Evaluation of the impact of natural and anthropogenic factors on river flow and groundwater in a Mekong River sub-basin, Laos

By
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Declaration

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

Somphasith Douangsavanh

Co-authorship

I am, Somphasith Douangsavanh, the primary author of this thesis and all the enclosed documents. Chapters 2, 3 and 4 were written as independent manuscripts in preparation for submission to a scientific water journal, in which the co-authors provided intellectual supervision and editorial comments.

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Thesis summary

Water is essential for all living things on the planet, growing the economy and sustaining the world's ecosystems. Human-made water infrastructure regulates about three-quarters of the world's river networks to meet the socio-economic development demand. A common approach applied involves upstream regulation of major rivers. However, this can significantly change river flow regimes and stages downstream. Many studies have assessed the impact of the use of surface water for hydropower development via scenarios and estimation of environmental consequences on river flows, fisheries, aquaculture, and livelihoods. However, little is known of the impact of change in the river flow regimes, as consequences of anthropogenic factors, on surface water-groundwater interactions and groundwater systems. This thesis contributes to reducing this knowledge gap by studying these impacts and effects by comparing the pristine and post-dam conditions of the Nam Ngum River Basin, a major tributary of the Mekong River in Laos.

This research addresses the impact of human activities and climatic factors from the pre- to post-dam period on river flow regimes and connected groundwater systems. Specifically, the aims of this research are as follows: (1) evaluating the impacts of anthropogenic induced changes in water yield by observing the trends and driving factors; (2) assessing the impact of irrigation water, diverted from the surface water, on different water balance components (i.e., groundwater recharge, actual evapotranspiration, surface runoff, and interception); (3) evaluating the impact of river stages, as a consequence of hydropower reservoir operations, on downstream groundwater systems. The body of the thesis consists of five chapters: Chapter 1 provides a global overview of river regulation and describes the geographical context for the study area with problem statements, research aims and contribution of the PhD research, while the main part of the thesis is Chapter 2 to 4, which are written in the style of potential academic

papers. Chapter 5 provides a summary of the main findings and conclusions from the three main chapters of the thesis as well as suggestions for the importance of future research.

The first part of this research (Chapter 2) examines the historically observed river flow patterns caused by anthropogenic and natural hydroclimatic drivers and investigates factors that significantly affect the river flow regime. This part also estimates how the river flow affects the water yield in a downstream basin (water productivity generated in the basin) from the pre- to post-dam period. Methods used are statistical trend analysis of relevant indicators such as GRACE total water storage, soil moisture, and actual evapotranspiration. The results show that the river flow was highly seasonal under pre-dam conditions, and the river was losing water to the groundwater in the dry season. However, in the post-dam period, the monsoonal peak flow decreased by 39%, while the flow increased by 120% in the dry season. Moreover, the river has become gaining year-round from 2001 onwards. It is concluded that the water infrastructure has a greater impact on the river flow regime than the climate-related factors. The annual and dry season water yield exhibit an increasing trend from the pre- to post-dam period.

The second part of the research (Chapter 3) evaluates the impact of irrigation water diverted from the river on groundwater recharge and other water balance components. This part aims to assess which portion of the groundwater recharge comes from irrigation schemes and will likely influence water yield in the downstream basin. The recharge and water balance components are quantified for the two different conditions: without irrigation schemes (pre-dam) and with irrigation (post-dam). The methodology is based on the WetSpass-M model. Estimated recharge is compared with assessments of the Water Table Fluctuation (WTF) method, showing an excellent agreement. It is concluded that irrigation has caused a relatively minor increase in groundwater recharge with an average of additional recharge (2012-2014) of 83 mm within the command irrigated areas and 6 mm for the basin-wide increase, resulting in a minimal influence on the water yield in the downstream part of the basin. The annual average recharge with irrigation schemes is assessed to be 444 mm, equivalent to 19% of the average annual rainfall.

The final part of the research (Chapter 4) investigates the impact of changes in river flow regime and river stages due to upstream reservoirs on surface water-groundwater interactions and groundwater systems in the downstream part of the Lower Nam Ngum River Basin. Elements studied are the river-groundwater budget, water table, and groundwater balance in the pre- and post-dam periods. The study develops an interpretive groundwater conceptual model, which focuses on demonstrating the status of groundwater systems when river stages are changed. The model is simulated for the pre- and post-dam conditions using the recharge estimated in the second part of the thesis, observed river stages, and aquifer properties obtained from well-tests. The result shows the status and change in river interaction. In the pre-dam period, the river and its tributaries were losing in the rainy season and gaining water in the dry season. However, they have become gaining year-round in the post-dam period, except for two tributaries upstream exhibiting slight changes from the pre- to post-dam period. The surface water-groundwater exchange has significantly declined in the post-dam period compared to the pre-dam period; the amount of water lost and gained by the river system has reduced by 53% and 23%, respectively. The total amount of water entering and leaving the groundwater system also declines by 22% compared to the pre-dam period. The increase in river stages in the dry season has raised the groundwater tables in the riparian and downstream areas in the post-dam period. Apart from a number of benefits from damming and regulating large rivers (i.e., energy production, flood and drought mitigation, and irrigation development), these research findings show the impacts of dam development on groundwater systems. The reduced surface water-groundwater interaction in the post-dam condition also has potential consequences for reduced hyporheic exchange and hence increased vulnerability of the surface water-groundwater quality and ecosystems in the lower basin.

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Chapter 1. Introduction

1.1 Background

Water is an essential resource for human's well-being, socio-economic development, and sustaining the world's ecosystems, but water resources are under threat of human activities and climate change (Meybeck, 2003; Nesbitt et al., 2004; WREA, 2008a; Vörösmarty et al., 2010; Wagener et al., 2010; Pelletier et al., 2015). Human-made water infrastructures regulate about three-quarters of the world's river networks to meet the growing socio-economic demand, which threatens ecosystem processes, biodiversity and services provided by these rivers (Grill et al., 2019). Only 37% of the world's rivers with a length longer than 1,000 km remain unregulated and in free-flowing conditions. Most are located in remote regions of the Arctic, the Amazon Basin, and the Congo Basin (Fig 1.1). Hydropower dams and reservoir operations in the upstream parts of the main rivers and their tributaries are the reason for the connectivity loss, i.e., causing the rivers to become regulated.

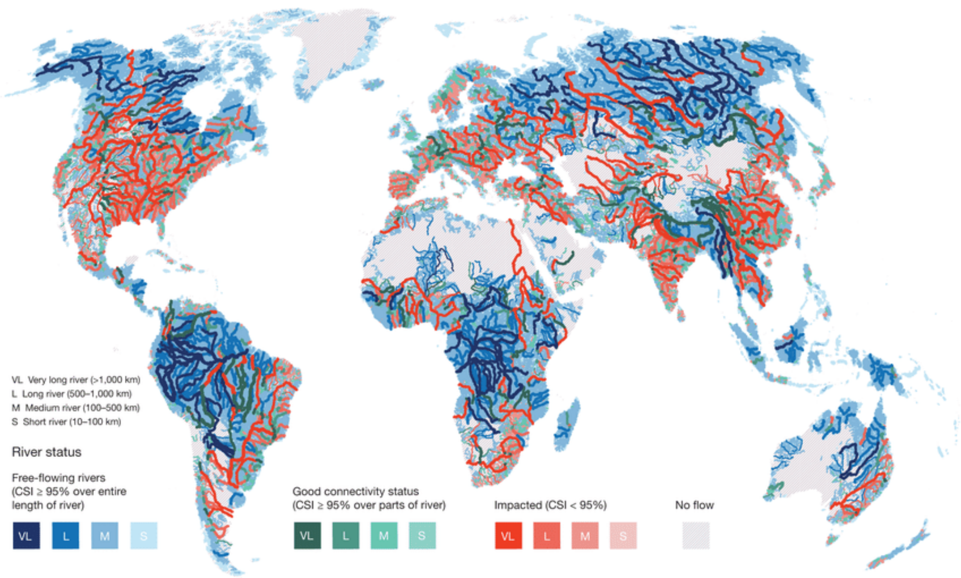

Figure 1.1. World's free-flowing river networks based on the connectivity status index (CSI) greater and smaller than 95%. The blue shades represent the magnitude of a free-flowing river; the green shades represent the magnitude of good connectivity; and the red shades describe the degree of impacted or disconnected condition (Grill et al., 2019).

Most unregulated rivers are situated in remote areas where it is difficult to exploit them for potential economic development. However, it appears inevitable that water resources are developed in regions with rapid economic growth, particularly in developing countries. Like other basins with emerging economies, the Mekong River, located in East Asia and Southeast Asia, is rapidly changing. The Mekong River has its sources on the Tibetan Plateau in China and flows more than 5,000 km to the Mekong Delta and, ultimately, discharge in the South China Sea. It is a transboundary river as it flows through six countries: China, Myanmar, Thailand, Lao PDR, Cambodia, and Vietnam. This region faces a strong rise in demand for energy, water supply, irrigation, and flood management. It increasingly requires engineering solutions such as hydropower electric dams and irrigation schemes. In 2017 there were in the Mekong Basin a total of 187 hydropower dams with a minimum installed capacity of 15 megawatt (MW) and 64 proposed hydropower dams. 18 dams are planned to be constructed in the Upper Mekong Basin, and another 46 dams will be built in the Lower Mekong Basin (Hecht et al., 2018) (Fig 1.2). Geographically, the basin is divided into the Upper and Lower Mekong Basin. The Upper Mekong Basin consists of the Tibetan Plateau in China's Yunnan Province and Myanmar, while the Lower Mekong Basin covers Lao PDR, Thailand, Cambodia, and Vietnam. Most of the annual river flow volume contributing to the Mekong River comes from tributaries in the Lower Mekong Basin, while the upstream river and tributaries contribute a much smaller proportion of the total flow of the Mekong River.

The Lower Mekong Basin is home to nearly 65 million people, of which 40% live within 15 km of the Mekong River. The river is an important driver for livelihood and economic growth, providing food and energy for the region. With rapid economic growth in the region, the energy demand for the Lower Mekong Basin is forecasted to grow at 6 - 7% annually. As of 2019, the total number of existing hydropower dams in the Lower Mekong Basin is 89 with a total installed capacity of 12,285 MW: 2 dams in Cambodia (401 MW); 65 dams in Laos (8,033

MW); 7 dams in Thailand (1,245 MW), and 14 dams in Vietnam (2,607 MW). It is anticipated that the energy production will be more than 30,000 MW by 2040 (MRC, 2016).

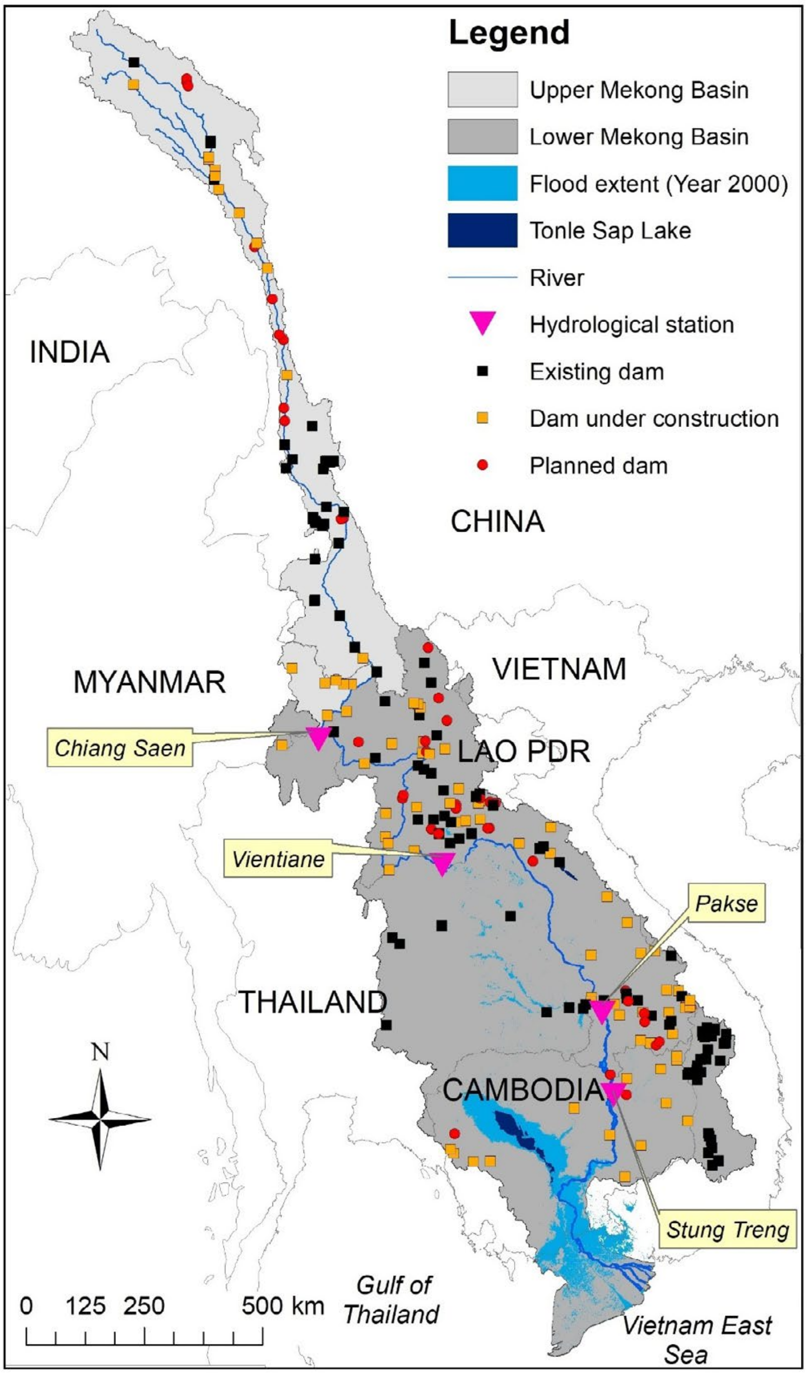

Figure 1.2. The Mekong River Basin with existing and proposed hydropower dams (Hecht et al., 2018)

1.2 Problem statement

Apart from the positive sides of hydropower development for socio-economic growth, mitigation of floods and droughts, and benefits for downstream irrigation areas (Lacombe et al., 2014), several studies have shown negative impacts as a consequence of dams in the Mekong Basin. Reservoirs impoundment have caused fertile agricultural lands to be inundated, and affected communities have been relocated to new settlements where farming is less productive (Zhang et al., 2013). Floodplains downstream of hydropower dams have reduced inundation, and fertilisation due to lower peak monsoon river flows and sedimentation, affecting the riparian farmers' crop productivity (ICEM, 2010; Intralawan et al., 2018). Dams can also block fish migration routes between the downstream floodplains and upstream tributaries, impacting fish productivity. Further, the loss of biodiversity and ecosystem productivity is a well-recognised effect of dam infrastructure (Dugan et al., 2010; Ziv et al., 2012). For instance, parts of the Tonle Sap Lake inundation areas in Cambodia have become permanently inundated due to dam-induced increase in dry season flows, degrading the floodplain vegetation and productivity of the ecosystem, and modifying the ecological habitats (Kummu and Sarkkula, 2008; Arias et al., 2012).

Most previous studies in the Lower Mekong Basin have focused on evaluating the impacts of hydropower dams on hydrological and environmental changes (Francis et al., 2010; Roy et al., 2015; Li et al., 2017a; Räsänen et al., 2017; Hecht et al., 2018; Grill et al., 2019). However, few studies have investigated the effects of anthropogenic and natural climatic-induced changes in river flow regimes on connected groundwater systems. The consequences of changes in the flow regime and river stages from the pre- to post-dam period on surface water and groundwater exchange and groundwater levels are poorly understood. Smith et al. (2016) claimed that "the upstream-downstream relationships typical for surface waters, with their associated power dynamics among water users, have little to do with groundwater, and the spatial and temporal scope of groundwater is very different to surface waters". However, this thesis hypothesises that the upstream surface water infrastructures also significantly impact the groundwater systems downstream. To better understand the consequences of human activities and climate variability on hydrological regimes, surface water-groundwater interaction and groundwater fluxes, this thesis focuses on the Nam Ngum River Basin (NNRB), Lao PDR. The Nam Ngum River is a major tributary of the Mekong River. Hydropower dams were intensively developed in the upper parts of the basin. In contrast, the lower part has very few dams and is developed for agriculture. But the development of groundwater resources is constrained by the limitation of understanding groundwater systems, resulting in ineffective water resources management (Pavelic et al., 2014; Viossanges et al., 2018).

1.3 Research aims

The broad aim of the research was to evaluate anthropogenic and natural climatic drivers on the river flow regime and connected groundwater systems before and after a series of hydropower dams were constructed and brought into operation. The study focused on the lower NNRB, where human activities and climate variability influences surface water and groundwater system conditions. Comparing the pre- to the post-dam period provided an opportunity to evaluate the changes in river flow patterns, water productivity, surface water-groundwater interaction, groundwater recharge, and water balance. The specific aims of this thesis were:

i. To attain confirmation of a change in river flow from the pre- to post-dam period and investigate the significant anthropogenic and natural hydroclimatic drivers controlling the flow regime. In order to reduce the ambiguity of how these drivers affect water yield in a downstream area, i.e., water productivity produced from the lower-NNRB and change in water storage compared to other relevant climatic and hydrological indicators.

ii. To evaluate groundwater recharge and other water balance components (i.e., surface runoff, actual evapotranspiration, interception) in the lower-NNRB for two conditions: with and without irrigation water. Furthermore, to determine the impact of irrigation water diverted from the river on groundwater recharge and other water balance components and assess which part of the groundwater recharge is derived from the irrigation schemes.

iii. To investigate the impact of changes in river flow regimes and river stages due to reservoir dam operations on surface water-groundwater interactions and groundwater systems in the downstream basin by assessing the status of river-groundwater interactions, groundwater budgets, water tables, and water balance for the pre- to post-dam period.

1.4 Contribution of this PhD

This PhD explores the impacts of anthropogenic and natural climatic drivers on river flow regimes and connected groundwater systems before and after installed hydropower dams. This study reduces the ambiguity in our understanding of the importance of human activity versus natural climatic drivers influencing the river flow regime. It advances the differential river flow methodology for defining the state and dynamics of river losing or gaining conditions from hydrological time series of the pre- to post-dam operation for a Mekong River sub-basin (Chapter 2). This approach is data-driven, simple and suitable for an area with limited hydrological and meteorological field observed data. It exploits publicly available remote sensing data sets. The results are validated using observed groundwater and river levels and model simulations (Chapter 4). The analysed river flow regime in the post-dam period aligns with other studies that have been conducted on the Lower Mekong Basin. However, this study also shows a change in water yield in the lower sub-basin as a consequence of regulated surface water. The application of global and publicly available remote sensing based data (i.e., actual evapotranspiration, soil moisture, landcover, and GRACE total water storage) as indicators of change in the basin was beneficial for the analyses. The approach offers a clear promise for use in other areas with limited field data.

