. However, there are few studies focused on South East Asia to assess the precipitation and temperature changes due to climate change using RCMs and GCMs. A study by *Lacombe et al.*, [2012] projected the precipitation and temperature trends of South East Asia using a RCM. *Västilä et al.*, [2010] simulated the climate change impacts in the Lower Mekong flood plains using re-scaled PRECIS RCM for baseline scenarios. *Eastham et al.*, [2008] used a statistical analysis to quantify the relative ability of each GCM in simulating climate over the Mekong Basin using 24 GCMs used in the AR4 report. Some of the GCMs in the AR4 report showed considerable capability at sub-continental scales even when assessed using daily frequency distributions. This builds confidence in using the GCMs for regional assessment [*Perkins et al.*, 2007].

The long-term variability of seasonal and sub-seasonal (e.g. monthly) streamflow is important especially for river basins where primary livelihood is based on rain-fed agriculture. Moreover, a prior understanding of spatial and temporal variability of streamflow is crucial for the sustainability of rural economies especially in a region where hydropower generation is important. Since streamflow is directly influenced by the precipitation distribution, the estimation of temporal and spatial variability of precipitation is an important consideration. Here we propose to study the influence of climate change on precipitation in rural river basins with limited data using the Nam Ngum River Basin (NNRB) in Laos. The region is well suited for this study because it is undergoing rapid development due to high hydropower generation capacity and population increase while rain-fed agriculture is still a priority. However, developing a reliable precipitation analysis in a rural river basin can be a challenge due to short and missing precipitation records, and limited hydrologic information. First, all of the above discussions identify the need to quantify the precipitation distribution in river basins that are vulnerable to extreme weather conditions. Second, a long term precipitation analysis for any temporal resolution should be able to preserve the temporal and spatial statistics and correlations of historical data so that the projected precipitation distribution is reliable.

The goal of this study is to improve a methodology developed by *Kim et al.,* [2008] to better project precipitation under climate change. The important considerations are bias correction, limited data availability, and applicability of RCMs. Therefore, this study is an extension of the work proposed by *Kim et al.,* [2008]. In the proposed work, the previous stochastic framework is extended for single- and multi-sites that simulates historical precipitation amounts (wet states) at individual locations using a discrete-time/space Markov chain based on historical conditional probabilities. Thereafter, the raw GCM precipitation amount is corrected using statistical bias correction of mean at each station. The proposed methodology is demonstrated for the NNRB to predict the long-term precipitation distribution for two time periods, 2011-2050 and 2051-2090.

2.2 Description of Nam Ngum River Basin, Laos

2.2.1 Physical Description

The NNRB which originates from the Tran Ninh Plateau, 1000 m to 1500 m above mean sea level (msl), is located in Northern Laos (Figure 2-1). The drainage area of NNRB at the main outlet close to the confluence with the Mekong River is 16,777 km^2 or 7.3% of the national area. The elevation of NNRB varies from 6 m to 2684 m above msl. The estimated mean slope of the NNRB basin is about 25.5%. It is the second largest river basin in terms of mean annual flow and population compared to the Sekong and Sebanghieng Basins and the fifth largest basin in terms of land area in the country. The estimated population of the basin is 502,150 in 2005 and this number is approximately 9% of the population of Laos [*WREA*, 2008]. The major land use types of NNRB are natural forest at 47%, shrub land at 34%, agriculture at 8%, grassland at 7%, water surface at 3.98%, and urban area at 0.02% of the total area [*WREA*, 2008; *WREA*, 2009].

2.2.2 Climate and Hydrology

The climate of NNRB is subtropical to tropical with a distinct wet season from May to October and mostly dry during the rest of the year. Most of the precipitation in the NNRB is due to the arrival of warm moist air during the south-west monsoon period. The hottest months are March to April during which the mean daily maximum temperature varies between from 28° to 34° C. The mean minimum daily temperature varies between 14° and 24°C between December and January at high elevations [*ADB*, 2008]. The mean annual precipitation of NNRB is 2000 mm, varying between 1400 to more than 3500 mm [*WREA*, 2009]. The mean annual Penman-Monteith potential evapotranspiration varies between 1060 mm and 1360 mm [*ADB*, 2008].

The mean annual flow to the Mekong River is about 22 billion m^3 (BCM) which is about 14.4% of the annual flow of the Mekong River. The annual water use of NNRB is about 0.9 BCM of which 99% is used by agriculture, 0.52% is by domestic water use, and 0.08% is for industrial purposes.

2.3 Precipitation Data

2.3.1 Data Sources

There are 40 weather stations available in and around the NNRB (Figure 2-1). Daily precipitation data are available for all 40 stations for different periods and the longest daily precipitation data are available at Vientiane from 1951 to 2000. Except for few weather stations, most other stations have missing precipitation records from 1961 to 2000. Luang Prabang, Nong Khai, Xiengkhouang, and Vientiane have daily precipitation records available for 40 years from 1961 to 2000 and other stations have daily precipitation records varying from 7 to 38 years for the same period. The period from 1961 to 2000 is comparable to the 20th century experiment (20C3M) period or the baseline period.

The density of weather stations of the study area is low especially in the eastern and north eastern parts of the study area and amounts to about one station per 2100 km^2. Since most weather stations have varying periods of missing precipitation data, it can be challenging to select the weather stations which are representative of precipitation characteristics of the basin.

2.3.2 Selection of Representative Stations

The purpose here is to identify the weather stations from the 40 available that can represent the precipitation pattern of the basin. A non-parametric bootstrap method and the Thiessen polygon spatial interpolation method were used to evaluate the uncertainty in the selection of representative weather stations. To develop a stochastic methodology to generate reliable precipitation data, there should be long historical observed precipitation of at least 30 to 40 years. Of the 40 weather stations, Luang Prabang, Nong Khai, Xiengkhouang, and Vientiane have 40 years of precipitation data from 1961 to 2000 whereas Ban Nasone, Thangone, Sengkhalok, Ban Hinheup, Ban Thouei, and Phonhong have precipitation data for 38, 36, 35, 34, 32, and 30 years, respectively. Remaining 30 stations have precipitation records for 7 to 38 years for the same period (Figure 2-1). Subsets of weather stations were selected randomly based on the availability of historical data. A subset of 10 weather stations from random sampling was selected for the bootstrapping uncertainty analysis, and to estimate areal mean annual precipitation and arithmetic mean annual precipitation (Figure 2-2). The selected 10 representative stations are Luang Prabang, Nong Khai, Xiengkhouang, Vientiane, Ban Nasone, Thangone, Sengkhalok, Ban Hinheup, Ban Thouei, and Phonhong. A non-parametric bootstrap random resampling technique (with a dimension of 1000) was used to evaluate if the selected 10 weather stations can be used to represent historical data both spatially and quantitatively. Figure 2-2 shows the mean annual precipitation estimated by resampling 10 to 40 stations among the 40 stations. The estimated mean areal annual precipitation using the 10 stations and the arithmetic mean are within the 95% confidence limit.

2.3.3 Missing Data

A study by *Teegavarapu and Chandramouli* [2005] provided a detailed discussion of different techniques for the estimation of missing precipitation records. They recommended that coefficient of correlation weighting method is one of the methods conceptually superior to other approaches due to its capability to ensure the existence of spatial autocorrelation in estimating the missing data. This study used coefficient of correlation to estimate the missing precipitation data. A previous study by *Kim et al.,* [2008] showed that a combination of local linear regression and coefficient of correlation methods is good for estimating missing precipitation data. As shown in Table 2-1, the 10 representative stations selected earlier are significantly correlated (p-values ≈ 0) among each other indicating that coefficient of correlation weighting method is suitable for the estimation of missing data for the historical period. The filling is performed at weekly time steps at the 10 representative stations such that complete records are produced from 1961 to 2000. The total mean annual precipitation changed approximately 2% from the observed values and the correlation coefficients among stations (not shown here) remained almost similar.

2.4 Methodology

This work simulates historical weekly precipitation non-occurrence (dry state, 0 mm) and occurrence (wet state, > 0 mm) at individual locations using a discrete-time/space Markov Chain based on conditional probabilities. A weekly time step is selected because it can better simulate both precipitation occurrence and non-occurrence compared to monthly time step. The spatial correlations in the simulated amounts are generated using spatially correlated yet serially independent random numbers. The methodology includes the following steps: (a) First representative precipitation stations are selected based on the availability of daily precipitation data to represent the baseline period from 1961 to 2000, (b) a single station (or key station) is selected among the 10 representative stations while for temporal generation preserving the temporal correlation structure, (c) the remaining representative stations are used for spatial generation preserving the spatial correlation, (d) bias correction is performed for the baseline period (20C3M) and future A2 emission scenario using the historical observed and generated precipitation amounts, and (e) perturbation conducted at each station by the CF method to project the future precipitation amounts.

2.4.1 Single Site Temporal Generation

A correlation analysis was performed to identify a key station that has the highest correlation of annual precipitation with the annual unregulated streamflow. Unregulated streamflow stations are located at Muang Kasi, Vangvieng, Ban Naluang, and the proposed dam site location (Figure 2-1). The weather station located at Luang Prabang (Figure 2-1) has the highest correlation ($r = 0.99$, p-value ≈ 0) with streamflow measured at the proposed dam site location. Therefore, Luang Prabang was selected as the key representative station. Since Luang Prabang is located outside the basin, the precipitation amounts do not physically contribute to the flow at the proposed dam site but the annual precipitation pattern is highly correlated with the annual unregulated streamflow at the proposed dam site (see Figure 2-1). Long-term weekly (temporal) precipitation is generated using a discrete-time Markov chain based on conditional probabilities at Luang Prabang and the long-term weekly (spatial) precipitation of remaining nine stations.

2.4.2 Markov Process

Markov process is a special type of stochastic process defined as a family of random variables $\{X(t), t \in T\}$ where t represents time and T is the index set or parameter space that is a subset of $(0, +\infty)$. The values assumed by the random variables X(t) are called states. A special case of this for a discrete-time/discrete-valued (DTDV) random process is called a Markov chain. Specifically, it has the property that the probability of the random process X[t] at time $t = t_0$ only depends upon the outcome or realization of the random process at the previous time $t = t_0-1$. This work deals with weekly precipitation amounts at the key precipitation station Luang Prabang.

The conditional probability (P_{ij}) of state *i* of the current week (*w*), given the state of the previous week (*w-1*) *j*, can be written as

$$P_{ij} = \Pr\left[X'(w) \in i \mid X'(w-1) \in j\right]$$

$$P_{ij} = \frac{\Pr\left[\left(X'(w) \in i\right) \cap \left(X'(w-1) \in j\right)\right]}{\Pr\left[X'\left(w-1\right) \in j\right]} \quad , \qquad (1)$$

where *i* and *j* represent current and previous states from 1 to N and N is the number of states corresponding to the standardized weekly precipitation X'. For example, dimensionless state 1 is defined as 0, state 2 as $0 \le X' < 1$, state 3 as $1 \le X' < 2$ and so on. N depends on the range of weekly precipitation data. In this study, N was computed by dividing the range of weekly precipitation observed over the historical 40-year period of 1961 to 2000 by the standard deviation of weekly observed precipitation values.

If the chain is previously in state X_j, then it moves to the current state X_i with the probability denoted by P_{ij}, and these probabilities are called conditional or transition probabilities. The conditional or transition probability matrix P_w for the current week can be constructed where the elements of P_w satisfy the following two properties; $0 \leq P_{ij}(w) \leq 1$, and $\sum_{all i} P_w = 1$. By using the historical weekly precipitation series for the key station, P_w can be computed.

A set of conditioned random numbers is required from a continuous uniform distribution to successively generate a time series of weekly standardized precipitation. Consider the states from 1 to N where each state has a specific probability density. Two sets of discrete uniform random number series from 1 to N are generated and conditioned (i.e. increase or decrease) for each state using a given marginal or conditional probability density. A set of conditioned discrete uniform random numbers C(1,N), can be generated as

$$C(1,N) = \left\{ [1]^{d_1}, [2]^{d_2}, \ldots [i]^{d_i}, \ldots [N]^{d_N} \right\} \tag{2}$$

where $[i]^{di}$ is the set of integer i which represents the state which has a dimension of d_i and d is the dimension of the conditioned discrete uniform random number matrix to be generated which is 1000 in this study. For each week, a series of discrete uniform random numbers were generated. It is considered that monthly values are represented over 4 weeks and the time series were generated for 100 equivalent annual periods consisting of 48 weeks each.

To generate states for week 1, the previous state j (i.e. jth column of P_1) is decided first from C(1,N) conditioned by the marginal probability of week 48, $\Pr[X(48) \in j]$ where 48 is week 48 which is the previous week. Likewise, current state i can be decided from C(1,N) conditioned by P_1 for a given j. In the same manner, the current state (week 2) i is used to decide the previous state j of week 1 so that the jth column of P_2 is used to decide the state of week 2, and so on. This process is continued and performed for a time length of 100 years.

After the generation of continuous uniform random numbers (e.g. 0 to 0.99 for state 2) conditioned by the previous state conditional probabilities, these random numbers need to be restored to its real weekly precipitation amounts, X, in mm by multiplying by the corresponding weekly standard deviations. Here, we assume the historical long-term weekly standard deviations will remain unchanged in future climatic conditions. By considering the conditional probabilities of historical states transitions and randomly generating the amount of precipitation within the range of a particular state of a given month, the discrete-time Markov chain stochastic process can simultaneously address temporal characteristics of historical data between successive weeks and randomness of weekly precipitation. Additional information is available from *Kim et al.*, [2008].

2.4.3 Multi Site Spatial Generation

For multi-site weekly precipitation generation, the temporal generation used in the single site scenario is extended between the key station and the representative stations except spatially to preserve the spatial correlation structure. For the historical period, as shown in Table 2-1, the key station Luang Prabang is highly correlated with the other representative nine precipitation stations with correlation coefficients of 0.75 with Station 2 (Vientiane) and 0.95 with Station 7 (Phonhong), and *p*-values close to zero. These statistics indicate that the mean weekly precipitation of the nine stations is closely correlated with the key station, therefore this relationship of conditional probability similar to the temporal condition probability (P^k_{ij}) can be written as,

$$P^{k}{}_{ij} = \Pr\left[X'(w,k) \in i \mid X'(w,k') \in j\right]$$

$$P^{k}{}_{ij} = \frac{\Pr\left[\left(X'(w,k) \in i\right) \cap \left(X'(w,k') \in j\right)\right]}{\Pr\left[X'\left(w,k'\right) \in j\right]} \qquad (3)$$

where *k* is now the target station number, *k'* is the key station, and other notations are same as given in Equation (1). As the series of state *j* for the key station was already generated in the earlier single site temporal generation, state *i* in the target station can be iteratively generated using C(1,N) conditioned by $P^{k}{}_{w}$ at the given *j* of the key station, where $P^{k}{}_{\mathbf{w}}$ is the matrix of $P^{k}{}_{ij}$ at the current week *w*. The overall process of generating precipitation for multi-sites is similar to the single site precipitation generation except using the target station number instead of the week.

2.4.4 GCM and Emission Scenario

This study used A2 emission scenario which is the most common scenario for mid and high ranges of emissions used in recent climate change impact studies [*Abbaspour et al.,* 2009; *van Roosmalen et al.,* 2009; *Anandhi et al.,* 2011; *Sulis et al.,* 2011], and for South East Asia by *Lacombe et al.,* [2012]. The A2 scenario emphasizes on local traditions, high population growth, and less concerns from rapid economic development. Also from an assessment view point, A2 scenario provides probably the worst case scenario for a country such as Laos that is rapidly undergoing development. *Eastham et al.,* [2008] conducted a statistical analysis to quantify the relative ability of each model to simulate climate over the Mekong River Basin using 24 different GCMs. Based on the pattern correlation and root mean square error of temporal and spatial pattern representation of monthly and seasonal precipitation over the Mekong Basin, the authors selected 11 GCMs. In this study, CGCM3.1 T63 [http://www.ec.gc.ca/ccmaccccma/default.asp?lang=En&n=1299529F-1, accessed March, 2012] and ECHAM5 [http://www.mpimet.mpg.de/en/science/models/echam/echam5.html, accessed March, 2012] were selected based on the ability to represent the temporal and spatial patterns of precipitation over the Mekong Basin. In addition, a RCM known as PRECIS (Providing REgional Climates for Impacts Studies) developed by the Hadley Center for Climate Change in UK is available for comparison with projections made by other GCMs [http://www.metoffice.gov.uk/precis, accessed March, 2012]. RCM simulations for the NNRB were conducted by the South East Asia Regional Center (START) in Thailand. [http://www.start.or.th/, accessed March, 2012].

Monthly precipitation fluxes for the baseline scenario (20C3M) period and for the future period for A2 scenario (2011-2090) were downloaded from the IPCC Data Distribution Center (DDC) [http://www.mad.zmaw.de/IPCC_DDC/html/SRES_AR4/index.html, accessed December 2010] for CGCM3.1 T63 and ECHAM5. The spatial resolution and the number of GCM grids covering the study area is shown in Table 2-2. Monthly precipitation amounts from PRECIS were available from the South East Asia-SysTem for Analysis, Research and Training (SEA-START) Center in Thailand for the control period from 1960 to 2004 and for the A2 scenario from 2010 to 2050.

Several methods have been proposed by [*IPCC*, 2007a] to apply the GCM outcomes to a small study area. The simplest application is the direct use of the raw GCM grid information to the nearest station in the study area. The main weakness of this method is that precipitation stations located close proximity but falling in different GCM grids, while having similar climatic conditions and characteristics, tend to assign different climatic conditions [*Kim et al.*, 2008]. As shown in Table 2-2, six to nine GCM grids are needed to cover the NNRB with 10 stations whereas 108 RCM grids are needed to cover the same NNRB. The monthly precipitation amounts at each GCM and RCM grid nodes were spatially downscaled to the 10 stations for the baseline scenario and A2 scenario periods. The inverse distance weighted method was used for spatial interpolation.

Regional climate change signals can be significantly different from those projected by GCMs, particularly in regions with complex orography. Normally, RCMs dynamically downscale the climate change signals projected by GCMs. A RCM is driven by sea surface temperatures and atmospheric lateral boundary values from the forcing GCM [*Déqué et al.,* 2005]. RCMs are known to better capture the effects of orographic forcing and provide improved simulation of higher moment climate statistics; hence providing more plausible climate change scenarios for extreme events and climate variability at the regional scale. Despite these improvements, there is a need [*Leung al.* 2003] for more research examining the statistical structure of climate signals at different spatial scales to establish whether RCMs can accurately predict regional-scale climate.

2.4.5 Bias Correction

Kim et al., [2008] compared the generated monthly precipitation series with the coarse scale monthly GCM precipitation amounts and assigned weights for each GCM based on observed accuracy. Comparing amounts from two precipitation series at two different spatial scales is not intuitively correct. Because, the resulting precipitation amounts at a weather station due to regional atmospheric conditions may be different from the atmospheric conditions occurring at the GCM scale. Further, *Kim et al.,* [2008] projected future monthly precipitation amounts by perturbing the generated monthly precipitation series at each location by interpolated percent change of precipitation using the values at the GCM node. The actual change of precipitation at a weather station at regional scale may be different compared to the spatially interpolated change using the GCM nodal percent change values. Therefore, we proposed a bias correction approach to transform GCM signals to the regional scale and to find the delta change at regional scale (at each weather location).

As shown in Figure 2-3, a comparison of raw mean monthly precipitation for the baseline scenario (20C3M) with historical observed at the 10 weather stations suggests that the observed and raw GCM mean precipitation amounts are biased and underestimating the historical climatic conditions. A comparison of monthly precipitation is performed here due to the unavailability of daily ECHAM5 precipitation fluxes for the baseline period and A2 emission scenario. A given downscaling method should be able to capture the variability of precipitation at a location. Moreover, the performance of downscaling methods varies across seasons, locations, GCMs, and regional features such as orography, proximity to sea, land use, and vegetation. Therefore, we assume that at a given location, the local climatic effects are reflected by its precipitation distribution. Since the variability of precipitation at a location depends on the amount, statistical properties of GCM values such as mean should be corrected to the statistical properties of observed values at weather stations.

The purpose of bias correction is to reduce the bias between the GCM precipitation amount of the baseline scenario and the historical observed precipitation amount at a given station. Transformation of precipitation distributions from coarse GCM scale to regional (observed) scale is conducted using the best-fitted parametric probability distribution. First, monthly baseline scenario (20C3M) GCM distribution and the observed historical (1961-2000) distributions are fitted to appropriate parametric probability distributions. For this purpose Exponential, Gamma, Weibull, and Log-normal distributions were considered and the best-fitting distributions are selected using histogram fits, quantile-quantile (Q-Q) plots, and correlation coefficients. Second, using the fitted parametric probability distribution of the GCM baseline precipitation as well as for the historical observed the corresponding cumulative probability function is computed. Third, the cumulative probabilities of the GCM distributions are then used with the fitted parametric probability distribution parameters of historical observed data to estimate the corrected GCM precipitation amounts. The same procedure is repeated for generated precipitation amounts and for future GCM distributions across two time periods, 2011 to 2050 and 2051 to 2090.

Since ECHAM5 data are available as monthly precipitation fluxes, monthly time scale is used for the distribution fitting. Parametric probability distributions are fitted for monthly precipitation amounts greater than zero.

For example, if monthly precipitation amounts follow the Gamma distribution, the probability density function, $f(x,\alpha,\beta)$ is

$$f(x;\alpha,\beta)=\frac{1}{\beta^{\alpha}\Gamma(\alpha)}x^{\alpha-1}\exp\left(-\frac{x}{\beta}\right)\ for\quad x>0 \tag{4}$$

where x is the monthly precipitation amount, and α and β are shape and scale parameters. It should be noted that the shape and scale parameters are station dependent. The shape and scale parameters can be determined using Maximum Likelihood Estimation. The cumulative distribution of the above probability densities can be written as,

$$F(x;\alpha,\beta) = \int_0^x f(t)dt \tag{5a}$$

$$F_{GCM}(x_{GCM};\alpha,\beta|_{GCM}) \Rightarrow F_{His}(x_{His};\alpha,\beta|_{His}) \tag{5b}$$

where x_{GCM} is the monthly precipitation of the GCM, and x_{His} is the historical observed/generated monthly precipitation. The corrected GCM precipitation for a given month can be estimated by taking the inverse of Eq. (5b)

$$x'_{GCM} = F_{GCM}{}^{-1}\left\{F_{His}(x_{His};\alpha,\beta|_{His})\right\} \tag{6}$$

The statistical bias-correction method is applied to the precipitation amounts of CGCM3.1 T63 and ECHAM5 baseline scenarios. The inverse distance weighted method was used to estimate precipitation at the 10 stations. This interpolation method was selected because the GCM nodal precipitation amounts are greater than zero for both GCMs when precipitation flux is converted to monthly precipitation amounts.

2.4.6 Perturbation by CF Method

In applying the CF method, it is assumed that the relative and/or absolute changes in precipitation between past and future climatic conditions have a strong physical basis and that precipitation recurrence patterns remain the same between the past and future periods [*Kilsby et al.*, 2007; *Akhtar et al.*, 2008]. Therefore, the scaled and baseline scenarios differ only in terms of their respective means, maxima, and minima.

After correcting the raw GCM precipitation for the mean amount at a station, the CF is calculated using the corrected future GCM scenario ($\mathrm{GCM}^{f}_{\mathrm{corr}}$) and corrected GCM baseline scenario (GCM^{b}_{corr}) at monthly time steps at each weather station. The CF of precipitation at a given station is calculated as

$$CF = \frac{GCM_{corr}^{f}}{GCM_{corr}^{b}} \tag{7}$$

The future precipitation (R_G^f) is estimated as

$$R_G^f = R_G^b \cdot CF \tag{8}$$

where R_G^b is the generated baseline precipitation.

2.5 Results and Discussion

2.5.1 Precipitation Generation and Spatial Correlation

The comparison of statistics between historical and generated weekly precipitation data at Luang Prabang (key station) and Nong Khai (furthest station) is shown in Figure 2-4. The results show excellent agreement between the historical and generated mean of weekly precipitation data. The mean absolute error statistics of ten precipitation stations are shown in Table 2-3 and it confirms that the Markov chain generated series is similar to the observed series with low mean absolute relative errors. Although not shown here, a similar excellent agreement of mean weekly precipitation amounts was observed with remaining eight representative stations as well. It was also found that the standard deviations of generated weekly precipitation data are satisfactorily reproduced and the estimated weekly maximum absolute error is 25 mm among the ten stations. The areal mean annual precipitation estimated using the generated values is about 3% higher compared to the historical value of 1767.6 mm.

Since the multi-site discrete-space Markov chain included the dry state (as zero precipitation) conditional probabilities, it is important to compare the proportion of dry days for the historical period with the proportion of dry days of the generated precipitation series. Figure 2-5 shows these results of dry days (as 0 mm) at Luang Prabang and Nong Khai. It is noted that the discrete-time/space Markov chain was able to reproduce the historical precipitation patterns with exact proportions of dry weeks across all stations. At Luang Prabang, the average proportion of dry days during dry months (Jan-Apr and Nov-Dec) and wet months (May-Oct) for the historical observed period (1961-2000) are 0.58 and 0.07, respectively whereas for the generated 100 years period, the values are 0.57 and 0.05, respectively. The average proportion of dry days at Nong Khai during dry months and wet months for the historical observed period are 0.35 and 0.06, respectively whereas for the generated 100 years period it is 0.34 and 0.05, respectively. These statistics clearly shows that this conditional generation method was able to preserve the temporal and spatial correlation structures in terms of precipitation amounts as well as the proportion of dry days for the key station and the other representative stations.

2.5.2 Bias Correction

In most cases, the best fitted distribution is Gamma and in some cases, Weibull and log-normal distributions were best fitted. In this study, statistical bias-correction was performed for both CGCM3.1 T63 and ECHAM5. For the sake of demonstration, the results of CGCM3.1 T63 results are shown in Figure 2-6. It is noted that the mean monthly precipitation from raw GCM values are biased probably due to the difference in spatial scales of simulations whereas the observed precipitation distribution is influenced by region-specific climatic conditions. It can be stated that the standard deviations of historical and corrected GCM are similar and have improved compared to the raw GCM statistics. Figure 2-7 shows the coefficient of variation (CV) for the same results. It is seen that CV is similar between observed and corrected monthly precipitation amounts compared to the raw GCM amounts even if the means are different. Although not shown here, the index of agreement between the corrected GCM and historical values is close to 1 whereas there is poor agreement between the raw GCM and historical values. Figure 2-8 shows that the statistical bias-correction of raw GCM has reduced the monthly mean absolute errors at multi-sites for the baseline scenario (20C3M) from 1961 to 2000. These results indicate that the statistical bias-correction procedure is capable of preserving the historical statistics of precipitation.

Figure 2-9 shows the goodness-of-fit results for wet (June) and dry (January) months using the Kolmogorov-Smirnov (K-S) test. These results at Luang Prabang suggest that the difference between the two samples for observed versus bias corrected and observed versus raw GCM is not significant enough to state that they have different distributions at the 5% significance level. Even though the distributions are not statistically different in the wet month of June, the maximum difference between the curves (k values) are lowest between observed and corrected ($k = 0.09$) as opposed to observed and raw GCM ($k = 0.23$) (Figure 2-9a). But, the K-S test for dry month (January) suggests that the difference between the two samples for observed versus raw GCM are statistically significant to state that they are different distributions and the maximum difference between the curves is high ($k = 0.54$) compared to observed versus corrected ($k = 0.12$). Although not shown here similar results were observed at other representative stations too. This goodness of fit test results suggest that the bias corrected monthly precipitation amounts match better with the observed precipitation amounts and follows the same distribution for a given weather station.

The *IPCC Report* [2007b] states that the most appropriate method to assess the validity of a particular GCM is by examining the historical climatic conditions. The mean absolute errors were used to evaluate the relative accuracy of each GCM and RCM. As shown in Table 2-2, CGCM3.1 produced the lowest mean absolute error of 0.47 because it simulated both the total amount and the trend of areal monthly precipitation for the historical period with minimum error. ECHAM5 also showed a mean absolute error of 0.65 because of its relative good performance in simulating the trend. The RCM produced a highest mean absolute error of 87.43 indicating its relatively poor performance in simulating the trend compared to the corrected GCMs. Here, the bias correction procedure is not used on raw RCM data because the RCM used dynamical downscaling technique incorporating regional physical and atmospheric processes. A further discussion related to the RCM data will follow in the next sections.

2.5.3 Projected Future Precipitation Distributions

The CF of precipitation mean at each station was used to perturb the generated baseline scenario to project future precipitation. The results of the perturbed series are given as the percent changes of mean monthly precipitation from the historical observed period in Table 2-6 in Appendix. The results show that there is a greater variation of percent changes of mean monthly precipitation in the dry season (November to April) compared to the wet season (May to October) at every station. The maximum increase of 112.2% occurs at Station 4 (Banhinheup) in January whereas the maximum decrease of 88.3% occurs at Station 9 (Thangone) in December from 2051 to 2090. The maximum variation of 173% of mean monthly precipitation occurs between at Station 4 (Banhinheup) and Station 9 (Thangone) in January whereas the minimum variation of 44% of mean monthly precipitation occurs at Station 4 (Banhinheup) and Station 6 (Ban Thouei) in June from 2051 to 2090. Therefore, it clear that the highest variation of percent changes occur in the dry season and this change is highest in the latter 40 years of the century.

It is noted from Table 2-6 in Appendix that statistical bias-correction reduced the inter-model difference significantly. The maximum percent change between the two GCM projections is about 15% at Station 7 (Phonhong) in November from 2011 to 2050 whereas the minimum percent change difference between the two GCM projections is almost zero at Station 10 (Luang Prabang) in August from 2051 to 2090.

Table 2-4 shows the comparison of areal mean monthly precipitation amounts estimated using the historical observed, GCM bias corrected baseline scenario, and RCM control for the period from 1961 to 2000. The perturbed precipitation series for the 10 stations were spatially averaged for each GCM. As shown in Table 2-4, each GCM shows different increases but with less inter-model difference for both monthly and annual precipitation. Both models projected an increase in the total annual precipitation. The results show that CGCM3.1 produced an increase of total annual precipitation of 12% and 13%, and ECHAM5 produced a corresponding increase of 11% and 13% for the time periods of 2011-2050 and 2051-2090, respectively.

The seasonal variation of precipitation is important information where variation of streamflow can occur due to the changes in precipitation. Wet season precipitation contributes 76% whereas dry season precipitation contributes 24% to the mean annual precipitation from 1961 to 2000. Both CGCM and ECHAM projected that the wet season precipitation contributes 75% whereas the dry season precipitation contributes 25% to the mean annual precipitation from 2011 to 2050 while the wet season contributes 72% and the dry season contributes 28% from 2051 to 2090. These statistics indicate that during the latter half of the century there will be an increase in mean dry season precipitation compared to the first half of the century. Figure 2-10 shows the spread and variations of annual, seasonal, and means monthly precipitation for the baseline and A2 scenarios. Both future GCM projections show a minimum inter-model difference for annual and seasonal variations and show an increase in mean annual precipitation for both time periods. The wet season precipitation (Figure 2-10c) contributes significantly to the variation of mean annual precipitation (Figure 2-10a) from each GCM. It is noticed that precipitation is distributed in a wide range in the dry season for both GCMs compared to the historical precipitation. The median precipitations for both seasons have increased compared to the historical amounts. Figure 2-10b shows that the 25th percentile of dry season precipitation has decreased during 2051 to 2090 whereas it has increased in the wet season compared to the historical amounts.

Table 2-5 provides a quantitative comparison of statistics of projected areal precipitation for wet and dry seasons of the study area. The maximum and minimum percent change of mean annual precipitation is 14.7% and 8.7% for CGCM3.1 and ECHAM5 scenarios, respectively, from 2011 to 2050. Both GCM projections are in agreement to show that maximum and minimum mean annual precipitations will increase during the next 80 years and the maximum and minimum mean annual will significantly increase during the second half of the century.

The variability of seasonal variation of precipitation is useful in long-term planning and management as it can affect agricultural activities, hydropower generation, and ecosystem functions. Table 2-5 shows that the maximum precipitation in the wet season will increase about 14% from 2051 to 2090 and the minimum precipitation will decrease about 3% according to the CGCM3.1 projections. Similarly, the maximum precipitation in the dry season will increase about 38% from 2051 to 2090 and the minimum precipitation will decrease about 25% according to the CGCM3.1 projections. Therefore, fluctuation of extremes precipitation events are highest during the dry season compared to the wet season.