Groundwater recharge of the aquifers systems of the Mekong sub-basin is dominated by precipitation as most recharge takes place during the rainy season. The additional groundwater recharge provided by irrigation water diverted from the river is minor compared to the recharge of the entire lower basin. Recharge within the irrigation command areas is slightly higher than in the non-irrigated areas; actual evapotranspiration and interception also exhibit a slight increase. The monthly and annual spatial recharge provides a distribution of recharge across the lower basin, allowing the recharge to be compared with the groundwater table fluctuation method.

Other studies have argued that the upstream-downstream surface water relationships have minor impacts on groundwater as groundwater's spatial and temporal scales are different from surface water. However, this study shows that the change in river stages significantly impacts groundwater systems due to regulating rivers upstream. The results of this thesis enable a much better understanding and, therefore, an opportunity to improve water management of surface and groundwater resources in the Lower Mekong Basin.

Chapter 2. Anthropogenic-induced changes in basin water yield: Trends and driving factors for a Mekong River sub-basin[1]

Abstract

Study focus: In many large river basins with significant anthropogenic modifications (e.g. dams), most studies have focused on the changes in the river flow regime. There is a lack of understanding in changes in the water yield, i.e. the within basin generated combined surface runoff and groundwater, surface water-groundwater interaction, and changes in storage. The study investigates the changes in the river flow and the water yield from the pre-dam period (1962-1972) to the post-dam period (1973-2016) in the Nam Ngum River Basin. Historical observed river flow, climatic, soil moisture, storage and landcover estimates are analysed using Mann-Kendall trend and Pettitt's step-change tests. A conceptual model explaining hydrological change and driving factors is developed.

New hydrological insights for the region: During the pre-dam conditions, the river flow was highly seasonal. However, under post-dam conditions, seasonal flow dynamics diminished; 39% lower monsoonal peak flow and 120% increased dry season flow. The water infrastructure shows a greater impact on the river flow than climate variability. In the post-dam period, the river is now year-round gaining groundwater. The annual and dry season water yields in the lower basin also exhibit an increasing trend, suggesting that the anthropogenic river water level and land use changes strongly impact the coupled groundwater-surface water system.

Keywords: water yield, Mekong Basin, anthropogenic-induced changes, flow, groundwater-surface water interaction

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[1] To be submitted to the *Journal of Hydrology: Regional Studies*

2.1 Introduction

Water is an essential natural resource for humans, industry, agriculture and ecosystems, and its use is under increasing pressure due to the anthropogenic impacts of climate change, hydropower dams, irrigation, and land cover change (Meybeck, 2003; Nesbitt et al., 2004; WREA, 2008a; Vörösmarty et al., 2010; Wagener et al., 2010; Pelletier et al., 2015). In approximately three-quarters of the world's river basins, water infrastructures such as reservoirs and hydropower dams directly regulate river water flows (Kummu and Varis, 2007; Zhao et al., 2012). Anthropogenic impacts and climate change contribute to changing water yields of these basins (Brown et al., 2005; López-Moreno et al., 2011). Water yield is defined as the net production of river flow, including surface runoff and groundwater discharge within a basin or part of it. It is an important hydrological concept as it characterises how much of the rainfall in a basin will contribute to river flow (Falkenmark and Rockström, 2006; 2010). Under pristine conditions, the water yield of a basin would be produced by surface runoff and baseflow, and therefore essentially be equal to the precipitation minus the basin evaporation and transpiration. However, as a result of anthropogenic influences, the water yield is affected by changing climatic conditions (Xin et al., 2019), land use change (Li et al., 2017b; Dennedy-Frank and Gorelick, 2019), surface water and groundwater abstractions (Van Oel et al., 2008), irrigation return flows (Wei and Bailey, 2019), diversions of water across basin boundaries (Ahn et al., 2016) or a combination of these influences (Sridhar et al., 2019).

The importance of water yield for water management is the sustenance of downstream water requirements for human activities (i.e., drinking water, irrigation, industries, fisheries), ecological and cultural values. For instance, in the Mekong River delta of Vietnam, irrigation demand is forecasted to exceed river flow in the critical dry season months, February-May, by 2050 (Nesbitt et al., 2004; Smajgl et al., 2015). Therefore, maintaining or improving water yield in upstream catchments is crucial for sustainable water resources in downstream areas

(Hoanh et al., 2010; Lacombe et al., 2014). However, few studies have investigated the combined impacts of climate and land use change on water yield (Zhang et al., 2018). There has been very limited research that has included analyses of the consequences of upstream river dam infrastructure on downstream basin water yields.

The Lower Mekong Basin (LMB) is an exemplary area undergoing rapid expansion in hydropower development and irrigation to meet the growing national and regional demands for energy and food. River infrastructure operations, including hydropower dams, cause not only a change in river flow regimes but also impact the connected groundwater systems as a result of the change in river stage and the hydraulic gradients between the river and aquifer (Seeboonruang, 2012; Zhang et al., 2012). Relevant studies on the impact of dam development and river operation, as well as land cover change on hydrological changes in the LMB, are summarised in Table 2.1.

The Nam Ngum River Basin (NNRB) (Fig. 2.1b), like many other sub-basins of the LMB, shows the rapid development of hydropower dams in the upper part of the basin, while agricultural production is expanding in downstream areas. Previous studies in the NNRB have attempted: (i) to assess environmental and social impacts of future proposed hydroelectric dams (ADB, 2007; China International Water & Electric Corp, 2007; Vattenfall Power Consultant AB, 2008; SD & XP consultants Group and Nippon Koei, 2009); (ii) to determine water resource availability for different river basin development scenarios (Sanyu Consultants Ltd, 2004; AFD & ADB, 2008; WREA et al., 2009; Lacombe et al., 2014); (iii) to determine economic trade-offs of multiple water uses in the basin, including hydropower generation, irrigation expansion, flood control, and transfer of water to neighbouring countries (Bartlett et al., 2012); and (iv) to establish the value of coordination among various water users for the cascade of hydropower dams in the basin (Jeuland et al., 2014).

Lacombe et al. (2014) investigated whether the development of hydropower dams would complement irrigation expansion by comparing the river flow under pre-dam, existing dams and proposed dams for several irrigation scenarios. Their study showed that: (i) hydropower dam development would increase dry season flow, enabling irrigation development downstream; (ii) without dam storage in the upstream part of the basin, irrigation expansion would not be compatible with required environmental flows in the dry season; and (iii) irrigated areas would not be able to expand to their full potential of 56,760 ha without the development of proposed hydropower dams. However, the study only considered hydropower dams and irrigation development as factors influencing water supply and demand. It did not investigate how the impacts of the changes in river flow in combination with climate and human activities affect the water yield, surface water-groundwater interactions, and change in storage in the lower basin.

To fill this knowledge gap, this study sets out to investigate the climatic and anthropogenic drivers to the change in river flow and basin water yield from the pre-dam to post-dam near-present period and conditions in the Lower NNRB. Therefore, the specific aims are: (i) to attain observational confirmation of a changed river flow regime; and (ii) to establish how this change in regime in combination with anthropogenic and climatic factors affect the water yield in the Lower NNRB.

Table 2.1. Summary of relevant recent literature on the impact of hydroelectric dam operations and land use change on river flow in the Lower Mekong Basin (LMB).

Study	Study Area	Aims	Method	Major outcomes
Homdee et al. (2011)	The Chi sub-basin of the LMB	Estimation of impacts of land cover changes on hydrologic response.	SWAT model	Land use changes affected strongly annual and seasonal water yield and ET.
Räsänen et al. (2012)	Upper Mekong Basin (UMB)	Downstream hydrological impact assessment of hydropower development.	VMod and a reservoir cascade optimisation (CSUDP) model.	Dry season flow increased by 90% and wet season flow decreased by 22% at the Saen Chiang gauging station.
Lacombe et al. (2014)	NNRB, a sub-basin of the LMB	Assessment of complementarity of hydropower and irrigation developments.	Observed river flow, dam and irrigation development scenarios.	Without dams, current irrigation needs would compete with environmental flow requirements during drier than normal years. Dry season flow increased while the peak flow decreased after dam operations.
Piman et al. (2016)	Srepok, Sesan and Srekong River LMB sub-basins	Determination of impact of operation of proposed dams on flow regimes and energy production.	SWAT and HEC-ResSim models.	Maximising energy production will significantly reduce the difference between wet and dry season. Dry season flow will increase by an average of 98% at the confluence of the three sub-basins.
Räsänen et al. (2017)	UMB	Analysis of downstream river flow regime due to the hydropower dam operations 1960-2014.	Observed river flow and a distributed hydrological model.	Results confirm model prediction of Räsänen et al. (2012), but the observed flow changes are partly larger and varied from year to year depending on dam operations.
Lyon et al. (2017)	33 unregulated sub-basins of the LMB	Detecting impact of changes in land use on hydrology.	Two-parameter GR2M and distribution-free statistical tests.	For those sub-basins with increasing trends in river flows, the trends are related to decreasing forest cover and increasing area of paddy rice.
Li et al. (2017a)	LMB	Characterisation of observed changes in flow regime as a result of dam operations in the UMB.	Observed flow, and indicators of hydrologic alteration.	A declining trend in annual stream flow at the upstream (Chiang Saen) has been found but no clear effect downstream (Stung Treng). The flow has reduced in the wet season but increased in the dry season.
Ngo et al. (2018)	Sesan and Srepok sub-basins of the LMB	Examination of the impacts of reservoir operation and climate change on the flow regimes.	SWAT and WEAP models.	Climate change is likely to reduce stream flows, but the changes in the seasonal and annual flows regimes are small, with 3-8% decrease and 3-13% increase.
This study	NNRB, a sub-basin of the LMB	Evaluation of the impact of natural and anthropogenic drivers on water yield	Analyses of time series of trends of observed river flow 1962-2016, precipitation, AET, soil moisture, TWS, and land cover	Reservoir operations have a greater influence on river flow than climatic drivers. The river has become year-round gaining, and there has been an increase in water yields in the Lower NNRB compared to the pre-dam period.

2.2 Study area

The Nam Ngum River Basin (NNRB) is a sub-basin of the Mekong River Basin (Fig. 2.1a). It is located in central Laos and has a total drainage area of 16,800 km^2 (Fig. 2.1b). Its elevation ranges from 155 m above mean sea level (m asl) at the confluence of the Nam Ngum River with the Mekong River to 2,820 m asl on mount Phou Bia (WREA, 2008b). The NNRB generates about 4.3% of the Mekong River's mean (1962-1984) annual flow (Lacombe et al., 2014). This flow is essential for power production, urban water supply and fishery (WREA, 2008b). The NNRB is home to about 502,000 people, representing approximately 9% of the total population of Laos PDR (WREA, 2008b).

The climate in this area is tropical, with a distinct wet season from May to October and a dry season from November to April (Jayasekera, 2013; Shrestha et al., 2013). Most of the rainfall in the NNRB is due to the arrival of warm moist air coming from East Asia and Indian Monsoons (Jayasekera, 2013; Lacombe et al., 2014). Annual rainfall at the Thangon station (1965-2014) varies between 1,278 – 2,771 mm, and the mean annual rainfall is 1,855 mm, 90.5% of which falls during the wet season.

The upstream part of the NNRB is hilly and mountainous and serves as the source area for several major tributaries of the Nam Ngum River. In this part, six hydropower dams are operational currently, while six more dams are planned to be developed in the near future (WLE, 2017). The downstream or lower part of the basin (Fig. 2.1c) consists mainly of floodplain areas, known as the Vientiane Plain, and covers 75% of the total irrigated area of the entire basin. In the Vientiane Plain, the goal is to expand irrigation and food production to meet the demand of population and socio-economic growth (Bartlett et al., 2012).

The flow of the Nam Ngum River is regulated since the construction of the first large dam (1968-1971) (Lacombe et al., 2014). The six hydropower dams operating in the upper part of the basin commenced between 1971 and 2011: Nam Ngum 1 (1971), Nam Lik 1 (2006), Nam

Ngum 2 (2010), Nam Ngum 5 (2011). The other two hydropower dams and their reservoirs: Nam Leuk (2000) and Nam Mang 3 (2005), are located outside the basin, but water released from the turbines of Nam Leuk is transferred into the upper basin to increase water storage for Nam Ngum 1. In addition, the Nam Mang 3 hydroelectric dam releases water for energy production and for irrigation of 2,900 hectares of paddy land in the lower Vientiane Plain. The Nam Mang 3 reservoir is located approximately 500 m above the nearby NNRB; hence it is possible to irrigate the lowland areas by gravity flow (Kouangpalath et al., 2016). The Nam Ngum 1 dam is the oldest in Laos and receives inflow from the upstream dams Nam Ngum 2 and Nam Ngum 5. Nam Lik 1 is located on the Nam Lik River, a tributary of the Nam Ngum River.

Essentially, two dams (Nam Ngum 1 and Nam Lik 1) control the river flow to the Lower NNRB or Vientiane Plain, the main study area (Fig. 2.1b). It is delimited by the Nam Ngum River basin area between the two gauging stations Pakanhoung and Thangon, and extends over 2,103 km^2 (Fig. 2.1c). Based on drilling logs for the groundwater development project in the Vientiane Province, conducted by JICA (1994), the Lower-NNRB is considered to be a shallow unconfined alluvium aquifer with a thickness of up to 40 m in the plain and decreasing towards the edge of the hills (Perttu et al., 2011; ACIAR, 2016). Most irrigation areas lie in the Vientiane formation, which consists of coarse sediments (N2-Q1vc) mixed with younger deposits (Qii-iii and Qiv). This formation has a hydraulic conductivity (K) ranging from 10^{-6} to 10^{-4} m/s, and a specific yield (S_y) ranging from 0.03 to 0.13. Hence, it is considered a potentially high productive aquifer (Takayanagi, 1993; Perttu et al., 2011). It is important to note that the Lower NNRB itself has no dam infrastructure on the main river. We, therefore, focus on the impacts of the upstream dam developments on the changes in the flow regime and the water yield of the Lower NNRB.

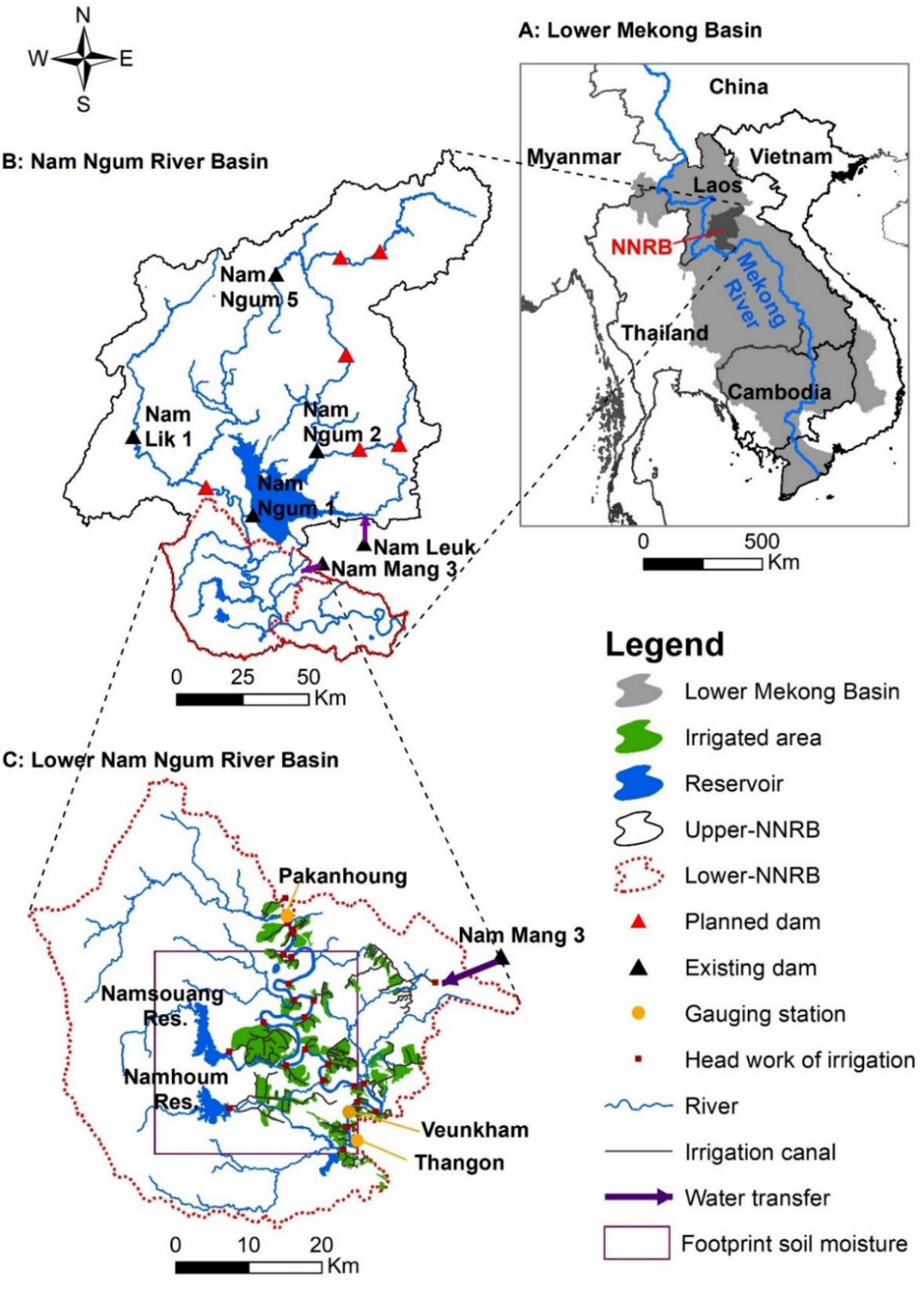

Figure 2.1. Study area (a). The Lower Mekong Basin with highlighted Nam Ngum River Basin (NNRB). (b). The Nam Ngum River Basin with existing and planned dams, reservoirs, and delineation of Lower NNRB. (c). The Lower NNRB, between gauging stations Pakanhoung and Thangon. Indicated are the Nam Mang 3 dam, reservoirs, major irrigation command areas with irrigation pumping stations, river gauging stations and the footprint of the soil moisture data. The locations of dams are derived from the map of dams in the Mekong Basin, available from https://wle-mekong.cgiar.org/.

2.3 Methods and data

2.3.1 Concepts

The complex relationship of water infrastructure, land cover and climate variability, as well as climate change in the NNRB, impacts the flow and water yield in the Lower NNRB. Therefore, this study identified and conceptualised the factors influencing the flow regime and water yield for the pre- and post-dam periods (Fig 2.2). This conceptual model defines the required data and methods for investigation, and these are described in more detail in the following sub-sections.

For the pre-dam period, the conceptual understanding of the Lower NNRB is characterised by a free-flowing river in the Upper NNRB, not regulated by dams (Fig. 2.2a). Therefore, the flow regime of the Lower NNRB can be determined by analysing the river flow of the downstream gauging station, Thangon. On the other hand, this flow, compared to the flow at the upstream, Pakanhoung station, provides information on the water yield of the Lower NNRB. Pre-dam, rainfall was the dominant water source for the paddy rice cropping. Hence, it is expected that under these low anthropogenic impact conditions, the river flow and water yield of the Lower NNRB, constituting the summation of the surface runoff and the baseflow, was highly seasonal.

The post-dam concept for the Lower NNRB is characterised by a regulated river flow resulting from installed dams upstream of the Lower NNRB (Fig. 2.2b). Further, significant anthropogenic impacts in the Lower NNRB between the upstream and downstream gauging stations are expected as a consequence of extraction of river water for irrigation, return flows and recharge from irrigation. Moreover, land use change, water storage in reservoirs within the basin, and transfers of water across the basin boundary by water diversions and seepage from a reservoir located outside the basin are possible influencing factors. Finally, there are the potential impacts of changes over time in rainfall and evapotranspiration.

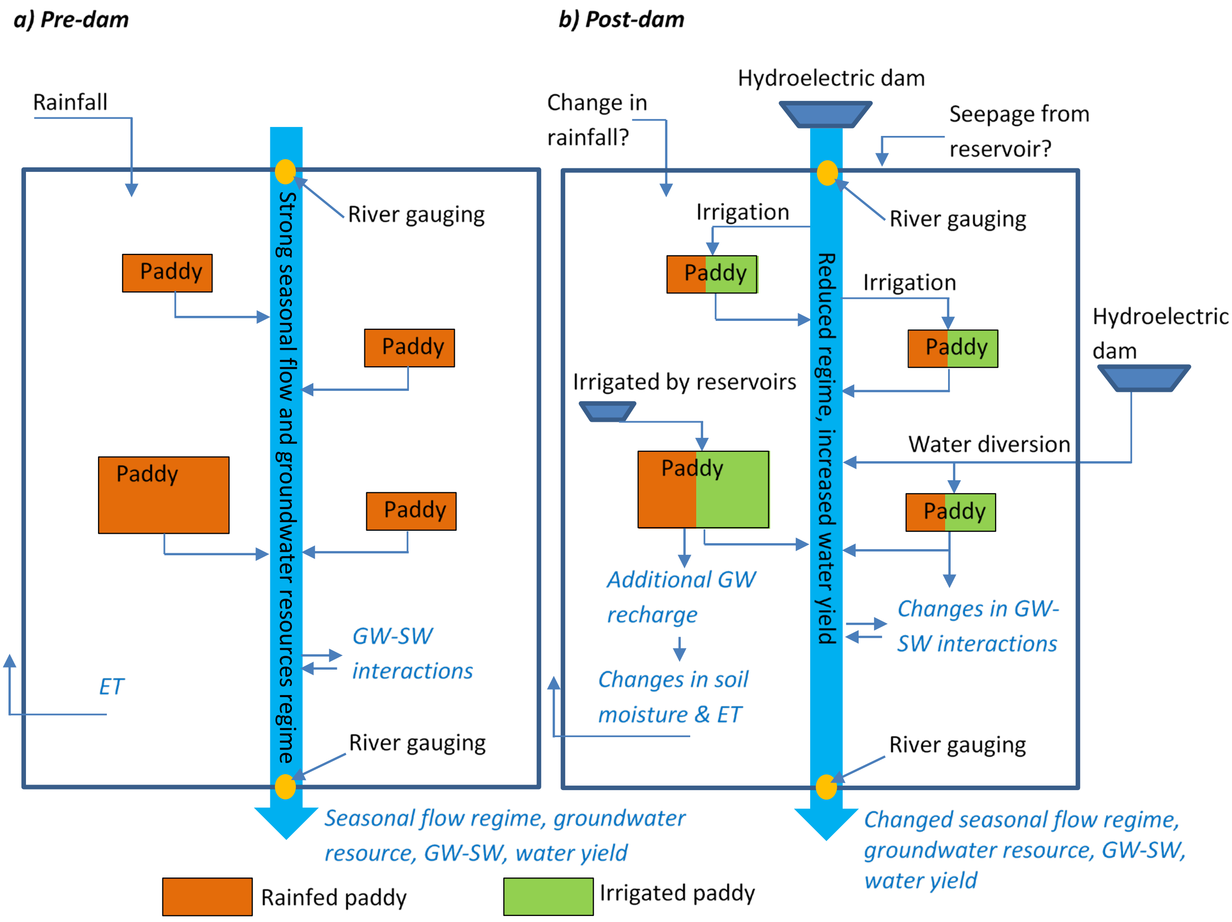

Figure 2.2. Conceptual diagram of factors influencing flow regime, groundwater resource, groundwater-surface water interaction and water yield in the Lower NNRB for the (a) pre-dam and (b) post-dam period.

2.3.2 Flow data

Three river gauging stations (Pakanhoung, Veunkham and Thangon) are located in the Lower NNRB. In total, 54-years of daily river flow data from 1962 to 2016 was obtained from the Lao Department of Meteorology and Hydrology (Fig. 2.3). Despite the relatively long flow record, the accuracy of the flow gauging is unknown, and the rating curve was not available. For the pre-dam period from 1962-1971, available flow data characterises the relatively pristine river condition with no reservoirs in operation. The post-dam period started in 1972 when water infrastructure construction commenced. Except for the earliest Nam Ngum 1 dam, all current hydropower dams have come into operation since the 2000s.

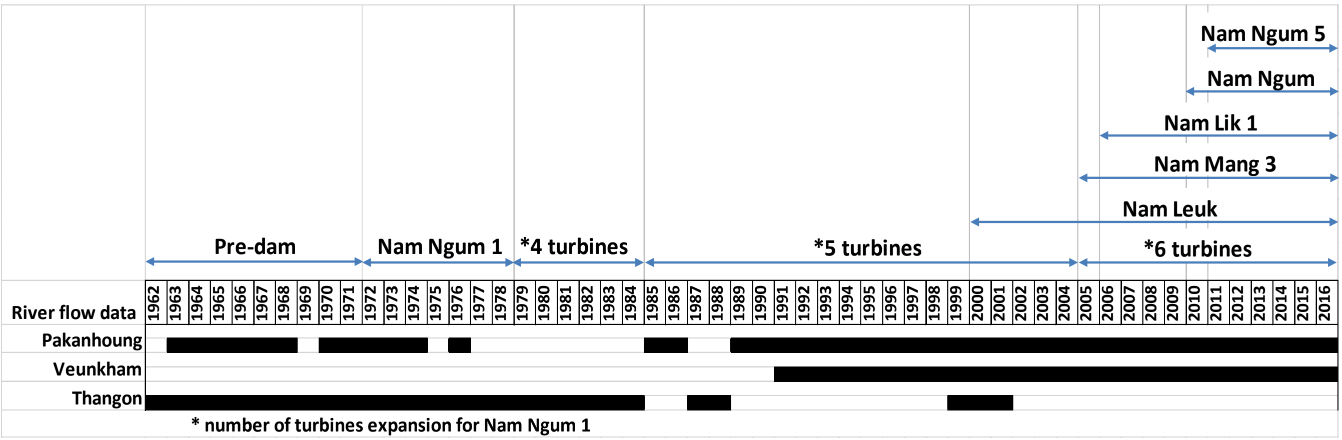

Figure 2.3. Development of dams over time in the Nam Ngum River Basin and available river flow data for the Pakanhoung, Veunkham and Thangon river gauging stations in the Lower Nam Ngum River Basin between 1962 and 2016. Available river flow data is shown in black, and blank years represent years with no data (data source: Department of Meteorology and Hydrology).

The upstream flow gauging station for the Lower NNRB is Pakanhoung, located 16.3 km downstream of the Nam Ngum 1 hydropower dam. The downstream gauging station for the Lower NNRB is Thangon and was selected over the Veunkham station because of its longer record of flow and greater reliability of flow measurements (Lacombe et al., 2011). Missing data till 2001 in the flow records of Pakanhoung and Thangon were estimated by linear regression (Lacombe et al., 2011). For the years 2002 till 2016, missing daily flow data for the Thangon gauging station ($Q_{Thangon}$ in m^3/s) were filled in by building a linear regression relationship for the years 1963 till 2001 using observed flow records of the Pakanhoung ($Q_{Pakanhoung}$ in m^3/s) and Thangon stations (Eq. 2.1). The additional incoming diversion from the Nam Mang 3 hydropower station, which started in 2005, is also accounted for in this relationship.

$$Q_{Thangon} = 1.0858 * Q_{Pakanhoung} + 16.264 \qquad \text{(Eq. 2.1)}$$

The relationship between the estimated and observed flow at Thangon shows a high goodness-of-fit with an R^2 of 0.94, a Mean Absolute Percentage Error of 14.1%, a Mean Bias Error of -0.024 m^3/s and a Nash-Sutcliffe Efficiency of 0.94 (Fig. S1(supplementary material)).

2.3.3 Change in flow regimes

The flow time series of Thangon, as the downstream gauging station of the Lower NNRB, was used to characterise the flow dynamics of the pre-dam (1962-1971) and post-dam period (1972-2016). Monthly average flow and monthly flow duration curves for 10-year pre-dam (1962-1971) and post-dam (2007-2016) periods were estimated. Average monthly flow indices for the periods of 10-yr were estimated to characterise the seasonality of the flow:

$$SI_j = 100 * \frac{Q_j}{\overline{Q}} \qquad \text{(Eq. 2.2)}$$

where SI_j (%) is the simple average seasonality index for month j (ranging from 1 to 12), Q_j is the 10-yr average flow of month j, and $\overline{Q}$ is the 10-yr yearly average flow. A seasonality index of 100% for a particular month means that the 10-yr average flow for this month is equal to the 10-yr average flow. The extent to which the monthly *SI* values deviate, above or below, from 100%, indicate the dynamics of the respective wet and dry season flows.

The flow time series were split into yearly wet (May-Oct) and dry season (Nov-Apr) flows, as most rainfall (90.5%) in the NNRB occurs during the wet season. The trends of the wet and dry season flows for 1962-2016 were estimated by using nonparametric Mann-Kendall tests (Mann, 1945; Kendall, 1975); trend and abrupt changes and driving factors on river discharge are detected using statistical analysis as a tool to guide reasoned interpretations of the change in flow regime. Additionally, the Pettitt's test (Pettitt, 1979) was used to determine if and when a step-change in the wet and dry season river flow occurred.

2.3.4 Change in water yield

For the pre-dam period, water yield in the Lower NNRB was quantified from the differential river flow between the two gauging stations (Thangon and Pakanhoung), assuming water yield is equivalent to total differential flow. For the post-dam period, the estimated differential river flow reflects a combination of the water yield and river flow extractions. To evaluate the change in water yield, firstly, the trend (Mann-Kendall) and homogeneity (Pettitt's test) of the differential flow from the pre-dam to the post-dam period on a wet, dry season, and annual basis was examined. Secondly, factors of change due to climatic drivers were examined; the trends of precipitation, actual evapotranspiration, soil moisture and Total Water Storage (TWS) were estimated within the Lower NNRB. Thirdly, factors of change due to human activities, land cover, irrigation and domestic water supply were investigated.

Precipitation and evapotranspiration

Precipitation is generally the main influencing factor that directly affects hydrological variability and changes in water yield. To evaluate the influence of possible non-stationary precipitation on change in river flow in the Lower NNRB, rainfall trends over 50 years using a Mann-Kendall test were analysed. The only rainfall time series data available was for 1965-2014 from the Thangon station, which was used to detect changes at monthly and annual time scales.

Similarly, a Mann-Kendall test was used to estimate a possible trend in evapotranspiration. A time series of actual evapotranspiration for 1963-2016 was obtained from the Global Land Data Assimilation System (GLDAS_NOAH) at a spatial resolution of 0.25 x 0.25 degree for the area 102.375E, 18.125N, 102.625E, 18.375N (Giovanni, 2019).

Soil moisture and groundwater storage

A time series of 0-10 cm depth soil moisture, at a spatial resolution of 0.25 x 0.25 degree, for 2000-2018 was also obtained from GLDAS_NOAH for the area bounded by 102.375E, 18.125N, 102.625E, 18.375N (Fig. 2.1c) (Giovanni, 2019). Again, the time series was subjected to a Mann-Kendall trend test.

Groundwater-surface water interactions during the pre- and post-dam period were assessed by two approaches. Firstly, the interaction was determined from the differential river flow

($Q_{Pakanhoung} - Q_{Thangon}$). Secondly, it was analysed by comparing observations of groundwater levels with surface water levels, as measured from wells and the river during the dry season of February 2019, using a Real-Time Kinematic GPS (RTK-GPS) (Rao et al., 2013). Groundwater head contours were generated from observed groundwater heads and river stage height elevations using diffusion interpolation with barriers techniques in ArcMap (Lilly, 2016; Theller, 2016).

A time series was obtained of reconstructed Total Water Storage (TWS) based on the Gravity Recovery and Climate Experiment (GRACE) mission (Humphrey and Gudmundsson, 2019) for evaluating the change in total basin water storage. The data is available from 1901-2014 for the area bounded by the coordinates 17.75N, 101.75E, and 18.75N, 103.25E. The trend (Mann-Kendall test) of TWS was analysed from 1962 to 2014.

Land cover

Land cover change is also a factor inducing hydrological change, especially when forest areas are converted to agricultural and built-up areas as a result of population growth and socio-economic development (Lacombe et al., 2014). To evaluate land cover change, the European Space Agency-Climate Change Initiative Land Cover product (CCI-LC) was used (ESA, 2017). The CCI-LC product is based on MERIS, SPOT-VGT, AVHRR and PROBA-V satellite imagery and has a 300 by 300 m of grid cell spatial resolution. The imagery was classified by using the UN Land Cover Classification System, which is compatible with the Plant Functional Type as used in many models (Li et al., 2018). Maps of the Lower NNRB were obtained for 1992, 2000, 2008 and 2015 to estimate the change in land cover.

Irrigation and urban water supply

The current volume of water used for irrigation was quantified based on the actual pumping calendar (number of pumping days per year, duration of operation) and the capacity of each water pump. Then the rate of pumped water was compared with the differential flow (water yield) to evaluate the magnitude of the impact of the irrigation schemes. Similarly, the amount of raw water that is lifted from the river for domestic water supply was assessed and compared with the differential flow.

2.3.5 Water balance

Monthly basin-wide change in water storage (DS) for the pre- to post-dam period (1965-2014) was assessed on the basis of a monthly water balance for the Lower NNRB.

$$DS = R_{in} + P + I - R_{out} - AET \quad \text{(Eq. 2.3)}$$

where R_{in} is the monthly river flow at Pakanhoung; P is precipitation over the basin area; I is inter-basin transfer; R_{out} is the monthly river flow at Thangon and AET is actual evapotranspiration over the basin, with all parameters expressed in 10^6 m^3. The estimated DS time series at yearly, wet and dry season time scales were subjected to trend and homogeneity tests.

2.3.6 Note on statistical tests and multiple lines of evidence

Amrhein et al. (2019) made a point of 'retiring statistical significance' in scientific studies and discourage significance tests, i.e. not to stop using p-values, but to stop interpreting them in a binary form of rejecting or supporting a scientific hypothesis. In this study, statistical tests are used, but it is avoided to interpret them categorically ('significant' or 'non-significant'). P-values are presented with precision and not as binary inequalities (Amrhein et al., 2019). With the multiple used datasets and performed trend tests (Wang et al., 2020), it is aimed to increase conceptual or perceptual process understanding of the complex change in hydrology and the driving factors of this change (Fig. 2.2). Hence, no simple rejection of a single hypothesis is sought, rather building support for multiple lines of evidence for multiple conceptual processes

(Enemark et al., 2019; Wagener et al., 2020). In this sense, the aim is here the scientific endeavour of increasing knowledge as a fundamental aspect of scientific progress (Bird, 2007).

2.4 Results

2.4.1 Change in flow regime

Monthly mean, minimum and maximum flow at the Thangon gauging station is presented for the pre-dam (1962-1971) and post-dam (2007-2016) period to identify the change in variability of the flow (Fig. 2.4). The monthly average precipitation for the pre- and post-dam periods is also presented for comparison, but the data is from a slightly different period due to data availability limitations (1965-1972 and 2007-2014). The seasonality indices are presented in Fig. S2 and show for the wet season strongly reduced and for the dry season months increased values.

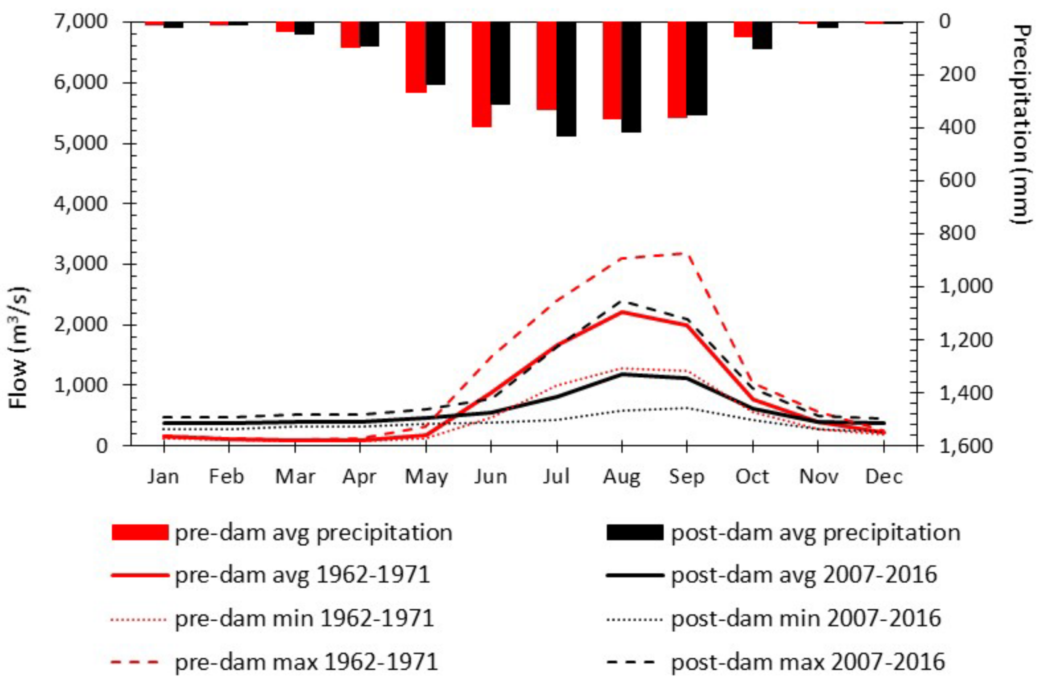

Figure 2.4. Mean, minimum and maximum monthly flow at the Thangon station for pre-dam (1962-1971) and post-dam (2007-2016) conditions. Precipitation for the Thangon station is for the pre-dam period from 1965-1972 and for the post-dam period from 2007-2014.