The spatial distribution of percent changes of projected mean annual precipitation is shown in Figure 2-11. Both GCMs projected an increasing trend of mean annual precipitation in the NNRB. The downscaled GCM mean annual precipitation shows that the northern and north eastern parts of the basin have the highest projected change of 14% to 17% in the next 80 years. The central region will have a change of 13 to 14% in mean annual precipitation. The lowest percent change of mean annual precipitation is projected in the southern and south western parts of the basin. As shown in Table 2-5, the percent change of mean annual precipitation is about 12% and 13% from 2011 to 2050 and from 2051 to 2090, respectively, according to both CGCM and ECHAM projections. These areal averages of mean annual precipitation estimated using the downscaled GCMs and spatial interpolated percentage change results are in good agreement for these future time periods. The increasing trend of mean annual precipitation could help to improve hydropower generation.

2.5.4 Comparison with the RCM

PRECIS uses a dynamical downscaling approach for a wide range of GCM scenarios for which the lateral boundary conditions (LBCs) have been included. The precipitation output from PRECIS was derived using the ECHAM4 LBCs as initial data for downscaling. As shown on Figure 2-12, the RCM model outputs underestimate the annual precipitation amounts at the selected 10 stations across all 40 years. The observed and total annual precipitations of PRECIS were compared to minimize the random effects. It is clear from Figure 2-12 that the PRECIS results cannot be directly used for climate change impact studies even though the outputs are available at much finer spatial scales. Also, the PRECIS results at monthly time scale produces relatively higher mean absolute errors compared to bias-corrected ECHAM5 results (Figure 2-13). Despite this discrepancy from PRECIS, Figure 2-13 provides a comparative insight of bias correction of GCMs for the study of climate change. The results clearly show that the mean absolute error is highest during the wet season in most stations. The results of this work shows that results from RCMs may not be directly applicable at the regional-scale and may need bias correction. This comparison also shows that GCMs projections can be used after bias correction that produce minimal mean absolute errors especially during the wet season.

2.6 Summary and Conclusions

The focus of this study is to develop an appropriate methodology to project future precipitation under climate change with limited data for rural river basins while preserving the historical temporal and spatial characteristics. The NNRB located in the Mekong River Basin was selected to demonstrate the applicability of the methodology where rain-fed agriculture and hydropower generation are priority economic activities.

Ten stations from 40 available weather stations were selected to represent the temporal and spatial characteristics of precipitation using a non-parametric bootstrapping technique. Missing precipitation data for the ten selected stations were filled using the coefficient of correlation weighting method to maintain a complete data record of 40 years which is similar to the temporal domain of the IPCC AR4 baseline scenario from 1961 to 2000.

The proposed methodology simulated weekly precipitation non-occurrence (dry state) and occurrence (wet state) at ten selected locations by preserving the historical temporal and spatial correlation structures using a discrete-time/space Markov chain based on conditional probabilities. At each location, the stochastically generated weekly precipitation series which consists of dry states and wet states were aggregated to monthly temporal scale. GCM precipitation bias at each station was corrected by transforming the coarse scale precipitation distribution to the region specific precipitation distribution. The bias-correction was performed by fitting statistical distributions to GCM and regional scale (observed or generated) monthly precipitation amounts. The main assumptions are (a) the historical temporal and spatial correlation structures remain unchanged, and (b) the location specific regional climatic conditions are representative of its precipitation distributions.

The bias correction approach reduced the error of mean monthly precipitation of raw GCM precipitation amounts at ten selected stations hence reduced the inter-model differences and spatial heterogeneity of precipitation CFs of GCMs. The CFs estimated using the corrected GCM scenarios were perturbed to generate 100 years precipitation amounts. Both GCMs, ECHAM and CGCM, projected an increase in the mean annual precipitation in the next 80 years. The highest percent changes of mean annual precipitation are about 13% from both CGCM and ECHAM for 2051 through 2090 whereas 12% and 11% from CGCM and ECHAM for 2011 through 2050, respectively. The results showed a highest precipitation increase in the dry season amounts to 31% from 2051 to 2090. The spatial distribution of projected mean annual precipitation showed a significant increase in the north eastern part of the study area. The RCM, PRECIS, provides precipitation projections from 2011 to 2050 while precipitation from 2051 to 2090 is not available. The spatial distribution of mean annual precipitation projected from 2011 to 2050 using PRECIS showed the highest annual precipitation amounts in the south eastern part of the basin. A comparison of RCM areal mean annual precipitation estimates for the baseline scenario and for A2 scenario from 2011 to 2050 showed that there will be only 0.7% increase. Compared to this 0.7% increase of areal mean precipitation, the bias corrected CGCM and ECHAM precipitation estimates showed 12% and 11% increase, respectively for the same time period.

It is a challenging task to assess the impacts of climate change in rural river basins where data and hydrologic information are limited. In the presence of these limitations, this study was able to use available data and information and demonstrate the applicability of the proposed methodology that projects reliable future precipitation patterns assuming that the historical correlation structure is preserved. In situations where climate models show noticeable bias in reproducing regional climate for the historical period, their capacity to represent future may be questionable. This study focused on bias-correction of raw GCM outputs even though the RCM outputs are available at much finer spatial scale. The methodology proposed in this study was able to minimize bias in reproducing regional climate for the historical (or baseline scenario) period. The estimated future precipitation amounts produced in this study can be easily used to investigate regional impacts due to climate change. The main advantage of the bias-correction approach compared to regional climate model outputs is the possibility to compare multiple GCMs due to reduced inter-model differences of raw GCM outputs for baseline conditions and for future emission scenarios.

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Table 2-1. Correlation coefficient matrix of the 10 representative stations for the historical period (lower triangle) and generated weekly precipitation (upper triangle).

Station	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1	1.00	0.94	0.80	0.92	0.95	0.94	0.81	0.93	0.82	0.80
2	0.98	1.00	0.78	0.94	0.97	0.94	0.77	0.90	0.79	0.73
3	0.82	0.81	1.00	0.80	0.77	0.85	0.71	0.83	0.65	0.75
4	0.93	0.96	0.82	1.00	0.95	0.93	0.81	0.90	0.78	0.75
5	0.95	0.97	0.81	0.96	1.00	0.93	0.80	0.90	0.80	0.74
6	0.93	0.94	0.88	0.94	0.94	1.00	0.79	0.91	0.78	0.78
7	0.84	0.82	0.73	0.83	0.81	0.81	1.00	0.79	0.97	0.92
8	0.92	0.91	0.90	0.90	0.91	0.94	0.80	1.00	0.78	0.82
9	0.83	0.81	0.69	0.82	0.82	0.80	0.98	0.78	1.00	0.90
10	0.78	0.75	0.77	0.77	0.76	0.79	0.95	0.82	0.93	1.00

Table 2-2. Description of the selected GCMs and PRECIS.

GCM/RCM[1]	**Spatial Resolution**[2]	**Number of Grids**[3]	**Mean Absolute Error**[4]
CGCM3.1_T63	2.79, 2.81	6	0.47
ECHAM5	1.865, 1.875	9	0.65
PRECIS	0.2, 0.2	108	81.43

[1] From the IPCC DDC. CCCMA_CGCM3.1_T63, Canadian Centre for Climate Modeling and Analysis (Third generation), ECHAM5, European Center Hamburg Model (5th generation), PRECIS_RCM, Providing REgional Climates for Impacts Studies, Regional Climate Model

[2] Mean resolution of GCMs and RCM in latitudinal and longitudinal degrees

[3] Number of grids covering the NNRB

[4] Computed using areal monthly precipitation absolute error of each GCM obtained for its baseline scenario (from 1961 to 2000) compared to the historical observed value

Table 2-3. Mean absolute relative error statistics from the Markov Chain process.

Site	**Mean**	**STD**[1]	**CV**[2]	**SK**[3]	**Range**
Ban Hinheup	0.15	0.10	0.10	0.23	0.08
Ban Nasone	0.13	0.11	0.11	0.38	0.10
Ban Thouei	0.17	0.11	0.10	0.24	0.07
Nong Khai	0.16	0.11	0.11	0.19	0.08
Phonhong	0.15	0.10	0.11	0.22	0.09
Sengkhalok	0.15	0.10	0.10	0.17	0.09
Thangone	0.19	0.11	0.13	0.20	0.08
Vientiane	0.13	0.09	0.10	0.22	0.08
Xiengkhouang	0.15	0.10	0.09	0.19	0.10
Luang Prabang	0.14	0.10	0.11	0.17	0.09

[1] STD: standard deviation

[2] CV: coefficient of variation

[3] SK: skewness coefficient

Table 2-4. Comparison of historical and generated areal mean monthly precipitation (in mm). The values in parentheses are percent changes from the baseline scenario.

Month	Historical (1961-2000)	RCM (1961-2000)	CGCM3.1			ECHAM5		
			20C3M Baseline Scenario	A2 2011-2050	A2 2051-2090	20C3M Baseline Scenario	A2 2011-2050	A2 2051-2090
January	53.9	4.1	53.9	57.2 (6)	82.0 (52)	53.7	57.8 (8)	82.4 (53)
February	53.8	6.4	53.8	64.2 (19)	65.7 (22)	53.6	63.9 (19)	66.0 (23)
March	75.3	18.1	75.3	79.0 (5)	88.8 (18)	76.0	78.3 (3)	89.2 (17)
April	117.7	55.1	117.5	145.5 (24)	148.9 (27)	119.7	144.2 (20)	144.7 (21)
May	226.2	132.1	225.8	269.8 (20)	233.9 (4)	226.5	268.8 (19)	234.3 (3)
June	257.5	322.6	257.2	264.4 (3)	252.2 (-2)	257.3	264.6 (3)	251.4 (-2)
July	259.2	314.1	258.9	266.0 (3)	299.5 (16)	258.9	266.7 (3)	299.7 (16)
August	283.9	277.6	283.7	326.4 (15)	284.7 (0)	283.8	326.0 (15)	284.8 (0)
September	194.0	146.1	192.9	211.0 (9)	226.8 (18)	195.1	207.5 (6)	225.4 (16)
October	98.8	36.9	98.9	110.5 (12)	123.4 (25)	98.9	109.9 (11)	123.5 (25)
November	57.2	7.5	57.0	85.1 (49)	93.3 (64)	55.9	87.3 (56)	95.9 (71)
December	54.4	2.2	54.4	56.6 (4)	60.5 (11)	54.1	57.3 (6)	60.7 (12)
Annual	1732.1	1322.8	1729.1	1935.8 (12)	1959.7 (13)	1733.7	1932.4 (11)	1957.9 (13)

Table 2-5. Percent changes of projected areal precipitation and historical precipitation.

Season	**Statistic**	**CGCM3.1**		**ECHAM5**	
		2011-2050	**2051-2090**	**2011-2050**	**2051-2090**
Annual	Max	14.7	12.0	9.6	11.9
	Mean	11.8	13.1	11.6	13.0
	Min	19.4	22.3	8.7	15.4
Wet	Max	9.1	13.8	8.8	14.0
	Mean	9.7	7.6	9.4	7.5
	Min	1.1	-2.8	0.4	-3.0
Dry	Max	23.3	38.0	22.2	37.9
	Mean	18.2	30.7	18.5	30.6
	Min	-1.6	-25.5	-1.4	-25.5

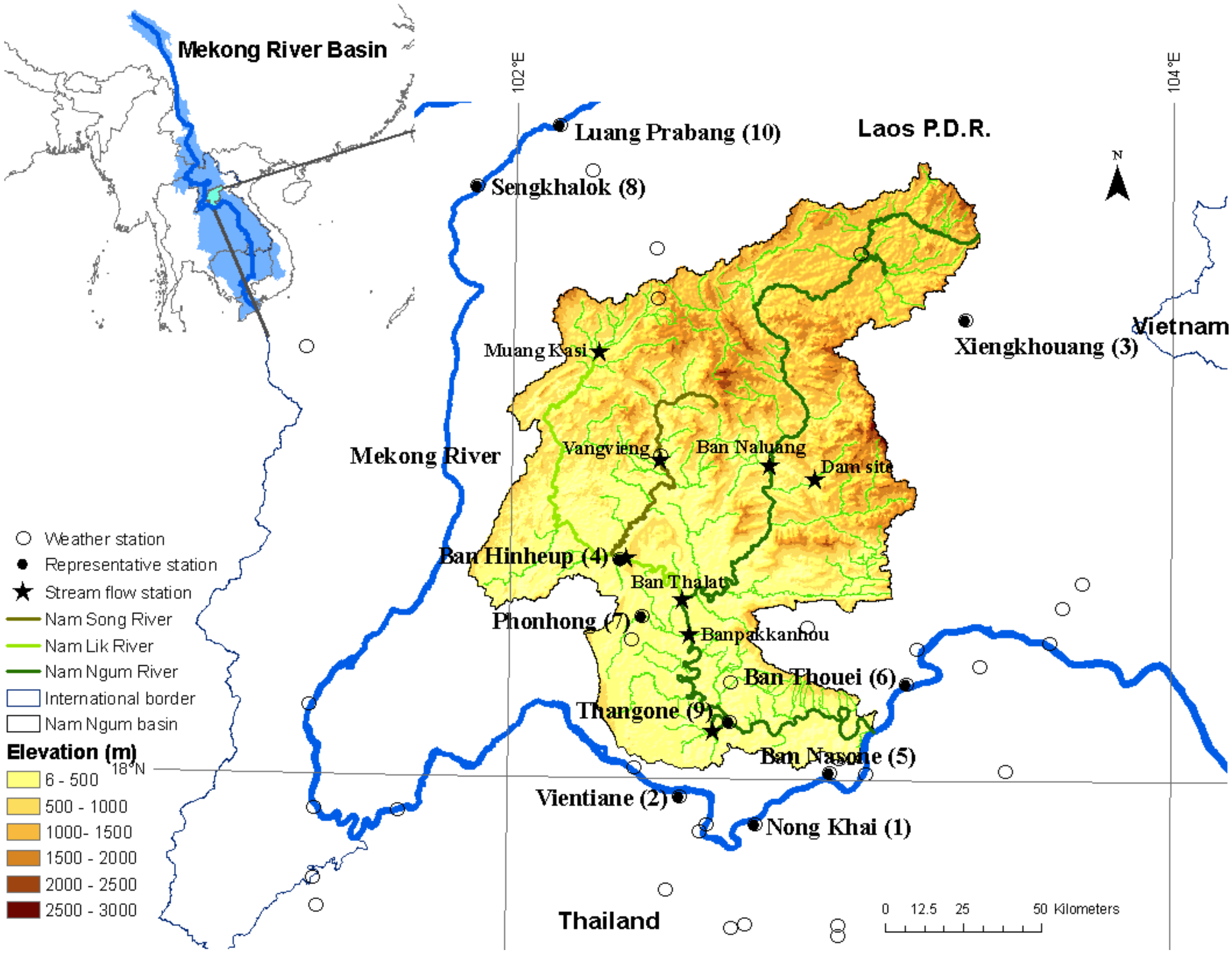

Figure 2-1. Layout of the Nam Ngum River Basin in Laos. The number following the station name indicate the ten representative stations used in the analysis while all 40 weather stations are shown in blank circles.

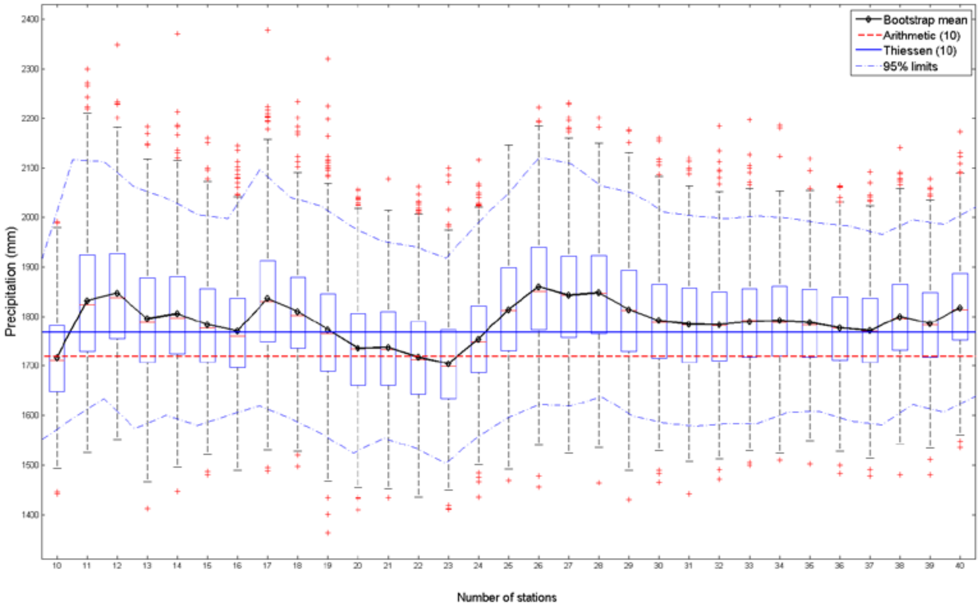

Figure 2-2. Box plots showing the estimated mean annual precipitation using different number of stations by the bootstrap method.

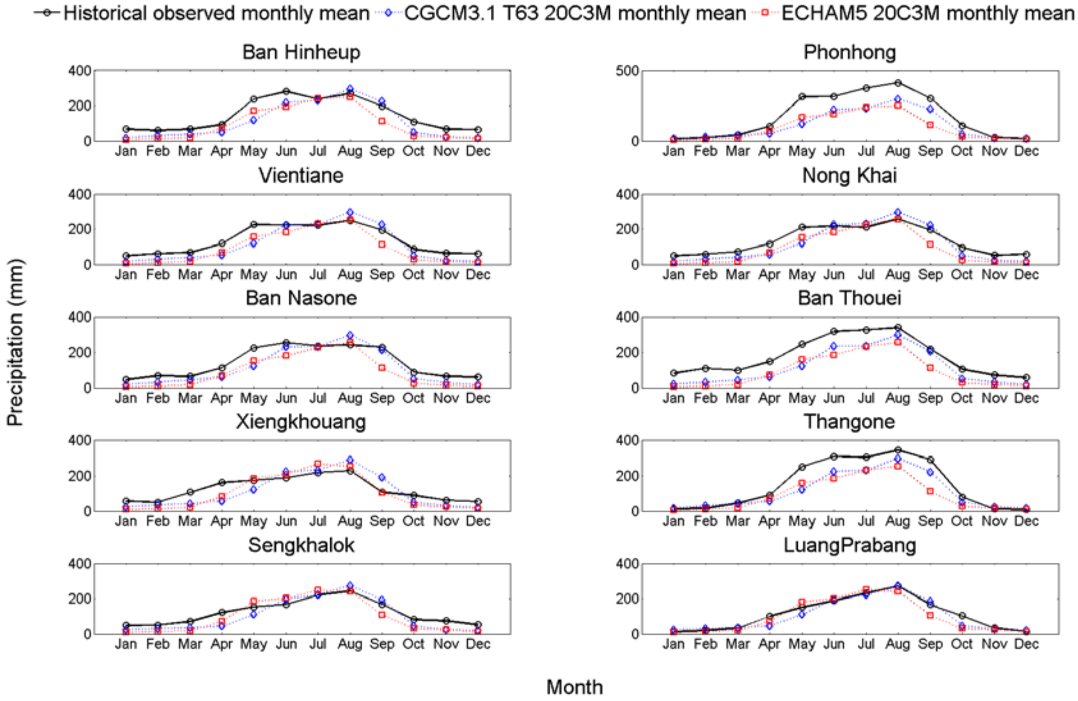

Figure 2-3. Comparison of raw GCM mean monthly precipitation for the baseline scenario (20C3M) with historical observed for the 40 year period from 1961 to 2000.

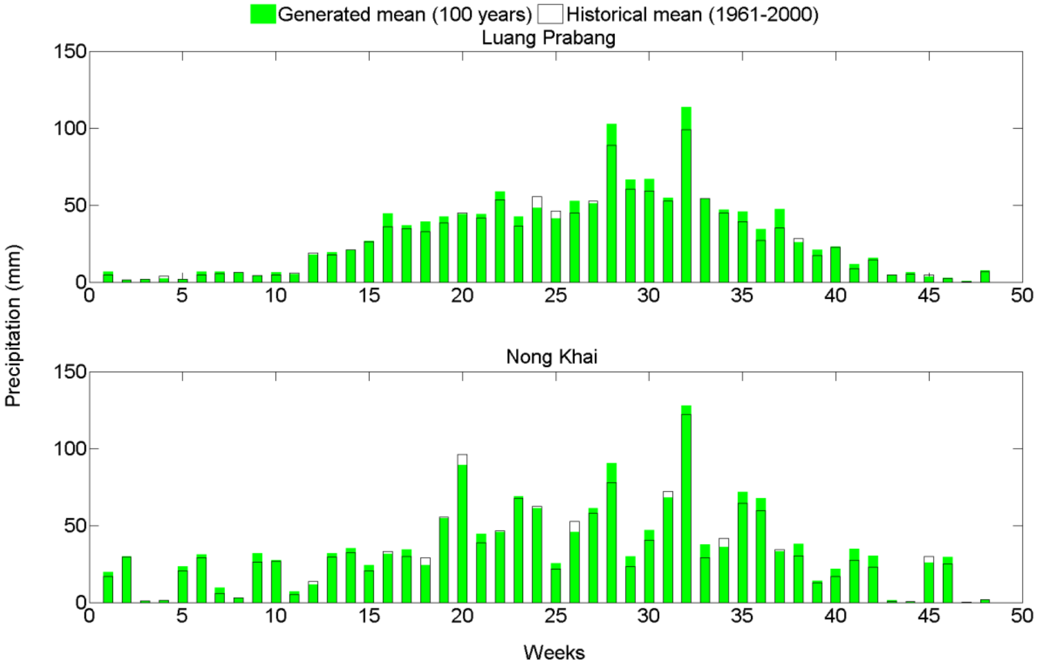

Figure 2-4. Comparison of mean historical and generated precipitation series. Blank and shaded bar graphs represent the mean of historical observed and generated values, respectively.

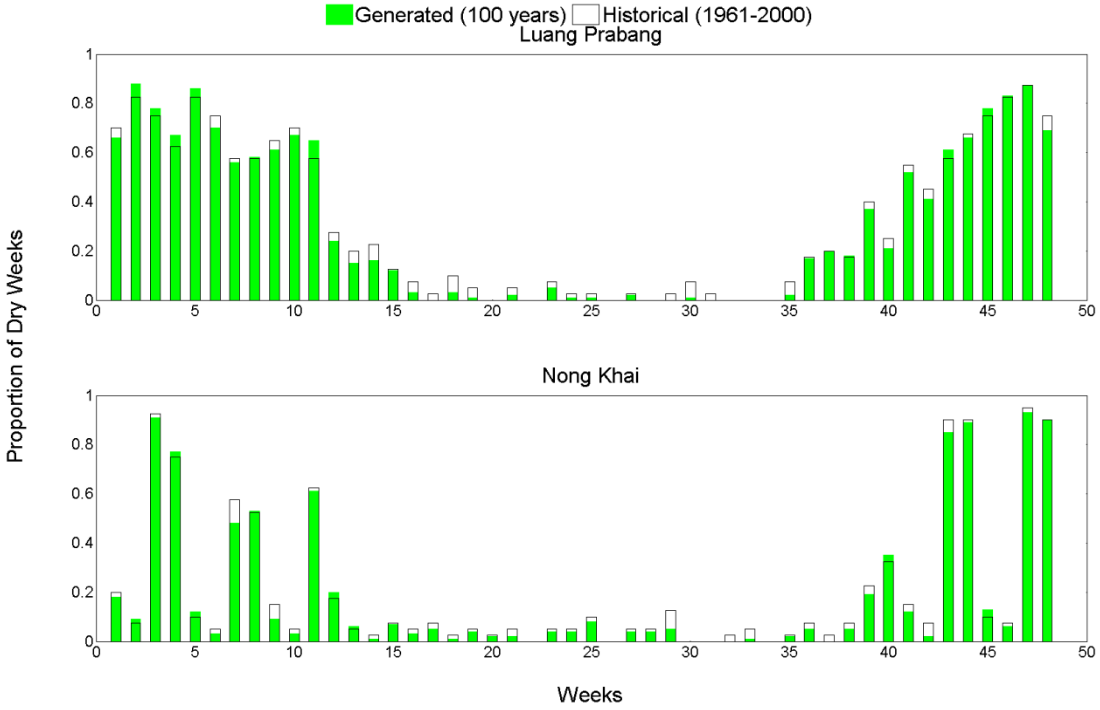

Figure 2-5. Comparison of historical and generated proportion of dry days.

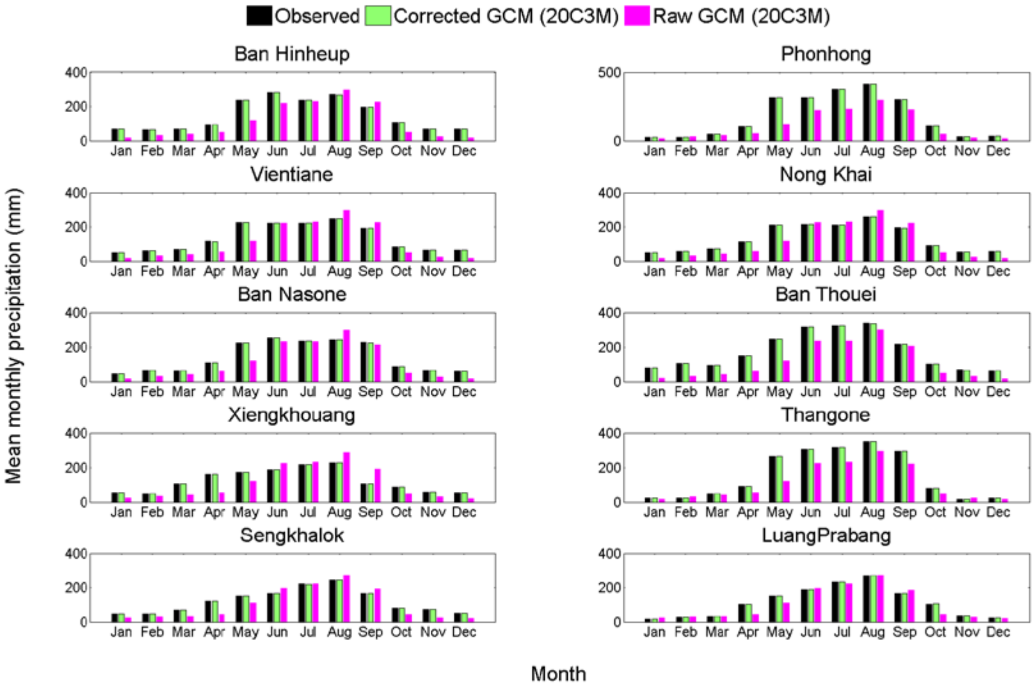

Figure 2-6. Comparison of observed, corrected, and raw GCM mean monthly precipitation for the baseline scenario (20C3M) from 1961 to 2000.

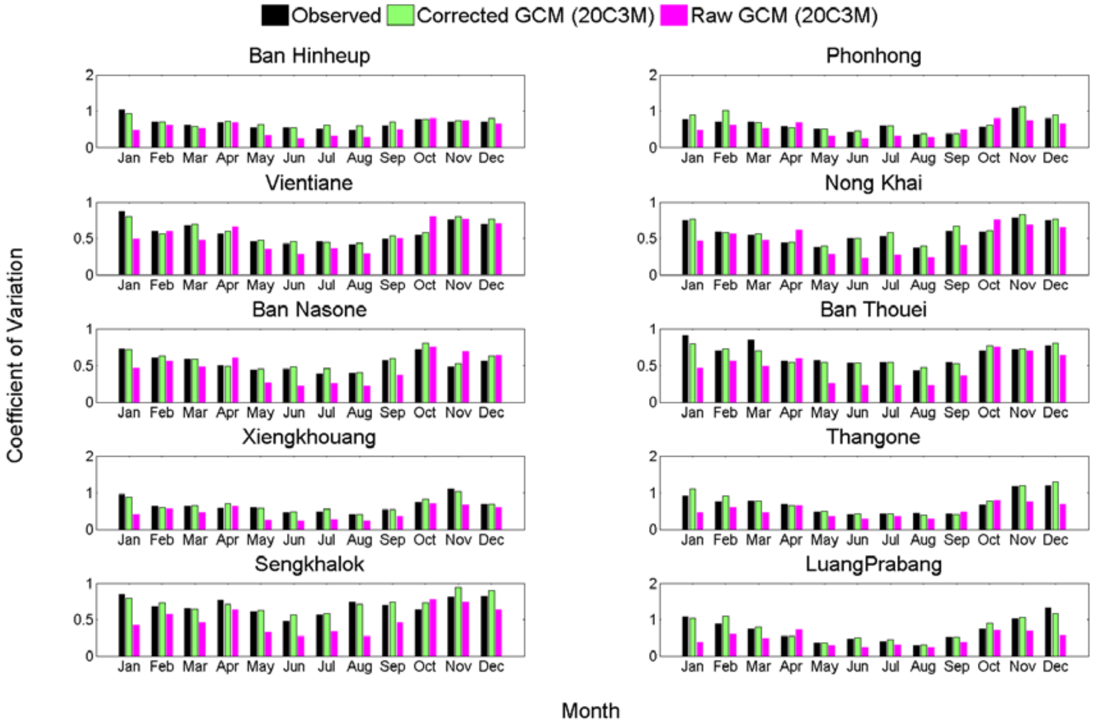

Figure 2-7. Comparison of coefficient of variation for observed, corrected, and raw GCM results of monthly precipitation for the baseline scenario (20C3M) from 1961 to 2000.

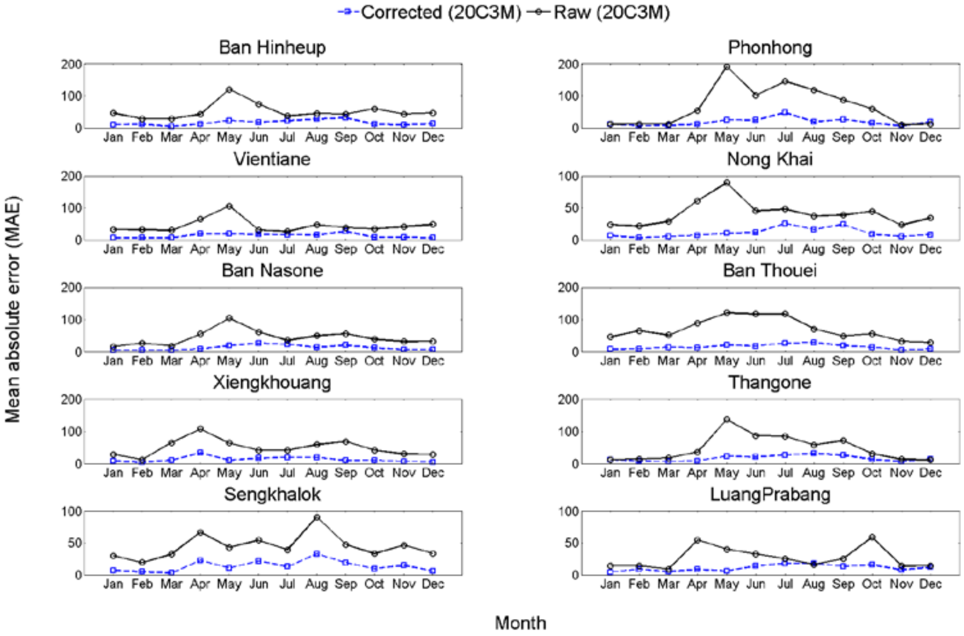

Figure 2-8. Comparison of monthly mean absolute error for the baseline scenario (20C3M) from 1961 to 2000.