The comparison of flow duration curves (FDC) for the pre- (1962-1971) and post-dam (2007-2016) periods further illustrates changes in flow regimes (Fig. 2.5). The Mann-Kendall trend test shows that there is a strong (p=0.0001) increasing (Sen's slope 4.776) trend in the mean dry season flow between 1962 and 2016 (Fig. 2.6a). Similarly, the Pettitt test shows an important step-change in mean dry season flow centred at 1980 (Fig. 2.6a). However, the wet season flow has a strong (p=0.0002) decreasing (Sen's slope 9.038) trend, and a step-change is identified to occur in 1982 (Fig. 2.6b).

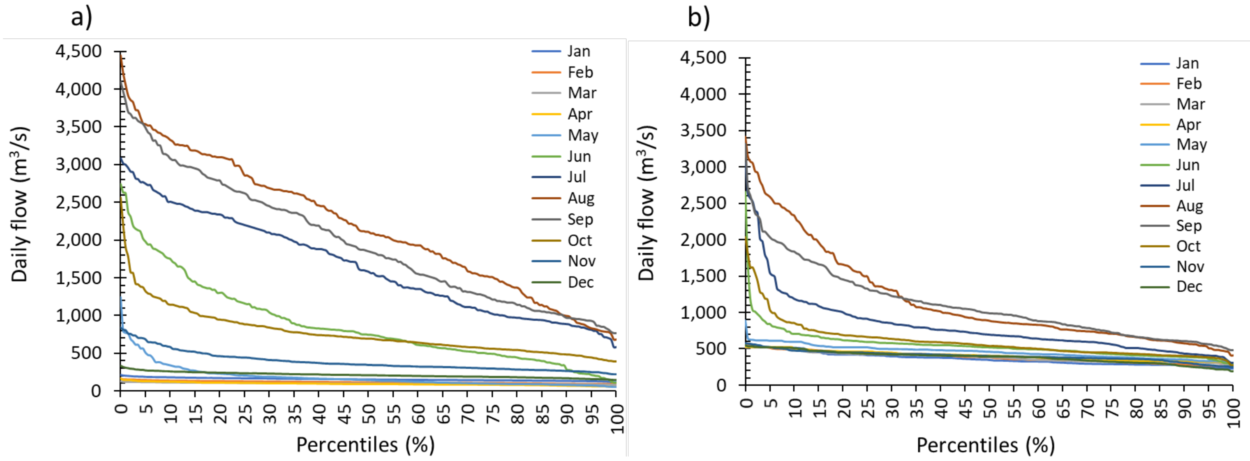

Figure 2.5. Monthly flow duration curves for daily flow exceedance at Thangon gauging station: (a) pre-dam period (1962-1971), and (b) post-dam period (2007-2016).

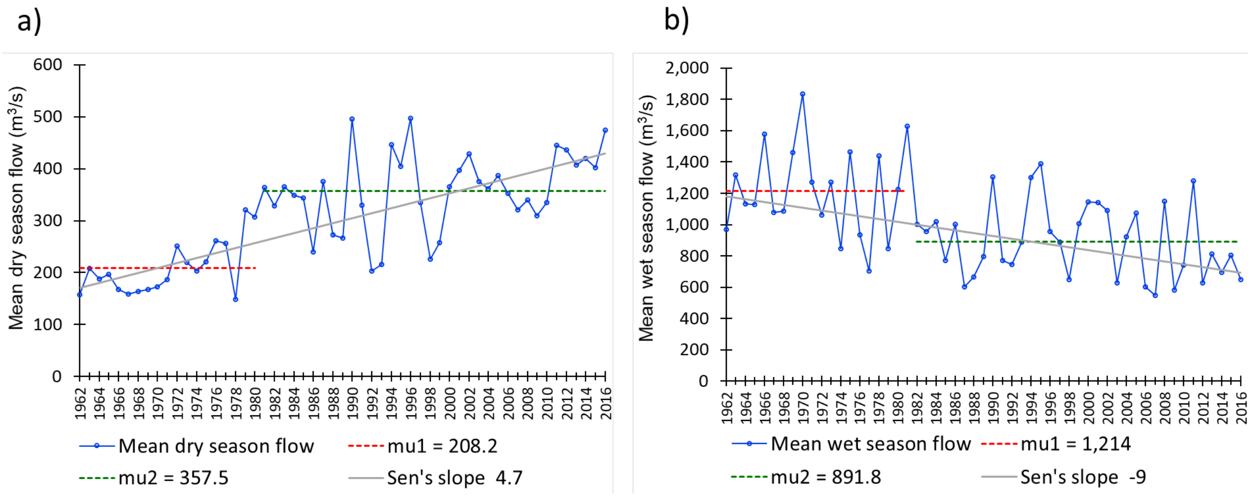

Figure 2.6. (a) Trend and step-change results for mean dry season flow; and (b) for mean wet season flow at the downstream gauging station (Thangon) for 1962-2016. The red dashed lines show the homogeneity of flow before shifting to the next green level; mu1 and mu2 are the corresponding average flows in m3/s. Note the different y-scales for the dry and wet-season flows.

2.4.2 Factors contributing to the changes in water yield

In this section, results on the analysis of changes in differential flow, precipitation, evapotranspiration, soil moisture, groundwater, land cover, irrigation and domestic water supply are presented as factors of understanding the evolution in water yield.

Water yield

As an indicator of water yield, change in differential flow was evaluated for the Lower NNRB between Pakanhoung and Thangon stations for the period 1963-2016. The monthly differential flow between the two gauging stations shows that the differential flow was mostly positive (Fig. 2.7). However, some years till 1999 and especially before 1977 showed negative differential flow, particularly during the driest months (January to April). However, after 2001 exclusively positive differential discharge is observed.

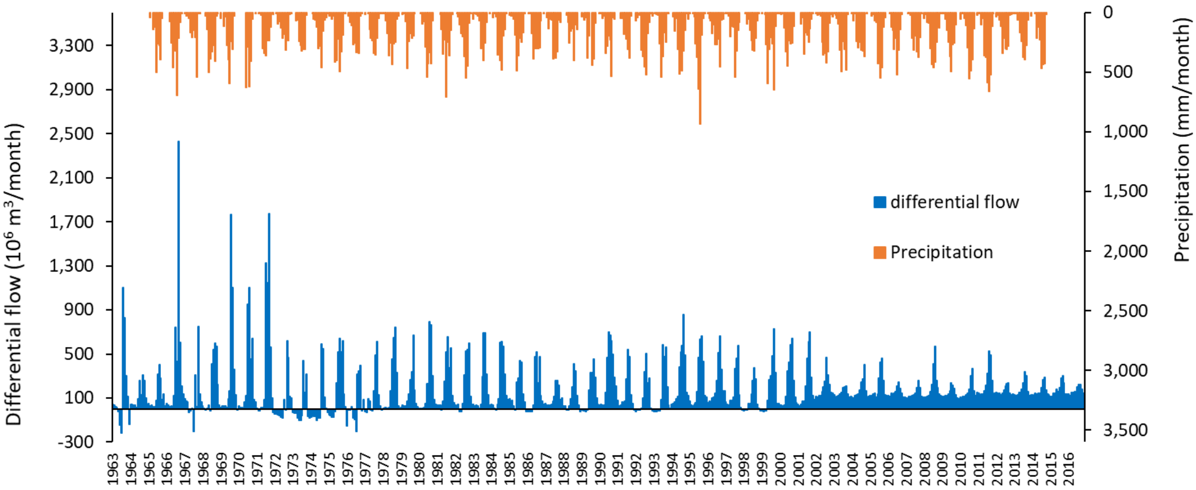

Figure 2.7. Monthly rainfall (1965-2014) and monthly differential flow between downstream and upstream Nam Ngum River (Thangon and Pakahoung) from 1963-2016.

The differential flow was also analysed at annual, wet and dry season time scales (Fig. 2.8). Fig. 2.8a shows that the yearly differential flow has a minor (p=0.54) increasing trend (Sen's slope is 4.57). It is also clear that the inter-annual variability is decreasing. The yearly wet-season differential flow shows a slightly decreasing (p= 0.11; negative Sen's slope of 12.37) trend, as well as a decreasing inter-annual variability (Fig. 2.8b). The yearly dry-season differential flow indicates a strongly increasing trend (p=0.0001; positive Sen's slope of 14.8), a 290% step-change up and a decreased inter-annual variability after the year 2000 (Fig. 2.8c).

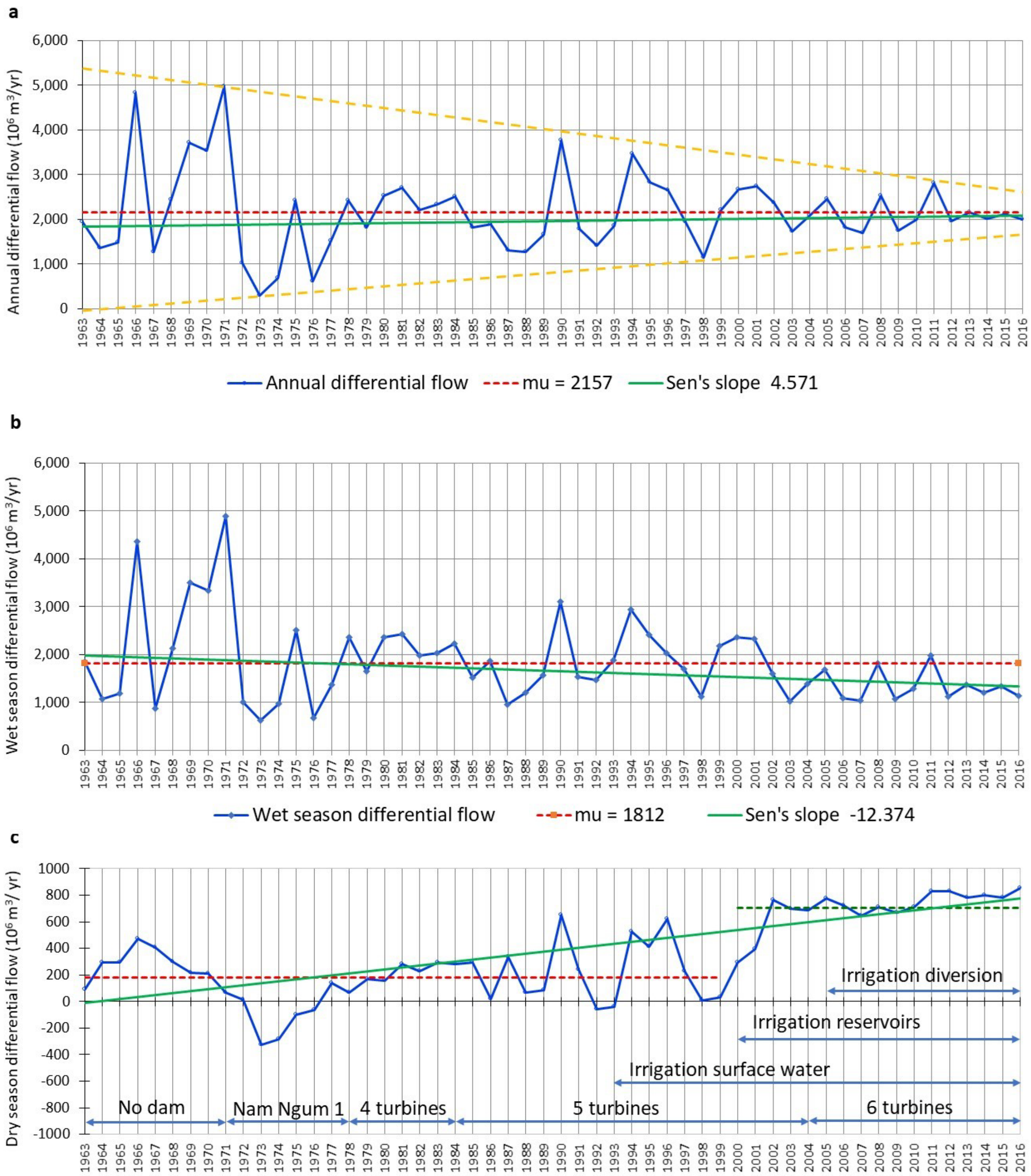

Figure 2.8. (a) Annual differential flow between Thangon and Pakahoung from 1963-2016 with trend line. The yellow-dashed line indicates the envelop or range of the inter-annual variability; (b) wet season differential flow and trend line; (c) dry season differential flow with timelines of Nam Ngum 1 hydropower development, irrigation schemes using water from the river, the regulation of reservoirs, and the Nam Mang 3 hydropower diversion. The red dashed lines show the level of homogeneity of flow before shifting to the next green level, mu1 and mu2 are the corresponding average flows in 10^6 m^3/yr.

Precipitation and evapotranspiration change

The monthly average precipitation for the pre-and post-dam period, respectively 1965-1972 and 2007-2014, is presented in Fig. 2.4. A t-test showed that there is a marginal difference in precipitation between the two periods (p=0.32). Moreover, the 1965-2014 precipitation time series at monthly and annual resolution revealed marginal trends (p=0.05) (Table S1). The Sen's slope is mostly zero or positive, except for negative slopes for May and June.

The results of the Mann-Kendall trend analysis for annual, wet and dry season GLDAS_NOAH actual evapotranspiration for 1963-2016 is summarised in Table S2. An increasing trend is observed for the dry season (p= 0.01), while the annual and wet season also show increasing trends, but much weaker (p=0.10 and p=0.31, respectively).

Soil moisture and groundwater change

Table S3 summarises the trend analysis of soil moisture data (GLDAS_NOAH) from 2000 till 2018 for the grid cell covering a significant part of the Lower NNRB (Fig. 2.1). Decreasing soil moisture trends are observed for the end of the dry and the beginning of the wet season months, April-June. On the other hand, the beginning of the dry season months, December-January, show an increasing soil moisture content.

Figure 2.9 presents the RTK-GPS mapped groundwater head and river water levels during the dry season of February 2019. Interpolated groundwater head contours show a general groundwater flow towards the Nam Ngum River.

The monthly and seasonal Total Water Storage (TWS) (1962-2014) trends showed to be positive, although the trends were marginal (Table S4 and Fig. S3).

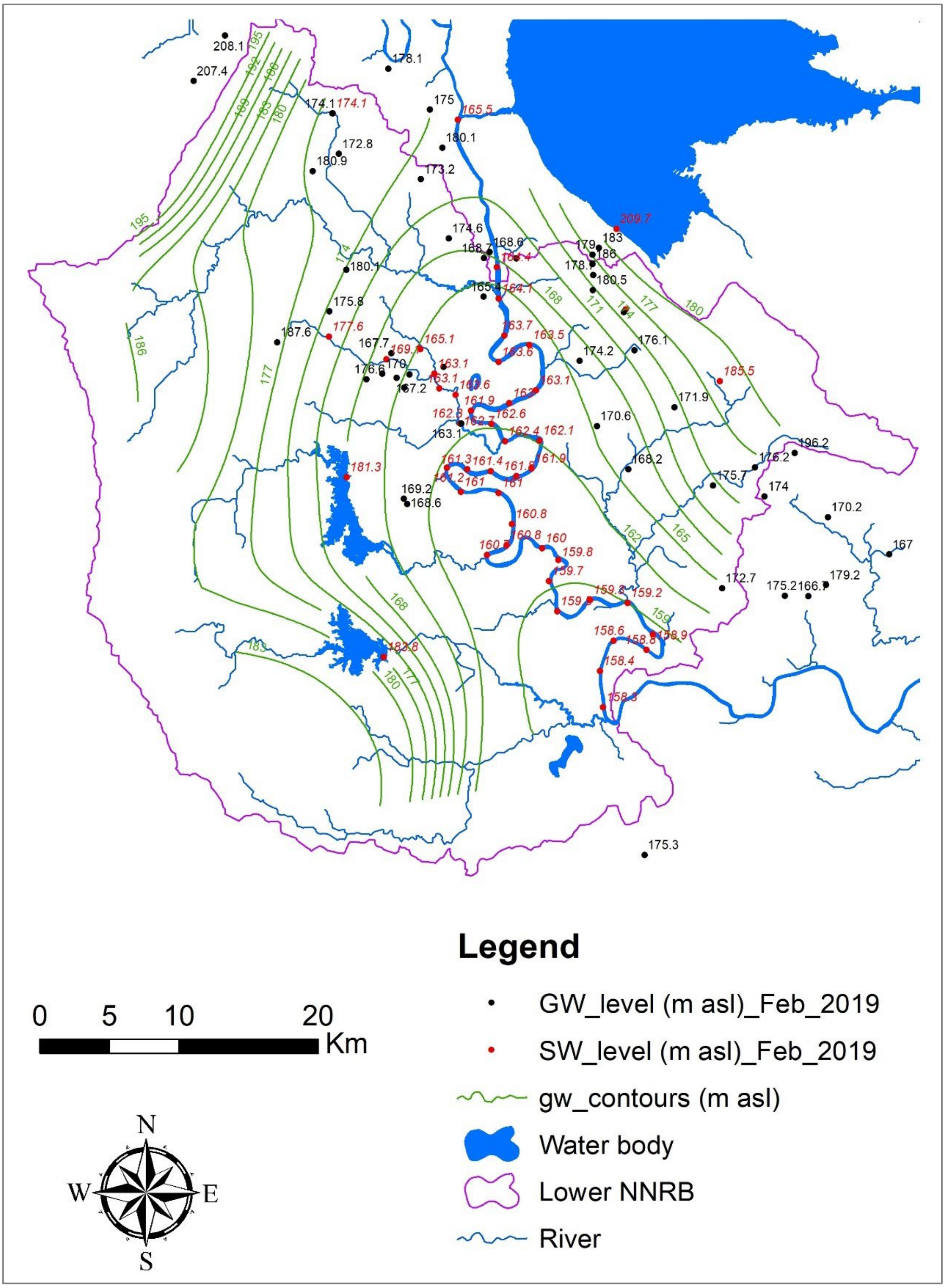

Figure 2.9. Interpolated phreatic head contours and measured groundwater and river water levels for the Lower NNRB.

Land cover change

The land cover of the Lower NNRB is dominated by rainfed cropland, shrubland and a mosaic of cropland and natural vegetation (Fig. S4). Over the evaluation period of 1992 till 2015, there has been a slight increase (from 35 to 36%) in coverage of rainfed cropland and (from 10 to 12%) in mosaic cropland/natural vegetation and a decrease (from 17 to 12%) in shrubland.

Irrigation and urban water supply

As of 2019, there were in total 23 pumping stations operating in the Lower NNRB (Fig. 2.1c). Most of them were installed between 1995 and 2003. Each station is equipped with 2 to 9 pumping units. The pumping capacity of each unit ranges from 233 – 1,100 l/s. They lift water from the Nam Ngum River up to main canals from where it is delivered to the fields by gravity flow, mostly for dry season rice cultivation from November to mid-April, with a total duration of irrigation of 152 days, while operating for 12 hours per day.

Two large irrigation schemes use water from the regulation of reservoirs: Nam Souang irrigation scheme, commenced in 2002 with an initial plan for dry season irrigation of 2,300 hectares; and Nam Houm irrigation scheme, commissioned in 2000 and has a capacity to irrigate 2,400 hectares of dry season crops (DOI and JICA, 2009). Moreover, the Nam Mang 3 irrigation scheme is the most recent project, which started to operate in 2005 and uses water sourced from diversions after energy production.

In total, the irrigation schemes along the Nam Ngum River extract water from the river at a rate of 151.1 x 10^6 m^3 per dry season, i.e. 25.1 x 10^6 m^3/month during dry season cultivation from November-April, while the mean dry season water yield in the most current period is 703.3 x 10^6 m^3, showing as a level of homogeneity of the current step change (Fig. 2.8c).

Urban water supply is produced from the Nam Ngum River through two water treatment plants (Dongmakkhai & Dongbang). The Donmakkhai treatment plant commenced in 2006 and lifts raw water from the river at an average extraction rate of 23,000 m^3/day to produce clean water, with a 22,600 m^3/day distribution capacity. The second treatment plant (Dongbang) commenced in 2010. It also uses raw water from the river at an average extraction rate of 18,000 m^3/day (Nampapa Nakhonluang, 2014; NewTap, 2015). The two water supply treatment plants withdraw the water from the river at the total rate of 14.4 x 10^6 m^3/yr.

Compared with the flow rate at the Thangon, the water withdrawn for irrigation and water supply is a relatively small proportion (about 2.5%) of the mean lowest flow in April at Thangon, which is 1,058 x 10^6 m^3/month.

Change in basin-wide water storage

Change in water storage in the Lower NNRB, based on the water balance analyses, was assessed at annual, wet and dry season scales for the pre- to post-dam period (Fig. 2.10). There is a slightly increasing trend ($p=0.157$ and Sen's slope of 12.779) and no step-change for the annual change in storage (Fig. 2.10a). However, the wet season change in storage shows a strongly increasing trend ($p=0.002$; Sen's slope of 23.586), with a step-change occurring in 2001 (Fig. 2.10b). The dry season change in storage indicates the opposite pattern of the wet season change, showing a strongly decreasing trend ($p=0.0001$ with negative Sen's slope of 12.798) with a step decrease centred around 1999 (Fig. 2.10c).

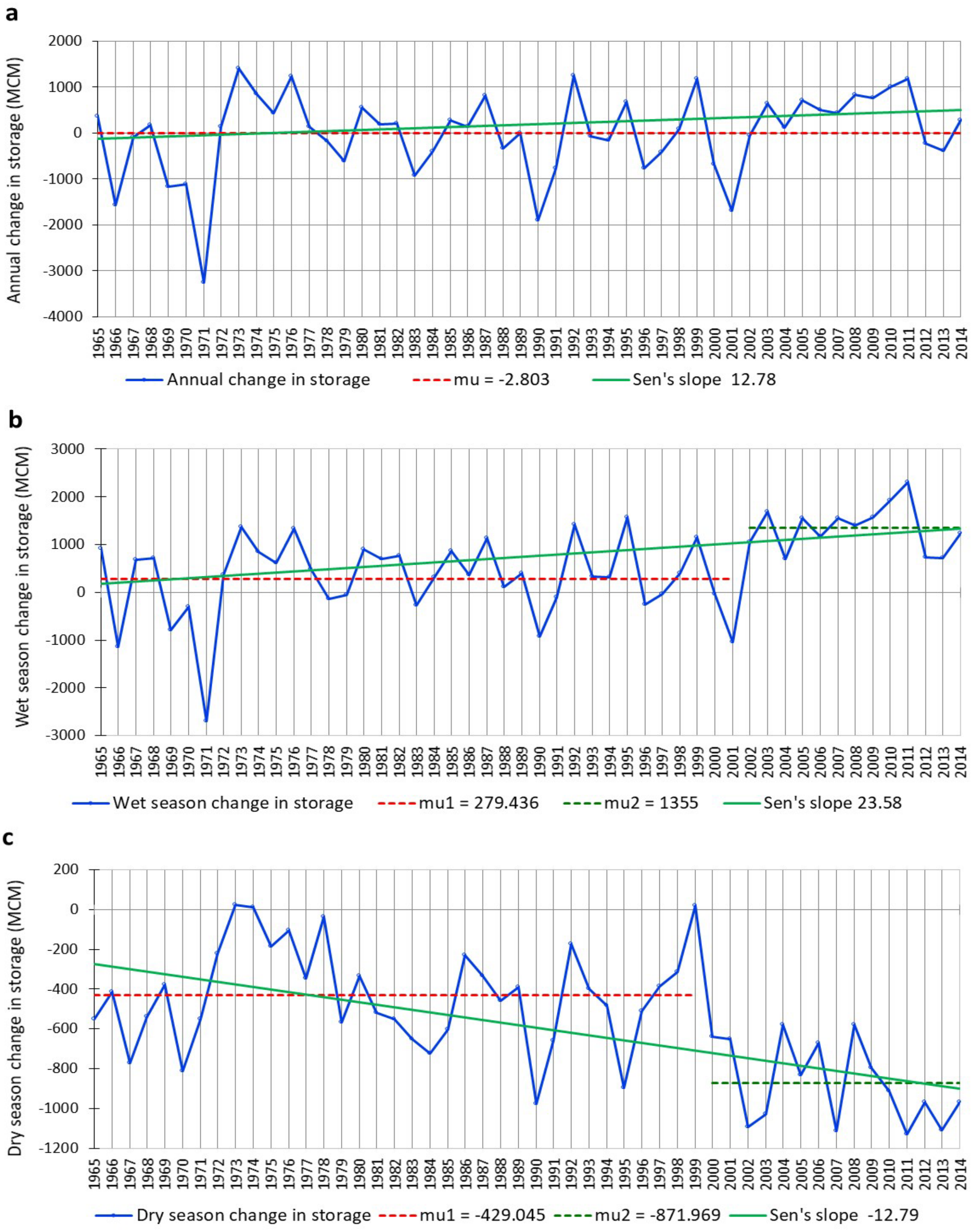

Figure 2.10. Water balance analysis. (a) change in groundwater storage in the Lower NNRB for 1965-2014 on an annual basis, (b) wet season and (c) dry season. The green straight lines show the trend of change in storage; the red dashed lines show the homogeneity of change in storage before (mu1 in 10^6 m^3) a step-change shifting to the next green level (mu2 in 10^6 m^3).

2.5 Discussion

2.5.1 Flow regime

The river flow regime in the Lower NNRB has been strongly impacted by river dam development and operation in the Upper NNRB. The dry season flow has increased, and the wet season flow has decreased. The seasonality analyses showed that the standard deviation of the seasonality index was larger than the average flow in the pre-dam period. In contrast, in the post-dam period, the standard deviation is less than half the average flow (Fig. S2). In Fig. 2.4, the mean dry season flow for the period of November to April 1962-1971 increased from 177 m^3/s to 389 m^3/s for 2007-2016, which is equivalent to a 120% increase. In comparison, during the wet season from May to October of 1962-1971, the average flow was 1,286 m^3/s and reduced to 789 m^3/s for 2007-2016, which is equivalent to a 39% reduction. For the month with the highest flows, August, the seasonality index reduces from 302 to 162%, while the seasonality index in the month with the pre-dam lowest flows, March, increases from 13 to 53% (Fig. S2).

Figure 2.5 showed that during the pre-dam period, the dry season flow of April at the 90% exceedance is 70 m^3/s, while in the post-dam period, this has increased to 334 m^3/s, an increase of 377%. On the other hand, at the 90% exceedance level of the pre-dam condition, the wet season flow of August was 994 m^3/s, but this reduces to 577 m^3/s (a decrease of 42%) under the post-dam conditions.

On the other hand, the Pettitt test for the full-time series shows somewhat lower figures with a dry season increase of 72% and a wet season decrease of 27% centred at respectively, 1980 and 1982 (Fig. 2.6). The increase in the dry season flow is largely due to the upstream release of water from the hydropower dams to produce electricity and to support the irrigation schemes for dry season rice cultivation (Lacombe et al., 2014), rather than due to climatic and land cover related factors (WREA, 2008a). While the decrease in wet season flow is mainly due to the build-up of storage in reservoirs, our findings on the change in flow regime align with previous studies by WREA. (2008a) and Lacombe et al. (2014). Similar to this study, Räsänen et al. (2012) showed that the impacts of a cascade of hydropower dams in the upstream part of the Mekong River (Lancang-Jiang, China) on downstream hydrology were an increased dry season flow of 90% and a decreased wet season flow of 22% at the Saen Chiang gauging station, Thailand. Our results confirm and highlight that large scale hydropower dam operations strongly alter downstream river flow regimes (Räsänen et al., 2012; Lacombe et al., 2014). A number of indicators as pieces of evidence of change are summarised in Table 2.2.

Table 2.2. Summary of evidence of changes to the flow regime and water yield in the Lower NNRB

Figure	Lines of evidence of change	Annual	Dry season	Wet season
2.4	Monthly mean, min, max flow, pre- (1962-1971) vs post-dam (2007-2016)	Reduced variability, more than halving of the seasonality standard deviation from 108 to 40.	120% increase in flow	39% decrease in flow
	Monthly average precipitation pre- (1965-1972) and post-dam (2007-2014)	Minor difference as p=0.32 by t-test		
2.5	90% exceedance flow, pre- (1962-1971) vs post-dam (2007-2016)		Increase by 377%	Decrease by 42%
2.6	Mean seasonal flow (1962-2016)		Increasing trend and increasing step of 72% at 1980	Decreasing trend and decreasing step of 27% at 1982
2.7	Monthly differential flow (1963-2016)		Before the year 2000 negative flows occurred	Decreasing
2.8	Annual and seasonal differential flows (1963-2016)	Minor increasing trend, reduced yearly variability	Increasing trend with Sen's slope at 14.8 and step change of 290% in 2000, reduced yearly variability esp. after 2000	Minor decreasing trend with Sen's slope at -12.3, reduced yearly variability esp. after 2000
2.9	Groundwater and surface water level mapping (Feb. 2019)		River shows a gaining conditions	
2.10	Storage change from 1965-2014 for annual, wet and dry season	Minor increasing and no step change	Decreasing trend and step change from 1999	Increasing trend and step change from 2001
Table S1	Yearly, monthly precipitation (1965-2014)	Minor trend		
Table S2	Annual, wet and dry season actual evapotranspiration (1963-2016)	Minor increasing trend	Increasing trend	Increasing trend
Table S3	Monthly soil moisture (2000-2018)		Increasing trend Dec-Jan.	Decreasing trends Apr-Jun.
Table S4	Monthly Total Water Storage (1962-2014)	Minor increasing	Minor increasing	Minor increasing
S2	Percentage of average seasonality index for the pre- and post-dam period	Decreasing standard deviation		
S3	2014-1962 Seasonal trend of monthly total water storage	Minor increasing trend		
S4	Land cover (1992-2015)	Increasing rainfed cropland, decreasing shrubland		
2.1c	Irrigation and domestic water supply (2019)		2.5% of flow	

2.5.2 Water yield

There has been a gradual increase (Sen's slope of 4.57) in annual water yield in the Lower NNRB from 1963 to 2016, which is equivalent to 242 x 10^6 m^3 or 13% increase over 54 years. Although the trend is marginal (p=0.546) (Fig. 2.8a), it does correspond with the slightly increasing trend in the Total Water Storage derived from GRACE (Fig. S3). Increasing total water storage will likely result in higher baseflow and hence higher water productivity or yield in the Lower NNRB.

The dry season water yield (Fig. 2.8c) exhibits a strongly increasing trend (p=0.0001), and the homogeneity test found an abrupt change in the water yield series occurring from 2001. The increase in dry season water yield can be explained by a number of irrigation schemes being developed in the Lower NNRB as indicated in the timeline (Fig. 2.8c), i.e., irrigation by surface water; irrigation by dam regulations (Nam Houm was commissioned in 2000 and Nam Souang in 2003); and irrigation by diversion from the Nam Mang 3 hydropower plant into the Lower NNRB commencing in 2005 with a mean flow to the Lower NNRB of 159.2 x 10^6 m^3/yr (2005-2015). As a result, groundwater storage is supplemented with additional recharge, which increases base flow in the dry season. Also, irrigation return flows would contribute to higher dry season flow. The increase in dry season irrigation schemes is consistent with the increasing trend in actual evapotranspiration and increasing soil moisture content in the dry season months (December-January) (Table S2 and S3, respectively) due to expanded dry season irrigated cultivation.

A second possible explanation for the increased dry season water yield lies in more groundwater stored in the aquifers as a result of a higher base drainage level in the Nam Ngum River. As the dry season river water level in the Nam Ngum River is, due to the dam water releases, higher in the post-dam than in the pre-dam condition, the groundwater hydraulic head profile in the aquifer will rise, i.e., more water will build up in the aquifer and consequently also more baseflow will be produced.

Water yield in the wet season shows a marginally decreasing trend (Sen's slope -12.3), and a more obvious reduced yearly variability, especially after 2000. There is no abrupt step change occurring in the time series, which has a mean water yield of 1,812 x 10^6 m^3 (Fig. 2.8b). The wet season water yield is mainly determined by the wet season precipitation regime. Hence, no significant change in the wet season water yield is expected, as the precipitation shows little change over time (Fig. 2.4, Table S1). The reduced variability in the wet season water yield is likely due to the larger, within the Lower NNRB basin, surface water storage (reservoirs, ponds, irrigation, etc.) build up over time (Fig. 2.1c). Figure 2.10b confirms that this storage system increased the wet season's ability to store more water, especially after 2000. These storages hold back temporally the peak rainfalls and hence reduce the variability in wet season water yield.

Further support for increased water yield over time comes from the analyses of the groundwater-surface water interaction derived from the monthly differential flow of the two gauging stations (Fig. 2.7). It shows that most of the differential flow was positive for the 1963-2016 period, suggesting that the river was in a state of gaining condition. However, during some years of the pre- and early post-dam period, there were negative differential flows recorded during the critical dry months (January to April). This shows that the river was losing water to the adjacent aquifer systems. The differential discharge measurements are exclusively positive after 2001, indicating that the river is in a permanent gaining condition. This change to continuous gaining conditions is, as postulated above, due to shallow return flows of large irrigation schemes and increased baseflow from the groundwater system contributing to the Nam Ngum River. The interpolation of the measured (dry season, Feb. 2019) groundwater and river water levels (Fig. 2.9) supports the concept of significant gaining dry season conditions as the general groundwater flow direction is towards the main Nam Ngum River.

Finally, the water balance analysis brings the different flow components together and allows understanding the increase in water yield in relation to the water storage in the basin. The water balance shows a strongly decreasing trend in negative change in storage for the dry season (Fig. 2.10c), indicating greater drainage of the groundwater system, producing more baseflow in the dry season. In comparison, the wet season shows an increasing change in storage, pointing to higher wet season storage capacity, holding more water and for a greater duration in the catchment during the wet season and possibly releasing later in the dry season. But higher wet season storage will also increase recharge and initiate stronger draining of the groundwater system in the dry season (Fig. 2.10b). Moreover, the weak trend of increasing annual storage change in the Lower NNRB (Fig. 2.10a) corresponds with the increasing trend of the Total Water Storage derived from GRACE (Fig. S3).

The anthropogenic post-dam conditions have led to increasing water storage in the wet season (Fig. 2.10b). Consequently, this increased storage induces stronger drainage of water from the basin during the dry season (Fig. 2.10c). As a result, the change in water storage (dynamics) between the wet and dry seasons has become much higher in the post-dam period. The water yield increases as a result mainly in the dry season (Fig. 2.8c). It should also be noted that the inter-annual dynamics in water storage, post-dam for both the wet and dry season, decreases (Fig. 2.10), indicating that the water yield not only increases but is also less dynamic (Fig. 2.8).

It is important to note that the uncertainty of the flow estimates also propagates into the water yield assessment, as the flow time series are derived via stage-discharge rating curves, which dominate the uncertainty of the flow rate (McMillan et al., 2012; Kiang et al., 2018). Thus, the absolute value of the increase in water yields is harder to capture precisely compared to their trends and homogeneity.

2.6 Conclusions

The analysis of historical observed river flow data at the downstream station (Thangon) reveals that the reservoir operations in the upper part of the basin have a stronger influence on river flow regimes than climatic factors and other human activities. As the hydropower reservoirs regulate the river flow, mean dry season river flow increased by 120%, whereas wet season river flow decreased by 39%, on average over a ten-year comparison between pre- and post-dam conditions. In the pre-dam period, the flow regimes correspond with the precipitation regime, while in the post-dam period, the reservoir operation rules determine the flow dynamics.

There has been an important change in groundwater-surface water interaction from the pre-dam to the current situation. In the post-dam period, the river system of the Lower NNRB has become year-round gaining (i.e. from 2001 onwards), which is also consistent with other field observations, including the groundwater levels of adjacent aquifers. While under pre-dam conditions, the river was losing during the critical dry season months.

There has been an increase in water yield during the dry season and annually in the Lower NNRB, which is most likely due to (1) large irrigation projects (i.e. irrigated by water diversion from Nam Mang 3 hydropower plant and dam regulators) as exhibited by trend analysis; (2) the increasing trend in storage change; and (3) increasing total water storage in the aquifers. These phenomena showed clearly that the impact of anthropogenic activities outweigh climatic factors on changes in the groundwater dynamics in the Lower NNRB as rainfall is comparable for the pre-dam and current situation. However, further investigation of the impact of the higher post-dam river water levels in the dry season on aquifer water storage and release versus the relative importance of irrigation groundwater recharge and possible increased shallow aquifer groundwater discharge is highly recommended. It is also important to investigate further the water quality implications of the intensive irrigation return flow, which is likely to localise water circulation and influence shallow groundwater quality.