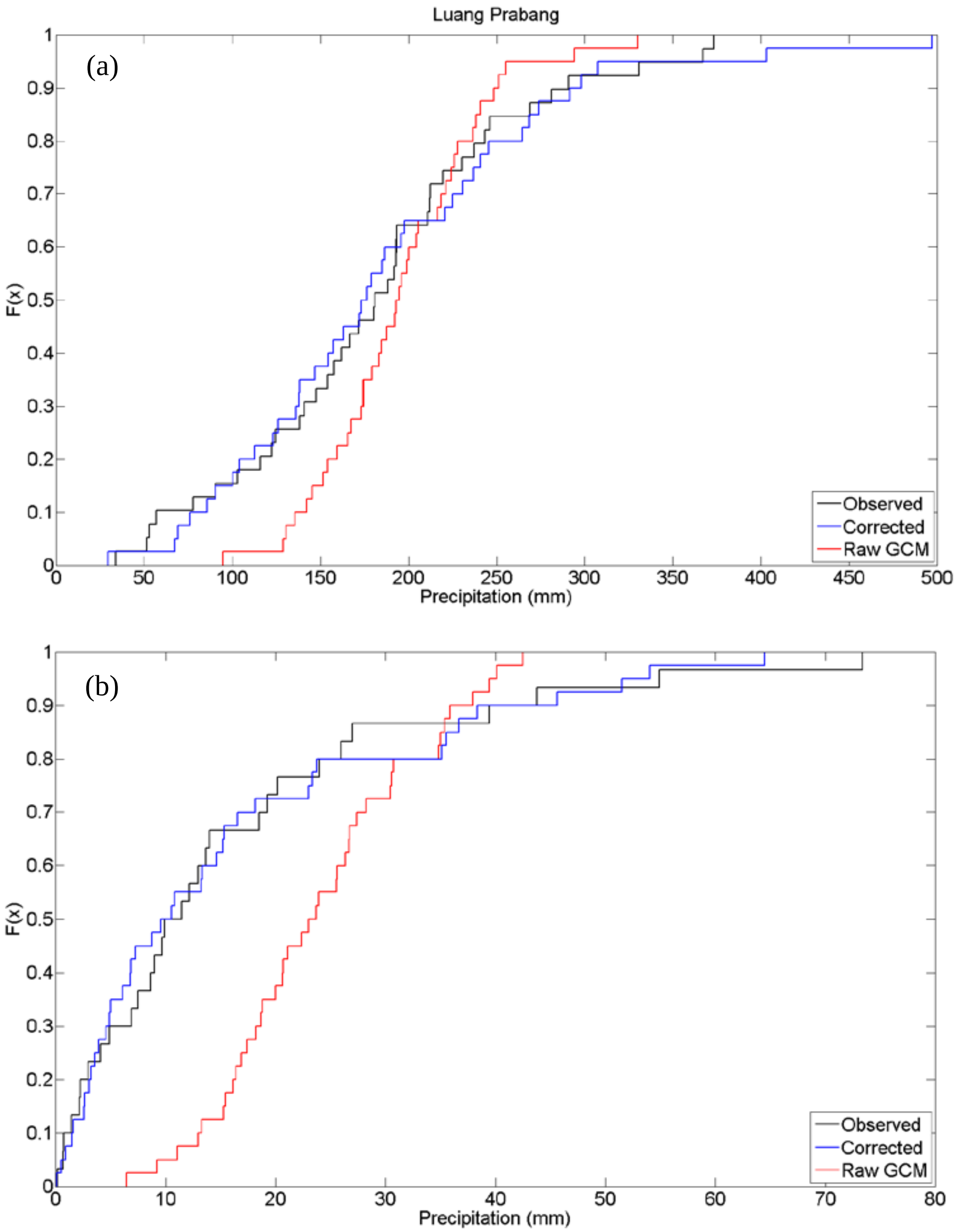

Figure 2-9. Comparison of results of goodness-of-fit (K-S) test for Luang Prabang (key station): (a) wet month (June), (b) dry month (January)

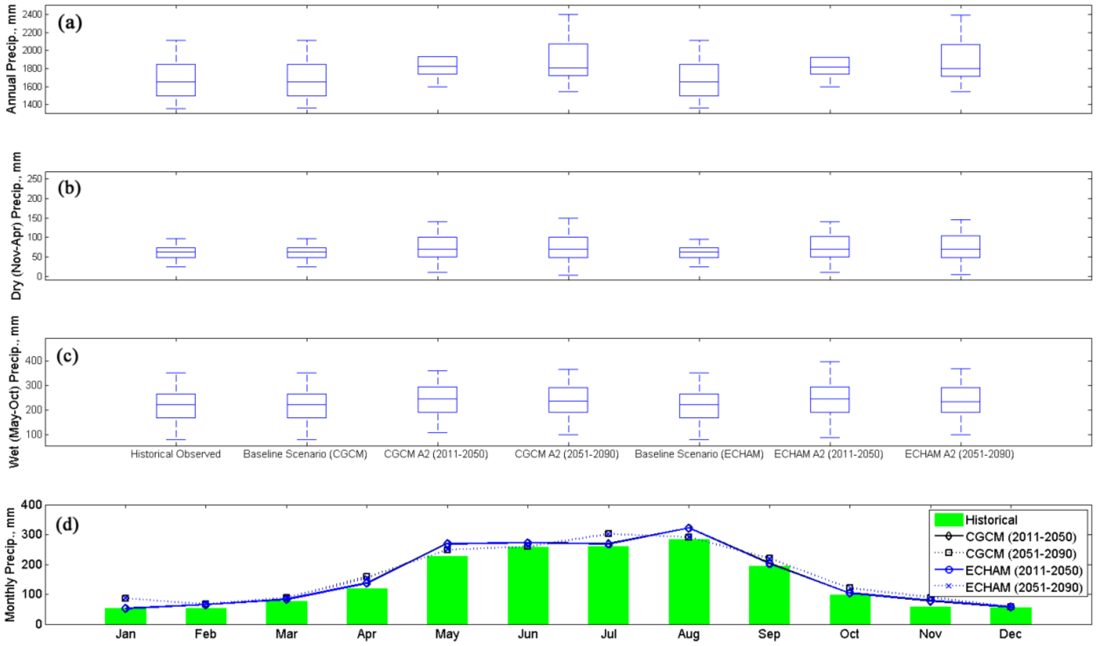

Figure 2-10. Box plot comparison of temporal characteristics of historical and projected precipitation from 2011 to 2090: (a) mean annual, (b) dry season, (c) wet season, and (d) mean monthly precipitation.

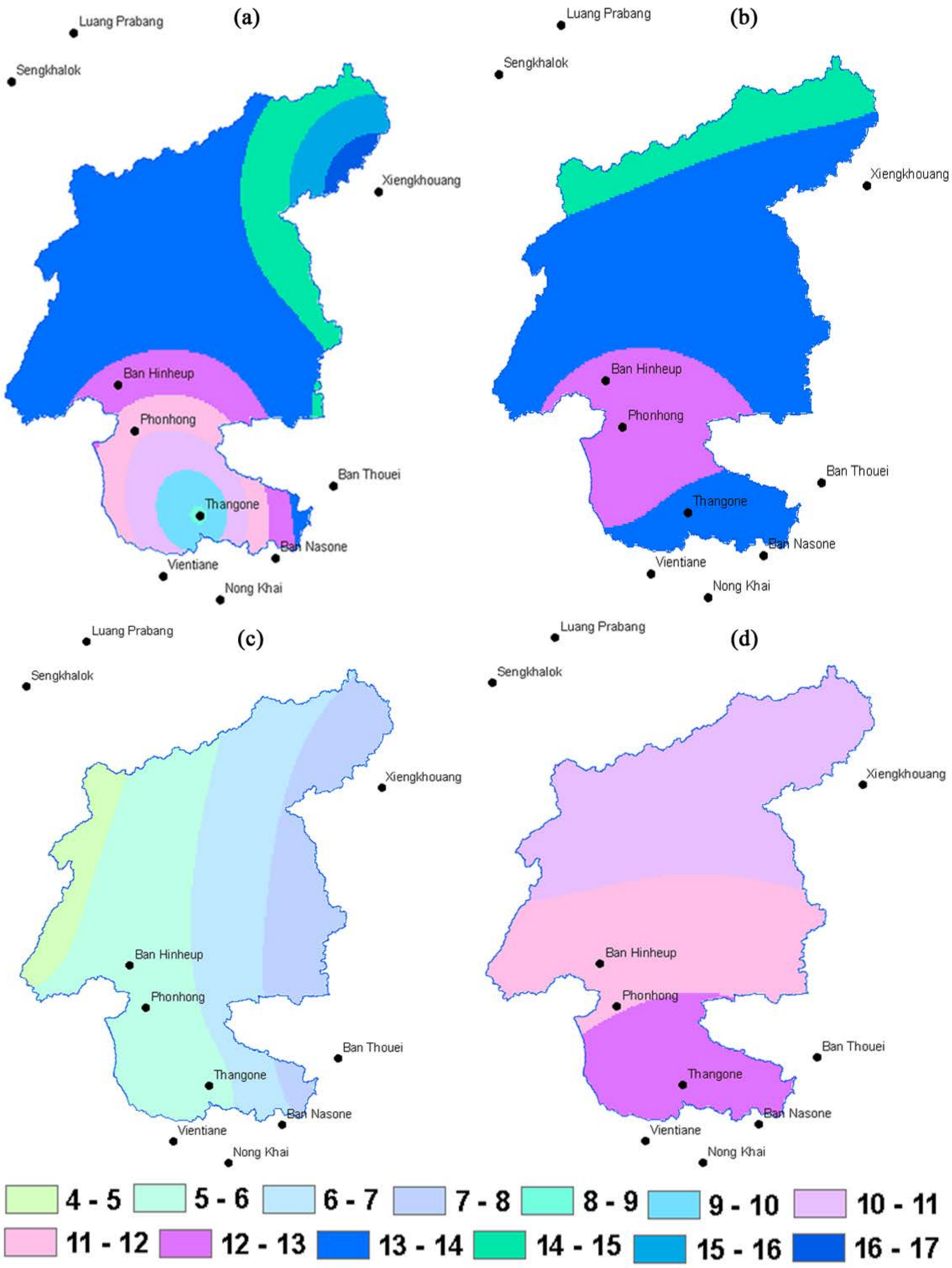

Figure 2-11. Spatial distributions of percent changes in mean annual precipitation from 2011 to 2090: (a) CGCM (2011-2050), (b) CGCM (2051-2090), (c) ECHAM (2011-2050), and (d) ECHAM (2051-2090).

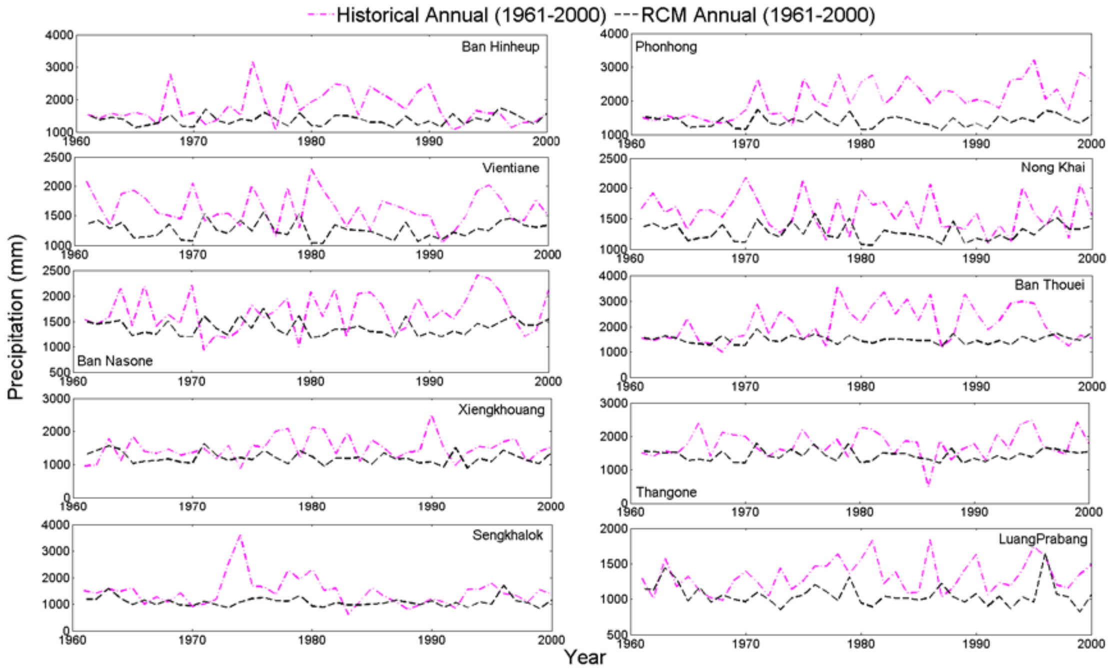

Figure 2-12. Comparison of time series of annual precipitation between the Regional Climate Model outputs and historical data from 1961 to 2000.

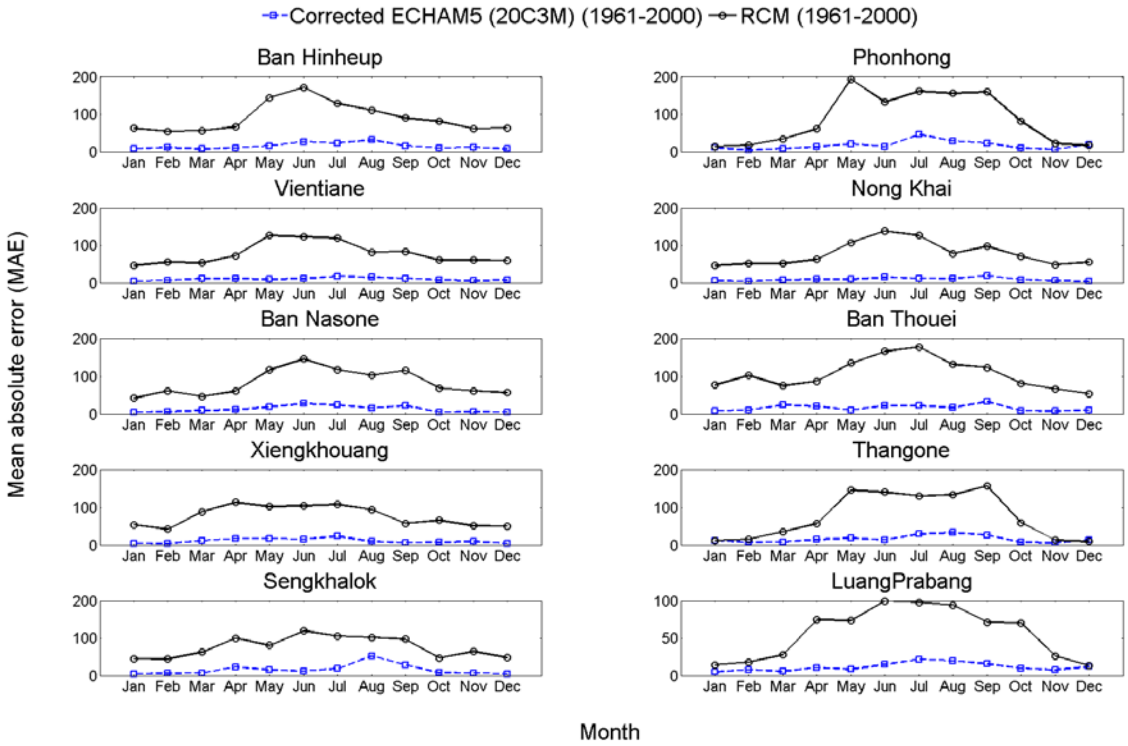

Figure 2-13. Comparison of MAE of the RCM and corrected ECHAM outputs at ten selected stations from 1961 to 2000.

APPENDIX

Table 2-6. Computed percent changes of downscaled mean monthly precipitations for the 10 selected stations from 2011 to 2090.

Station	**Period**	**GCM**	**Month**											
			Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1	2011-2050	CGCM	1.1	33.7	21.2	-7.0	-17.6	18.6	12.9	14.3	28.9	17.6	43.9	-14.6
		ECHAM	1.4	30.0	21.3	-7.4	-17.7	18.5	13.7	13.9	26.1	16.9	43.5	-14.3
	2051-2090	CGCM	10.8	30.6	4.6	27.8	-14.7	-2.4	9.2	16.7	-1.7	38.6	104.8	0.2
		ECHAM	11.5	29.0	3.8	24.0	-14.5	-1.6	9.0	16.7	-3.4	38.1	105.5	-0.1
2	2011-2050	CGCM	43.1	23.5	49.6	47.2	13.6	-10.8	-3.1	-1.3	36.2	12.2	-7.6	6.1
		ECHAM	33.9	24.2	48.2	45.4	13.6	-10.8	-3.3	-1.3	35.2	11.4	-4.7	6.4
	2051-2090	CGCM	38.0	5.0	39.0	3.7	-21.1	6.5	-24.2	-27.0	25.4	3.1	1.6	-7.2
		ECHAM	39.2	5.4	37.3	1.0	-21.0	5.2	-24.0	-27.0	24.7	3.0	3.5	-6.8
3	2011-2050	CGCM	-0.2	46.0	14.2	3.2	41.2	12.6	7.0	14.8	21.2	-0.5	66.1	37.2
		ECHAM	3.7	47.4	13.2	2.3	40.5	12.3	7.7	14.6	16.3	-0.9	75.5	39.2
	2051-2090	CGCM	3.6	24.0	24.9	44.8	1.8	11.9	24.7	-19.6	37.8	-17.3	80.8	26.9
		ECHAM	5.0	25.0	29.0	40.6	1.8	11.4	24.8	-19.4	36.6	-17.5	93.7	26.5
4	2011-2050	CGCM	12.5	5.5	-11.1	64.5	6.8	-3.6	13.6	22.8	4.1	12.3	55.2	-20.3
		ECHAM	12.1	3.7	-11.3	63.7	6.4	-3.3	14.3	22.7	2.5	11.7	54.6	-19.3
	2051-2090	CGCM	111.8	38.7	1.2	32.1	3.1	-20.5	13.9	3.6	12.3	48.0	82.4	19.8
		ECHAM	112.2	39.6	-0.3	28.1	3.2	-20.4	14.0	3.6	11.0	48.4	83.2	20.5
5	2011-2050	CGCM	33.3	17.1	-0.9	13.7	22.1	23.4	-0.2	9.5	10.3	49.4	15.7	7.5
		ECHAM	33.5	14.2	-0.3	12.5	22.4	23.3	0.4	9.0	7.6	48.6	15.5	7.2
	2051-2090	CGCM	3.1	-1.2	16.3	-11.6	26.2	-3.7	5.6	30.1	-13.6	1.3	30.3	14.0
		ECHAM	3.4	-3.7	15.3	-14.5	26.5	-3.3	5.7	30.1	-14.1	1.5	30.2	13.9
6	2011-2050	CGCM	12.0	25.8	24.9	27.4	28.2	-3.3	2.9	-1.3	42.4	20.1	20.5	42.3
		ECHAM	12.6	24.0	25.4	24.2	27.6	-3.3	2.7	-1.4	39.9	19.1	23.2	43.9
	2051-2090	CGCM	40.8	2.1	25.3	17.8	0.1	24.3	12.6	4.8	14.1	55.1	-12.0	5.1
		ECHAM	41.4	2.1	23.4	14.6	1.0	24.4	13.0	5.0	13.3	55.0	-10.3	5.7
7	2011-2050	CGCM	-42.0	-5.2	3.6	-13.3	15.0	10.2	-10.0	15.2	11.1	28.5	17.3	6.6
		ECHAM	-42.3	-3.1	-2.7	-14.1	14.6	10.3	-11.1	15.1	10.4	27.2	32.6	8.0
	2051-2090	CGCM	-32.8	-33.1	30.6	-6.4	-4.1	8.0	22.7	-0.3	12.1	8.7	2.2	-25.0
		ECHAM	-32.8	-31.5	28.5	-8.8	-4.0	6.2	22.6	-0.4	11.6	8.5	7.7	-24.2
8	2011-2050	CGCM	45.5	19.7	4.8	18.1	26.1	-5.8	-13.3	18.8	22.0	1.0	36.9	23.5
		ECHAM	52.9	18.2	5.5	16.9	25.1	-6.1	-13.4	18.4	20.6	0.7	39.9	23.7
	2051-2090	CGCM	-36.2	-9.6	-0.1	28.5	23.2	6.0	-9.7	25.8	19.2	81.8	39.0	-2.4
		ECHAM	-37.0	-9.3	0.0	25.4	22.7	5.5	-9.7	26.5	19.1	82.0	40.0	-1.4
9	2011-2050	CGCM	-32.7	18.8	-4.7	8.7	27.2	2.1	-22.3	-3.3	-22.0	3.1	3.2	-34.4
		ECHAM	-32.1	20.1	-4.1	7.9	27.3	2.2	-21.7	-3.4	-22.3	2.3	11.2	-33.9
	2051-2090	CGCM	-61.2	20.9	61.1	-19.9	10.6	3.9	6.7	10.1	19.5	25.7	62.9	-88.3
		ECHAM	-60.7	19.4	58.8	-22.1	10.9	3.8	6.9	9.9	20.5	25.7	72.2	-88.1
10	2011-2050	CGCM	15.8	28.9	17.6	10.0	2.8	2.4	17.8	37.0	19.5	10.8	43.4	12.6
		ECHAM	25.7	29.6	15.1	9.0	2.5	2.3	18.2	36.9	18.5	10.8	46.5	14.1
	2051-2090	CGCM	-24.2	-0.2	-36.7	36.7	30.1	20.8	13.3	27.0	24.3	20.9	5.2	-52.6
		ECHAM	-23.3	2.6	-37.3	33.5	30.5	20.8	12.9	27.0	24.3	21.2	-4.9	-51.0

CHAPTER 3

WATER AVAILABILITY AND ALLOCATION CHALLENGES IN THE NAM NGUM RIVER BASIN OF LAOS UNDER CLIMATE CHANGE [1]

Abstract

The Nam Ngum River Basin (NNRB) located in Laos has a high hydropower generation capacity of which less than 3% is currently developed. Given the need to assess the future development of hydropower in the presence of challenges such as population growth, land use changes, and climate change, a suitable basin scale model is required. Climate change may alter the performance of water supply systems and water availability at water demand sites due to rapid hydropower developments. The evaluation to which water demand sectors (i.e. agriculture, domestic and hydropower) need to be given water allocation priority and the water availability to meet the agricultural and domestic water demands under rapid hydropower developments is becoming more important for long-term planning in developing regions. The integrated water resources management framework is developed within WEAP21 modeling environment that is capable of analyzing rainfall-runoff relationships and trade-offs between water allocation and sustainable water availability for agriculture and domestic water user sectors under different priority scenarios. Model calibration and validation was conducted successfully from 1991 to 1998. Hydrological processes and water infrastructure operations were modeled for historical and projected climatic conditions using the A2 emission scenario of CGCM3.1 T63 data.

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The results indicated that the NNRB is affected by climate change and the impacts will be higher during the latter part of the 21st century. Sustainability index, a quantitative estimation of degree to which a priority action or policy contributes to a sustainable improvement in meeting water demands at each water users, is calculated to identify areas of water users of potential improvement and regions at risk of water shortages Under the status-quo ("do nothing") condition, the average dry season and annual streamflows at the basin outlet are significantly reduced. The agricultural sector is affected due to low sustainability while hydropower generation is increased under the equal priority water allocation scenario.

This research provides an insight to the sustainability impacts on climate change and sustainability of water resources on a rural river basin such as the NNRB where hydropower generation is crucial.

3.1 Introduction

Climate change is anticipated to affect rainfall and temperature patterns and consequently water availability, streamflows, and seasonal availability of water supply [*Arnell et al.*, 2011]. Demand for freshwater increases due to variety of factors including population growth, economic growth, water quality concerns, land use changes, and climate change render its availability into the future uncertain [*Davies and Simonovic,* 2011]. South East Asia (SEA) is considered one of the world's most vulnerable regions to the impacts of climate change [*Zuang et al.,* 2010]. The region has a population of about 563 million with an average annual population growth of about 2% compared to the 1.4% global average. SEA has an annual average urban population growth of 3.5% compared to 2.6% and 2.1% in developing areas of Asia and globally, respectively [*World Bank,* 2008]. The Intergovernmental Panel on Climate Change [*IPCC,* 2007] reported an increasing trend in mean surface air temperature of SEA during the past several decades, with 0.1 to 0.3°C increase per decade recorded between 1951 and 2000. Rainfall is trending downwards and the frequency of extreme weather events is increasing. Heavy rainfall events rose significantly from 1900 to 2005 [*IPCC,* 2007]. These climatic changes have led to damaging floods, landslides, and droughts in many parts of the SEA region. Climate change is also exacerbating water shortages in many areas, constraining agricultural production and threatening food security [*ADB,* 2009].

Climate change may alter the reliability of water supply systems via direct impacts on hydrology and source supplies. Water provider's fundamental mission is at least to provide reliable supply of water. Therefore, evaluation of climate change scenarios is becoming more important for long-term planning. The planning of water resources systems requires a multi-disciplinary approach because water management is often influenced by a set of interconnected physical, biological, and socioeconomic drivers that include climate, land use, soils, water quality, ecosystems, demographics, institutional arrangements, and infrastructure [*Bouwer,* 2000; *Zalewski,* 2002]. Factors related to the socio-economic management system are driven largely by human demand and operations and management for water, such as how water is stored, allocated, and delivered within or across watershed or basin boundaries. Therefore, it is necessary to develop a good understanding of how a natural hydrologic system behaves prior to any hydrologic manipulations [*Muttiah and Wurbs,* 2002]. This type of analysis relies on the use of hydrologic modeling tools that simulate physical processes such as rainfall, evapotranspiration, runoff, and infiltration. To analyze the effect of water infrastructure operations, it should also be considered the construction of hydraulic structures, such as dams and diversions, and their management. The purpose of an integrated water allocation and priority management framework of this study is to govern the allocation of water between competing demands, namely the consumptive demand for agricultural or domestic water supply or the non-consumptive demand for hydropower generation or ecosystem protection.

In the context of water resources systems planning and management, integrated water resources management has received significant attention due to the growing pressures and competing demands in water resources systems caused by growing population and socio-economic developments [*Loucks*, 1995; *GWP-TEC*, 2000]. The Technical Advisory Committee of Global Water Partnership [*GWP-TEC*, 2000] defines IWRM as a “process which promotes the coordinated development and management of water, land, and related resources, in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems.”

The Mekong Region of SEA is a region consisting of mostly developing countries and its rapid development over the past 20 years has contributed to Asian economic growth [*ADB-GMS*, 2010]. Recently published reports [e.g., *Eastham et al.*, 2008, *ADB*, 2009*; TKK* and *SEA START RC*, 2009] show a growing international concern about the potential impacts of climate change in this region, which is highly dependent on agriculture and fisheries for food security and income generation. Moreover, a good review of research studies conducted on hydrology and water resources of the Mekong River Basin is provided by *Takeuchi* [2008] and *Costa-Cabral et al.*, [2008].

The major challenges of SEA are (a) population increase, (b) urbanization and resource depletion, and (c) rapidly developing economies of riparian countries. Due to these major challenges and competing resource demands, the region is vulnerable to the additional challenges posed by climate change [*IPCC*, 2001]. Furthermore, disparities are growing, particularly between urban and rural areas, and water and related resources are under increasing pressure. Some countries such as Laos have a high potential for hydropower development and place a high priority on reducing poverty and hunger. Capitalizing on hydropower potentials by investing in hydropower generation has become a key concern in the region. This is important because the demand for electricity has risen in recent decades due to the rapid economic development of the riparian countries and other parts of SEA. Compared to other countries in the region, Laos has low per capita electricity consumption and therefore the lowest domestic electricity demand [*MRC,* 2010]. Due to this reason, Laos has the potential for power exports to neighboring countries. The river network within Laos contributes around 35% to the Mekong River flow and has an estimated 18,000 MW of exploitable hydropower production potential of which less than 3% is currently developed (International Rivers, 2008). Nevertheless, the existing hydropower projects have produced uncompensated losses and unmitigated impacts. Poor planning and implementation have exacerbated poverty amongst affected villagers [*International Rivers,* 2008]. Therefore, it is a questionable whether this planning is likely to maximize electricity production or revenue, especially under climate change.

In this study, we selected the Nam Ngum River Basin (NNRB) located in Laos which is undergoing rapid development due to hydropower generation, population increase, and rain-fed agriculture. The purpose of this work is to demonstrate the applicability of a water resources planning system to assess the hydrologic response and watershed impacts due to projected climate change. The key to this proposed system is the Water Evaluation And Planning System (WEAP21), a spatially based mathematical model capable of calculating the changes in the hydrologic cycle, incorporating changing climatic conditions, and representing the human managed water infrastructure operations such as dams, diversions, and hydropower projects. Moreover, this modeling framework allows the users to incorporate downscaled global climate models and calculate impacts and possible adaptation strategies within one framework [*Yates et al.,* 2009].

Specific objectives of this work are (1) to present an integrated water resources management framework and implementation of the WEAP21 model for seven NNRB watersheds, (2) describe the calibration and validation of the modeling system for unimpaired historical flows, and (3) to present the status-quo condition of water allocation trade-offs and the need for any future adaptation strategies under projected climate change conditions.

3.2 Details of the Nam Ngum River Basin

3.2.1 Physical Description

The NNRB has a drainage area of about 16,777 km^2 at the basin outlet close to the confluence with the Mekong River (Figure 3-1). The elevation of NNRB varies from 6 m to 2684 m above mean sea level (msl). The estimated mean slope of the basin is about 25.5%. The NNRB's annual flow contribution to the Mekong River is about 14% of the 40% from country's contribution. The estimated population of the basin is 502,150 in 2005, which is approximately 9% of the population of Laos [*WREA*, 2008]. The major land use types are natural forest at 47%, shrubland at 34%, agriculture at 8%, grassland at 7%, water surface at 3.98%, and urban area at 0.02% of the total area [*WREA*, 2008; *WREA*, 2009].

3.2.2 Climate and Hydrology

Climate of the NNRB is subtropical to tropical with a distinct wet season from May to October and mostly dry during the rest of the year. Most of the rainfall in the NNRB is due to the arrival of warm moist air during the south-west monsoon. The hottest months are March to April and the mean daily maximum temperature varies between from 28° to 34° C. The mean minimum temperature varies between 14° and 24°C and occurs between December and January at higher elevations [*ADB*, 2008]. The mean annual rainfall of the NNRB is 2000 mm, varying between 1400 to more than 3500 mm [*WREA*, 2009]. The mean annual Penman-Monteith potential evapotranspiration (PET) varies between approximately 1060 mm and 1360 mm [*ADB*, 2008].

3.2.3 Geography

Figure 3-1 shows the watersheds WS1 through WS7 of the NNRB. The historical observed mean annual unimpaired runoff from 1991 to 1998 of WS1 is approximately 4.8 billion cubic meters (BCM). The largest watershed of the NNRB is WS1 with an area of 4617 km^2 whereas the smallest has an area of 997 km^2. As shown in Table 3-1, WS6 and WS7 have slightly higher drainage densities compared to other watersheds indicating a higher tendency to generate more surface runoff and a higher erodibility of surface materials. Therefore, WS6 and WS7 tend to have limited infiltration capacity and promote runoff.

The northern part of the basin is at a higher elevation with a mean elevation of about 1173 m whereas the southern parts consist mostly of plains with elevations of less than 250 m. The northern watersheds are steep at their headwaters with slopes that generally decrease toward the Vientiane Plain. The estimated base flow index using daily streamflow for the Ban Naluang and Ban Hinheup watersheds are 0.66 and 0.63 respectively, indicating that the influence of soil and geology on river flows is almost similar in both watersheds.

3.3 Methodology

The Stockholm Environment Institute’s Water Evaluation and Planning System (WEAP21), is a spatially explicit rainfall-runoff model, capable of simulating flow in natural or managed flow systems. In this work, hydrology for the historical period from 1991 to 1998 and for the future from 2011 to 2090 is simulated using WEAP21. Once natural hydrology is modeled, infrastructure elements can be added to represent human-driven hydrologic manipulations [*Yates et al.*, 2005]. This study uses monthly time steps at a watershed scale for all streams within the modeled domain. The land area covers each contiguous watershed originating from the Tran Ninh Plateau located in Northern Laos to the basin outlet close to the confluence with Mekong River encompassing an area of approximately 16,777 km^2. A schematic representation of these watersheds of the NNRB, hydrologic operations, and water infrastructure operations under the existing conditions is shown in Figure 3-2.

3.3.1 Hydrologic Modeling

WEAP21 is a comprehensive, integrated watershed analysis system. WEAP21 models the terrestrial water cycle to represent physical hydrology using a one-dimensional, two-storage soil compartment water balance [*Yates et al.*, 2005; *Young et al.*, 2009; *Null et al.*, 2010]. WEAP21 uses a mass water balance approach to partition rainfall, runoff, or infiltration depending on air temperature, land cover, soil depth, and previous soil moisture conditions. Meteorological data (air temperature, rainfall and water vapor pressure deficits) and land cover data are the inputs to WEAP21. Since land cover vegetation affects evapotranspiration (ET) and soil depth affects soil moisture capacity, land cover vegetation types and soil types and depths are classified using the land cover and soil type maps provided by the Forestry Department of Laos. The drainage areas of Ban Naluang, Banhinheup and Ban Pakanhoung stream flow stations were identified using point watershed delineation capability in ArcGIS. It should be noted that WS1 drains only to Ban Naluang streamflow station whereas both WS4 and WS5 drain to the Banhinheup streamflow station. All WS1, WS2, WS3, WS4, and WS5 watersheds drain to the Ban Pakanhoung streamflow station.

A one-dimensional, 2-tank (or “bucket”) soil moisture accounting scheme is used in WEAP21 using empirical functions that describe ET, surface runoff, sub-surface runoff, (i.e. interflow), and deep percolation for a watershed unit [*Yates*, 1996]. Water retained in the top layer near the surface is available to plant roots whereas water in the deeper layer is transmitted as baseflow or groundwater recharge. Rainfall is partitioned as runoff or infiltration depending on air temperature, land cover, soil depth, and antecedent soil moisture conditions. Soil moisture in the top layer is further partitioned into ET, interflow, and deep percolation or storage based on the soil moisture capacity.

Meteorological data are available from the Luang Prabang weather station. Model calibration and verification were conducted from 1991 through 1998 due to the availability of observed streamflow data and climatic data. The Thiessen polygon method was used to interpolate rainfall data using the ten representative stations at monthly time steps and extracted for each watershed modeled in the NNRB. Chapter 2 results showed that these ten stations can represent the rainfall characteristics for the historical time period from 1961 to 2000.

3.3.2 Model Calibration and Validation

Observed streamflow data for the historical time period of 1991 through 1998 are unavailable for every watershed but daily streamflow data are available for the Ban Naluang and Ban Hinheup streamflow stations (Figures 3-1 and 3-2). Monthly time steps were selected for model calibration and validation. The model calibration period is from 1991 to 1996 and validation was from 1997 to 1998.

In the NNRB, measured flows are significantly affected by human abstractions and water infrastructure developments and operations such as reservoirs, dams and diversions. Therefore, the two upstream streamflow measuring stations with natural flows, Ban Naluang and Ban Hinheup, were selected for calibration and validation. The construction of Nam Song Reservoir and a diversion project occurred from 1994 to 1996 (Figure 3-2). Model calibration was performed using the model independent nonlinear Parameter Estimation (PEST) technique. The calibrated model parameters for each watershed are; soil water capacity, deep water capacity, runoff resistance factor, root zone conductivity, deep conductivity, preferred flow direction, and the crop coefficient.

A study by *Moriasi et al.,* [2007] recommended three quantitative statistics for model performance evaluation. These statistics are Nash-Sutcliffe Efficiency (NSE), percent bias (PBIAS), and root mean square error to standard deviation ratio (RSR). This study used these statistics to evaluate model performance. The acceptable values of these indices are (a) very good ($0.75 < \mathrm{NSE} \le 1.00$; $\mathrm{PBIAS} < \pm 10$; $0.0 \le \mathrm{RSR} \le 0.50$), (b) good ($0.65 < \mathrm{NSE} \le 0.75$; $\pm 10 \le \mathrm{PBIAS} < \pm 30$; $0.5 < \mathrm{RSR} \le 0.6$), (c) satisfactory ($0.5 < \mathrm{NSE} \le 0.65$; $\pm 15 \le \mathrm{PBIAS} < \pm 25$; $0.6 < \mathrm{RSR} \le 0.7$), and (d) unsatisfactory ($\mathrm{NSE} \le 0.5$; $\mathrm{PBIAS} \ge \pm 25$; $\mathrm{RSR} > 0.7$).

3.3.3 Climate-Forcing Data

This study uses data from the Canadian Center for Climate Modeling and Analysis (CGCM3.1 T63) with an A2 emission scenario for future climatic conditions from 2011 to 2090. For detailed analysis of climate change driven impacts, the 21st century results of this work are grouped into two time slices; 2011 to 2050, and 2051 to 2090. The reason in the selection of CGCM3.1 is because this GCM simulated both monthly rainfall amounts, and seasonal and annual trends of real monthly rainfall for the historical period with minimum mean absolute error (see Chapter 2). The rationale for the selection of the A2 scenario for the projected climate change impact assessment is that A2 estimates the worst case scenario and if a system can adapt to a larger climate change, then the system can easily adapt to smaller climate changes. Climate-Forcing data for CGCM3.1 T63 for 20th century experiment (20C3M) and the A2 emission scenario data were downloaded from Canadian Center for Climate Modeling and Analysis website [http://www.cccma.ec.gc.ca/data/cgcm3/ data/cgcm3/cgcm3.shtml, accessed March, 2012].

The weather stations in Luang Prabang and Nong Khai were selected for bias correction and to compare with the 40 year historical time period (1961-2000) and with 20C3M data. Maximum temperature, minimum temperature, relative humidity and wind speed data were conditionally generated for the future time period from 2011 to 2090 using the approach discussed in Chapter 2 for the NNRB.

For temperature, the absolute change is used to estimate the change factor (CF) values,

$$T^{f}{}_{G}(j) = T^{b}{}_{G}(j) + CF(j) \tag{1}$$

where $T^f{}_G$ is future temperature, $T^b{}_G$ is generated baseline temperature, and subscript j stands for month. CF is given by corrected future GCM scenario ($GCM^f{}_{corr}$) and corrected GCM baseline scenario ($GCM^b{}_{corr}$) at monthly time steps at the Luang Prabang and Nong Khai weather stations.

$$CF(j) = GCM^{f}{}_{corr}(j) - GCM^{b}{}_{corr}(j) \tag{2}$$

Relative humidity is estimated for the baseline (20C3M) and the A2 emission scenarios at monthly time steps. An empirical formula is used to compute wind speed at daily time step and then aggregated to estimate the monthly average wind speed to compare with observed wind speed data at the two weather stations [Personal Communication, Dr. Viatcheslav Kharin, Canadian Center for Climate Modeling and Analysis, April 2, 2012].

3.3.4 Assessment of Impacts

Impacts on hydro-climatic regimes are assessed through the changes of rainfall (P), potential evapotranspiration (PET), and stream flow (Q). One other common indicator used to measure the hydro-climatic stress is the aridity index (Φ) defined as PET/P. *Ponce et al.*, [2000] classified watershed hydro-climatology as humid when $0.375 \le \Phi < 0.75$, semi-humid when $0.75 \le \Phi < 2$, semi-arid when $2 \le \Phi < 5$, and arid when $5 \le \Phi < 12$. The changes in the aridity index imply changes in the hydro-climatic regimes when climate change is due to changes in meteorological variables such as rainfall, temperature, relative humidity, and wind speed.

Human impacts are assessed through unmet water demands for each water user at each watershed at monthly time steps. The water demands for domestic users are estimated using the current water use rates and population growth. The water demands for agricultural users are estimated using the current water use rates for paddy and other crops and agricultural land area increase for paddy and other crops. The unmet demands are integrated with performance criteria in meeting monthly water demands for water users that capture and reflect the essential and desired sustainable characteristics of the integrated water resources management system. The most commonly used performance criteria, reliability, resiliency, and vulnerability are also used here [*Hashimoto et al.,* 1982].

Supply reliability is the probability that the available water supply meets the water demand during the period of simulation [*Klemes et al.,* 1981; *Hashimoto et al.,* 1982]. For each time period *t*, where deficit is D^i_t (positive when the target is higher than the supply and zero when target demand is fully met), water demand is $X^i_{\mathrm{Target},t}$ and water supply for *i*th user is $X^i_{\mathrm{Supplied},t}$, time-based reliability (Rel^i) over *n* months is defined as [*McMahon et al.,* 2006]:

$$\mathrm{Re}l^i = \frac{No.of\ times\, D^i{}_t = 0}{n} \tag{3}$$

Resiliency is a system’s capacity to adapt to changing conditions [*WHO,* 2009]. Because climate conditions are not steady, resilience must be considered as a statistic that assesses the ability of water management policies to adapt to changing climatic conditions. Resiliency (Res^i) is the probability that a successful period follows after a failure period (the number of times $D^i_t = 0$ after $D^i_{t-1} > 0$) for all failure periods (the number of times $D^i_t > 0$ occurred) and defined as:

$$\mathrm{Re}\,s^i = \frac{No.of\ times\, D^i{}_t = 0\ follows\, D^i{}_t > 0}{No.of\ times\, D^i{}_t > 0\ occurred} \tag{4}$$

Vulnerability is the likely value of deficits that may occur [*Hashimoto et al.,* 1982]. In other words, it is a measure of the likely damage in a failure event and refers to the likely magnitude of a failure, if one occurs. Vulnerability can be expressed as the average failure [*Loucks and van Beek*, 2005], the average of maximum shortfalls over all continuous failure periods [*Hashimoto et al.*, 1982; *McMahon et al.*, 2006], or the probability of exceeding a certain deficit threshold [*Mendoza et al.,* 1997]. This study uses the first approach, the expected value of deficits, and the dimensionless vulnerability (Vul^i) is defined for the *i*th water user as:

$$Vu\ln erability^i = \frac{\dfrac{\left(\sum_{t=0}^{t=n} D^i_t\right)}{No.of\ times\, D^i_t > 0\, occured}}{Water\ demand^i} \tag{5}$$

This study normalizes the expected value of deficits divided by the water demand to estimate the dimensionless vulnerability for each water user. Normalization was performed for comparison purpose since the magnitude of water demand for each water user is different.

3.3.5 Sustainability

Climate change impacts and corresponding mitigation or adaptation issues need to be addressed for extended periods, such as decades. In such conditions, sustainability of the resources and the system needs to be clearly understood. In this work, the sustainability index (SI) is defined as a summary index that measures the sustainability of the water resources system and helps in comparing several proposed management policies. If a proposed policy makes the system more sustainable, the index will show that the system will have a larger adaptive capacity. SI is an integration of performance criteria that captures the essential and desired sustainable characteristics of the basin.

Frequently, indices are criticized because these are seen as a sum of unrelated indicators [*Hopkins*, 1991], and therefore people in the water sector are reluctant to use indices [*Brown et al.,* 1972]. On the other hand, SI is commonly used by the scientific community [*Loucks,* 1997; *McMahon et al.,* 2006; *Ray et al.,* 2010; *Sandoval-Solis et al.,* 2011]. This study uses reliability, resiliency, and vulnerability to estimate sustainability and can be estimated for each water user or group. *Loucks* [1997] proposed SI for the *i*th water user as:

$$SI^{i} = \mathrm{Re}\,liability^{i} * \mathrm{Re}\,siliency^{i} * \left(1 - Vu\ln erability^{i}\right) \tag{6}$$

The SI proposed by *Loucks* [1997] is used in this study because it is appropriate in the context of integrated water resources management system to evaluate the performance of meeting the water demand for each water user. The SI has the following properties: (1) its values vary from 0-1; (2) if one of the performance criteria is zero, the sustainability will also be zero; and (3) there is an implicit weighting because the index gives added weight to the criteria with the worst performance. The multiplicative form of the SI considers each criterion as essential and non-substitutable. *Sagar and Najanm* [1998] suggested multiplicative form of SI as the proper manner for integrating performance criteria. For example, *Reiquam* [1972] used the multiplicative form for the environmental stresses index.

Sandoval-Solis et al., [2011] used a weighted sustainability group index for a transboundary basin with improvements in its structure, scale and content to make it more flexible and adjustable to the requirements of each water user, type of use, and basin. The weighted sustainable group index is used by *Sandoval-Solis at al.* [2011] to assess the changes of water management policies by different countries. But our study calculates the group sustainability indexes to summarize the results for groups of water users within the basin. In this study, the sustainability index by water users is calculated to identify areas of water users and regions at risk of water shortages. An efficient water management and allocation priority should improve the reliability and resilience of meeting water demands of water users while reducing vulnerability. To evaluate overall performance of the water management under various allocation priorities, we can calculate sustainability measure by combining reliability, resilience and vulnerability [*Loucks*, 1997]. Sustainability index is a quantitative estimation of degree to which a priority action or policy contributes to a sustainable improvement in meeting water demands at each water user node or group. The sustainability index for each water user identifies priority action or policies that preserve or improve the desired water demand management characteristics of the basin in the future. To compare different groups of water users, the sustainability by group (SG) is estimated as an average of sustainability indexes of different water users in a group. SG is defined for a group, *k,* with *i*th to *j*th water users in this group and with *n* water users as:

$$SG^{k} = \frac{1}{n} * \sum_{i=1 \in k}^{i=j \in k} SI^{i} \tag{7}$$

3.4 Results and Discussion

3.4.1 Model Calibration and Validation

Model calibration and validation are used to predict average monthly streamflows at the Ban Naluang and Ban Hinheup stations in upstream watersheds, WS1, WS4, and WS5 and the results are shown in Figure 3-3. The results show that WEAP satisfactorily represents the hydrological behavior of WS1, WS4, and WS5 from 1991 to 1996. While a few peak values were not matched correctly, WEAP managed to capture the hydrologic behavior and the trends of the peak values. One reason for not capturing a few peak flows could be due to the Nam Song Diversion project that started in late-1993 and was completed in mid-1996. It is also important to notice that WEAP captured the low-flow periods which are important for hydropower generation. The calibrated model parameters of WEAP are given in Table 3-2. Although not shown here, the soil moisture accounting parameters of WS2 and WS3 were calibrated against the observed average monthly flows at Ban Pakanhoung, which is located downstream of the Nam Ngum 1 Dam. The performance of WEAP was tested against observations of streamflows and hydropower generation at the Nam Ngum 1 Dam site. In addition to hydrographs, statistics NSE, PBIAS, and RSR are computed to assess model performance and are given in Table 3-3. The estimated NSE, PBIAS, and RSR values for the calibration period at Ban Naluang are 0.8, -3.8 and 0.5 respectively, and at Ban Hinheup are 0.6, 4.3 and 0.6 respectively.

According *Moriasi et al.*, [2007], the estimated statistics of NSE, PBIAS, and RSR range from “satisfactory” to “very good.” Similarly, these statistics also ranked “satisfactory” for the validation period. Therefore it is possible to conclude that the calibrated WEAP model is capable of simulating the hydrologic behavior of the selected watersheds at monthly time steps. A comparison of average monthly simulated and observed flows suggests that WEAP can simulate the average streamflows of the upstream watersheds. For example, the observed and simulated average monthly streamflows at Ban Nalunag are 143.3 and 148.7 m^3/sec, respectively, during the calibration period, and 123.9 and 134.5 m^3/sec, respectively, during the validation period. Similarly, the observed and simulated average monthly streamflow amounts at Ban Hinheup are 209.6 and 200.6 m^3/sec, respectively, during calibration and 170.7 and 199.2 m^3/sec, respectively, during validation. Therefore, the calibrated WEAP model with corresponding soil moisture accounting model parameters can be used to project monthly average streamflow amounts satisfactorily under future time periods, assuming that these parameter values will remain unchanged.

Figure 3-4 shows the predicted and observed reservoir storage and hydropower generation values at the Nam Ngum 1 Dam site from 1991 through 1998. In this simulation, priorities between hydropower, irrigation, and municipal demands are kept the same. The results show that WEAP is capable of simulating reservoir volumes as well as hydropower generation satisfactorily at the Nam Ngum 1 Dam for the baseline period. The results of Figures 3 and 4, together with the statistics given in Table 3-3, show that, when calibrated, WEAP is capable of simulating the hydrologic behavior and the corresponding water allocation framework and infrastructure operations of the NNRB.

3.4.2 Impacts on Hydro-Climatic Regimes

Table 3-4 shows climate change driven seasonal changes for the 40 year future time periods (such as the wet and dry season) and average changes in rainfall, PET, and aridity compared to the baseline period. Percent changes in the aridity index is preferred because it reflects the percent changes in rainfall and the overall changes of other meteorological variables such as temperature, relative humidity, and wind speed under different climatic conditions. The overall watershed hydro-climatology of the NNRB remains “humid” under the existing and future climatic change conditions. In the first half of the century dry conditions were exhibited by WS1, WS6, and WS7 due to the increase of PET. However, these extremes are somewhat minimized in the same time period by increased rainfall as high as 58.6% from the average values. Therefore, aridity in the first part of the century does not appear to be high, except marginally with WS7. When comparing the wet and dry seasons for the same time period, the observations are similar because the increased PET is counterbalanced by increased rainfall. In general WS7 was most affected, with a high increase of PET and a marginal increase of rainfall, making this watershed more arid than the baseline period.

The predicted hydrologic-climate regime in the second half of the century is similar in trend except the changes in PET are much higher. WS1, WS2, WS6, and WS7 consistently show a higher increase of PET compared to the first part of the century. Rainfall, on the other hand, has increased significantly compared to the first part of the century, making the NNRB more humid. As before, WS7 is affected much more in the second part of the century, with a lower percent of increase in dry season rainfall as opposed to high increases in PET, compared to the first part of the century, and also compared to all other watersheds, indicating climate change impacts are significant.

The rainfall patterns show that the average rainfall amounts increase compared to the baseline period across the NNRB for the future time periods. The wet season average rainfall amounts increase approximately by 15% and 13%, whereas the dry season rainfall amounts increase by 40% and 53% from 2011 to 2050, and from 2051 to 2090, respectively. The percent increase in rainfall is significantly higher in the northern and central parts compared to the southern parts of the NNRB. It is also notable that the percent changes in rainfall are relatively higher in the dry season compared to the wet season. The maximum percent increase in rainfall during the wet and dry seasons is observed in WS5 compared to other watersheds.

Table 3-9 in the Appendix shows climate change driven seasonal changes for the 8 year future time periods compared to the 8 years baseline period. It is seen that the conditions are almost similar except average percent changes of PET are relatively lower during the first half of the century compared to the 40 years future time period from 2011 to 2050. The predicted hydrologic-climate regime in the second half of the century is similar in trend for both PET and rainfall except the changes in PET are much higher.

3.4.3 Assessment of Watershed Impacts

Watershed impacts are assessed using the percent unmet demands of each water user and the corresponding performance criterion. Figure 3-5 shows the percent unmet water demands for the baseline period from 1991 to 1998 and the future time periods from 2011 to 2090. Domestic water use is less affected compared to the agricultural water use in the same period. Agricultural water uses in WS1, WS2, WS3, WS4, and

WS5 are mostly affected due to water shortages. Although not shown here, there are no statistically significant trends observed in the time series of PET or rainfall for the baseline period. The reason could be due to high PET amounts during the dry season compared to the wet season. Aridity indices of WS1, WS2, WS3, WS4, and WS5 for the dry season are 0.5, 0.7, 0.7, 0.3, and 0.3, respectively. Existing high conveyance water losses in irrigation canals and high water demand for paddy cultivation during the dry season resulted in water shortages in northern and central parts of the watersheds under the equal priority scenario. Results showed that even though rainfall amounts are higher than PET amounts in northern and central parts of the basin, dry season aridity indices of WS6 and WS7 are 1.7 and 0.9, respectively. These indices indicates high PET amounts compared to rainfall amounts in southern parts (WS6 and WS7) of the basin, and, with the existing conveyance losses, even creates a high water demand for irrigation, mainly for paddy cultivation. Under the equal priority scenario, water is supplied from a nearby source or from a reservoir located upstream to minimize water shortages. The percent unmet irrigation water requirements in WS1, WS2, WS3, and WS5 are about 3% compared to 0% in WS6 and WS7 (Figure 3-5a). Agricultural and domestic water requirements are fully met during the wet season. Maximum dry season percent unmet water requirements are observed in WS1, WS2, and WS3 and percentages of unmet water requirements are 15% for the same watersheds. Average dry season aridity index values of WS1, WS2, WS3, WS4, WS5, WS6, and WS7 for the baseline period are 0.53, 0.68, 0.74, 0.26, 0.29, 1.69, and 0.86, respectively whereas the average wet season aridity index values are much lower at 0.33, 0.35, 0.23, 0.13, 0.13, 0.26, and 0.30, respectively. It is estimated that the irrigated land areas of WS1, WS2, WS3, WS4, WS5, WS6, and

WS7 are approximately 231, 23, 65, 136, 79, 553, and 287 km^2, respectively. It is seen that WS1, WS2, and WS3 has high dry season aridity index compared to WS4 and WS5. WS1 has a high irrigated land area of 231 km^2 compared to other upstream watersheds and is located further upstream in the NNRB. The high dry season aridity index and low dry season rainfall of WS1, WS2, and WS3 resulted in a high percentage of unmet irrigation water requirements. It is notable that during the baseline period the dry season agricultural water demands of WS6 and WS7 is fully met amidst the high dry season aridity index and low dry season rainfall because they are located downstream of the Nam Ngum 1 Dam, and therefore the water irrigation demands are satisfied with available water from streamflow or reservoir.

Figure 3-5b shows that watershed impacts, in terms of water shortages, increase from 2011 to 2050, compared to the baseline period. The majority of water shortages are in agricultural water use rather than domestic water use under the equal priority allocation scenario. It is clear that the future water shortages are highest during the dry season compared to the wet season for agricultural water uses in WS1, WS2, WS3, WS4, and WS5 (Figure 3-5b). The major reason for the high water shortages are due to the annual 1% growth in cultivated land areas for irrigation, mainly for paddy. The reason for the highest water shortage in the dry season is due to the highest percent share of annual water demand required during the dry season for paddy cultivation and lower water available for use. Other reasons are high irrigation transmission losses and high annual water use rates of 15 million m^3 per km^2 for paddy and 0.5 million m^3 per km^2 for vegetables and other crops. It is also observed that the average water shortages increase in the wet season under climate change in WS1, WS2, and WS3. During the second half of the century, the average water shortages for agriculture and domestic purposes further increase, including the wet season water shortages compared to the first half of the century. As seen in Figures 5b and 5c, upstream watersheds are affected due to the water shortages during both future time periods. Compared to the baseline period, the wet season agricultural and domestic shortages increase across the NNRB. Under the equal priority scenario with existing demands, percent average water shortages will drastically increase.

To estimate the overall watershed impacts of the NNRB, the changes in average annual flow at the outlet to the Mekong River were calculated. Compared to the baseline period, Table 3-5 shows that the average annual flow at outlet decreases by 60% and 72% from 2011 to 2050, and from 2051 to 2090, respectively. It is shown that the average annual flow reduction for future time period from 2011 to 2018 and from 2051 to 2058 are more or less similar compared to the flow reductions for 40 years future time periods. Moreover, wet season streamflow at the outlet decreases by 53% and 62% from 2011 to 2050, and from 2051 to 2090, respectively whereas the dry season percent flow reduction is 74% and 92% for the same time periods. In terms of flow reduction, a significant decrease in streamflow at the outlet is observed during the second half of the century. Possible reasons for this flow reduction even with a high percent of increased rainfall in the dry season are (1) equal priority for hydropower generation and therefore reservoirs are filling up and there is increased water storage in large upstream reservoirs, (2) relatively high PET compared to the increasing rainfall in downstream watersheds, namely WS6 and WS7, (3) high agricultural water demand, especially for paddy, and (4) high domestic water use.

3.4.4 System Sustainability

Sustainability in meeting water demands for different water users depends on the water allocation priority decisions. Different priorities for different water demand sectors will affect the availability of water for different water users. SI is estimated using reliability, resiliency and vulnerability for each water user. This study used unmet water demand (deficits) for each water user at monthly time steps for the baseline period and for future time periods. The estimated SI of each water user is used to calculate water user group sustainability (SG) for agricultural and domestic groups for the baseline period and for future periods. The results are shown in Table 3-6 for the equal priority scenario. A comparison of SI for different water users under the existing conditions shows that sustainability is highest (~100%) for agricultural water users in WS6, WS7, and domestic water users in the Bolikhamsay province, located in the southern parts of the NNRB. Although not shown here, it is estimated that 61% of the irrigated lands are located in WS6 and WS7, whereas 39% of the irrigated lands are located in WS1 for the baseline period. Estimated population distributions of domestic water users for the baseline period are 1.0, 0.3, 30.9, 53.9, and 13.9% in Luang Prabang (D_LP), Bolikhamsay province (D_BP), Vientiane Municipality (D_VM), Vientiane Province (D_VP) and Xiengkhouang (D_XK), respectively. The highest population, which is 53.9%, is located in Vientiane Province, whereas the lowest is 0.3% in Bolikhamsay Province. The domestic water user in the Bolikhamsay Province showed the highest sustainability of 100% for both time periods of 2011 to 2050, and from 2051 to 2090. The reason is due to having the lowest population percent share and its downstream location in the basin. Compared to the upstream agricultural water users, sustainability of agricultural water users in WS6 and WS7 is high in both future time periods. On average net water losses are higher in WS6 and WS7 due to percent increase in PET amounts and increasing rates of change in PET compared to rainfall for both future time periods. Further expansion of existing land area for agriculture produces higher irrigation and also domestic water demands in WS6 and WS7. The results are almost similar for the 8 years future time period compared to the 40-year time periods mainly for the agricultural water users compared to domestic water users.

The watersheds located upstream, WS1, WS2, WS3, WS4, and WS5 produce a net gain in water due to the high percent changes in rainfall as opposed to the percent changes in PET in the first half of the century. Under future development scenarios, all reservoirs will be located upstream and, therefore, the equal priority scenario maximizes reservoir water storage and hydropower generation, subject to water availability. When water is released from reservoirs for hydropower generation, water is not available for upstream watersheds for irrigation and domestic water uses, which produces a high water deficit in the dry season. Even though there is a net gain in the upstream watersheds, it is still a challenge to determine which sector to prioritize for water allocation under competing demands. Therefore, it is essential to estimate group sustainability in terms of meeting the demands of each water user sector. Allocation calculations are carried out sequentially at each times step. At runtime the users with same priority are assigned to an *equity group*. The water allocation is carried out by a linear program (LP) algorithm that iterates from one equity group to another. The first iteration of the LP algorithm occurs at the equity group consisting of the top priority users. The objective of the LP algorithm is to maximize the coverage of all user demands in that group. Under the equal priority condition, water allocation priorities are equal for every water user in the same equity group and for different equity groups. The linear allocation routine of WEAP21 minimizes the water shortages subject to the availability of water in streams and reservoir releases for a given water user, such that the downstream water shortages are minimal compared to upstream water shortages.

Table 3-7 shows the SG results for the different groups. The results show that compared to the existing conditions, sustainability in agricultural water use is significantly reduced compared to domestic water use due to future water infrastructure developments and operations under equal priority scenario. As shown in Table 3-7, the estimated SG index for the agricultural water user group decreases by 87% and 97% from 2011 to 2050, and from 2051 to 2090, respectively. Percent decrease in the SG index for domestic water user group is low compared to the agricultural water use group, with amounts of 43% and 60% for the same future time periods. The major reasons for this low sustainability of the agricultural water user group are (1) increased dry season PET compared to the baseline period, (2) high water demand for paddy, and (3) high irrigation water losses due to unlined irrigation water canals. Another reason for further decreases in the SG index during the latter part of the century could be because the percent increase in PET is higher compared to rainfall in the wet season of WS1, WS6, and WS7. The estimated percent ET in WS1, WS2, WS3, WS4, and WS5 are 37%, 22%, 14%, 10%, and 6%, respectively, from the total ET of the NNRB from 2011 to 2050, whereas 41%, 21%, 8%, 8%, and 5% from 2051 to 2090, respectively. The reason for high ET percentages are due to the combined effect of an increase in irrigated agricultural lands, deforestation, and an increase in urban land use types, causing a decrease in grasslands and shrub lands in the future time periods. It is noticed that ET percentages of WS1 are higher than the percent increase in rainfall for both time periods. Therefore, the high water losses by ET, irrigation transmission losses, and high water use for paddy, produces water stress in WS1, WS2, WS3, WS4, and WS5. This could be the reason for lower SG indices for agriculture in the upstream watersheds compared to the downstream watersheds. As shown in Table 3-7, percent reduction of sustainability group index values for agriculture sector is almost similar for the 8-year periods compared to the 40-year future time periods. The lowest domestic SG index of 9% during the period from 2011 to 2018 is due to the low population growth compared to 2051-2058 period.

3.4.5 Hydropower Generation

Projected climate changes can affect hydropower generation based on water availability, streamflows, and water allocation priority. Table 3-8 shows the results from different water allocation priority scenarios for each water user group. Allocation priorities are assigned based on the water user group. The three groups considered are irrigation, domestic, and hydropower. The last two priority scenarios in Table 3-8 are produced considering the domestic and agricultural water users below the Nam Ngum 1 Dam. The results show that the average annual hydropower generation is highest when hydropower is given the highest priority, which is no surprise. It is noticed that the average annual hydropower generation is increased by 31% and 42% if priority is higher for hydropower generation over irrigation and domestic water users during 2011 to 2050, and from 2051 to 2090, respectively. However, the average annual hydropower generation is reduced by 3% and 1% if the priority is lowered for hydropower generation over irrigation and domestic water user groups. This is a not a significant reduction of hydropower generation if the allocation priority is changed from the highest to the lowest for the hydropower water user group. The reason could be that under the equal priority scenario, water allocation aims to release water to minimize water shortages at the demand sites from a nearby water supply, such that multiple reservoirs are needed to release water to meet the water demand at the target sites. When hydropower generation is given the highest priority, water is stored in reservoirs, but other constraints such as maximum turbine flow, plant factor, and generating efficiency, limits hydropower generation. It should be noted that this study assumed the hydraulic constraints, such as maximum turbine flow, plant factors, and turbine efficiencies will remain unchanged during the simulation period from 2011 to 2090. It also noticed that the proposed developments of dams and reservoirs are located upstream to the Nam Ngum 1 Dam and prioritizing hydropower generation has reduced the average annual hydropower production. The reason may be the large upstream reservoirs tend to store water for hydropower production but other constraints limit hydropower production. This reasoning is further supported by the historical hydropower generation amounts for the same scenario. Prioritizing hydropower over other demands increased the average hydropower production for the historical time period due to the non-existence of the proposed new dams and reservoirs upstream to the Nam Ngum 1 Dam. In contrast, irrigation and domestic water demands given the highest priority further reduce hydropower generation since the reservoirs tend to store water, yet other constraints limit power generation.

For both future time periods, from 2011 to 2050, and from 2051 to 2090, the total annual hydropower generation is highest when hydropower is given the highest priority

(Table 3-8). The second highest average annual hydropower outputs occur when the downstream water demand sites are given the highest priority over the upstream water demand sites for both future time periods. The annual hydropower generation amounts are lowest when hydropower generation is given the lowest priority. The moving average for a 12-month period was calculated for total monthly hydropower generation using six dams and the results are shown in Figure 3-6a and b. It is seen that the trends of the moving average are somewhat increased during the first half of the century whereas it is decreased during the second half of the century. The moving averages of total monthly hydropower generation are high for scenario 2 (S2) compared to other scenarios for both future time periods. It is seen that there is no significant difference between the trends in the moving averages and the total monthly hydropower generated for scenarios 1, 3, 4, and 5, except the amounts are slightly lower for scenario 3 in both time periods. Therefore, water managers should consider the trade-offs between the benefits of different water allocation priority decisions among different water users and possible outcomes that would occur.

3.5 Summary and Conclusions

An integrated water resources management modeling framework is developed using WEAP21 to predict natural historical flow regimes and water allocation of the NNRB of Laos. Given the low per capita electricity consumption within Laos and the high potential to develop hydropower when only 3% is currently developed, Laos has the potential to attract foreign investments and income from hydropower generation. While these attractive potentials exist for Laos, climate change related hydrologic impacts can affect these opportunities. Therefore, there is a need to understand these climate change-driven impacts through a systematic development of an integrated water resources modeling framework. The purpose of the modeling framework is to predict the natural streamflows, water availability, and impacts on water infrastructure driven operations under projected climate change. The model considers the hydrologic processes and water infrastructure operations, and therefore it will be a powerful tool in assessing climate change impacts and identifying required adaptation options for decision making by watershed planners and managers. This modeling framework aids in estimating the watershed impacts in terms of unmet water demands at watershed scale and sustainability in meeting water demands for different water users and groups.