Supplementary Material

Table S1. Results of Mann-Kendall trend analyses for Thangon rainfall (P; mm) for 1965-2014.

Month	Min.P	Max.P	Mean P	Std. deviation	Kendall's tau	p-value	Sen's slope
Jan	0	69	9	18	0.20	0.06	0.00
Feb	0	68	14	16	0.12	0.24	0.05
Mar	0	157	46	41	0.00	0.98	0.00
Apr	0	267	91	68	0.03	0.80	0.15
May	0	595	260	125	-0.05	0.62	-0.49
Jun	67	630	317	120	-0.07	0.50	-0.80
Jul	0	708	339	141	0.14	0.15	1.88
Aug	172	932	369	148	0.12	0.23	1.28
Sep	102	646	315	123	0.06	0.55	0.81
Oct	0	234	79	55	0.06	0.56	0.36
Nov	0	129	12	24	-0.04	0.72	0.00
Dec	0	53	4	10	0.04	0.71	0.00
Annual (mm)	1,278	2,771	1,855	341	0.08	0.40	2.79

Table S2. Mann-Kendall trend test results for annual, wet and dry season GLDAS_NOAH actual evapotranspiration 1963-2016.

Actual ET	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope	Trend
Annual (mm)	753	1,048	854	60.6	0.15	0.10	0.83	marginal
Wet season (mm)	506	703	558	38.5	0.09	0.31	0.33	marginal
Dry season (mm)	237	361	296	27.0	0.25	**0.01**	0.69	**strong**

Table S3. Results of the soil moisture (kg/m2) trend analysis (2000-2018) performed with the Mann-Kendall test. The soil moisture units are equivalent to mm, and as they refer to 0-10 cm depth they are also equivalent to a volumetric unit of 10-2 m3/m3.

Month	Soil moisture (kg/m^2)			Std. deviation	Kendall's tau	p-value	Sen's slope
	Min	Max	Mean				
Jan	12.3	19.1	16.5	1.98	0.37	0.03	0.15
Feb	11.3	18.9	14.7	2.37	0.05	0.78	0.03
Mar	12.4	21.6	16.3	2.53	-0.13	0.45	-0.10
Apr	16.3	26.6	20.9	2.58	-0.42	0.01	-0.24
May	24.0	31.0	27.2	2.02	-0.36	0.03	-0.22
Jun	24.6	32.1	30.3	1.65	-0.42	0.01	-0.12
Jul	29.9	32.8	31.6	0.77	-0.11	0.53	-0.01
Aug	30.8	32.7	31.9	0.47	-0.11	0.53	-0.01
Sep	29.8	32.0	31.0	0.56	-0.17	0.33	-0.01
Oct	22.6	29.7	28.0	1.69	0.12	0.49	0.03
Nov	18.0	27.3	23.5	2.36	0.20	0.24	0.12
Dec	14.9	23.5	19.6	2.37	0.35	0.04	0.19

Table S4. Results of Mann-Kendall trend analyses of monthly Total Water Storage (TWS with unit in cm) for 1962-2014. TWS was derived from GRACE covering the Lower NNRB with boundaries 17.75N, 101.75E, and 18.75N, 103.25E.

Month	Min	Max	Mean	Std. deviation	p-value	Sen's slope
Jan	-18.1	9.7	-3.8	6.0	0.38	0.06
Feb	-23.1	1.9	-10.0	5.2	0.30	0.06
Mar	-28.5	-5.1	-17.0	4.7	0.22	0.05
Apr	-27.1	-5.9	-17.1	4.7	0.37	0.04
May	-24.9	-2.2	-14.0	5.6	0.42	0.05
Jun	-22.4	8.8	-6.5	6.6	0.77	0.01
Jul	-12.1	19.0	4.0	7.9	0.94	0.01
Aug	-0.6	31.3	15.9	8.5	0.61	0.05
Sep	8.7	52.0	26.0	9.1	0.50	0.07
Oct	2.7	43.8	22.1	9.0	0.49	0.06
Nov	-6.4	29.7	11.5	8.1	0.62	0.04
Dec	-13.1	18.0	2.4	7.0	0.59	0.05

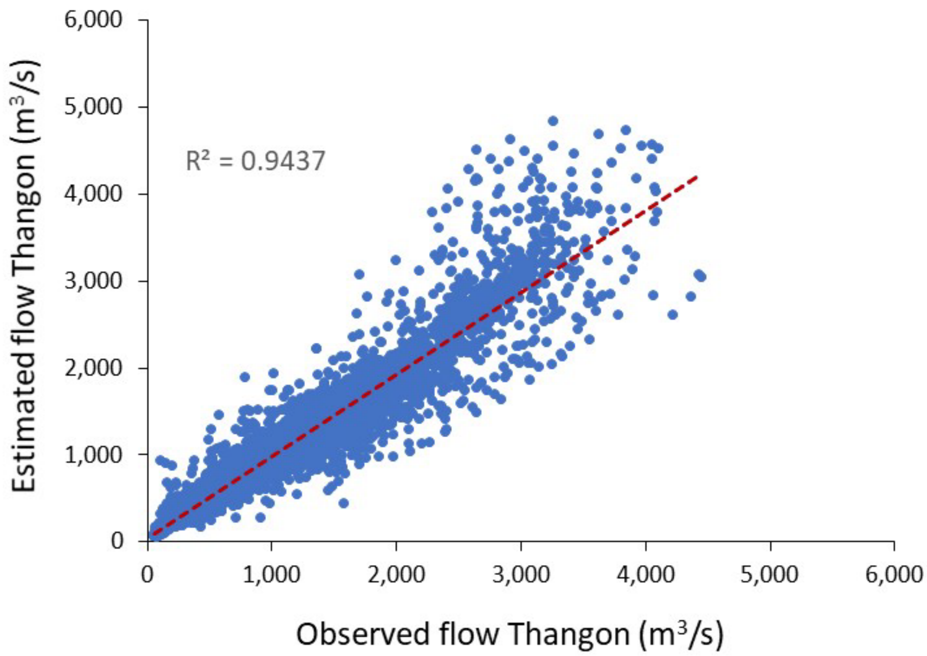

Figure S1. Linear regression relationship between estimated daily river flow and observed flow for Thangon station for the years 1963 to 2001.

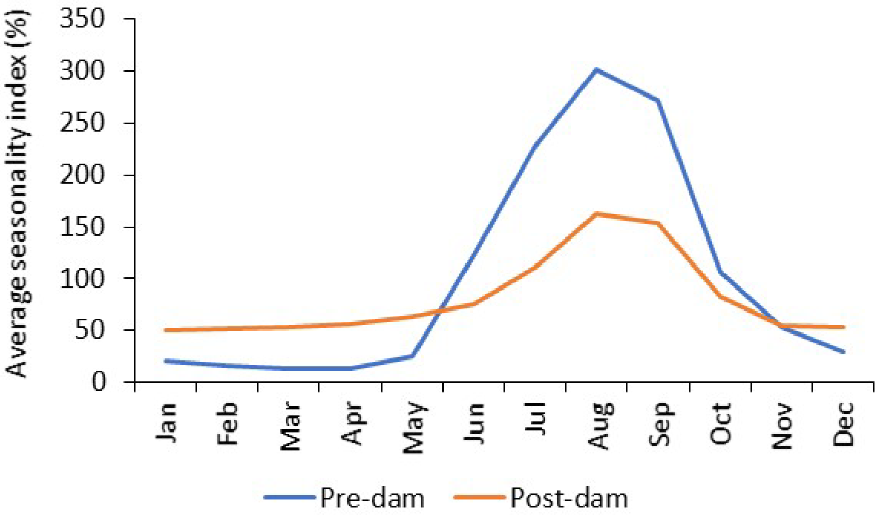

Figure S2. Simple average seasonality index (%) for the pre-dam (1962-1971) and post-dam (2007-2016) monthly average flows. The respective standard deviations are 108% and 40%.

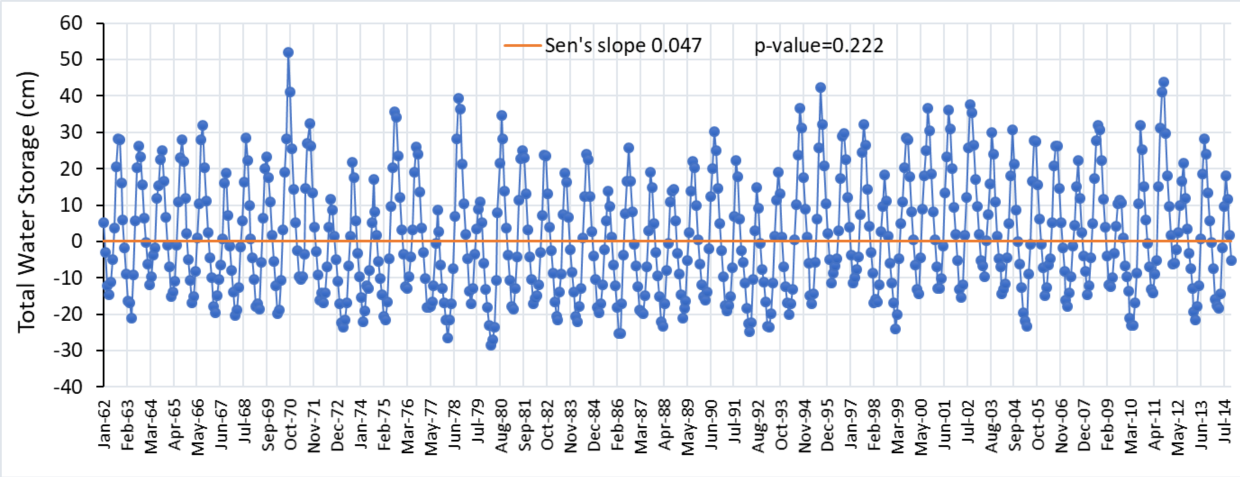

Figure S3. Time series of monthly Total Water Storage (cm) and seasonal trend , showing a minor (p=0.222) increasing trend with a positive Sen's slope of 0.047. The time series is based on reconstructed GRACE data (Humphrey and Gudmundsson, 2019) for the area covering the Lower NNRB (17.75N, 101.75E, and 18.75N, 103.25E) for the years 1962 to 2014.

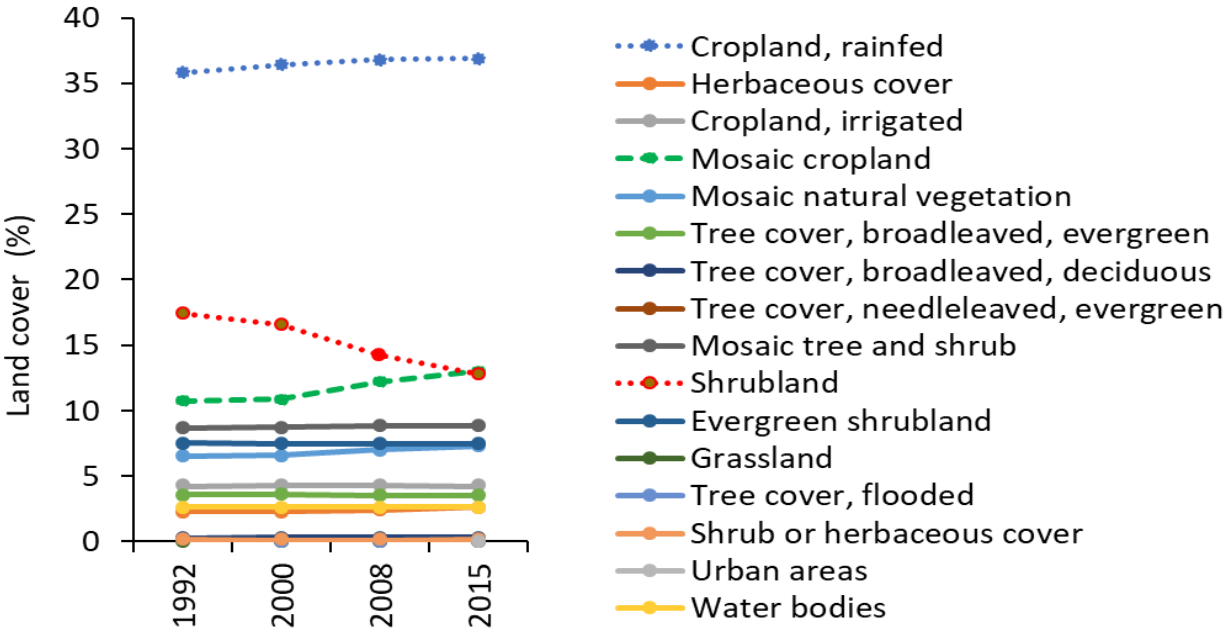

Figure S4. Major land cover in the Lower NNRB for 1992, 2000, 2008 and 2015, obtained from the European Space Agency-Climate Change Initiative (ESA, 2017).

Chapter 3. Assessing the impact of irrigation water on water balance components: a case study in the Lower-Nam Ngum River Basin, Lao PDR[2]

Abstract

Groundwater recharge is a fundamental component sustaining aquifer budgets and the hydrological cycle. Groundwater is recharged naturally through precipitation and artificially through anthropogenic processes, which are complex and nearly impossible to measure directly. This study focuses on the Nam Ngum River Basin (NNRB), Laos, a major tributary of the Mekong River, where hydropower dams were developed in the upper part of the basin. In contrast, the lower part is undammed and intensively developed for irrigation and agriculture. This paper aims to evaluate the impact of irrigation water diverted from surface water on groundwater recharge and other water balance components (actual evapotranspiration (AET), surface runoff, and interception). The spatiotemporal variable recharge and water balance components were assessed for two different scenarios: with and without irrigation water by the spatially distributed monthly based water balance model WetSpass-M and validated with the Water Table Fluctuation (WTF) method. The results show that irrigation development has caused the recharge to increase by 83 mm within the command areas and 6 mm on average for the entire lower NNRB, resulting in a minimal change at the basin level. The annual average recharge (2012-2014) was assessed to be 444 mm, equivalent to 19% of the annual rainfall. The AET and interception also show a slight increase of 6 mm and 1 mm respectively, for the entire lower basin. The recharge is also strongly varied spatially, depending on different combinations of soil texture and land cover. Overall, this study shed light on the magnitude of the impact caused by irrigation water on hydrological water balance components, and this new understanding can help improve groundwater resources management.

Keywords: WetSpass-M, Water Table Fluctuation (WTF), Groundwater recharge, Nam Ngum River Basin, Lao PDR.

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[2] To be submitted to the *Journal of Hydrology: Regional Studies*

3.1 Introduction

Many countries in Southeast Asia are experiencing rapid population growth, putting stress on their food security and water resources (FAO, 2017; Trisurat et al., 2018) and energy consumption (Kumar, 2016; MRC, 2018). Also, in the Lower Mekong Basin (LMB), hydropower development and irrigation expansion are expected to increase in order to meet socio-economic demands and reduce risks from climate change. In the LMB countries, rice cultivation in the highlands is primarily rain-fed with rare access to irrigation. As a result, it is typically less productive compared to lowland rice cultivation. Therefore, irrigation for dry season rice in floodplains and lowland areas is a key driver for food security, especially when wet season rice fails due to flooding (Hoanh et al., 2009). However, regulation of rivers for irrigation schemes has the potential to cause changes in the river flow patterns, groundwater recharge, groundwater fluxes, and total water storage due to irrigation returnflow (Healy, 2010; Essaid and Caldwell, 2017; Pokhrel et al., 2018; Taniguchi et al., 2019). Therefore, it is essential to understand the regulation, including use for irrigation, for proper water resources planning and management.

Groundwater recharge is an essential flux for sustaining the subsurface component of the hydrological cycle and groundwater-connected ecological systems, but it is difficult to measure precisely (Alley et al., 2002). Often a distinction in recharge estimation is made between direct (diffuse) and indirect (secondary) recharge (Healy, 2010). Previous studies in the LMB heavily attempted to evaluate the impact of overexploitation and climate change on aquifer storage (Wagner et al., 2012; Erban et al., 2014; Shrestha et al., 2016; Minderhoud et al., 2017) and the impact of decreasing inundation areas on groundwater storage (Kazama et al., 2007). Few studies have focused on quantifying the recharge mechanism in the LMB (ACIAR, 2016; Lacombe et al., 2017). But none have investigated the impact of irrigation water diverted from surface water on (indirect) groundwater recharge and other water balance components such as actual evapotranspiration (AET), surface runoff and interception. Therefore, the changes in water balance components due to irrigation in this region remain unknown.

Recently, Lacombe et al. (2017) assessed groundwater recharge across the LMB by selecting 65 gauging stations, where the daily discharge was available and not regulated by reservoir hydropower dams. Using the local minimum filtering method, the baseflow was then calculated for the 65 sub-basins. Based on the assumption that the baseflow is approximately equal to recharge, a multiple linear regression model was developed with various climatic and geomorphologic characteristic variables of each of the 65 catchments. These variables were then used to predict baseflow in ungauged areas in the LMB. This procedure allowed obtaining a spatially distributed groundwater recharge with a resolution of 0.25 degrees. This recharge distribution is reasonably reliable at a regional scale. However, inaccuracies have been identified compared with previous local studies, which are most likely due to heterogeneities in soils and geology (Lacombe et al., 2017). Besides, the baseflow separation approach is based on subjective choices of factors in the mathematical algorithms, which can cause the baseflow estimated by different algorithms to vary depending on the setting factors (Nathan and McMahon, 1990; Döll and Fiedler, 2008). Also, it is unable to detect the seasonal spatial distribution of evapotranspiration and recharge (Nathan and McMahon, 1990; Lacombe et al., 2017). Moreover, Lacombe et al. (2017) do not consider the impact of irrigation water on groundwater recharge. As the infiltrating irrigation return flow can cause groundwater levels to increase artificially, it is important to understand the impact of irrigation water withdrawn from surface water on the hydrological water balance components. Extensive irrigation schemes can also increase groundwater discharge to streams and groundwater storage when the source of the irrigation water is mainly diverted from rivers (Essaid and Caldwell, 2017), which potentially influences the water productivity generated from lower basins. However, estimation of groundwater recharge from irrigation is difficult to quantify and not straightforward (Qin et al., 2011; Séraphin et al., 2016; Meredith and Blais, 2019).