The projected climate change was simulated using third generation coupled general circulation model, CGCM3.1 T63, and the A2 scenario that provides probably the worst case scenario. Rainfall and temperature distributions using the bias-correcting statistical downscaling approach for two time periods, 2011-2050, and 2051 to 2090, were previously developed by Jayasekera and Kaluarachchi (see Chapter 2). The results of this work indicate that the water demands are affected under the projected climatic change conditions. Due to climate change impacts, population growth, an increase in agricultural land areas, and the rapid development of dams and reservoirs, reduce streamflow at the basin outlet significantly towards the end of the century. Water shortages for agricultural water use become a significant issue from 2011 to 2090. The climate change threats and impacts are critical during the second part of the 21st century. Sustainability in meeting the water demands for agricultural and domestic water users sectors is impacted due to climate change and human induced changes of population increase and land use changes. The agriculture water user sector is critically affected compared to the domestic water use sector, resulting in high vulnerability mostly in the upper parts of the NNRB. Hydropower generation increases, due to the proposed hydropower generation plants but to which sector water allocation should be prioritized, will be a critical water management decision. The water manager can consider the tradeoffs among outcomes of possible water allocation decisions and provide highest priority for hydropower generation to maximize hydropower generation outputs. If foreign income growth is the major priority, not surprisingly prioritizing hydropower generation over irrigation and domestic water use will satisfy the objective. However, concerns related to sustainability of other water sectors and corresponding vulnerability will be concerns under the priority for hydropower generation. In such a situation, investigation of options for climate change adaptation and system improvements are needed to improve sustainability and in reducing vulnerability in long-term basin planning.

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Table 3-1. Description of physical characteristics of individual watersheds.

Watershed	**Area (km^2)**	**Mean Rainfall (mm/year)**	**Mean Elevation (m)**	**Mean Slope (%)**	**Drainage Density (km/km^2)**
WS1	4617.4	1499.2	1172.5	29.8	0.20
WS2	1848.3	1835.0	958.6	37.1	0.19
WS3	2250.1	2078.6	440.9	22.2	0.20
WS4	3130.3	1713.5	589.8	30.2	0.17
WS5	1826.0	1788.2	622.0	33.7	0.23
WS6	2136.4	1975.0	232.2	6.1	0.25
WS7	997.2	1775.6	223.9	5.0	0.29

Table 3-2. Land use parameters used in model calibration and validation of WEAP21.

Watershed		WS1				WS4			WS5			
Parameter		Land Use Type										
	Unit	Forest	Irrigated	Grassland	Urban	Forest	Irrigated	Grassland	Forest	Irrigated	Grassland	Urban
Crop coefficient (Kc)	-	0.2	2.0	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Soil water capacity	mm	495.5	500.0	400.0	180.0	300.6	301.0	301.0	313.0	312.0	312.0	312.5
Runoff resistance factor	-	8.0	3.7	5.0	0.5	10.0	10.0	10.0	10.1	10.1	10.1	10.0
Root zone conductivity	mm/month	158.1	100.0	500.0	300.0	500.0	500.0	500.1	501.0	500.6	500.0	500.5
Preferred flow direction	%	0.01	0.01	0.01	0.01	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Deep water capacity	mm	100				100			100			
Deep water conductivity	mm/month	165.2				140.6			140.6			
Initial storage fractions (z1)	%	2	3	2	2	2	2	2	2	2	2	2
Initial storage fractions (z2)	%	5				8			8			

Table 3-3. Performance indicators for model calibration and validation from 1991 to 1998.

Streamflow Station	**Calibration (1991-1996)**							**Validation (1997-1998)**						
	NSE[1]	**PBIAS**[2]	**RSR**[3]	**r**[4]	**R^{2}**[5]	**$\bar{Q}_{obs}$**[6]	**$\bar{Q}_{sim}$**[7]	**NSE**[1]	**PBIAS**[2]	**RSR**[3]	**r**	**R^{2}**	**$\bar{Q}_{obs}$**	**$\bar{Q}_{sim}$**
Ban Naluang	0.8	-3.8	0.5	0.9	0.8	143.3	148.7	0.5	-8.5	0.7	0.7	0.5	123.9	134.5
Ban Hinheup	0.6	4.3	0.6	0.8	0.6	209.6	200.6	0.5	-16.7	0.7	0.7	0.5	170.7	199.2

[1]NSE: Nash-Sutcliffe efficiency; [2]PBIAS: percent bias; [3]RSR: RMSE / $STDEV_{obs}$; [4]r: coefficient of correlation; [5]R^2: coefficient of determination; [6]$\bar{Q}_{obs}$: mean monthly observed flow (m^3/sec); [7]$\bar{Q}_{sim}$: mean monthly simulated flow (m^3/sec)

Table 3-4. Comparison of the percent changes of potential evapotranspiration (PET), rainfall (P) and aridity index (Φ) for 40-years future time period compared to the baseline period of 1991-1998.

Watershed	**ΔPET (%)**						**ΔP (%)**						**ΔPET/P (%)**	
	2011-2050			**2051-2090**			**2011-2050**			**2051-2090**			**2011-2050**	**2051-2090**
	Wet[1]	**Dry[2]**	**Average**	**Wet[1]**	**Dry[2]**	**Average**	**Wet[1]**	**Dry[2]**	**Average**	**Wet[1]**	**Dry[2]**	**Average**	**Average**	
WS1	18.7	18.9	18.8	52.7	53.5	53.1	28.0	45.1	36.6	19.5	54.1	36.8	-15.1	10.2
WS2	9.2	9.9	9.5	18.5	19.8	19.2	26.7	46.3	36.5	26.9	64.4	45.7	-20.5	-19.9
WS3	-13.3	-12.9	-13.1	-38.6	-38.1	-38.3	11.2	39.8	25.5	8.7	48.9	28.8	-34.0	-55.0
WS4	-0.3	-0.2	-0.2	-0.9	-0.4	-0.6	36.6	58.9	47.7	40.9	84.2	62.5	-29.6	-37.9
WS5	0.4	0.5	0.5	0.8	1.3	1.1	40.3	76.9	58.6	42.0	110.8	76.4	-33.7	-42.3
WS6	24.8	25.4	25.1	85.7	87.3	86.5	2.1	32.6	17.4	2.8	24.6	13.7	-3.5	53.8
WS7	27.7	28.7	28.2	90.0	92.2	91.1	9.9	7.6	8.8	12.1	5.7	8.9	18.6	79.9

[1] Wet: Average percent change during wet season from May to October

[2] Dry: Average percent change during wet season from November to April

Table 3-5. Comparison of changes in streamflow at the outlet of the NNRB. The values in parentheses are percent changes from the baseline scenario.

	Streamflow (BCM)				
	Observed historical	**With proposed reservoirs/dams**			
	Baseline period (1991-1998)	**A2 (2011-2018)**	**A2 (2051-2058)**	**A2 (2011-2050)**	**A2 (2051-2090)**
Wet season	12.8	5.8 (-55)	4.9 (-62)	6.0 (-53)	4.8 (-62)
Dry Season	6.4	2.3 (-64)	0.6 (-91)	1.7 (-74)	0.5 (-92)
Annual	19.2	8.1 (-58)	5.4 (-72)	7.6 (-60)	5.3 (-72)

[1] Two reservoirs are operating during the baseline period (1991-1998)

[2] Nine reservoirs are planned to operate during this period (2011-2090)

Table 3-6. Sustainability of water users under the equal priority scenario.

Water User	Sustainability (as a percentage)				
	1991-1998	2011-2018	2051-2058	2011-2050	2051-2090
Agriculture (WS1)	40.4	0.0	0.0	0.0	0.0
Agriculture (WS2)	40.4	0.0	0.0	0.0	0.0
Agriculture (WS3)	40.4	0.0	0.0	0.0	0.0
Agriculture (WS4)	26.0	0.2	0.0	0.9	0.0
Agriculture (WS5)	25.3	0.2	0.0	0.8	0.3
Agriculture (WS6)	100.0	20.1	5.9	23.6	5.7
Agriculture (WS7)	100.0	6.5	3.4	23.6	5.8
Domestic water use (Bolikhamsay Province)	100.0	100.0	100.0	100.0	100.0
Domestic water use (Luang Prabang)	46.1	78.4	14.9	38.1	10.7
Domestic water use (Vientiane Municipality)	100.0	98.7	16.6	32.8	11.8
Domestic water use (Vientiane Province)	30.2	2.8	1.6	2.3	0.9
Domestic water use (Xieng Khouang)	30.1	0.4	0.0	0.1	0.0

Table 3-7. Sustainability Group (SG) indices for different water user groups.

Time period	**Sustainability Group**		**% change from Baseline**	
	Agriculture	**Domestic**	**Agriculture**	**Domestic**
1991-1998	0.53	0.61	-	-
2011-2018	0.04	0.56	-93	-9
2051-2058	0.01	0.27	-97	-57
2011-2050	0.07	0.35	-87	-43
2051-2090	0.02	0.25	-97	-60

Table 3-8. Comparison of average annual hydropower production under different water allocation priorities for the historical and future time periods.

Priority Scenario	**Simulated Million kWH**					**Percent change compared to historical observed[3]**	
	1991-1998[1]	**2011-2018[2]**	**2051-2058[2]**	**2011-2050[2]**	**2051-2090[2]**	**2011-2018**	**2051-2058**
Hydropower = Irrigation & Domestic	925	3269	3115	3312	3000	272	255
Hydropower > Irrigation & Domestic	928	4164	4224	4329	4233	374	381
Hydropower < Irrigation & Domestic	924	3198	3015	3225	2889	264	243
Upstream > Downstream	925	3256	3094	3297	2980	271	252
Upstream < Downstream	930	3277	3121	3317	3144	273	255

[1] Hydropower generation is only by Nam Ngum 1 Dam

[2] Hydropower generation by six dams

[3] Historical observed average annual amount is 878 Million kWH

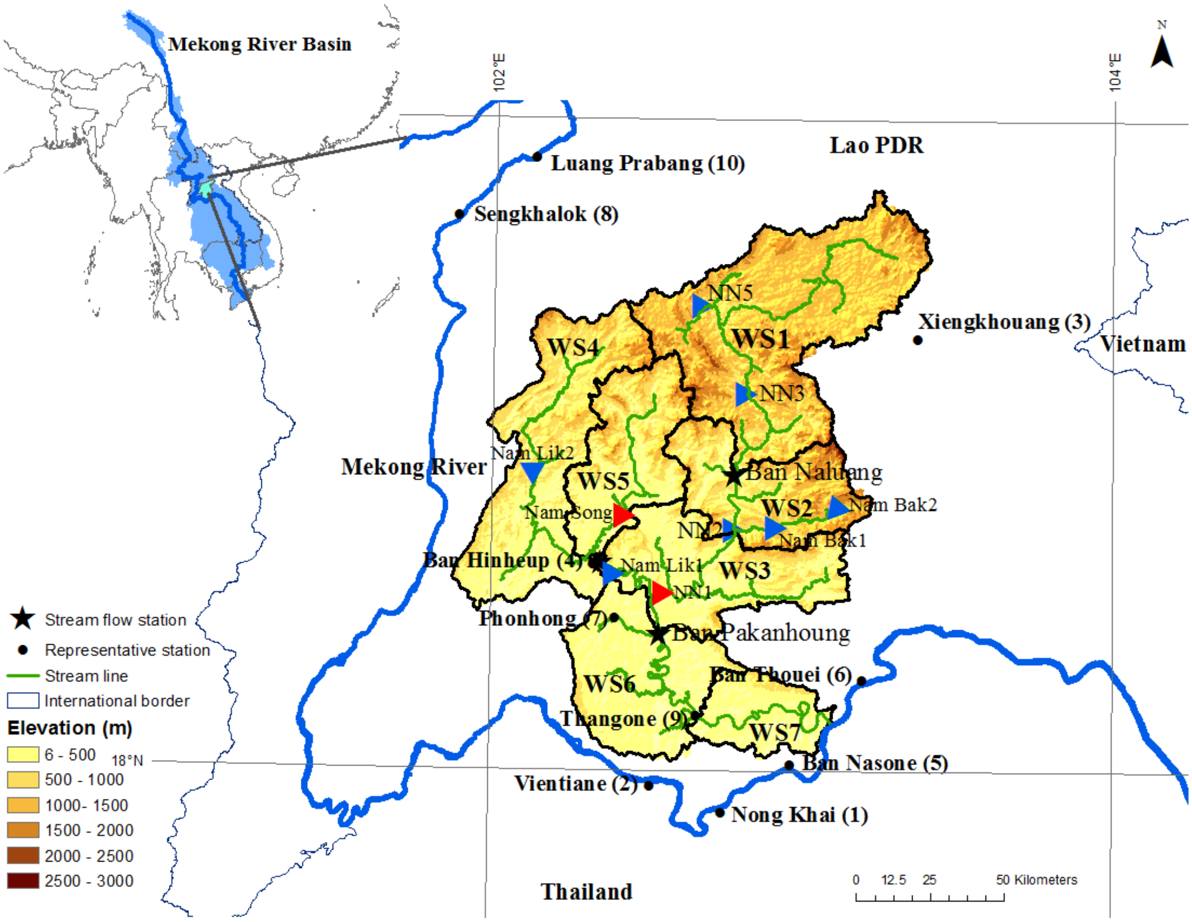

Figure 3-1. Physical layout the NNRB of Laos showing watersheds and other key features. Colored triangles represent existing (red) and under construction/planning stage (blue) reservoirs/dams.

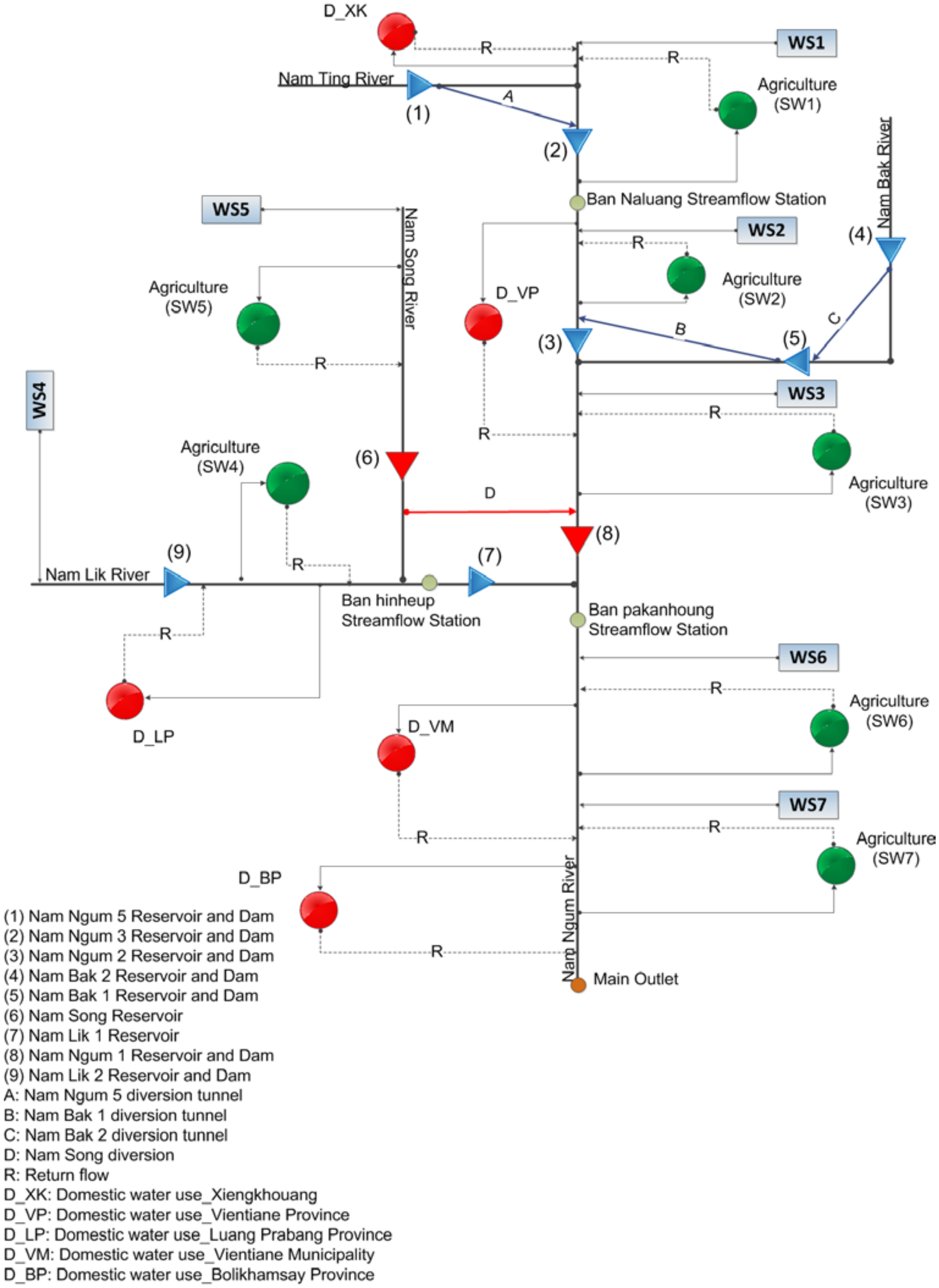

Figure 3-2. Schematic representation of watersheds and water infrastructure operations of the NNRB. Red triangles and solid red lines represent existing conditions and blue triangles and solid blue lines represent future conditions.

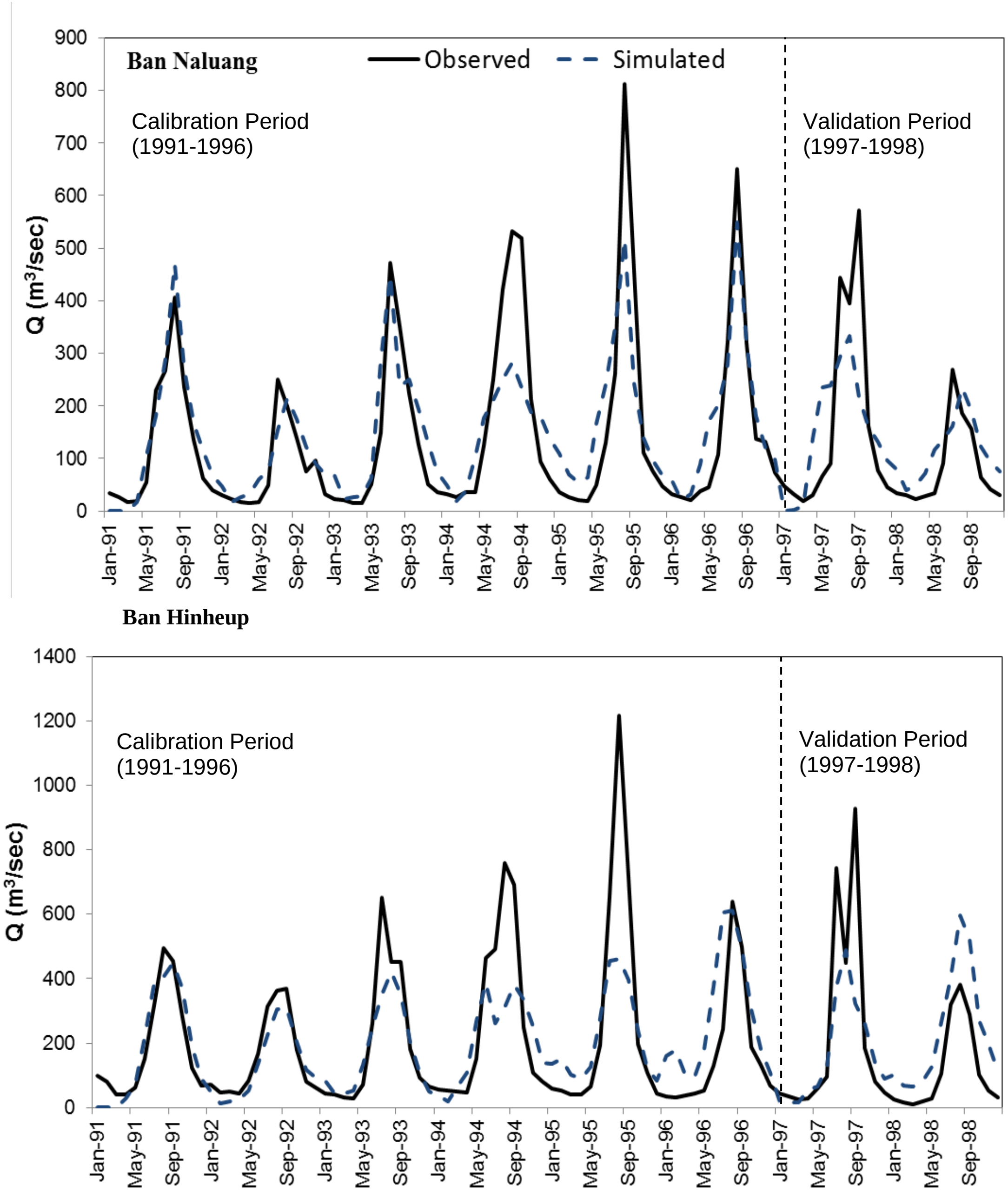

Figure 3-3. Comparison of simulated and observed average monthly streamflow at Ban Naluang and Ban Hinheup stations from 1991 to 1998.

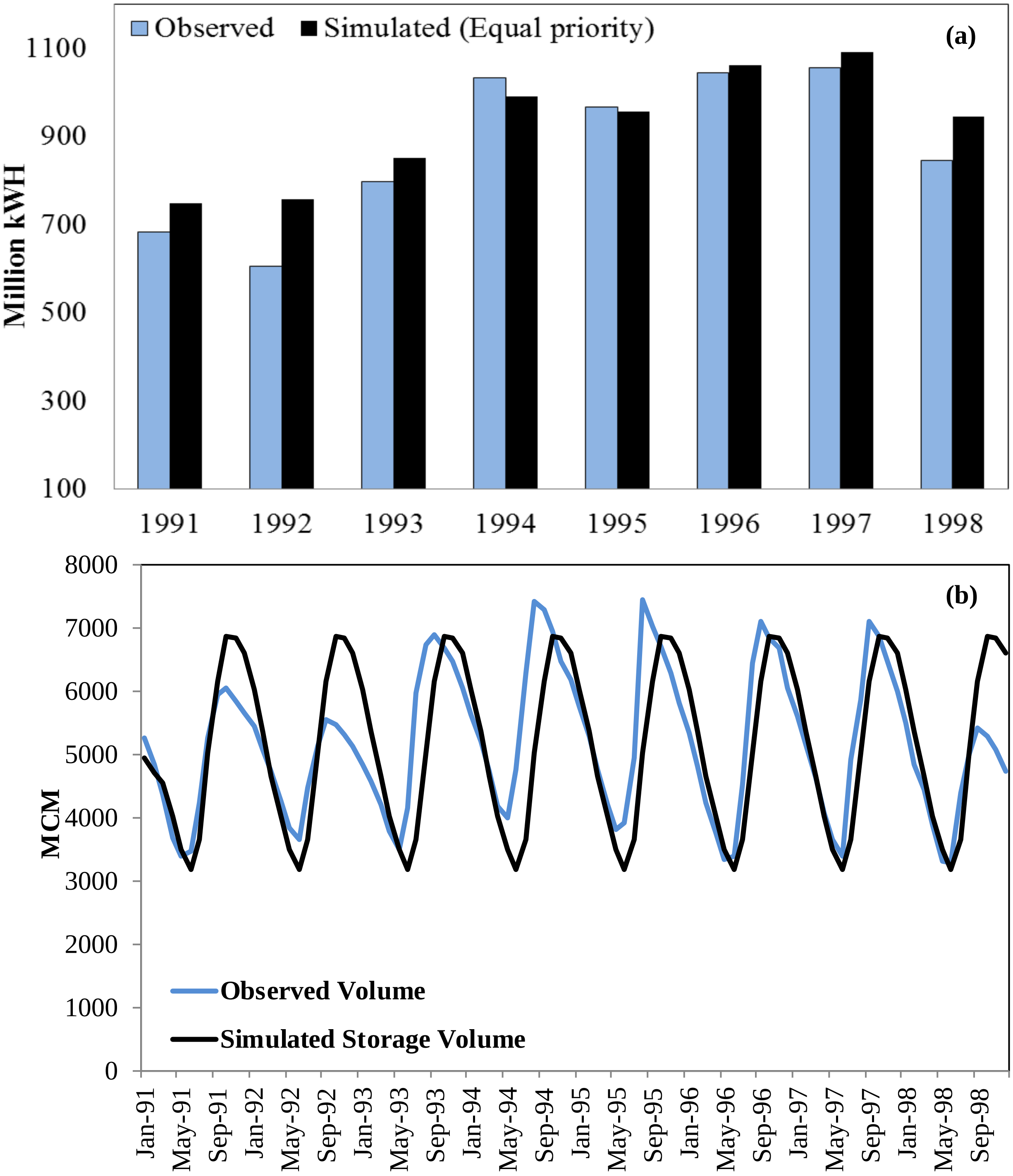

Figure 3-4. Comparison of observed and simulated values of (a) total annual hydropower generation, and (b) reservoir water volume at Nam Ngum 1 from 1991-1998.

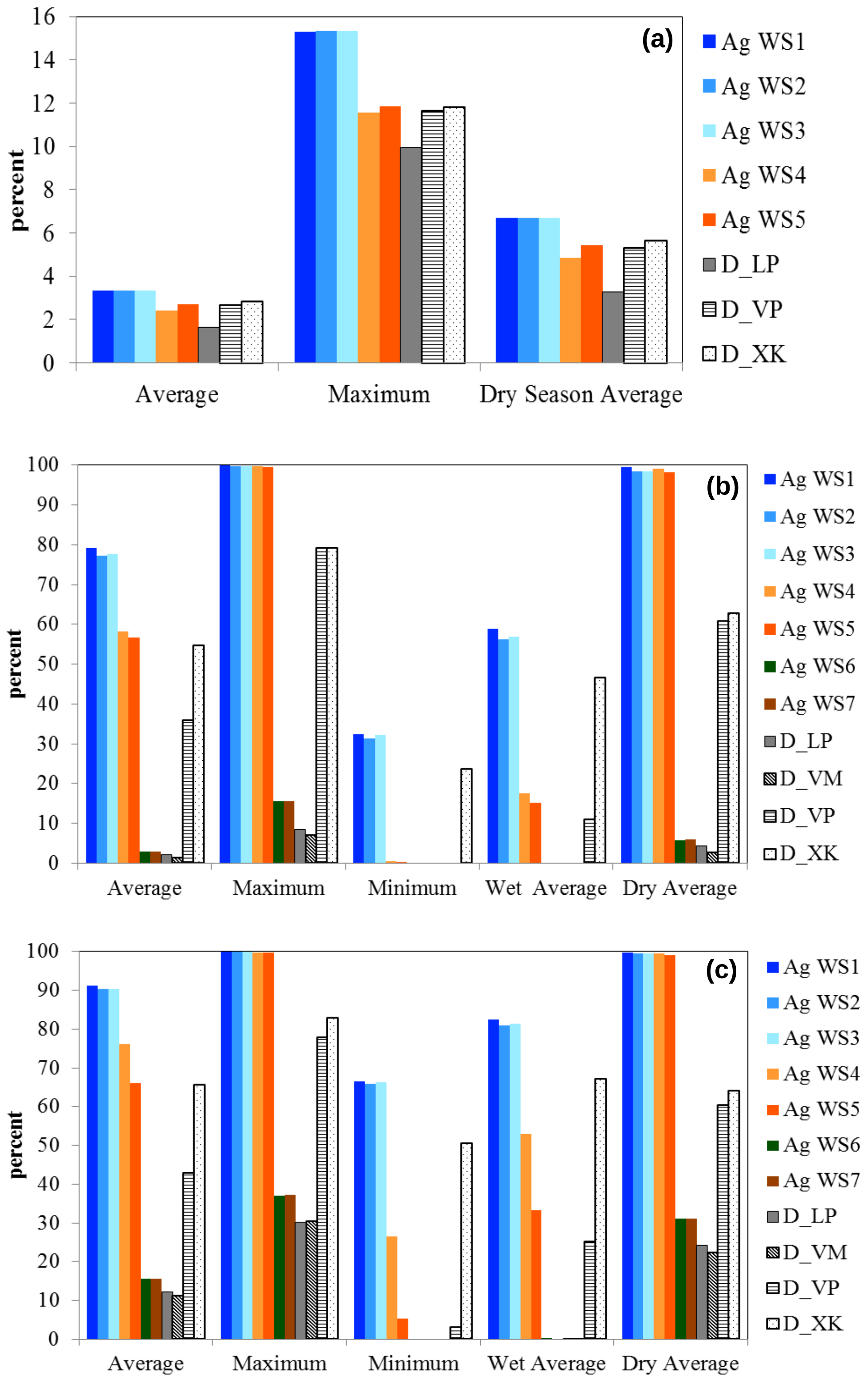

Figure 3-5. Comparison of percent unmet demand for agricultural and domestic water uses for (a) baseline (1991-1998), (b) 2011-2050 and (c) 2051-2090 time periods.

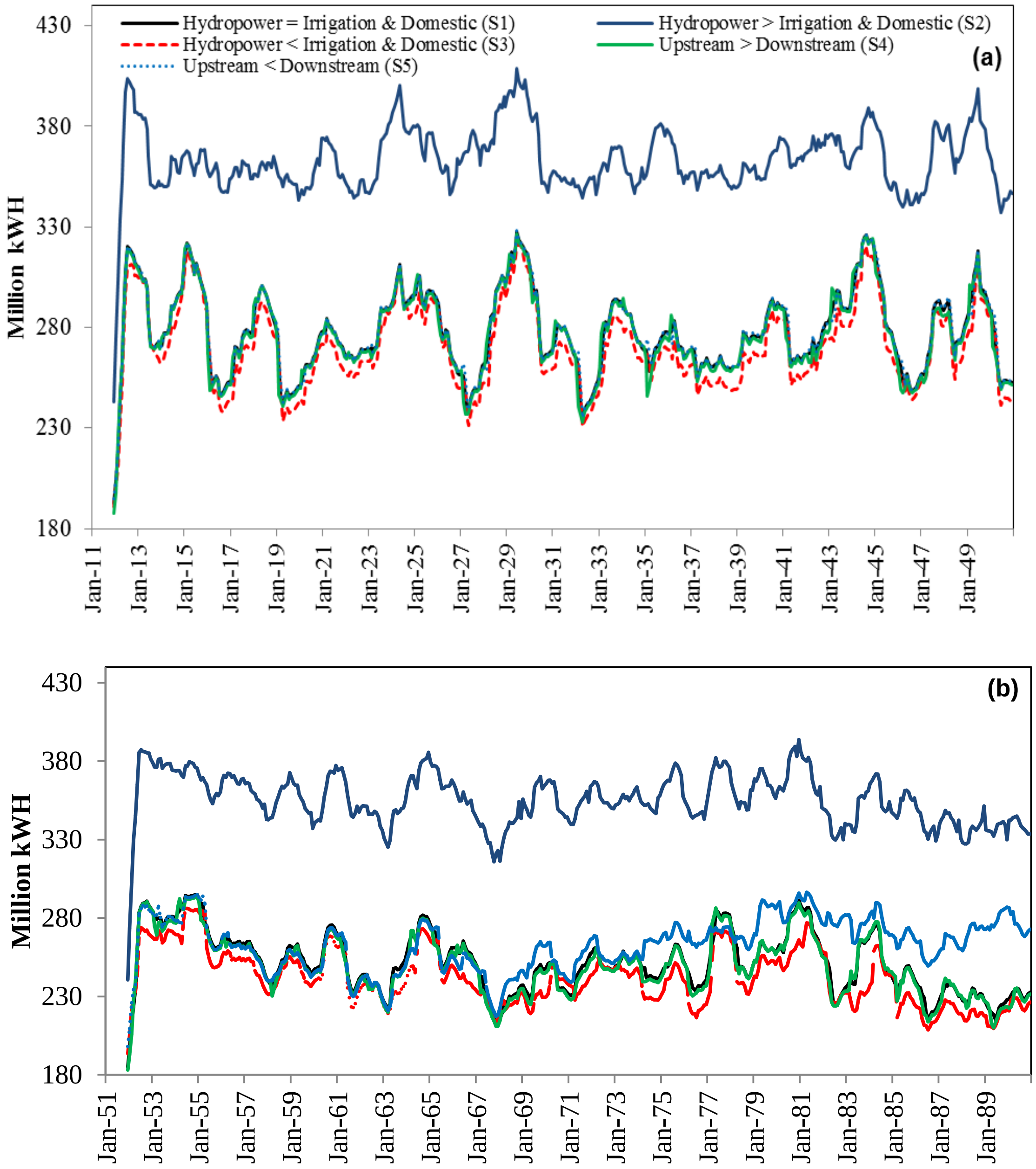

Figure 3-6. Comparison of 12-month moving averages of total monthly hydropower generation for different water allocation priority scenarios: (a) 2011-2050 and (b) 2051-2090.