Therefore, this paper aims to investigate the spatiotemporal distribution of recharge in the Lower-Nam Ngum River Basin (Lower-NNRB), which is a sub-basin of the LMB (Fig.3.1c). In this basin dry season, rice irrigation is a common practice. Hence, the specific aims of this paper are: (i) To assess the water balance components in the Lower-NNRB for two different scenarios: with and without irrigation schemes. (ii) To assess the relative contribution of the recharge component from irrigation return flow at the irrigation command area and river basin scales.

3.2 Study area

The Nam Ngum River Basin (NNRB), a sub-basin of the Mekong River Basin, is home to about 502,000 people (2011). It is located in the centre of Laos (Fig. 3.1). The NNRB has a total drainage area of 16,800 km^2, which produces about 4.3% of the annual discharge of the Mekong River, and plays an important role in power production, urban water supply, and fisheries (WREA, 2008b). The elevation in the NNRB ranges from 155 m above mean sea level (masl) at the confluence of the Nam Ngum River with the Mekong River to 2,820 m asl in the Phou Bia Mountain (WREA, 2008b). The upper part (in the north) of the basin is hilly and mountainous areas. Here are the sources of several streams and rivers and the locations where hydropower dams are developed intensively. In contrast, the lower part (in the southeast) of the basin is primarily a plain known as the Vientiane Plain, featuring 75% of the total irrigated area of the entire basin. In the Vientiane Plain, food production and irrigation are planned to be expanded to meet the population's requirements and socio-economic growth (Bartlett et al., 2012).

The Nam Ngum River has been regulated since the construction of the first large dam (1968-1971). At present, six hydropower dams are operating in the upper part of the basin, commenced between 1971 and 2011: Nam Ngum1 (1971), Nam Lik1 (2006), Nam Ngum 2 (2010), and Nam Ngum 5 (2011). The other two hydropower dams and their reservoirs Nam Leuk (2000) and Nam Mang 3 (2005), are located outside the basin. But the water released from the turbines of Nam Leuk is transferred into the upper basin to increase water storage for Nam Ngum 1. In addition, the Nam Mang 3 hydroelectric dam releases water for energy production and irrigation of 2,900 hectares of paddy land in the lower Vientiane Plain. The Nam Mang 3 reservoir is located approximately 500 m above the nearby NNRB, allowing irrigation of the lowland areas by gravity flow (Kouangpalath et al., 2016).

Most of the irrigation schemes in the Lower-NNRB use water from the three different sources for dry season rice cultivation from November-April (Fig 3.1c). (i) The irrigation schemes along the Nam Ngum River extract water from the river to the main canals before distributing it to minor canals by gravity supply. (ii) Two large irrigation schemes use water from reservoirs: Namsouang irrigation scheme, commenced in 2002 with an initial plan for dry season irrigation of 2,300 hectares; and Namhoum irrigation scheme, started in 2000 and can irrigate 2,400 hectares dry season crop (DOI and JICA, 2009). (iii) The Nam Mang 3 irrigation scheme is the most recent project, which started operating in 2005 and uses water from diversions after energy production. The Lower-NNRB area, between the two gauging stations Thangon and Pakanhoung, is the focus area of groundwater recharge and hydrological water components analysis of this study.

There are six geological units present in the Lower-NNRB. The Champa Formation (K_2cp) is Cretaceous in age, which mainly comprises sandstone, siltstone, brownish sandstone, and white arkose sandstone lying along the east and west side of the catchment. Further to the eastern and western hilly-mountainous edge of the catchment is the Phu Pha Nang Formation of Jurassic to Cretaceous age (J-Kpn), composed of sandstone bearing mica, white siltstone, and brown sandstone. The Nam Ngum River floodplain is shaped by three Quaternary depositional phases of alluvium, termed Qii-Qiv, containing sand, clay, peat, and gravel. In the southeast of the catchment occurs the Cretaceous Tha Ngon Formation (K2tn), which includes Na-salt, potash salt, claystone, siltstone, sandstone, gypsum and anhydrite, rhyolite, and tuff. In the south, the dominant geological unit is the Vientiane Formation (N2-Q1vc), a Neogene to Quaternary unit of gravel, shingle, sandy kaolinite, and laterite (Geological and Mineral Map of Vientiane Plain, scale 1:200,000; Ministry of Energy and Mines).

The sandstone and siltstone (J-Kpn and K2cp) have low storage and groundwater yield in the hilly areas, but the alluvium such as sand, gravel, clay (Qii-iii and Qiv) located in the central part of the study area has high groundwater potential. The alluvium thickness is limited near the hills but increases toward the Nam Ngum River with a maximum thickness of 40 m, which is found to the north of the study area (ACIAR, 2016). The Lower-NNRB is defined to be a shallow unconfined alluvium aquifer according to well drilling reports conducted by JICA (1994), and this aquifer receives additional recharge from irrigation.

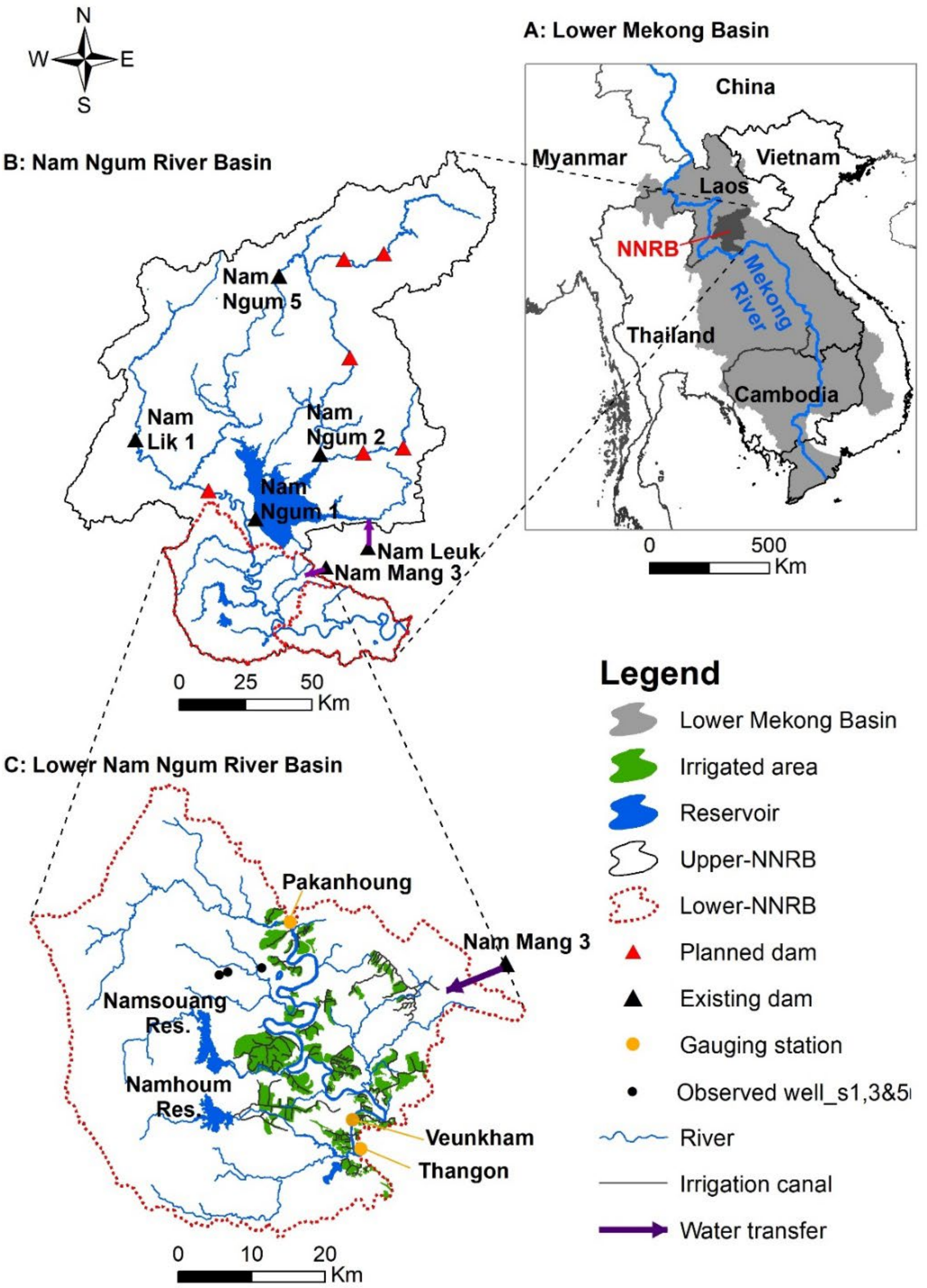


Figure 3.1. Study area: (a) The Lower Mekong Basin with highlighted Nam Ngum River Basin (NNRB); (b) The Nam Ngum River Basin with the location of existing and planned dams, reservoirs, and delineation of Lower NNRB; c. The Lower-NNRB, between gauging stations Pakanhoung and Thangon, which is the focus area of the groundwater recharge analysis of this paper. Indicated is the Nam Mang3 dam, reservoirs, major irrigation command areas with irrigation pumping stations, river gauging stations. The locations of dams are derived from the map of dams in the Mekong Basin, available from https://wle-mekong.cgiar.org/.

3.3 Methods and data

3.3.1 Methods

Hydrological and climatological data availability at daily temporal resolution in the study area is limited. Therefore, the WetSpass-M model (Water and Energy Transfer between Soil, Plants, and Atmosphere under quasi-steady state) at monthly resolution was used to assess water balance components from 2012-2014 (Batelaan and De Smedt, 2007; Abdollahi et al., 2017). The model is physically based, simulates, and produces water balance components, including spatially distributed raster maps of recharge, interception, surface runoff, and AET. The original WetSpass model was developed and operated as an extension for the GIS ArcView 3.2 and simulated seasonal water balances (Batelaan and De Smedt, 2007). As the Python programming language is freely available and open-source for sharing in the scientific community, a new version WetSpass-M was developed in IronPython v2.7 (Abdollahi et al., 2017). This allowed the model to have greater flexibility to run as a stand-alone application under Microsoft Windows.

The model is a raster-based monthly water balance model in which each raster cell divides the amount of precipitation into four main components: interception, surface runoff, evapotranspiration and groundwater recharge (Fig 3.2). The WetSpass-M model aggregates a fraction of precipitation for each raster cell and simulates surface runoff from different land cover types such as impervious runoff, vegetated runoff, bare-soil runoff and open water. However, the model does not estimate the re-infiltration of surface runoff and land drainage; the land drains generally do not occur in the study area due to its significant plain area. The model requires two types of input data: (i) spatially distributed data (ASCII file) of soil, Digital Elevation Model (DEM), slope, land use, temperature, precipitation, potential evapotranspiration (PET), wind speed, groundwater depth, and (ii) a text file of soil parameters, runoff coefficients, land-use parameters, and the number of rainy days. The model processes and relevant elements of each stage are illustrated in Figure 3.3. The process starts from data collecting and data formatting before setting up the model; the four main water components considered as a fraction of precipitation for each raster cell are computed by the following equations.

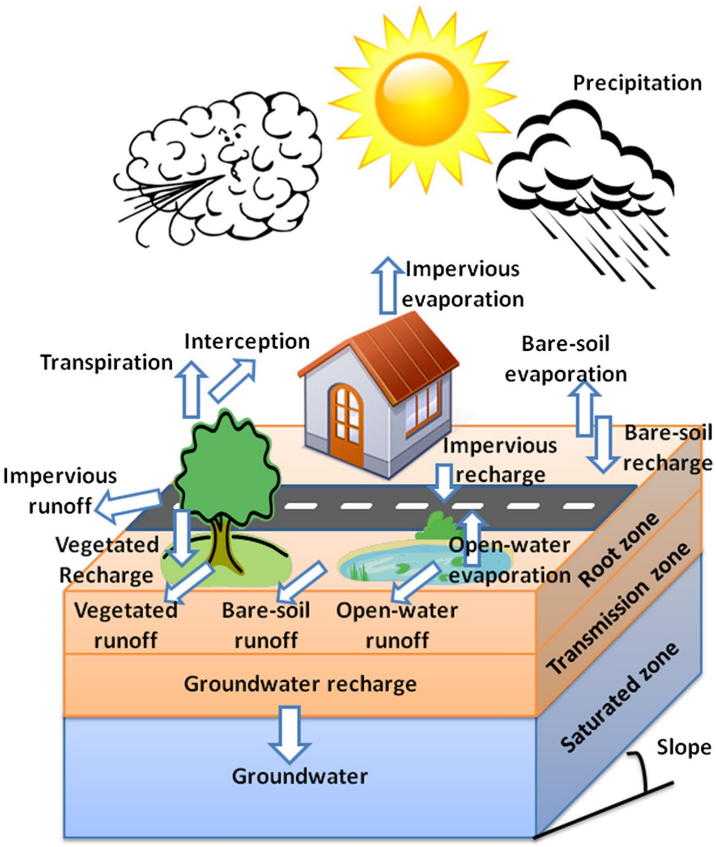


Figure 3.2. WetSpass-M conceptual model for a non-homogenous land cover in a grid cell (Batelaan and De Smedt, 2007; Abdollahi et al., 2017)

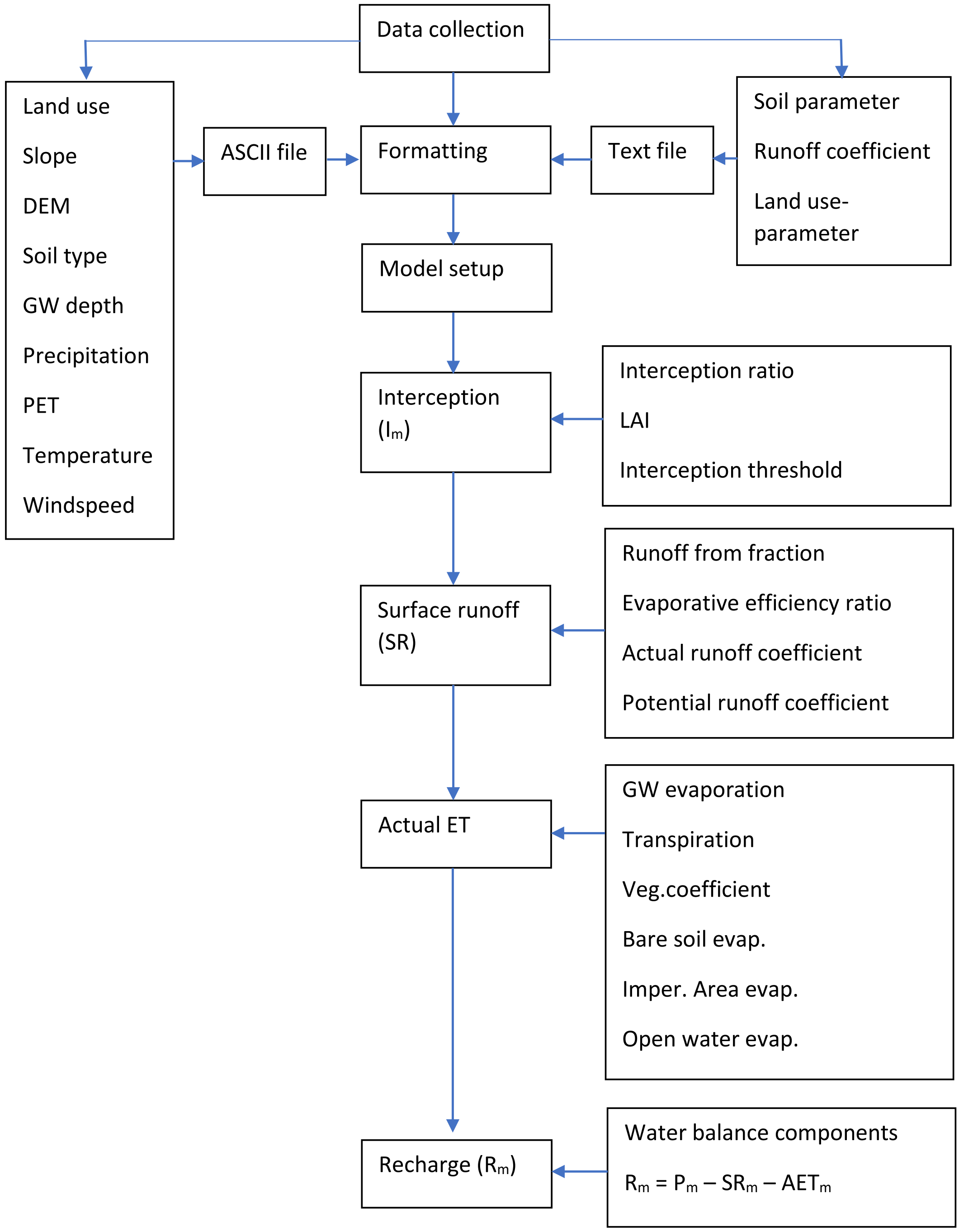


Figure 3.3. A flowchart of the WetSpass-M model processing

Interception is considered a fraction of the precipitation depending on land cover and land use; thus, changing land use would alter the leave area index (LAI), which impacts the magnitude of interception. Monthly interception is computed as:

$$I_m = P_m I_R \qquad \text{(Eq. 3.1)}$$

$$I_R = \frac{I_m}{P_m} = 1 - exp\left(\frac{-I_D dp}{P_m}\right) \qquad \text{(Eq. 3.2)}$$

$$I_D = \text{aLAI}\left(1 - \frac{1}{1+\frac{Pm[1-\exp(-0.463\text{LAI})]}{a\text{LAI}}}\right) \qquad \text{(Eq. 3.3)}$$

Where I_m is the interception (mm/month), P_m is monthly precipitation (mm/month), I_R is the interception ratio introduced by De Groen and Savenije (2006), dp is the number of rainy days per month, I_D is the daily interception threshold depending on land use and introduced by Sutanto et al. (2012), and a is an interception parameter which is set to be 4.5 mm (Sutanto et al., 2012).

Surface runoff is the flow of rainwater on the ground surface when the precipitation intensity is in excess of the soil infiltration capability. The WetSpass-M computes monthly surface runoff (SRm) by a rational method using coefficients in terms of potential runoff coefficient, evaporative efficiency ratio, and actual runoff coefficient. The monthly surface runoff is calculated as:

$$SR_m = C_{sr}\, C_h \left(P_m - I_m \right) \qquad \text{(Eq. 3.4)}$$

Where SR_m is the monthly surface runoff, C_{sr} is an actual runoff coefficient (-), and C_h is a coefficient (-) corresponding to the condition of soil moisture (Bahremand et al., 2007). Since the availability of monthly soil moisture data is limited, it is considered to vary between 0-1 and integrated from the evaporative efficiency ratio (Zhang and Lindström, 1997; Creutzfeldt et al., 2010) into the adapted method of Turc (1955) at monthly scale (Pistocchi et al., 2008; Abdollahi et al., 2017).