APPENDIX

Table 3-9. Comparison of the percent changes of potential evapotranspiration (PET), rainfall (P) and aridity index (Φ) for 8-years future time period compared to the baseline period of 1991-1998.

Watershed	ΔPET (%)						ΔP (%)						ΔPET/P (%)	
	2011-2018			2051-2058			2011-2018			2051-2058			2011-2018	2051-2058
	Wet	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Wet	Dry	Average	Average	
WS1	5.0	3.7	4.4	71.9	72.2	72.0	25.4	39.4	32.4	21.3	55.5	38.4	-15.0	24.0
WS2	4.1	2.9	3.5	17.4	16.9	17.2	16.6	39.9	28.2	22.0	82.4	52.2	-20.3	-23.6
WS3	-1.7	-2.9	-2.3	-36.6	-36.9	-36.8	-2.1	29.9	13.9	-32.3	2.0	-15.1	-19.0	-28.0
WS4	-0.5	-1.7	-1.1	-1.1	-1.0	-1.1	26.5	43.1	34.8	38.1	113.3	75.7	-27.0	-44.2
WS5	-0.3	-1.6	-0.9	0.3	0.4	0.4	25.7	59.0	42.4	37.9	149.2	93.6	-30.6	-48.1
WS6	7.1	5.5	6.3	93.8	92.4	93.1	3.3	32.1	17.7	104.9	153.7	129.3	-13.1	-16.1
WS7	9.5	8.3	8.9	98.3	97.5	97.9	15.3	8.6	12.0	107.2	122.4	114.8	-1.6	-6.8

CHAPTER 4

ANALYSIS OF LONG-TERM TRENDS OF WATERSHED IMPACTS AND CLIMATE CHANGE ADAPTATION STRATEGIES FOR THE NAM NGUM RIVER BASIN, LAOS [1]

Abstract

The Nam Ngum River Basin (NNRB) of Laos is expected to undergo rapid economic development and population growth in the coming decades since it has a high potential for hydropower generation for income growth. This study assesses the hydrological and human influence impacts under climate change and explores potential adaptation measures to minimize negative consequences. Using the third generation coupled general circulation model (CGCM3.1 T63) and A2 emission scenario, the trends of rainfall, potential evapotranspiration (PET), and streamflow changes were investigated using the seasonal Mann-Kendall Trend test. The results showed high upward rates of change of PET compared to the upward trends of rainfall for almost all watersheds under the status-quo. Streamflows showed downward trends in north, central, and southern parts of the basin in the latter half of the century. With the proposed climate change adaptation measures to improve water productivity with improved irrigation practices and reduced water conveyance losses, streamflows produced an increasing trend compared to the status-quo and reduced water shortages while improving sustainability in both agricultural and domestic

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[1] Coauthored by Dumindu Jayasekera and Jagath J. Kaluarachchi

water use sectors. This work considered five priority water allocation scenarios. As a result of the proposed climate change adaptation measures, total hydropower generation increased in all scenarios for both future time periods. The results showed the possibility of maintaining sustainability in the 21st century by implementing adaptation strategies to improve water productivity under climate change for all allocation scenarios.

4.1 Introduction

Climate change is expected to have significant impacts on large river basins in sub-tropical and tropical regions [*IPCC*, 2007a]. The impacts are projected to be drastic, particularly in South-East Asia (SEA), according to *Hinkel and Menniken* [2008]. International river basins, such as the Mekong River Basin, provide vital resources to support the livelihoods and the development of societies. Yet the availability of transboundary water resources is vulnerable to stressors, such as climate change, growing populations, and developing economies [*World Water Assessment Programme,* 2009]. Climate change impacts in developing countries are likely to bring new challenges and magnify existing problems, thus impacting both livelihood and food security. Even though the magnitude of the estimated climate change impacts depends on a particular scenario, increases in global temperature are expected to continue for decades, even if greenhouse emissions are stabilized today [*IPCC*, 2007b]. Therefore, actions are needed to respond to these impacts and the corresponding discussions about climate change have consequently shifted from mitigation towards adaptation. Climate change adaptation has thus become one of the focal points of current development discussions given the multiple linkages that climate change has with development [*Le Blanc*, 2009]. Previous research studies highlighted the need for adaptation to address such challenges in international river basins [*Drieschova et al.,* 2008; *Eckstein,* 2009; *Lebel et al.,* 2010; *Cooley and Gleick*, 2011] and in the Lower Mekong River Basin [*Keskinen et al.*, 2010]. Ideally, a comprehensive climate change strategy should include adaptation and mitigation, however, for most people whose livelihoods are already affected by climate change, adaptation is the more urgent issue [*IFAD*, 2008]. Intergovernmental Panel on Climate Change (IPCC) AR4 Report [*IPCC*, 2007c] defined climate change adaptation as "adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities" and established adaptation measures as actual adjustments, or changes in decision environments, which might ultimately enhance resilience or reduce vulnerability to observed or expected changes in climate [*Adger et al.*, 2007].

Climate change poses a threat for developing countries and communities as they work towards sustainable development. The key issue for millions of people in Asia is how to adapt to the uncertainties posed by climate change, across multiple sectors. In the context of development, the challenge is to understand how planning and decision-making need to change in order to strengthen resilience and reduce climate-related risks. A study conducted in 2009 by the United Nations Food and Agricultural Organization (FAO) and the International Water Management Institute (IWMI) found that without dramatic improvements in irrigation, many highly populated Asian countries will have a one-quarter deficit in their grain supply by 2050 [*The Scientist*, 2013]. Furthermore, the FAO estimated that by 2050, the world must grow enough food to support 2.7 billion additional people and it must do so with much less water [*The Scientist*, 2013]. The structure of a basin, in terms of water use, is more important even if basins are located in a similar climatic zone where predicted climate change effects may be similar [*Nicole et al.,* 2010]. For example, Mekong River Basin's main challenge is hydropower development. Mekong is an international river basin that requires adaptation because it has become vulnerable to climate related and human induced stressors [*Grumbine and Xu,* 2011]. Thus, the success of adaptation measures also requires addressing non-climatic issues and drivers of vulnerabilities at the local level [*World Bank*, 2010]. In the case of the agricultural sector, for example, the implications of climate change might need to be viewed in conjunction with other stresses, such as water availability, demographic trends, and trends in trade and commodity prices. Such integrated information is important to both national governments and external donors, to facilitate meaningful integration of adaptation at the sector level. A report from the Asian Development Bank (ADB) by *Zuang et al.*, [2010] reviewed adaptation measures for SEA and identified five sectors: (a) water resources, (b) agriculture, (c) forestry, (d) coastal and marine resources, and (e) health. The report concluded that the water resources sector needs adaptation strategies to address water shortages in SEA countries. It also mentioned that integrated water management, including flood control and prevention schemes, irrigation improvements, and demand-side management, should be applied widely to capture multiple benefits. *Keskinen et al.*, [2010] stated an exception to the opposing effects of climate change and hydropower development where the dry season water level is estimated to increase due to both hydropower development and climate change in the Lower Mekong River Basin. Given the negative consequences that are expected to occur in the floodplain ecosystems of the Lower Mekong Basin [*Kummu* *and Sarkkula,* 2008], this combined impact of increased dry season water level poses a serious concern to the floodplains.

The different adaptation strategies may include anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation [*Lasco et al.,* 2011]. Reactive adaptations are those that are implemented after the impacts of climate change are experienced, while anticipatory adaptations are proactive and are undertaken before the impacts of climate change are fully realized [*Dolan et al.,* 2001]. Autonomous adaptations are responses to changes in climate that do not require the intervention of other institutions or sectors (i.e. policy, research) in their implementation [*FAO,* 2007]. On the other hand, planned adaptations are those formulated with the involvement of institutions and the use of policies where the goal is the enhancement of adaptive capacity through a maximization of opportunities and the use of new technologies and infrastructure [*Dolan et al.,* 2001; *FAO*, 2007]. The final goal of all adaptation mechanisms is to address climate risks, enhance resilience, and reduce vulnerability [*O'Brien et al.,* 2008].

The way land use changes as a country develops also plays a significant role in the changes to hydrologic regimes, especially with rapid economic and societal developments. Urbanization increases surface runoff and decreases evapotranspiration and groundwater flows [*Jonathan et al.,* 2005]. Moreover, with the increase in population and economic developments, domestic water demand and irrigation affect water supply through withdrawals and diversions. Because of these complex interactions, it becomes important to understand the changing trends in rainfall, potential evapotranspiration, and runoff in a watershed.

The Nam Ngum River Basin (NNRB) is a part of the Mekong River Basin undergoing rapid changes due to economic growth, land use changes, and population growth. Previous work focused on understanding the climate change impacts and predicted the hydrologic regime changes under climate change [see Chapter 2]. Jayasekera and Kaluarachchi [see Chapter 3] demonstrated the applicability of a water resources planning system to assess the hydrologic response and watershed impacts due to projected climate change. Jayasekera and Kaluarachchi [see Chapter 3] developed a Water Evaluation And Planning System (WEAP21) modeling framework at the watershed-scale, incorporating the climate change driven hydrologic cycle and water infrastructure operations, such as dams for hydropower and water storage and diversions for irrigation. The results from both studies showed climate change affects rainfall and potential evapotranspiration (PET). A significant increase in rainfall was observed in the dry season but a high percent increase of PET, mostly in the northern and southern parts of the NNRB, was also noticed using CGCM3.1 T63 data for the 21st century. Given the hydrologic impacts due to climate change and human induced water infrastructure and land use changes, the NNRB may require adaptation measures to overcome potential negative impacts due to climate change. As a first step in this direction, this study investigates the trends of hydrologic and watershed responses under climate change to confirm adaptation measures are needed. If there are negative impacts, then adaptation strategies are investigated.

The goal of this work is to quantify the climate change related impacts in the NNRB and identify the potential adaptation measures that may minimize the negative consequences of climate change. We will study the trends of precipitation (P), potential evapotranspiration (PET), and runoff (Q) in different watersheds of the NNRB, identify the probable causes (climate or human) for trends, and propose appropriate adaptation measures to help mitigate the negative impacts of climate change. This study will focus on trends and the water availability to meet water demands under different allocation priority scenarios between hydropower, irrigation, and domestic uses.

4.2 Methodology

This study is a continuation from the earlier work related to the hydrologic modeling of the NNRB under climate change using the WEAP 21 modeling system (see Chapter 3). This study uses the CGCM3.1 T63 general circulation model with the A2 emission scenario that provides the worst case scenario for greenhouse gas emissions in the 21st century. First, the climate change impacts are assessed using the annual trends of climatic variables and percent changes in precipitation and PET during the wet and dry seasons at the watershed scale compared to the baseline period. Human impacts are assessed by estimating the percent of unmet demands (or water shortages) for agricultural and domestic water users at each watershed. At this stage, suitable adaptation measures will be identified and applied in the analysis to assess if these strategies can help reverse the negative impacts of climate change in the 21st century. These adaptation analyses will be conducted for different sectors consisting of domestic, forestry, and agriculture.

4.2.1 Description of the Nam Ngum River Basin

The NNRB has a drainage area of about 16,777 km^2 at the main outlet close to the confluence with the Mekong River (Figure 4-1). The elevation of NNRB varies from 6 m to 2684 m above mean sea level (msl). The mean slope of the basin is about 25.5%. The

NNRB's annual flow contribution to the Mekong River is about 14% of the 40% of the country's contribution. The estimated population of the basin is 502,150 in 2005, which is approximately 9% of the population of Laos [*WREA*, 2008]. The main land use types of the NNRB are natural forest at 47%, shrubland at 34%, agricultural at 8%, grassland at 7%, water surface at 3.98%, and urban area at 0.02% of the total area [*WREA*, 2008; *WREA*, 2009].

The climate of the NNRB is subtropical to tropical with a distinct wet season from May to October and mostly dry during the rest of the year. Most of the rainfall is due to the arrival of warm moist air during the south west monsoon. The hottest months are March to April and the mean daily maximum temperature varies between from 28° to 34° C. The mean minimum temperature varies between 14° and 24°C and occurs between December and January at higher elevations [*ADB*, 2008]. The mean annual rainfall of the NNRB is 2000 mm, varying between 1400 to more than 3500 mm [*WREA*, 2009]. The mean annual Penman-Monteith PET varies between approximately 1060 mm and 1360 mm [*ADB*, 2008].

Figure 4-1 shows the proposed watersheds consisting of WS1 in the north to WS7 in the south. The historic observed mean annual unimpaired runoff from 1991 to 1998 for WS1 is approximately 4.8 billion cubic meters (BCM). The largest watershed of the NNRB is WS1 with an area of 4617 km^2 whereas the smallest has an area of 997 km^2. According to Table 4-1, WS6 and WS7 have slightly higher drainage densities compared to the other watersheds, indicating a higher tendency to generate more surface runoff and a higher erodibility of surface materials. Therefore, WS6 and WS7 tend to have limited infiltration capacity and promote runoff.

The northern part of the NNRB is at a higher elevation with a mean elevation of about 1173 m, whereas the southern parts consist mostly of plains with elevations less than 250 m. The northern watersheds of the NNRB are steep at their headwaters with slopes that generally decrease toward the Vientiane Plain. The estimated base flow index using daily streamflows for the Ban Naluang and Ban Hinheup Watersheds are 0.66 and 0.63, respectively, indicating that the influence of soil and geology on river flows is similar in both watersheds.

4.2.2 Long-Term Trends in Climate and Hydrologic Variables

The analysis of rainfall trends is important for monitoring the hydrologic response of watersheds to climate change. Similarly, the analysis of runoff trends is important for understanding human influence on hydrology. While observed trends of P and PET are associated with climate change, the trends in Q cannot entirely be due to the changes in climatic variables, but may be due to a combination of climatic and water management effects (human influence). Trends in P, PET, and Q were estimated using the Seasonal Mann-Kendall (SMK) Trend test using monthly data. In this work, a SMK statistic at 5% significance level (p-value ≤ 0.05), and a Sen Slope were estimated. The 12-month period from January to December was selected for the trend analysis for both future time periods from 2011 to 2050 and from 2051 to 2090. Variance was corrected for serial dependency and autocorrelation was considered using the approach proposed by *Hamed and Rao* [1998].

Probable causes for the trends can be described as follows: (a) a trend in P alone could be due to climate, (b) a trend in PET alone could also be due to climate, (c) trends in Q indicate human influence, and (d) trends in P, PET and Q indicate a combined effect of climate and human influences.

4.3 Adaptation Strategies

4.3.1 Agriculture Sector

It is estimated that the under status-quo condition, the annual agricultural water demand will increase due to the increase of irrigated area by 2% [*World Food Programme,* 2013]. According to *ADB* [2005], there are high transmission losses in unlined canals with permeable soils and only about 10-20% of the water reaches the tail of the irrigation area. An assessment of the impacts on the agricultural sector was performed using the percent of unmet water demand for irrigation for each watershed.

With the proposed adaptation strategies of using FAO recommended seasonal rice water requirement of 700 mm with alternate wetting and drying, the average percent of water shortages for agriculture is reduced. Furthermore, the annual increase in land area for irrigated agriculture, including paddy cultivation, is increased by 1%. Paddy cultivation area is calculated based on the population growth and assuming that the average annual per capita rice consumption and yield remain constant. The same assumptions were followed for other crop varieties too.

Recent reports by *ADB* [2009] and *Lasco et al.,* [2011] identified the common adaptation techniques of SEA to be changes in cropping patterns and the cropping calendar, improved farm management, and the use of climate-resilient crop varieties.

Changes in farm management practices and the irrigation methods used to manage the lands can be another adaptation measure in SEA. The concept behind this practice is to increase the chances of harvest even in the event of extreme rainfall events and variable water availability. *Tabbal et al.,* [2002] compared rice yield, water use, and water productivity on rice cultivation in the Philippines under alternate wetting and drying and continuously flooded conditions. The results showed that alternate wetting and drying improves water productivity to 0.61 g grain kg^{-1} water and yield to 4.3 tons per hectare with a total water input of 700 mm. According to *Tabbal et al.,* [2002] this is a significant improvement compared to continually flooded conditions. Furthermore, *FAO* [1986] recommends the seasonal crop water need for rice to be between 450-700 mm. This study proposed alternate wetting and drying and the FAO seasonal crop water requirements, and specified the minimum, maximum, and target water depths for ponding water requirements for northern and southern parts of the basin. Since the highest agricultural water use is for paddy cultivation, this study will consider an annual irrigated area increase of 1% by using the future population growth rate projected for Laos [*United Nations,* 2011], with an average annual rice consumption of 163 kg per person [*IRRI,* 2012], and an average rice yield of three tons per hectare for the wet season in the lowlands, wet season uplands, and dry season irrigated [*USDA*, 2011]. Apart from the improvements in water productivity, this study proposes to investigate the demand management of agricultural water by reducing irrigation water conveyance losses by 50% through canal lining. This measure will improve water availability for agriculture compared to the existing 80-90% losses in the permeable soils [*ADB*, 2008].

4.3.2 Domestic Water Use Sector

The Government of Lao has promoted the adoption of integrated water resources management (IWRM) since 1998 to exploit the considerable potential of water resources without compromising the long-term quality of the environment and the well-being of local communities [*WREA*, 2008]. This study uses the *WHO* [2003] recommended domestic water consumption rates for drinking, cooking, washing dishes and clothes, and bathing as an adaptation strategy to climate change for the purposes of drinking, food preparation, washing, and bathing.

4.3.3 Forestry Sector

Kamusoko et al., [2013] simulated future forest cover changes in Pakxeng District, Luangprabang Province in Laos under the status-quo conditions and identified “hot spot” areas where rapid decline in current forest areas would likely to occur in the future. This scenario indicated increased forest loss and degradation in the future if no immediate mitigation measures are undertaken. Under the most optimistic scenario, current forest areas increased mainly due to forest regrowth. This conclusion suggests that sustainable forest management efforts should encompass strategies, such as strict enforcement of forestry laws, which would enhance forest regrowth. The implications of the simulated future forest cover changes under the optimistic scenario for sustainable forest management are critical.

Recognizing the value of forests on its economy and livelihood of people, the Laos Government has set a long term goal of increasing forest cover by 70 to 79% by 2020 [*Ministry of Agriculture and Forestry,* 2005; *Baccam,* 2008]. Meantime, Laos' forests have steadily shrunk over the past 15 years, from 47% in 1992 to 41% in 2002, and now 35%, because of illegal loggings and indiscriminate concessions. Since 2000, there have been over 2,600 ha of new forest planted in the capital city of Vientiane, and in the Vientiane and Xiengkhouang Provinces which are three important regions of the NNRB [*Water Resources Coordination Committees,* 2007].

Using the goal of the Laos Government in increasing the forest area of the country, application of agroforestry can be a better climate change adaptation strategy for the NNRB. Agroforestry is the practice of planting woody perennials (i.e. trees or shrubs) on the same land management unit as agricultural crops and these forest lands can be integrated with vegetable crops or tree integration in vegetable productions system. This can be a viable farming system in mountainous areas. Trees on farmlands enhance soil and water conservation and efficient nutrient cycling and conservation. Furthermore, an increase in forest area improves better interception of rainfall, and slow absorption of water and moisture retention in the soil. Previous work (see Chapter 3) showed the potential future reduction of dry season streamflow at the basin outlet under status-quo, an increase in average annual rainfall mainly in the north, north-east, western, and central parts of the basin, and an increase in dry season average PET. This study therefore proposes agroforestry as an adaptation strategy. As a part of this strategy, the annual forest cover area will be increased in the north, north-eastern and central parts of the basin. The annual percent increase to the existing forest cover land area is 0.1% in WS1, WS2, WS3, and WS5, and by 0.01% in WS4 from 2011 to 2050. Similarly, the proposed annual forest cover area increases of WS1, WS2, and WS4 is 0.01%, and WS3 and WS5 is 0.1% from 2051 to 2090. The primary objective of increasing the forest area is to increase interception and water infiltration. The other benefits of increasing forest cover are the protection of soil and water, particularly in sensitive areas, and the recovery of leached or drained nutrients by the deep tree roots. It also enriches the soil organic matter by tree litter and dead tree roots.

4.4 Results and Discussion

4.4.1 Trends of Climate and Hydrologic Regimes

The results of the assessment of long-term trends of P and PET are presented in Table 4-2. Of the seven watersheds in the NNRB, WS7 and WS2 show statistically significant (p-value ≤ 0.05) highest and lowest increasing trends of P of 0.32 mm per year and 0.08 mm per year, respectively, from 2011 to 2050. WS3 shows a statistically significant decreasing rate of change in rainfall of 0.19 and 0.18 mm per year from 2011 to 2050 and from 2051 to 2090, respectively. It is notable that there is an increasing rate of change in rainfall in the southern parts of the basin compared to the north, north-eastern, and central parts of the basin. Although downtrends of rainfall were observed in WS1, WS2, WS4, and WS5 for the latter part of the century, these trends were not statistically significant.

A comparison of PET trends shows that the statistically significant 0.96 and 0.95 mm per year increasing rate of change is present in WS1 from 2011 to 2050 and from 2051 to 2090. The lowest statistically significant increasing trend of 0.23 mm per year in PET is observed in WS3. Increasing rates of change in PET are statistically significant in most parts of the basin. Overall results indicate that the rates of change in PET trends are higher compared to the rates of change of rainfall for both future time periods.

Table 3 shows the comparison of changes in hydrologic regimes using rates of change and trends in streamflow under different priority allocation scenarios. The Seasonal Mann-Kendall Trend test results indicated statistically significant downtrends in streamflow under the status-quo condition from 2051 to 2090 at the Ban Naluang and Ban Hinheup stations. The majority of downtrends were observed in the Ban Naluang streamflow station located in the north-eastern part of the basin during the latter part of the century. This could be due to the combined effects of climate and human influence with the increase in land use change for agricultural and domestic water uses. As seen in Table 4-2, rainfall from 2051 to 2090 is decreasing (while not statistically significant) at a rate of 0.01 mm per year whereas the rate of change in PET is upward (statistically significant) at 0.95 mm per year.

As shown in Table 4-3, water availability is decreasing at the basin outlet when hydropower generation is given highest relative priority over other water users for both future time periods. One reason is that water is stored in reservoirs for hydropower generation. The maximum statistically significant upward trend is 0.34 mm per year at the basin outlet is observed when water users downstream to Nam Ngum 1 reservoir is given highest relative priority over water users upstream.

4.4.2 Assessment of Climate Change Impacts

A climate change impact assessment was conducted using the estimated changes in average annual rainfall, wet and dry season rainfall, average wet and dry season PET, average aridity index, change in the runoff ratio at the basin outlet, and the change in the average wet and dry season streamflows at the basin outlet. Figure 4-3 shows the climate change impacts from 2011 to 2050 and from 2051 to 2090. It can be seen that the percent of average annual rainfall increased in most parts of the basin except in WS6. The highest increases of 42% and 46% were observed in WS5 from 2011 to 2050 and from 2051 to 2090, respectively. There was a reduction of 4% and 1% average annual rainfall in WS6 for the same periods. It is notable that the percent increase in dry season average rainfall is significantly higher compared to the wet season average rainfall (Figure 4-3). The highest increases in percent dry season rainfall of 68% and 103% were observed in WS5 from 2011 to 2050 and from 2051 to 2090, respectively. The highest increases in percent wet season rainfall were 34% and 30%, which were also observed in WS5 for the same future time periods. Therefore, it is important note that the highest average annual dry and wet season rainfalls occur in WS5 for both future time periods. Compared to rainfall, the highest average dry season PET increases of 29% and 92% and the wet season PET increases of 28% and 90% occur in WS7 from 2011 to 2050 and from 2051 to 2090, respectively. It is notable that the percent increase in average dry and wet season PET is higher compared to the percent increase in average dry and wet season rainfalls of WS1 from 2051 to 2090. This is due to the changes of minimum and maximum temperatures, relative humidity, and wind speed. Runoff ratio at the basin outlet decreases for both time periods but the highest decrease in runoff ratio of 69% during the wet season and 95% during the dry season occurs in the latter part of the century. A comparison of streamflows at the basin outlet shows that the average wet and dry season streamflows decrease for both future time periods. The highest percent decrease of 62% for the average wet season and 92% for the average dry season occurs from 2051 to 2090. The annual streamflow at the basin outlet is estimated at 7.6 billion m^3 (BCM) and 5.3 BCM from 2011 to 2050 and from 2051 to 2090 with percent decreases of 60% and 72%, respectively. The reasons for the decrease in streamflows are due to the reservoirs, consumptive use due to population and irrigation water demands, and high evaporation due to temperature increases.

Previous results revealed that statistically significant increasing rates of PET are higher than the increasing rates of change in rainfall in almost all parts of the basin for both future time periods. Statistically significant decreasing rates of streamflow, mostly at the northern parts of the basin, confirm that this climate change and human induced changes affect downstream water users, also confirming that adaptation measures are needed to improve water availability and system sustainability.

4.4.3 Effectiveness of Adaptation Measures

4.4.3.1 Agricultural Sector

According to Figure 4-3, the percent of unmet water demand is highest in the north and north-eastern parts of the basin for both future time periods under the equal priority scenario. The highest average unmet water demands of 79%, 78%, and 77% for agriculture were observed in WS1, WS3, and WS2, respectively from 2011 to 2050. The highest average unmet water demands of 91%, 90%, and 90% for agriculture were observed in WS1, WS2, and WS3, respectively, from 2051 to 2090. The results show that average unmet water demands of WS4 and WS5 were 58% and 57% from 2011 to 2050, whereas they were 76% and 66% from 2051 to 2090. The lowest average agricultural water shortages were observed in WS6 and WS7 of 3% each from 2011 to 2050, and 16% each from 2051 to 2090. Domestic water use was less impacted compared to the agricultural water use. The highest average water shortages of about 55% and 66% for domestic water use were seen in the Xienkhouang Province from 2011 to 2050 and from 2051 to 2090, respectively. This is probably due to the higher water demand from paddy cultivation in the order of 1.5 million m^3 per km^2 or 1500 mm per year. Furthermore, the high transmission losses of water in unlined canals, amounting to 80-90%, require more water to meet the irrigation water demands. The overall results indicate that the average water shortages for agricultural and domestic sectors are high in the latter half of the century.

The percent of water shortage reductions of 23%, 53%, 53%, 19%, 19%, 100%, and 100% were achieved in WS1, WS2,WS3, WS4, WS5, WS6, and WS7 from 2011 to 2050, whereas there were reductions of 13%, 46%, 46%, 24%, 26%, 100%, and 100% from 2051 to 2090. It is observed that by using these adaptation measures, the agricultural water requirements of WS6 and WS7 are fully met.

4.4.3.2 Domestic Water Use Sector

It is seen that the domestic water demand is less impacted compared to the agricultural water demands for both future time periods under the status-quo condition. As seen in Figure 4-3, domestic water use in the Xiengkoung Province is heavily affected with an average unmet water demand of 55% compared to the average unmet water demand of 66% from 2011 to 2050 and from 2051 to 2090, respectively. Compared to the Xiengkoung Province, domestic water use in the Viantiane Province is less affected with average percent water shortages of 36% and 43% from 2011 to 2050 and from 2051 to 2090, respectively. It is notable that the domestic water shortages are significantly higher in the upstream areas compared to the downstream areas of the basin. With the adaptation of WHO recommended domestic water use consumption rates for drinking, cooking, washing dishes and clothes, and bathing, domestic water shortages are reduced significantly for both future time periods. Furthermore, this adaptation measure significantly minimized the domestic water shortage in the Xiengkoung Province by 36% and 33% from 2011 to 2050 and from 2051 to 2090, respectively. Water shortages in the downstream areas were completely resolved by this adaptation strategy.

4.4.3.3 Forestry/Land use Sector

With an annual increase in forest cover to practice agroforestry (i.e. the integration of agricultural crops and forest lands), the changes in hydrologic regimes are compared with the status-quo condition. It is notable that the frequency of statistically significant uptrend of streamflows is increased as per Table 4-3. This means that the availability of water is increased. Also, the frequency of statistically significant downtrends of streamflow was decreased and a higher frequency of statistically significant uptrend of streamflow was observed at Ban Naluang, Ban Hinheup, and the basin outlet. This overall improvement in hydrologic regimes in terms of statistically significant uptrends in streamflows indicates that the water availability is increased. Moreover, the highest statistically significant of 0.23 mm per year in streamflow at Ban Naluang was observed from 2051 to 2090 for the priority scenario 3 (i.e. priority for irrigation and domestic water use is greater than hydropower). An uptrend of streamflows was observed from 2011 to 2050 for all streamflow stations. It is interesting to note that with climate change adaptations in place and with all water allocation scenarios from 1 to 5, statistically significant uptrends in streamflows were observed at the basin outlet from 2011 to 2050. On the other hand, a downtrend at the basin outlet was observed for the same time period without the adaptation measures. The reasons for this uptrend in streamflow with adaptation measures in place are due to the increase in urban land cover with a population increase, more water availability from improved irrigation practices, and the reduction of conveyance losses in irrigation canals by 50%. Although not shown here, population is increasing and therefore domestic water demand increases. On the contrary, with climate change adaptations in place for every water allocation scenario from 1 to 5, statistically insignificant downtrends in streamflow were observed at the basin outlet from 2051 to 2090. The reason could be due to the downtrends in rainfall in most upstream watersheds and statistically significant uptrends in PET in most watersheds. Even though the downtrend of streamflow at the basin outlet is not statistically significant, it is notable that the wet and dry season average streamflows at the basin outlet increased compared to the status-quo condition for both future time periods under the equal priority scenario. Under the equal priority scenario, and with adaptation in place, it is estimated that the dry season average streamflows increased from 1.7 to 7.0 BCM from 2011 to 2050 and from 0.5 to 6.9 BCM from 2051 to 2090. For the same scenario, wet season average streamflows increased from 6.0 to 9.8 BCM from 2011 to 2050 and from 4.8 to 9.0 BCM from 2051 to 2090. The reason could be that with increased water availability due to adaptation measures, water allocation for each water demand sector attempts to minimize water shortages subjected to water availability from a nearby supply source.

4.4.4 Unmet Water Demands, Hydropower Generation, Sustainability, and Vulnerability

In general, water shortages of agricultural and domestic water users are highest in the northern and northeastern parts of the basin. Table 4-4 shows the percent changes of unmet water demands of agricultural and domestic water users compared to the status-quo condition. It can be seen that climate change adaptation measures reduced the percent unmet water demand in all water users. It is also observed that the downstream agricultural unmet water demands in WS6 and WS7 are fully met with the proposed climate change adaptations measures. According to Table 4-2, WS1 is affected by high PET rates compared to other parts of the NNRB. The percent change of average rainfall amounts of WS1 are about 37% for both future time periods and the average PET amounts are about 19% and 53% from 2011 to 2050 and from 2051 to 2090, respectively. Table 4-4 shows that the maximum average percent reduction of 89% of unmet water demand is achieved under scenario 5 (i.e., upstream is given a lower priority than downstream). The maximum average dry season percent reduction of 91% unmet water demand is achieved under scenario 1 (i.e., equal priority is given for hydropower, irrigation, and domestic water use). Domestic water demands of the Bolikhamsay Province are fully met under all water allocation priority scenarios. The reason could be its close location to the basin outlet and having the lowest population compared to other domestic water demand sites. With the proposed climate change adaptation measures, domestic water demands of the Vientiane Municipality are fully met.

Hydropower generation is favored by the proposed climate change adaptation measures according to Figure 4-4. As shown in Figure 4-4, the change of priority water allocation scenarios considered as adaptation strategies for the hydropower generation sector compared to the status-quo condition. It is noticed from Figure 4-4 that changing priority allocation between water user sectors and hydropower generation is adopted as an adaptation strategy in the hydropower sector under future climate change conditions. It is notable that hydropower generation increased in almost all water allocation priority scenarios compared to the status-quo. Compared to other scenarios, scenario 3 produced a maximum total average percent increase of 32% and 38% from 2011 to 2050 and from 2051 to 2090, respectively. Although not shown here, with the proposed climate change adaptation measures, the maximum average hydropower generation outputs of 4784 and 4225 million kWH are achieved with water allocation scenario 2, whereas the minimum average hydropower generation outputs of 4268 and 3987 million kWH are from water allocation scenario 3, from 2011 to 2050 and from 2051 to 2090, respectively. Figure 4-5 shows a comparison of a 12-month moving average of total hydropower production with adaptation measures for future time periods. It is seen that the monthly averages of total hydropower outputs increased with adaptation measures for all scenarios compared to the status-quo. It is evident from the percent of increase in hydropower production and the increase in streamflow, that water availability is increased. As shown by in chapter 3, and further seen in Figures 4-5a and b, the difference between the moving average monthly hydropower generation for different scenarios decreased with adaptation measures. Also, the percent increase of total annual hydropower production is low for scenario 2 (i.e., hydropower generation is given highest relative priority over irrigation, and domestic water use) compared to other scenarios. These observations suggest that even though water availability is increased by climate change adaptation measures, hydraulic and operational constraints limit hydropower generation for scenario 2. It is assumed that the hydraulic constraints, such as maximum turbine flow, and operational constraints, such as plant factors and turbine efficiencies, remain unchanged with adaptations measures during the simulation period from 2011 to 2090. Also the percent increase in hydropower generation outputs are lower for scenario 2 compared to the status-quo condition. These results show that hydropower generation can also be increased with any other water allocation scenario with the proposed adaptation measures in place. The reasons are the availability of water, priority allocation, and hydraulic and dam operation constraints. Except for scenario 2, water allocation priority for hydropower is equal or lower to other water demands. Due to the increased streamflow with adaptations in place, the allocations attempt to minimize water shortages for other demands for domestic and irrigation users. Therefore, water is released from reservoirs to minimize water shortages for irrigation and domestic users.

With scenario 2, high priority is given to store water in reservoirs for hydropower generation. Even though water availability increases and priority is higher for hydropower generation, hydraulic and dam operation constraints limit hydropower generation compared to other scenarios. Therefore, water available is used to satisfy the demands for domestic and irrigation water users. The results shown in Table 4-4 confirm this observation. It is seen from Table 4-4 that the average percent of reduction of water shortages are relatively higher for agricultural and domestic users with scenario 2 compared to other scenarios. This implies that high water availability does not necessarily increase hydropower generation and may produce diminishing marginal returns. The increase in water availability with adaptations measures is also in agreement with the results of chapter 3, especially regarding rainfall. They found that the percent of increase in average wet and dry season rainfall from 2051 to 2090 was higher compared to 2011 to 2050 in all watersheds in the northern and central parts of NNRB. It is also noteworthy to mention that the effect of a high percent increase in PET compared to the percent increase in rainfall during the latter part of the century was nullified by the adaptation measures in place to increase water availability.

Table 4-5 shows the comparison of performance indicators for agricultural and domestic water users under status-quo condition and with adaptation strategies in place for the future 40 year time periods. It can be seen that both agriculture and domestic water use sectors are benefited by the climate change adaptation strategies in place.

Favorable improvement of performance indicators is observed in terms of reliability, resiliency and vulnerability in meeting the water demands under the equal water allocation priority scenario. Although not shown here, reliability, resiliency, vulnerability and sustainability of meeting the water demands of agricultural and domestic water users are improved under different water allocation priority scenarios. The improvement of the performance indicators and hence the sustainability indicates that the adaptation measures are effective.

SI, in meeting the agricultural and domestic water demands is considered under different water allocation priority scenarios. Table 4-6 shows the improvements of SI in agricultural and domestic water sectors with adaptation measures in place. It can be seen that the SI increased under every water allocation scenario. It is noteworthy to mention that SI decreased significantly compared to the baseline condition under the status-quo condition, which means that these adaptation measures are essential. It is observed that the maximum percent of increase in SI was achieved for agricultural and domestic sectors under allocation scenario 1. It is also interesting to note that the maximum decrease of SI occurred under allocation scenario 1 compared to the baseline condition.

Figure 4-6 shows a comparison of vulnerability between status-quo and with the proposed adaptation measures for the equal priority scenario. The results show that there is higher likelihood for water shortages to occur in WS4 and WS5 during the first part of the century. The main reason for this observation with the equal priority scenario is due to the continuous population increase in the Vientiane Province (VP) which reaches a maximum of about 380,000 cap towards the end of the first half of the century compared to other watersheds. The VP consists of WS4, WS5, WS2, and WS3 and has the highest population compared to other domestic water users in the basin. The lowest population of about 2100 cap is observed in the Bolikhamsay Province (D_BP) (Figure 4-2). Other reasons for this observation could be (1) high increasing rates of PET compared to low increasing rates of rainfall during the first half of the century, (2) two reservoirs (Nam Lik 1 and Nam Song) will be operating for water storage and Nam Lik 2 Reservoir will generate hydropower, and (3) the Nam Song water diversion. Under the equal priority scenario, reservoir filling, water diversion, and hydropower generations are equally prioritized with domestic and irrigation water uses. Therefore, this combination of climatic impacts due to increasing PET, human induced impacts due to water diversions, reservoir storages, hydropower generation, and high population growth will result in a higher probability for water shortages. It is also observed that the population growth rates decrease during the second half of the century compared to the first half, which could be the reason for lower vulnerability for water shortages compared to the first half (Figure 4-6b). This observation confirms that the agricultural water users are more vulnerable to water shortages compared to the domestic water users. The reason for high vulnerability for downstream agricultural water users (WS6 and WS7) during the second half of the century may be due to the increasing PET compared to rainfall. The results shows that the proposed adaptation measures improve the overall system vulnerability and reduce water shortages in the agricultural sector in northern and central parts of the basin (Figure 4-6c and d) compared to the status-quo condition.

4.5 Summary and Conclusions

An integrated water resources management framework is used to assess the hydrologic and human induced impacts under climate change and to explore climate change adaptation measures for the NNRB in Laos. The NNRB is undergoing rapid changes due to hydropower development, population growth, and land use changes. High hydropower development potential and low per capita electricity consumption of Laos has received the attention of foreign investors. From a long-term planning and management standpoint, it is necessary to understand the trends and impacts due to rapid water infrastructure developments and climate change. The analysis of climate change trends, watershed impacts, and sustainability issues under the status-quo condition is important to decide whether adaptation measures are required, and if required, appropriate adaptation measures need to be identified to minimize negative impacts. For this purpose, an integrated water resources management framework was developed at basin-scale. This overall understanding of climate change trends and water resources impacts will aid in the planning and management at the basin-scale.

A third generation coupled general circulation model (CGCM3.1 T63) and A2 emission scenario were used to assess the trends of rainfall, potential evapotranspiration (PET), and streamflow changes into the future time periods. Watershed impacts were assessed based on the water shortages at the watershed-scale and sustainability in meeting water demands for agricultural and domestic water user groups. The results of this work indicated that the increasing rates of potential evapotranspiration (PET) are higher than the increasing rates of rainfall, mostly in the north and central parts of the NNRB. Jayasekera and Kaluarachchi (see Chapter 3) found that the agricultural sector is heavily impacted due to low sustainability in meeting the future water demands due to the increase in agricultural land use. Domestic water demands are less impacted compared to agricultural demands. Compared to the baseline period, sustainability of agricultural and domestic water user groups was reduced by 87% and 43% for the period from 2011 to 2050 and by 97% and 60% for the period from 2051 to 2090. The assessment of the status-quo condition reveals that the agricultural practices have high water use rates due to paddy cultivation, high irrigation water conveyance losses, and irrigation practices such as continuous flooding for paddy cultivation. The proposed irrigation practice for paddy cultivation uses FAO recommended total water input and minimum, maximum, and target water depths for ponding in northern and southern parts of the basin. This study proposed a demand management measure of a 50% reduction in irrigation conveyance losses. The aim of adaptation measures is to improve water productivity, conveyance efficiencies, and irrigation practices. The results showed that water resources system improvements helped improve sustainability for agricultural and domestic water user groups, increased hydropower generation, and reduced system vulnerabilities at the watershed scale. Hydropower generation with adaptation measures in place, mostly during the latter part of the century, showed a reduction in hydropower generation when hydropower generation is given higher relative priority over other water demands due to the constraints related to the hydraulics and dam operations. This is an important implication for decision-makers and planners to improve the system performance related to hydropower generation with these climate change adaptation measures. The overall results reveal that the proposed adaptation measures improved water resources system sustainability, the ability to meet future water demands for agricultural and domestic use, and also to increase hydropower generation. In summary, this study provides an insight to the assessment of basin-scale water resources and human induced impacts under climate change and to identify appropriate adaptation options to minimize negative impacts.

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Table 4-1. Description of physical characteristics of individual watershed.

Watershed	**Area (km^2)**	**Mean Rainfall (mm/year)**	**Mean Elevation (m)**	**Mean Slope (%)**	**Drainage Density (km/km^2)**
WS1	4617.4	1499.2	1172.5	29.8	0.20
WS2	1848.3	1835.0	958.6	37.1	0.19
WS3	2250.1	2078.6	440.9	22.2	0.20
WS4	3130.3	1713.5	589.8	30.2	0.17
WS5	1826.0	1788.2	622.0	33.7	0.23
WS6	2136.4	1975.0	232.2	6.1	0.25
WS7	997.2	1775.6	223.9	5.0	0.29

Table 4-2. Comparison of rate of change (ROC, mm yr^{-1}) and long-term trend (T) of monthly rainfall (P) and potential evapotranspiration (PET) across seven watersheds. Bold letters indicate statistically significant results.

Watershed	**Period**	**P**			**PET**		
		ROC	***p*[a]**	**T[b]**	**ROC**	***p***	**T**
WS1	2011_2050	0.04	0.2760	+	**0.96**	**< 0.0001**	**+**
	2051_2090	0.01	0.8009	-	**0.95**	**< 0.0001**	**+**
WS2	**2011_2050**	**0.08**	**0.0191**	**+**	**0.86**	**< 0.0001**	**+**
	2051_2090	-0.02	0.5111	-	**0.76**	**< 0.0001**	**+**
WS3	**2011_2050**	**-0.19**	**< 0.0001**	**-**	**0.23**	**< 0.0001**	**+**
	2051_2090	**-0.18**	**< 0.0001**	**-**	-0.03	0.3285	-
WS4	**2011_2050**	**0.09**	**0.0073**	**+**	**0.20**	**< 0.0001**	**+**
	2051_2090	-0.05	0.0773	-	**0.26**	**< 0.0001**	**+**
WS5	**2011_2050**	**0.09**	**0.0105**	**+**	**0.35**	**< 0.0001**	**+**
	2051_2090	-0.05	0.0773	-	**0.26**	**< 0.0001**	**+**
WS6	**2011_2050**	**0.29**	**< 0.0001**	**+**	**0.36**	**< 0.0001**	**+**
	2051_2090	**0.28**	**< 0.0001**	**+**	**0.33**	**< 0.0001**	**+**
WS7	**2011_2050**	**0.32**	**< 0.0001**	**+**	**0.36**	**< 0.0001**	**+**
	2051_2090	**0.28**	**< 0.0001**	**+**	**0.33**	**< 0.0001**	**+**

[a] Statistical significance estimated at 5% confidence level ($p \le 0.05$).

[b] ± sign indicate the direction of the trend

Table 4-3. Comparison of rate of change (ROC, mm yr^{-1}) and long-term trend (T) of monthly streamflow (Q) under different water allocation scenarios, with and without adaptation to climate change. Bold letters indicate statistically significant results.

Priority Scenario[a]	Period	Station	Q					
			Without Adaptation			With Adaptation		
			ROC	***p*[b]**	**T[c]**	**ROC**	***p*[b]**	**T[c]**
1	2011-2050	Ban Naluang	-0.03	0.5816	+	0.07	0.1506	+
		Ban Hinheup	**0.18**	**0.0002**	**+**	**0.11**	**0.0187**	**+**
		Main outlet	0.04	0.3748	-	**0.12**	**0.0222**	**+**
	2051-2090	Ban Naluang	**-0.15**	**0.0013**	**-**	0.03	0.4597	+
		Ban Hinheup	**-0.09**	**0.0209**	**-**	**-0.13**	**0.0019**	**-**
		Main outlet	**0.28**	**< 0.0001**	**+**	-0.06	0.1863	-
2	2011-2050	Ban Naluang	0.01	0.8880	-	0.02	0.6224	+
		Ban Hinheup	0.03	0.4750	+	**0.10**	**0.0356**	**+**
		Main outlet	**-0.21**	**< 0.0001**	**-**	**0.12**	**0.0136**	**+**
	2051-2090	Ban Naluang	-0.07	0.0732	-	0.01	0.7801	+
		Ban Hinheup	**-0.09**	**0.0065**	**-**	**-0.14**	**0.0008**	**-**
		Main outlet	**-0.10**	**0.0078**	**-**	-0.06	0.1269	-
3	2011-2050	Ban Naluang	0.01	0.8934	-	**0.13**	**0.0039**	**+**
		Ban Hinheup	0.07	0.1187	+	**0.11**	**0.0173**	**+**
		Main outlet	-0.06	0.1265	-	**0.12**	**0.0172**	**+**
	2051-2090	Ban Naluang	**-0.09**	**0.0339**	**-**	**0.23**	**< 0.0001**	**+**
		Ban Hinheup	**-0.11**	**0.0048**	**-**	**-0.13**	**0.0020**	**-**
		Main outlet	**0.25**	**< 0.0001**	**+**	-0.06	0.1932	-
4	2011-2050	Ban Naluang	-0.03	0.5816	+	0.07	0.1491	+
		Ban Hinheup	0.07	0.1331	+	**0.11**	**0.0184**	**+**
		Main outlet	0.05	0.2116	-	**0.12**	**0.0226**	**+**
	2051-2090	Ban Naluang	**-0.15**	**0.0013**	**-**	0.03	0.4597	+
		Ban Hinheup	**-0.10**	**0.0175**	**-**	**-0.13**	**0.0019**	**-**
		Main outlet	**0.17**	**< 0.0001**	**+**	-0.06	0.1863	-
5	2011-2050	Ban Naluang	-0.03	0.5816	+	0.07	0.1491	+
		Ban Hinheup	0.07	0.1314	+	**0.11**	**0.0187**	**+**
		Main outlet	-0.08	0.0597	-	**0.12**	**0.0225**	**+**
	2051-2090	Ban Naluang	-0.07	0.1000	+	0.03	0.4597	+
		Ban Hinheup	0.01	0.7530	+	**-0.13**	**0.0019**	**-**
		Main outlet	**0.34**	**< 0.0001**	**+**	-0.06	0.1863	-

[a] 1; Hydropower = Irrigation & Domestic, 2; Hydropower > Irrigation & Domestic, 3; Hydropower < Irrigation & Domestic, 4; Upstream (water users upstream to Nam Ngum 1) > Downstream (water users downstream to Nam Ngum 1), 5; Upstream < Downstream

[b] Statistical significance estimated at 5% confidence level ($p \leq 0.05$)

[c] ± Sign indicate the direction of the trend

Table 4-4. Comparison of percent changes of unmet water demands for agricultural and domestic water users/sectors with adaptation compared to the status-quo condition. Note * indicates zero unmet demand in both conditions. BP, LP, VM, VP, and XK are domestic demands from Bolikhamsay Province, Luang Prabang, Vientiane Municipality, Vientiane Province and Xieng khouang, respectively.

User/sector	**Time**	**Scenario 1**			**Scenario 2**			**Scenario 3**			**Scenario 4**			**Scenario 5**		
	Period	**Mean**	**Wet[a]**	**Dry[b]**	**Mean**	**Wet[a]**	**Dry[b]**	**Mean**	**Wet[a]**	**Dry[b]**	**Mean**	**Wet[a]**	**Dry[b]**	**Mean**	**Wet[a]**	**Dry[b]**
Agri_WS1	2011-2050	-22	-1	-91	-55	-3	-16	-1	-91	-33	-3	-22	-1	-89	-54	-3
	2051-2090	-13	-27	-2	-15	-31	-2	-13	-27	-2	-13	-27	-2	-13	-27	-2
Agri_WS2	2011-2050	-53	-11	-100	-86	-34	-28	-10	-100	-33	-26	-60	-6	-100	-99	-41
	2051-2090	-46	-77	-20	-43	-84	-10	-57	-99	-24	-46	-77	-20	-46	-77	-20
Agri_WS3	2011-2050	-53	-11	-100	-86	-34	-28	-10	-100	-33	-26	-60	-6	-100	-99	-41
	2051-2090	-45	-76	-20	-43	-84	-10	-57	-99	-24	-45	-76	-20	-45	-76	-20
Agri_WS4	2011-2050	-19	-2	-100	-89	-7	-19	-2	-100	-89	-7	-19	-2	-100	-89	-7
	2051-2090	-24	-63	-4	-24	-63	-4	-24	-63	-4	-24	-63	-4	-24	-63	-4
Agri_WS5	2011-2050	-19	-3	-100	-61	-12	-15	-3	-100	-22	-12	-16	-3	*	-88	-12
	2051-2090	-25	-80	-7	-35	-77	-7	-24	-80	-7	-25	-80	-7	-28	-83	-7
Agri_WS6	2011-2050	-100	-100	*	*	-100	-100	-100	*	*	-100	*	*	*	*	*
	2051-2090	-100	-100	-100	-100	*	-100	-100	*	-100	-98	*	-98	-100	*	-100
Agri_WS7	2011-2050	-100	-100	*	*	-100	-100	-100	*	*	-100	*	*	*	*	*
	2051-2090	-100	*	-100	-100	*	-100	-100	*	-100	-98	*	-98	-100	*	-100
BP	2011-2050	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	2051-2090	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
LP	2011-2050	-92	-75	*	*	-92	-45	-51	*	*	-45	*	*	*	*	*
	2051-2090	-98	-100	-98	-70	*	-70	27	*	27	-75	*	-75	-98	-100	-98
VM	2011-2050	-100	-100	*	0	-100	*	*	*	*	*	*	*	*	*	*
	2051-2090	-100	-100	-100	*	*	*	*	*	*	*	*	*	*	*	*
VP	2011-2050	-23	-12	*	-65	-15	-20	-11	*	-18	-21	-42	-6	*	-100	-41
	2051-2090	-38	-86	-18	-33	-82	2	-36	-98	-22	-24	-87	2	-27	-88	2
XK	2011-2050	-37	-9	-100	-86	*	-22	-11	-100	-22	-22	-25	-7	-100	-58	-22
	2051-2090	-33	-67	1	-33	-71	-5	-22	-50	-14	-29	-67	9	-34	-68	0

[a]Wet season average unmet water demands; [b]Dry season average unmet water demands

Table 4-5. Comparison of performance indicators for agricultural and domestic water users for status-quo condition and with climate change adaptation under equal priority allocation scenario. Values in parentheses are with adaptation strategies in place.

User/Sector	**Reliability**		**Resiliency**		**Vulnerability**		**Sustainability**	
	2011_2050	**2051_2090**	**2011_2050**	**2051_2090**	**2011_2050**	**2051_2090**	**2011_2050**	**2051_2090**
Agri_WS1	0.01 (0.16)	0 (0.03)	0.01 (0.09)	0 (0.02)	0.51 (0.16)	0.51 (0.14)	0 (0.01)	0 (0)
Agri_WS2	0.01 (0.23)	0 (0.18)	0.01 (0.12)	0 (0.09)	0.51 (0.13)	0.51 (0.14)	0 (0.02)	0 (0.01)
Agri_WS3	0.01 (0.23)	0 (0.17)	0.01 (0.12)	0 (0.09)	0.51 (0.13)	0.51 (0.14)	0 (0.02)	0 (0.01)
Agri_WS4	0.23 (0.45)	0.02 (0.21)	0.11 (0.15)	0.01 (0.1)	0.65 (0.23)	0.52 (0.16)	0.01 (0.05)	0 (0.02)
Agri_WS5	0.20 (0.27)	0.09 (0.30)	0.10 (0.12)	0.07 (0.14)	0.62 (0.16)	0.55 (0.18)	0.01 (0.03)	0 (0.04)
Agri_WS6	0.78 (1.0)	0.52 (1.0)	0.36 (1.0)	0.17 (1.0)	0.15 (0)	0.36 (0)	0.24 (1.0)	0.06 (1.0)
Agri_WS7	0.78 (1.0)	0.52 (1.0)	0.36 (1.0)	0.17 (1.0)	0.15 (0)	0.36 (0)	0.24 (1.0)	0.06 (1.0)
BP	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)	1.0 (1.0)	0 (0)	0 (0)	1.0 (1.0)	1.0 (1.0)
LP	0.83 (1.0)	0.57 (0.99)	0.46 (1.0)	0.19 (0.33)	0.01 (0.06)	0.02 (0.04)	0.38 (0.94)	0.11 (0.32)
VM	0.87 (1.0)	0.60 (1.0)	0.38 (1.0)	0.20 (1.0)	0.01 (0)	0.02 (0)	0.33 (1.0)	0.12 (1.0)
VP	0.22 (0.34)	0.12 (0.42)	0.11 (0.16)	0.08 (0.16)	0.04 (0.03)	0.04 (0.04)	0.02 (0.05)	0.01 (0.07)
XK	0.04 (0.28)	0.01 (0.15)	0.03 (0.13)	0.02 (1.0)	0.05 (0.04)	0.06 (0.04)	0 (0.03)	0 (0.14)

Table 4-6. Comparison of group SI for agricultural and domestic water sectors for different priority allocation scenarios with the status-quo condition and climate change adaptation.

	Time period	Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5	
		Agriculture	**Domestic**	**Agriculture**	**Domestic**	**Agriculture**	**Domestic**	**Agriculture**	**Domestic**	**Agriculture**	**Domestic**
Baseline	1991-1998	0.53	0.61	0.37	0.51	0.53	0.61	0.29	0.43	0.49	0.59
Staus-quo[a]	2011-2018	0.16 (-70)	0.56 (-8)	0.05 (-85)	0.51 (0)	0.29 (-46)	0.62 (2)	0.05 (-81)	0.50 (18)	0.29 (-41)	0.60 (0.7)
	2051-2058	0.03 (-95)	0.27 (-57)	0.12 (-67)	0.50 (-2)	0.21 (-61)	0.51 (-18)	0.02 (-93)	0.50 (16)	0.28 (-43)	0.48 (-19)
	2011-2050	0.07 (-87)	0.35 (-43)	0.15 (-58)	0.56 (11)	0.29 (-46)	0.62 (1)	0.04 (-87)	0.49 (15)	0.29 (-41)	0.60 (0)
	2051-2090	0.02 (-97)	0.25 (-60)	0.08 (-78)	0.57 (12)	0.03 (-94)	0.52 (-15)	0.01 (-96)	0.56 (31)	0.08 (-83)	0.45 (-24)
Adaptation[b]	2011-2018	0.31 (94)	0.60 (8)	0.31 (468)	0.49 (-4)	0.34 (18)	0.63 (2)	0.12 (123)	0.49 (-2)	0.31 (7)	0.60 (1)
	2051-2058	0.30 (984)	0.48 (80)	0.31 (161)	0.48 (-3)	0.31 (50)	0.49 (-3)	0.11 (451)	0.37 (-25)	0.30 (10)	0.48 (0)
	2011-2050	0.31 (338)	0.61 (75)	0.31 (100)	0.55 (-2)	0.33 (15)	0.63 (1)	0.13 (242)	0.50 (1)	0.31 (6)	0.60 (1)
	2051-2090	0.30 (1665)	0.50 (104)	0.31 (277)	0.51 (-10)	0.31 (932)	0.53 (1)	0.12 (952)	0.89 (59)	0.30 (264)	0.51 (12)

[a] Values in parentheses are percent changes from the baseline scenario

[b] Values in parentheses are percent changes from the status-quo condition

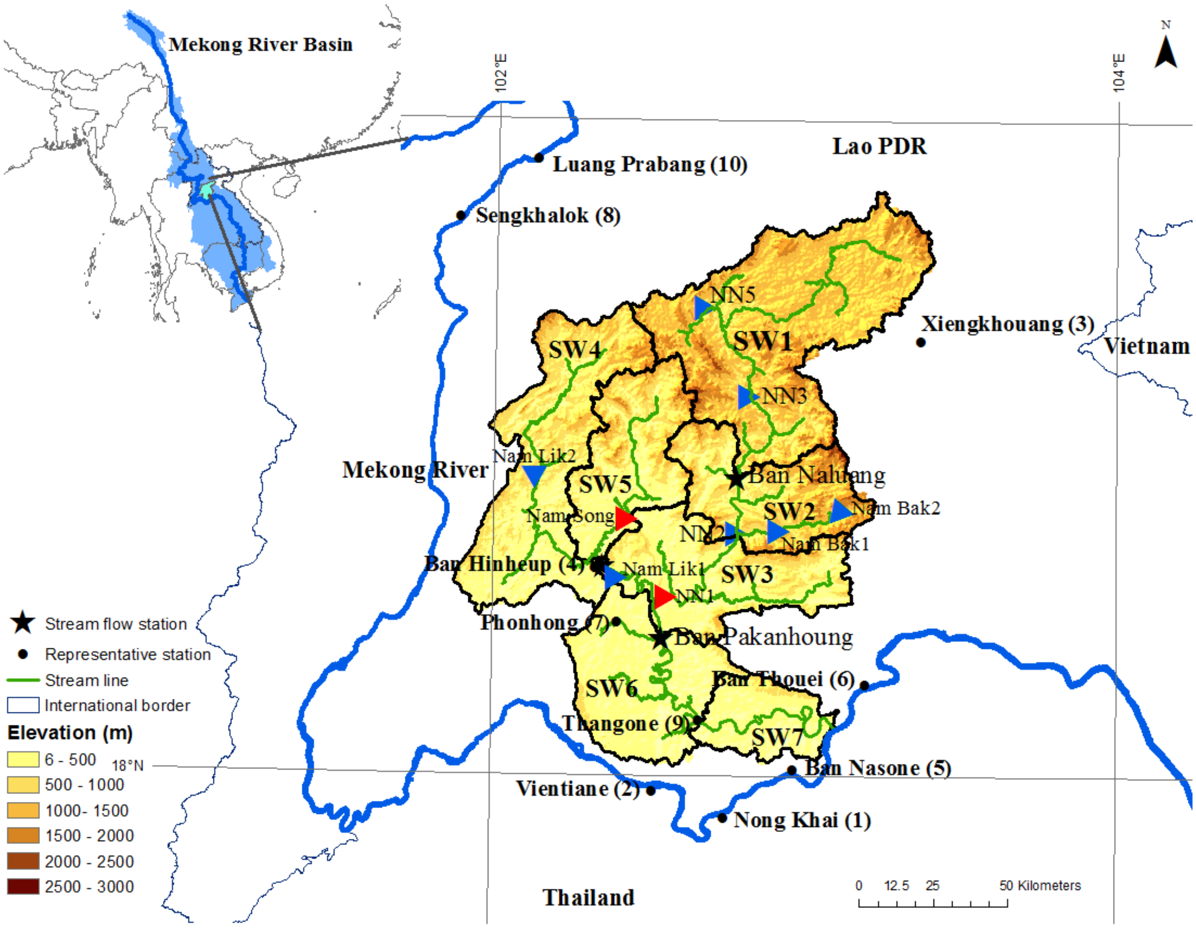


Figure 4-1. Physical layout of the NNRB of Laos showing watersheds and other key features. Colored triangles represent existing (red) and under construction/planning stage (blue) reservoirs/dams.

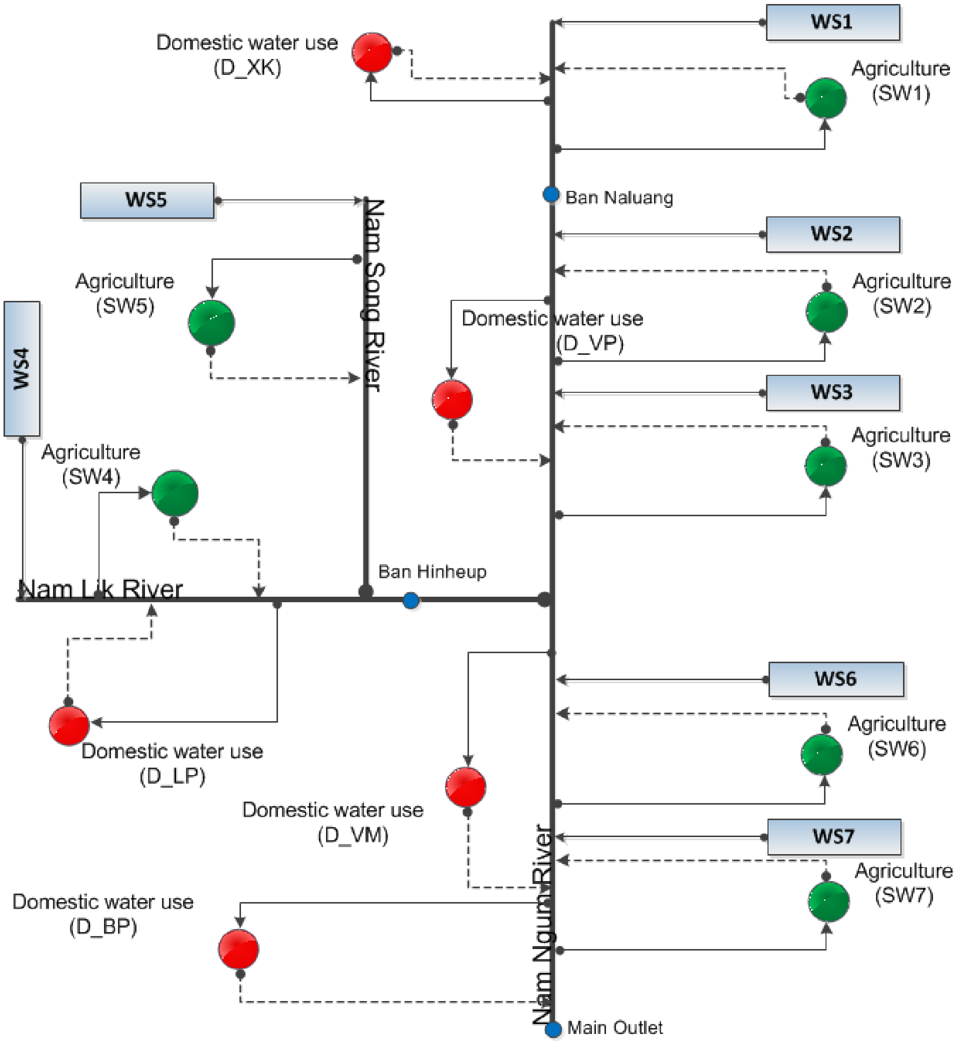
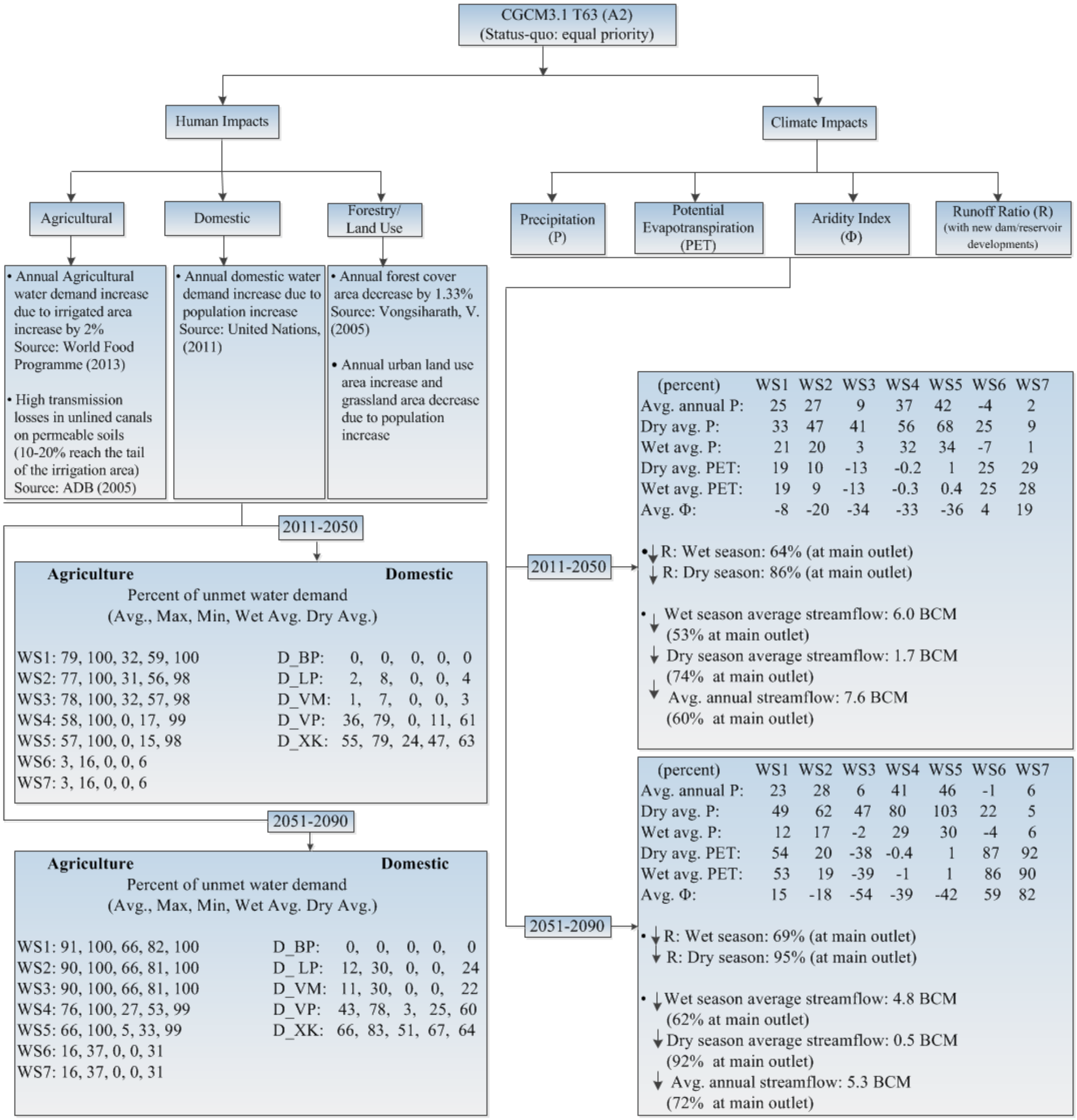


Figure 4-2. Schematic showing the different agricultural and domestic water uses in the NNRB.



- Annual Agricultural water demand increase due to irrigated area increase by 2% Source: World Food Programme (2013)
- High transmission losses in unlined canals on permeable soils (10-20% reach the tail of the irrigation area) Source: ADB (2005)

- Annual domestic water demand increase due to population increase Source: United Nations, (2011)

- Annual forest cover area decrease by 1.33% Source: Vongsiharath, V. (2005)
- Annual urban land use area increase and grassland area decrease due to population increase

2011-2050

Agriculture **Domestic**

Percent of unmet water demand
(Avg., Max, Min, Wet Avg. Dry Avg.)

Agriculture						Domestic					
WS1:	79	100	32	59	100	D_BP:	0	0	0	0	0
WS2:	77	100	31	56	98	D_LP:	2	8	0	0	4
WS3:	78	100	32	57	98	D_VM:	1	7	0	0	3
WS4:	58	100	0	17	99	D_VP:	36	79	0	11	61
WS5:	57	100	0	15	98	D_XK:	55	79	24	47	63
WS6:	3	16	0	0	6						
WS7:	3	16	0	0	6						

2051-2090

Agriculture **Domestic**

Percent of unmet water demand
(Avg., Max, Min, Wet Avg. Dry Avg.)

Agriculture						Domestic					
WS1:	91	100	66	82	100	D_BP:	0	0	0	0	0
WS2:	90	100	66	81	100	D_ LP:	12	30	0	0	24
WS3:	90	100	66	81	100	D_VM:	11	30	0	0	22
WS4:	76	100	27	53	99	D_VP:	43	78	3	25	60
WS5:	66	100	5	33	99	D_XK:	66	83	51	67	64
WS6:	16	37	0	0	31						
WS7:	16	37	0	0	31						

2011-2050

(percent)	WS1	WS2	WS3	WS4	WS5	WS6	WS7
Avg. annual P:	25	27	9	37	42	-4	2
Dry avg. P:	33	47	41	56	68	25	9
Wet avg. P:	21	20	3	32	34	-7	1
Dry avg. PET:	19	10	-13	-0.2	1	25	29
Wet avg. PET:	19	9	-13	-0.3	0.4	25	28
Avg. Φ:	-8	-20	-34	-33	-36	4	19

- ↓ R: Wet season: 64% (at main outlet)
  ↓ R: Dry season: 86% (at main outlet)

- ↓ Wet season average streamflow: 6.0 BCM (53% at main outlet)
  ↓ Dry season average streamflow: 1.7 BCM (74% at main outlet)
  ↓ Avg. annual streamflow: 7.6 BCM (60% at main outlet)

2051-2090

(percent)	WS1	WS2	WS3	WS4	WS5	WS6	WS7
Avg. annual P:	23	28	6	41	46	-1	6
Dry avg. P:	49	62	47	80	103	22	5
Wet avg. P:	12	17	-2	29	30	-4	6
Dry avg. PET:	54	20	-38	-0.4	1	87	92
Wet avg. PET:	53	19	-39	-1	1	86	90
Avg. Φ:	15	-18	-54	-39	-42	59	82

- ↓ R: Wet season: 69% (at main outlet)
  ↓ R: Dry season: 95% (at main outlet)

- ↓ Wet season average streamflow: 4.8 BCM (62% at main outlet)
  ↓ Dry season average streamflow: 0.5 BCM (92% at main outlet)
  ↓ Avg. annual streamflow: 5.3 BCM (72% at main outlet)

Figure 4-3. Assessment of climate change impacts under climate change for the status-quo condition.

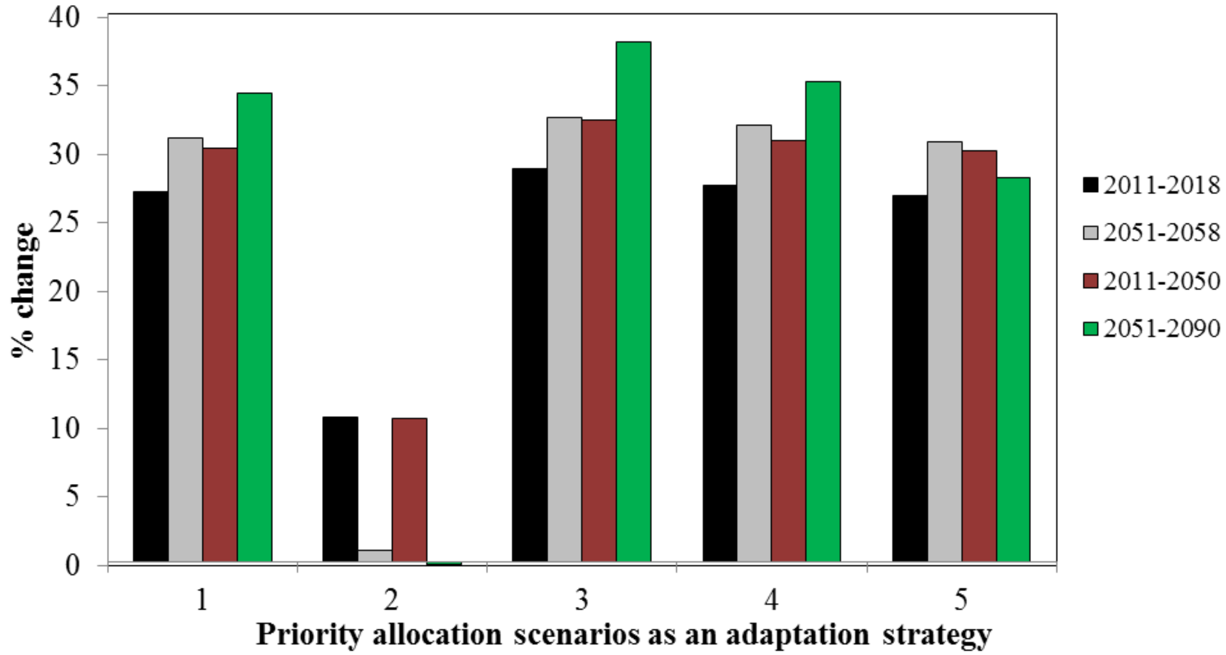


Figure 4-4. Percent increase in hydropower generation with climate change adaptation compared to the status-quo condition.

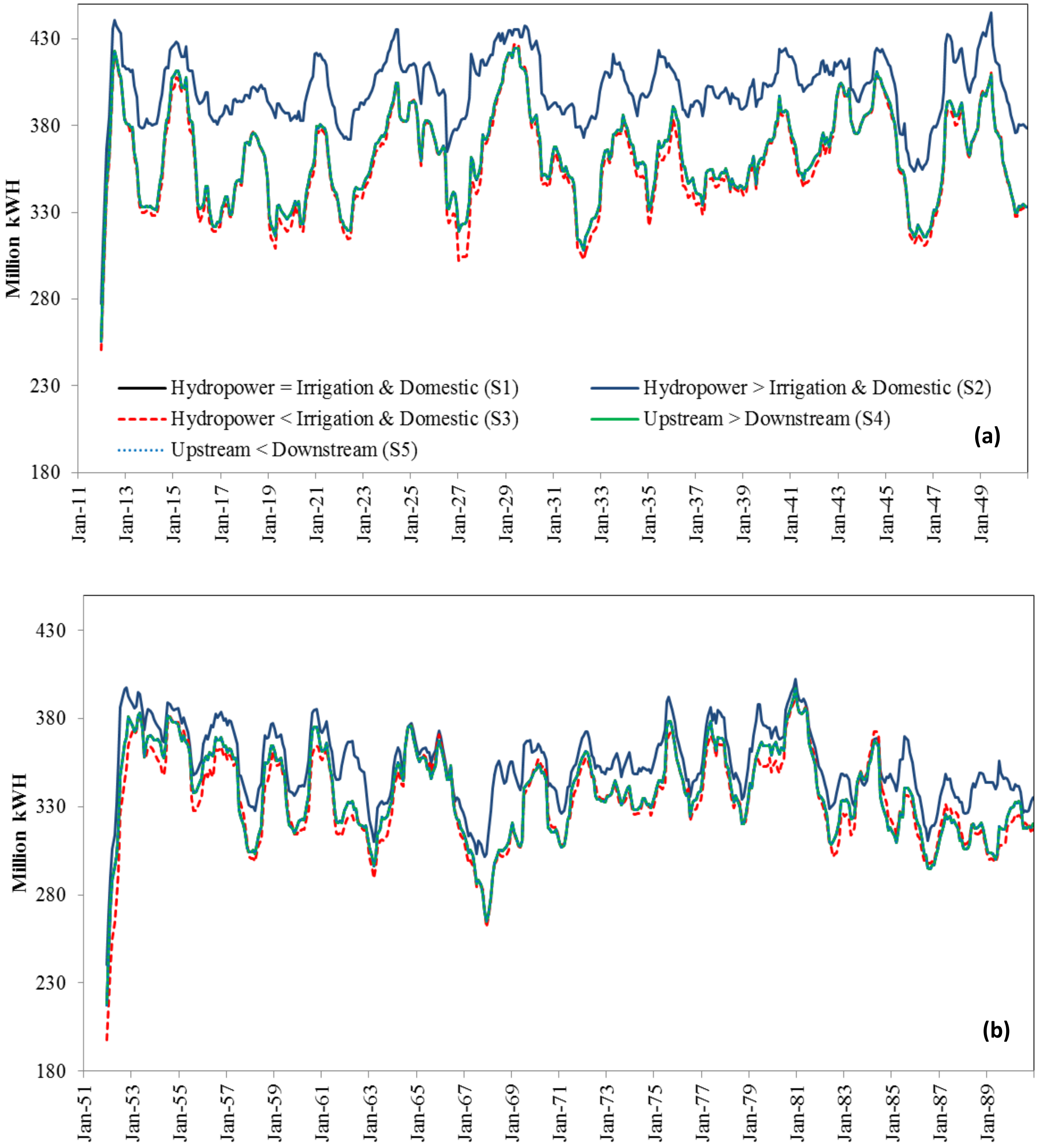


Figure 4-5. Comparison of 12-month moving averages of total monthly hydropower generation for different water allocation priority scenarios with adaptation: (a) 2011-2050 and (b) 2051-2090.

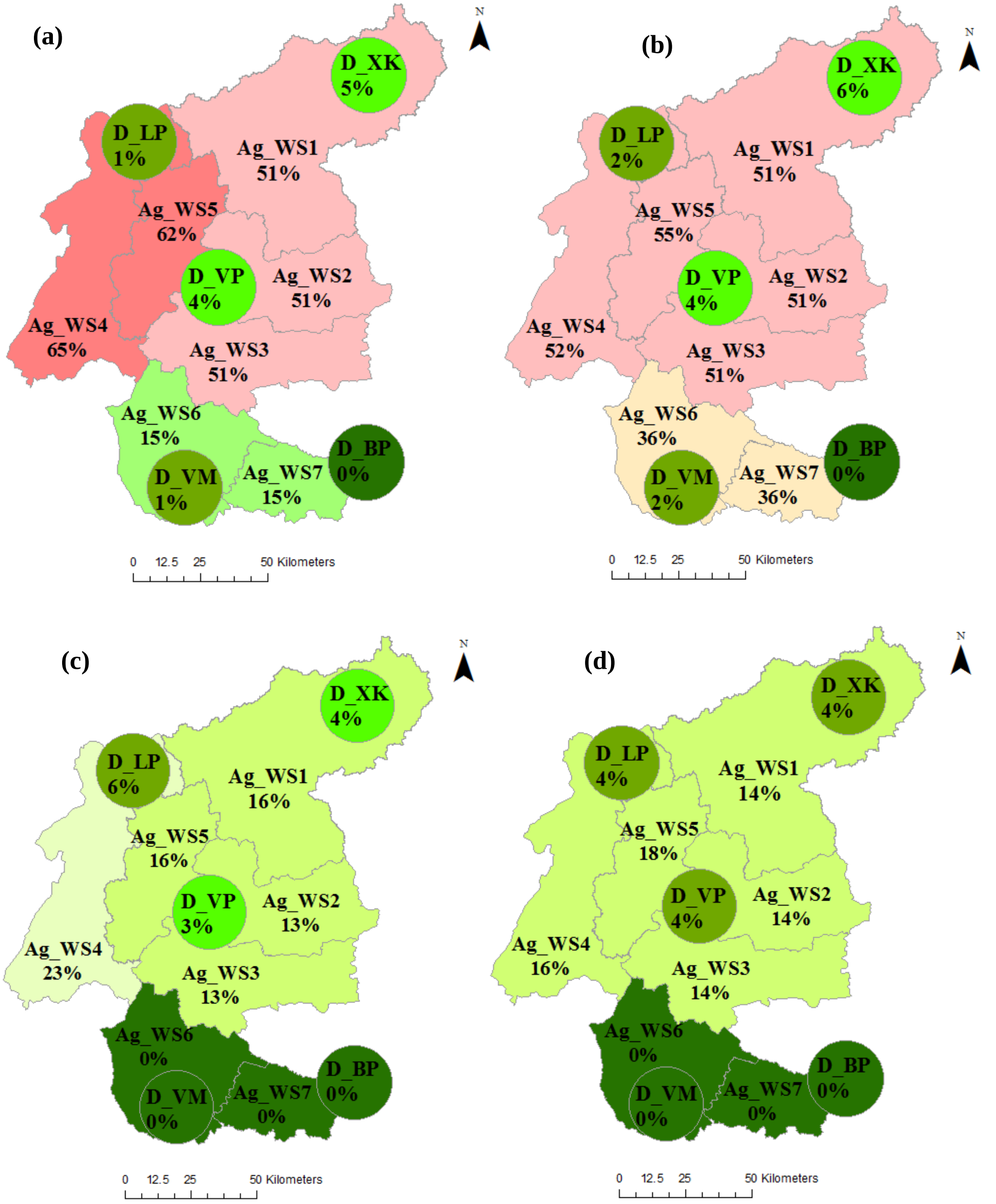


Figure 4-6. Comparison of vulnerability for different water users under the equal priority scenario of climate change (a) status-quo (2011-2050), (b) status-quo (2051-2090), (c) with adaptation (2011-2050) and (d) with adaptation (2051-2090)

CHAPTER 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This dissertation is a step towards integrating the impacts due to climate change and watershed scale impacts due to human induced changes and water infrastructure operations in the Nam Ngum River Basin (NNRB), Laos. The NNRB is undergoing rapid changes due to high hydropower development potentials, but reliable and high resolution hydrologic data are limited. This dissertation has improved the reliable projection of climatic variables and developed an integrated water resources management framework capable of assessing the impacts of climate change in terms of the changes in hydrologic regimes, water resources impacts, and climate change adaptation strategies. Instead of using highly complex hydrologic modeling approaches with limited hydrologic data for climate change and water resources management related impacts assessment, a simple, yet reliable, integrated water resources management framework was developed for the study area. This chapter provides a summary, conclusions, and recommendations for further study.

5.1 Summary and Conclusions

The major findings and results obtained can be summarized in four major categories.

5.1.1 Estimation of Climatic Variables

Various methods have been developed to accurately reproduce the observed patterns of climatic variables at multiple sites with fine temporal scale. However, recently developed methods are not suitable for application to the study area due to high computational efforts and data requirements. The method proposed in Chapter 2 is an improvement and extension to the work of *Kim et al.,* [2008] to generate future precipitation under climate change but has the capability of reproducing temporal and spatial correlation structures of observed climatic variables (i.e. weekly precipitation and temperature from 1961 to 2000) of the study area. This work was improved by including the bias-correction method to downscale from the GCM scale of climatic variables to multiple sites to construct the baseline scenario. Future climatic variables are estimated by adopting the bias-correction method using the future climate change A2 emission scenario.

5.1.2 Baseline and Future Climate Change Scenarios Using GCMs and RCMs

Since each GCM simulates different changes in climatic variables for a region of interest, it is typically difficult to select the outcomes of single GCMs for a region. This dissertation used outcomes of CGCM3.1 T63, ECHAM5 and PRECIS RCM to identify the ability of representing the climate for the baseline period (1961 to 2000). Six to nine grids that cover the entire study area, depending on the resolution of each GCM, and 108 grids covered the entire study area by RCM. The bias-correction method is used to statistically downscale the two GCMs whereas PRECIS RCM outcomes resulted from a dynamical downscaled approach for which the lateral boundary conditions of ECHAM5 have been included. Therefore, bias-correction is not performed for RCM outcomes. CGCM3.1 T63 showed the lowest mean absolute error compared to ECHAM5 and RCM showed the highest mean absolute error compared to the bias-corrected ECHAM5 results. The future climate change scenarios were constructed by perturbing the baseline climate scenario. This dissertation used an A2 future emission scenario of CGCM3.1 T63. The potential evapotranspiration series was estimated by the Penman-Monteith method using temperature, relative humidity and wind speed series generated for the future A2 emission scenario.

As a result, the climate change scenario showed that the spatial distribution of projected mean annual precipitation showed a significant increase in the north-eastern and central parts of the study area. The highest percent changes of mean annual precipitation are about 13% from both CGCM and ECHAM for 2051 through 2090, whereas they were 12% and 11% from CGCM and ECHAM for 2011 through 2050, respectively, while showing small inter-model differences. The highest precipitation increase during the dry season was 31% from 2051 to 2090. The projected percent increase in potential evapotranspiration for the future A2 emission scenario over the study area, compared to the baseline period, is 8% and 22% from 2011 to 2050 and from 2051 to 2090, respectively.

5.1.3 Assessment of Climate Change Impacts on Water Resources under Status-quo

In Chapter 3, the integrated water resources management modeling framework developed in WEAP21 successfully simulated natural historical flow regimes and water allocation under the equal priority scenario of the NNRB of Laos. The model considers the hydrologic processes and water infrastructure operations and was used in assessing climate change impacts under status-quo conditions. This modeling framework aids in estimating the watershed impacts in terms of unmet water demands at the watershed scale and sustainability in meeting water demands for different water users and groups. Sustainability is estimated using the reliability, resiliency, and vulnerability of each water user and for each water user group.

The projected climate change was simulated using the third generation coupled general circulation model, CGCM3.1 T63, and the A2 scenario that provides probably the worst case scenario. The agricultural sector is critically affected showing unsustainable conditions during both future time periods compared to the domestic water use sector, mainly in the upper parts of the NNRB. Under status-quo conditions, critical conditions occur in terms of streamflow reduction at the main outlet, the amount of hydropower generated, and sustainability in meeting water demands during the period from 2051 to 2090. Annual wet and dry season streamflow is reduced by 72%, 62%, and 92% compared to the baseline period, during the latter part of the century. The amount of hydropower generation is reduced for every allocation scenario and is reduced by about 9% under the equal priority scenario compared to the first half. The agricultural and domestic water user group sustainability index is reduced by 97% and 60%, respectively, compared to the baseline conditions during the second half of the century.

5.1.4 Assessment of Climate Change Adaptation Strategies

An integrated water resources management framework is used to assess the long-term hydrologic and human induced impacts under climate change and to explore climate change adaptation measures for the NNRB in Laos. An analysis of long-term trends due to climate change was performed using a CGCM3.1 T63 A2 emission scenario. The trend analysis showed higher statistically significant increasing trends of potential evapotranspiration rates compared to the statistically significant increasing trends of precipitation throughout the NNRB for both future time periods. Watershed impacts were assessed based on the water shortages at the watershed scale and sustainability in meeting water demands for agricultural and domestic water user groups. Under status-quo conditions, agricultural and domestic water user sectors are affected due to water shortages, but the agricultural sector is highly impacted compared to domestic water user sector.

Climate change trends and watershed impacts show water shortages for agricultural and domestic water use and related low sustainability under status-quo conditions. This indicates that climate change adaptation measures are necessary to minimize the negative impacts in terms of water shortages. The assessment of the status-quo condition reveals that agricultural practices require high water use rates mainly due to paddy cultivation, high irrigation water conveyance losses, and irrigation practices such a continuous flooding for paddy cultivation. Therefore, adaptation measures were aimed to improve water productivity, conveyance efficiencies, and irrigation practices. Results showed an improvement by reducing overall system vulnerability, and reduced water shortages in the agricultural sector in northern and central parts of the basin compared to the status-quo condition. Hydropower generation was improved for all allocation scenarios, but with a low percent increase under a scenario with a relatively high priority for hydropower generation. For hydropower sector, hydropower generation under different allocation priority scenarios across water demand sectors such as agricultural, domestic and hydropower is adopted as a climate change adaptation strategy. This indicates that water availability is increased with climate change adaptation measures in agricultural, domestic and forestry sectors but further improvements to the system performance for hydropower generation will be required.

The results produced in this dissertation are significant in providing decision-relevant information for the development and management of future water resources of the Nam Ngum River Basin. This dissertation presents the following contributions:

1. A better understanding of climate change impacts on regional water resources by applying GCMs after bias-correction. This dissertation compares the direct use of the regional climate model outcomes with bias-corrected GCM results for regional climate change impact studies.
2. A broad understanding of the hydrologic aspects and water resources management in the study area through developing an integrated water resources management modeling framework. The integrated water resources management modeling framework provides an insight to climate change and water resources impacts at the watershed scale under the status-quo condition.
3. Quantitative measures of climate change impacts, watershed impacts and sustainability issues on hydrologic regimes under competing demands, water resources systems, and water user sectors using appropriate indicators.
4. A preliminary assessment of watershed scale climate change trends, planned adaptation strategies for agricultural, water resources, and forestry sectors, and water allocation challenges under competing demands.

The climate change A2 emission scenario based on CGCM3.1 T63 GCM is not forecast of future climate, but can be the possible results of future climate change. The simulation results for the first half and second half of the future time periods aid to the water resources planners and decision-makers in understanding the possible range and trend of climate change and their sequential impacts. These impacts include a generally increasing trend of precipitation in northern, north-eastern, western, and southern parts of the study area, and a decreasing trend of precipitation in some central parts of the study area during the first half of the century. Central parts of the study area will be impacted due to a decreasing trend of precipitation during the latter half of the century. Potential evapotranspiration generally showed an increasing trend in the future. Moreover, different priority based water allocation scenarios for competing water demands and sustainability indices in meeting those demands provide an insight to the decision making process and what tradeoffs have to be made. To be beneficial to Laos and other countries, technical cooperation between countries in the Mekong basin should be negotiated by sharing future water resources.

Several limitations were present in this dissertation in modeling and assessing hydrology and water resources of the study area. As such, the following future research directions are suggested.

1. The proposed Markov chain based conditional generation method needs a stronger validation with a wide range of spatial coverage. The validation process can guarantee the conditional generation method can be used as a generalized scheme to reproduce historical temporal and spatial correlation structures of climatic variables at any basin.
2. In the same context, hydrologic monitoring systems (e.g. temporal and spatial resolutions of observation) should be improved for developing distributed hydrologic modeling. Physically-based distributed hydrologic modeling will mitigate the uncertainty in predicting runoff at both gauged and ungauged watersheds.

3. Further studies should be carried out to analyze the agricultural productivity for crop varieties, including paddy for different water use rates, and their yield response to water and temperature changes. Since most agricultural activities in the study area are greatly dependent on the amount and timing of precipitation, future food security could then be assessed by comparing the future crop yields with future demand.

5.2 Management Recommendations for Policy Makers

The Nam Ngum River Basin (NNRB) located in Laos has a high hydropower generation potential and it is undergoing rapid changes due to hydropower developments. In developing regions such as NNRB, where development goals are mainly geared towards hydropower developments, water resources planning and management will be a critical issue in the future for water resources planners and managers. Exacerbating water shortages under existing water management practices constraining agricultural production and threatening food security, causing forest degradation are major concerns in the basin. Climate change will pose an additional threat to these ongoing problems affecting water shortages for agricultural and domestic purposes.

Estimation of precipitation and potential evapotranspiration (PET) under climate change is carried out after bias-correction of CGCM3.1 T63 using A2 emission scenario outputs for seven watersheds in the NNRB for monthly time steps. The integrated water resources management modeling framework is developed in WEAP21 environment to include hydrological processes and water infrastructure operations. The calibrated and validated hydrological and water allocation model is used to assess the water allocation priority trade-offs under status-quo (“do nothing”) conditions and sustainable water availability conditions in agricultural and domestic water user sectors. Results indicate that increasing rates of PET surpass increasing rates of precipitation across the NNRB for both future time periods from 2011 to 2050 and from 2051 to 2090. Aside to this change, continuation of current water use and watershed management practices and priority actions in the NNRB will result unsustainable conditions in meeting water demands mainly for agricultural purposes. Under status-quo condition, annual agricultural water demand will increase due to the increase of irrigated area by 2%. Moreover, 80-90% transmission losses in unlined irrigation canals with permeable soils will demand for more water for agricultural practices. Previous studies have identified rapid decline in current forest areas would likely to occur in the future. With multiple reservoir operations, water availability for agricultural practices and domestic use under status-quo ("do nothing") condition in the presence of climate change will be an alarmingly critical issue in coming few decades.

Policy makers need to change current irrigation practices and reduce water requirements mainly for paddy cultivation by significant efficiency improvements to the irrigation conveyance systems. Current irrigation practice of continually flooded conditions requires extremely higher amount of water whereas alternate wetting and drying irrigation for paddy cultivation will reduce the total water input improving water productivity and yield. Meantime, policy makers also need to consider the Food and Agriculture Organization (FAO) recommended seasonal crop water requirement for paddy cultivation with alternate wetting and drying and specifying the minimum, maximum and target water depths for ponding water requirements. Since paddy cultivation is the highest agricultural water user, policy makers must consider annual irrigated area increase of 1% for the future population growth rate projected. Apart from the improvements in water productivity, policy makers need to implement irrigation system efficiency improvements to manage water demand for agricultural activities mainly for paddy by reducing irrigation water conveyance losses by 50% through canal lining.

For domestic water use, policy makers need to consider the World Health Organization (WHO) recommended domestic water consumption rates for the region and revise the current annual domestic water consumption rates for domestic water use in municipalities since current water use rates are very high compared to the WHO recommended water use rates for the region.

In forestry sector, sustainable forest management efforts should encompass strategies, such as strict enforcement of forestry laws, which would enhance forest regrowth. For this purpose policies need to formulate in such a manner to promote the integration of agricultural lands with forest lands. Agroforestry is the practice of planting woody perennials (i.e. trees or shrubs) on the same land management unit as agricultural crops and these forest lands can be integrated with vegetable crops or tree integration in vegetable productions system. This is a viable farming system in mountainous areas. As a part of best management practices, reforestation programs need to be implemented with the aim of increasing annual forest cover area in the north, north-eastern and central parts of the basin. Starting from next few decades, the annual percent increase to the existing forest cover land area needs to be increased by 0.01% to 0.1%.

As a best management practice for climate change adaptation strategy, changing water allocation priorities between consumptive (i.e. agricultural and domestic) and non-consumptive (hydropower) water use sectors should be practiced. In the presence of climate change, changing water allocation priority between consumptive uses (i.e. agriculture and domestic) and con-consumptive (hydropower) uses plays as an adaptation strategy and a best watershed management practice. With adaptation practices in place for agriculture, domestic and hydropower sectors, sustainability of meeting the water demands for the consumptive water user (agriculture and domestic) sectors is improved. Policy makers need to consider hydropower system capacity improvements along with climate change adaptation practices in place. Hydropower generation outputs can be further increased under any water allocation priority decision. Overall, climate change adaptation strategies across agriculture, domestic and hydropower sectors improve the water resources system performance in terms of sustainability in meeting the water demands across consumptive water use.

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EDUCATION

Doctor of Philosophy (Jan. 2008 – Aug. 2013)
Major: Water Resources Engineering
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Master of Science (Jan.2005 – Dec. 2007)
Major: Water Resources Engineering
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Major: Agricultural Engineering
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RESEARCH INTERESTS

Climate change impacts on water resources
Groundwater hydrology
Computer-assisted integrated water resources management modeling
Stochastic/deterministic hydrology
Probability and statistical modeling
Water resources system model evaluation and optimization
Water conservation and management

PROFESSIONAL EXPERIENCE

Research Assistant, Utah Water Research Laboratory
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Agricultural Engineer, United Nations Development Programme (UNDP)
Colombo-Kandy, Sri Lanka (Jan. 2004 – Dec. 2004)

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Engineer-in-Training Certification (aka Fundamentals of Engineering) (Oct.2009)
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Member: American Geophysical Union (AGU) (2007-present)
Member: American Society of Civil Engineers (ASCE) (2007-present)

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PhD Research Fellowship (May-2009)
International Water Management Institute (IWMI)
Vientiane, Laos

Subsurface Science Graduate Fellowship Award (Oct.2007-Sep. 2008)
U.S. Department of Energy / Inland Northwest Research Alliance (INRA)

MS Research Fellowship (Jan.-Jun, 2006)
International Water Management Institute (IWMI)
Colombo, Sri Lanka

Merit Scholarship (Sep. 1997-Apr. 2002)
Government of Sri Lanka, Ministry of Higher Education Sri Lanka

PUBLICATIONS

Journals

Jayasekera, D., J.J. Kaluarachchi, and K. G. Villholth (2011). Groundwater stress and vulnerability in rural coastal aquifers under competing demands: a case study from Sri Lanka. Environmental Monitoring and Assessment, Vol. 176 (1), pp.13-30, DOI 10.1007/s10661-010-1563-8.

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Technical Reports

Jayasekera, D., and J.J. Kaluarachchi (2009). Nam Ngum River Basin, Lao People's Democratic Republic: Preliminary assessment of hydrologic data

COMPUTER SOFTWARE SKILLS

- Hydrologic and Hydraulic Modeling Software: HEC-HMS, HEC-RAS, HEC-ResPRM, ResSim, DAMBRK
- Water Allocation and Planning: WEAP 3.4
- Water Quality: QUAL2K
- Optimization Tools: LINGO
- Image Processing: ERDAS IMAGINE
- Drafting Tools: AutoCAD
- Programming Languages and Tools: Visual C++. NET, Visual Basic, VBA in MS Excel
- Mathematical Software: MATLAB 12.0, MathCAD 14.0
- Geographic Information Systems: ESRI ArcGIS (ArcMap) 10.1
- Statistical Software: R, SAS 9.0, MINITAB 14.0.
- Storm Water Management: SWMM
- Web Design and Video Editing Software: Macromedia Dreamweaver MX 2004, Corel Video Studio Pro X3
- Microsoft Office: Microsoft, Word, Excel, PowerPoint, Visio, Project, Access-2010