The model calculates the actual evapotranspiration (ET) from the monthly potential evaporation and vegetation coefficients. The total actual evapotranspiration is calculated by summing up actual evapotranspiration from different spatial distributed land cover fractions per grid cell,

$$ET_m = a_v ET_v + a_s ET_s + a_o ET_o + a_i ET_i \quad \text{(Eq. 3.5)}$$

Where ET_m is the total actual evapotranspiration for a grid cell, a_vET_v are area fraction and evapotranspiration for vegetation, similar to bare soil (a_sET_s), open water (a_oET_o), and impervious surface (a_iET_i) (Batelaan and De Smedt, 2001; 2007).

Groundwater recharge at a monthly time scale for each grid cell is calculated from the water balance components,

$$R_m = P_m - SR_m - AET_m \quad \text{(Eq. 3.6)}$$

Where R_m is the total monthly recharge per grid cell, P_m is monthly precipitation, and AET_m is the total actual evapotranspiration, and SR_m is the monthly surface runoff.

To evaluate the impact of irrigation water on groundwater recharge, firstly, water balance components were assessed with and without irrigation scenarios (Fig. 3.4). The figure shows a schematic diagram of water balance analysis for this study and illustrates the model setting for the two different scenarios from 2012 to 2014. The irrigation water, which was computed from pump characteristics and operation calendars from mid-November to April (Lacombe et al., 2014), supplemented the precipitation within the irrigated command areas. However, some irrigation projects occasionally deliver water for supplemental irrigation in the monsoon season. This has not been accounted for in the analysis due to the small proportion compared to the dry season irrigation and unavailability of operation calendars. Secondly, the recharge plus surface runoff was compared with observed differential flow between up and downstream river gauging stations (Pakanhoung and Thangon), assuming the differential flow represents the summation of surface runoff and base flow generated within the Lower-NNRB. Thirdly, the annual groundwater recharge simulated by WetSpass-M was also compared against the recharge calculated by the water table fluctuation method (WTF). This method is widely used to estimate groundwater recharge or calibrate and validate models (Zhang et al., 2017). The groundwater recharge (R) obtained by the WTF method was calculated from the observed groundwater levels at three monitoring wells located at sites 1; 3; and 5 (Fig. 3.1c) in the Lower-NNRB. The recharge is obtained through Equation (3.7).

$$R = S_y \times \sum \Delta h \qquad \text{(Eq. 3.7)}$$

where: R is annual groundwater recharge (mm); Sy is the specific yield; $\sum \Delta h$ is a total effective water level rise measured from a master recession curve (m). The water level rise was measured from the lowest point of an extrapolated recession curve to the time of peak for each recharge event. The master recession curve is traced by the Ground-Water Hydrograph Analysis Toolbox (GWHAT). Basically, this toolbox is developed and designed to support the interpretation of hydrographs measured from monitoring wells and estimate groundwater recharge using daily water levels, soil moisture, and weather data (Gosselin, 2016). The software package is a non-commercial and open-source application written in the Python 3 programming language, allowing the program to function stand-alone and be executed on multiple platforms. However, this application requires a high frequency of soil moisture and weather data unavailable for the Lower-NNRB. Therefore, only the recession curve and the effective water level rise were computed from this toolbox. The total effective water level rise is the sum of water level rises influenced by different rainfall events during the year.

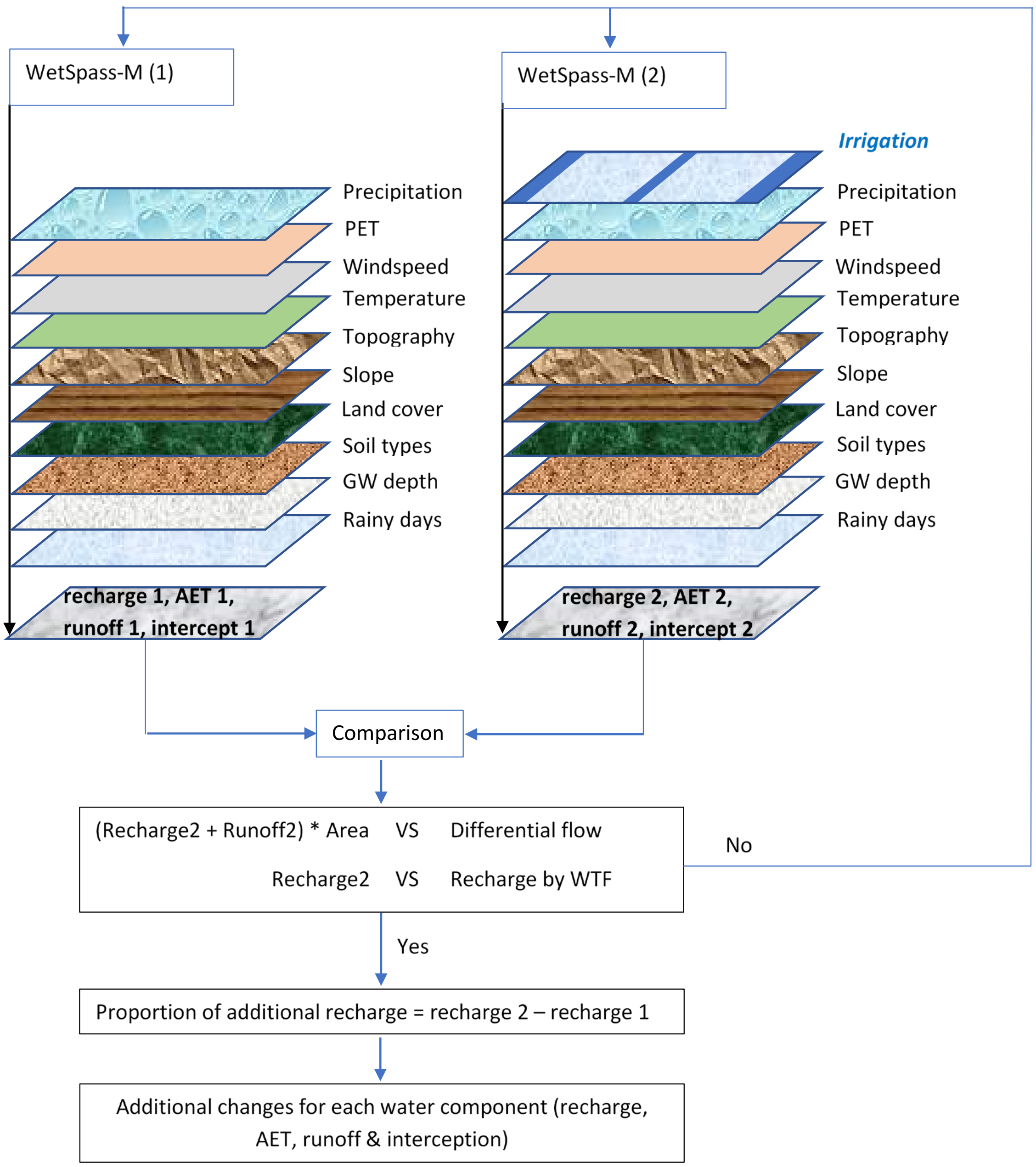


Figure 3.4. Schematic diagram of water balance analyses

It is also important to note that the recharge obtained from the WetSpass-M model and the WTF method were computed from different years, 2012-2014 and 2019, respectively, due to insufficient data to analyse the recharge by the WTF method for the year 2012. However, the observed groundwater levels and precipitation of the two periods are not significantly different. The two sets of rainfall time series were analysed by an inferential statistic, t-test, to determine if there is a significant difference between the two sets of precipitations. The t-test was conducted by setting a two-tailed and paired distribution. The probability p-value indicated that there is a non-significant difference between the two rainfall patterns as the p-value > 0.05 (p=0.67), meaning that the chance that the data is randomly distributed is greater than 67%. Moreover, a rainfall analysis for 1964-2016 also indicates no significant trend in the rainfall time series (chapter 2). Therefore, it was considered reasonable to compare the recharge computed from the observed water levels in 2019 by WTF with the recharge simulated by the WetSpass-M in 2012. Moreover, the comparision between the two approaches can improve the reliability of recharge estimation, because most approaches based on groundwater data are likely to provide estimates of actual recharge (Scanlon et al., 2002).

3.3.2 Data

The description of spatiotemporal input data for the WetSpass-M model is provided in Table 3.1. All input data were prepared in the form of raster grids (ASCII) at 100 by 100 m resolution, including soil, Digital Elevation Elevation Model (DEM), slope, land use, temperature, precipitation, potential evapotranspiration (PET), wind speed, groundwater depth and the number of rainy days.

Table 3.2. Summary of input data for the WetSpass-M model

Data	Source	Processed resolution	Original resolution
Soil	National Agriculture and Forestry Research Institute (NAFRI)	100 x 100 m	Polygon shapefile
Topography (DEM)	Mekong River Commission (MRC)	100 x 100 m	Raster 50 x 50 m
Slope	Computed from DEM	100 x 100 m (%)	Raster 50 x 50 m
Land use (2015)	European Space Agency-Climate Change Initiative (ESA-CCI)	100 x 100 m	Raster 300 x 300 m
Temperature	Observed by the Department of Meteorology and Hydrology (DMH)	100 x 100 m (degree Celsius)	Tabula statistics from 6 stations
Precipitation	Observed, DMH	100 x 100 m (mm/month)	Tabula statistics from eight stations
PET	Monthly PET derived from MOD16	100 x 100 m (mm/month)	Raster 1 x 1 km
Wind speed	Observed, DMH	100 x 100 m (m/s)	Tabula statistics from six stations
Groundwater depth	Observed by the International Water Management Institute (IWMI)	100 x 100 m (m)	Tabula statistics 28 existing drilled wells in the Lower-NNRB
Number of rainy days	Observed, DMH	100 x 100 m	Tabula statistics from eight stations

The soil classification was developed by the National Agriculture and Forestry Research Institute (NAFRI), Ministry of Agriculture and Forestry, using the FAO/UNESCO 1990 soil classification system. Based on this classification, a soil map was produced from the national soil survey conducted in 1994. Soil samples were taken between 0-30 cm depth for soil texture analysis from each district in the country. Based on the soil textures mapping of the ground-truth survey, polygons were roughly delineated for the spatially distributed soil texture across the nation. The thickness of the soil ranges from 30-50 cm; 50-75 cm; 75-100 cm, and greater than 100 cm. In the Lower-NNRB, seven different types of soil textures are presented (Fig.

3.5a); however, three types of soil are the most dominant: loam (32.8%), clay loam (19.0%), and sandy loam (17.2%).

A land cover map (2015) was obtained from the European Space Agency-Climate Change Initiative (ESA-CCI) and is presented in Figure 3.5b. The ESA-CCI land cover is a consistent global land cover map provided on an annual basis with a spatial resolution of 300 by 300 m in a raster format. The land cover classification was developed by the Food and Agriculture Organization of the United Nations (FAO) in comparison and validation with the GlobCover products. The accuracy of the land cover map of the year 2015 was assessed by the GlobCover 2009, comparing the contingency matrix calculated from the two products to confirm the homogeneity. The comparison indicates that the accuracy is 75.4% (ESA, 2017). The ESA-CCI land cover shows the highest accuracy for the land use classes rainfed and irrigated croplands, broadleaved evergreen forest, urban areas, bare areas, water bodies and permanent snow (ESA, 2017). At the global scale, the land cover map has 22 classes, while in the Lower-NNRB there are 15 classes. The land cover in the study area is mainly dominated by cropland (36%), mosaic cropland (13%), and shrubland (12%).

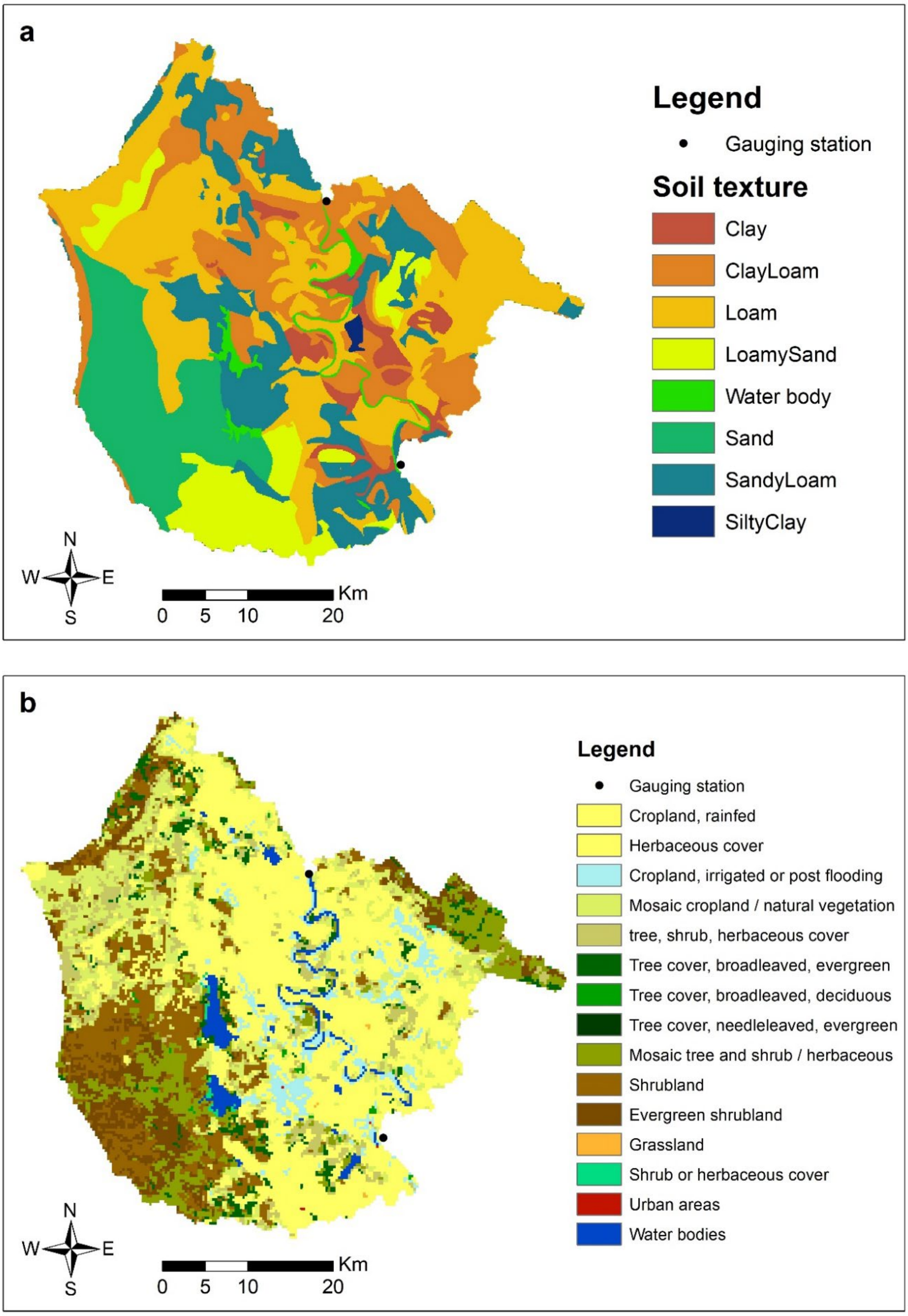


Figure 3.5. (a) Spatial distribution of soil texture; (b) landcover classification (2015)

The hydrological and meteorological data, daily precipitation, temperature, and wind speed, were obtained from the Department of Hydrology and Meteorology (DMH) of Laos. The data sets were recorded from six stations, which are in and nearby the Lower-NNRB for the year 2012 to 2014. The data sets were then interpolated by an inverse distance weighted (IDW) technique available in ArcGIS from point data to raster grids with 100 by 100 m spatial and a monthly time resolution.

The climate in this area is tropical, with a distinct wet season from May to October and a dry season from November to April (Jayasekera, 2013; Shrestha et al., 2013). Most of the rainfall in the Lower-NNRB is due to the arrival of warm moist air coming from East Asia and Indian Monsoons (Jayasekera, 2013; Lacombe et al., 2014). Annual rainfall at the Thangon station (1965-2014) varies between 1,278 – 2,771 mm. The mean annual rainfall is 1,855 mm, 90.5% of which falls during the wet season.

The groundwater depths were measured on a monthly basis from 28 drilled wells located in and nearby the Lower-NNRB. The monthly groundwater depths were then converted by an IDW technique into raster maps corresponding to the same grid cell size of the climate distributed maps. More detail of groundwater levels and flow directions are available from Chapter 2.

The potential evapotranspiration (PET) was derived from the MODIS Global Terrestrial Evapotranspiration Product (MOD16), which is developed by the NASA/EOS project to estimate global terrestrial evapotranspiration for the land surface by using satellite remote sensing data (Mu et al., 2005; Running et al., 2019). The MOD16 evapotranspiration was calculated using the Penman-Monteith equation (Monteith, 1965) and stored in HDF format files with 1 by 1 km resolution. The terrestrial evapotranspiration is the sum of evaporation from the soil, rainwater intercepted by the canopy, and the transpiration from plant leaves and stems (Mu et al., 2007; 2011). Monthly PET data from 2012 to 2014 were then extracted and prepared for the Lower-NNRB at the same spatial scale as other input layers.

The Digital Elevation Model (DEM) was developed and provided by the Mekong River Commission (MRC), covering the entire Lower Mekong Basin with a resolution of 50 by 50 m (Heinimann et al., 2005). The DEM were extracted and then upscaled to 100 by 100 m of resolution to be compatible with other input files. The slope maps (gradient or steepness) for each cell of a raster were then calculated from DEM using ArcGIS tools package.

The applied irrigation water was estimated based on the irrigation stations and the capacity of their pumps, as provided by the Lao Department of Irrigation and Provincial Agriculture and Forestry Office. In 2019, there were a total of 23 pumping stations operational in the Lower-NNRB (Fig. 3.1c). Most of them were installed between 1995 and 2003. Each station is equipped with 2 to 9 pumping units. The pumping capacity of each unit ranges from 233 – 1,100 l/s. They lift water from the Nam Ngum River up to main canals from where it is delivered to the fields by gravity flow. The irrigation is mostly for dry season rice cultivation from November to mid-April, with a total duration of irrigation of 152 days while operating for 12 hours per day. The irrigation water estimated from the pumping operation schedules was added to the precipitation on a monthly basis for November to April. Figure 3.6 shows the variation of an annual spatially distributed precipitation and irrigation water on the command areas across the Lower-NNRB.

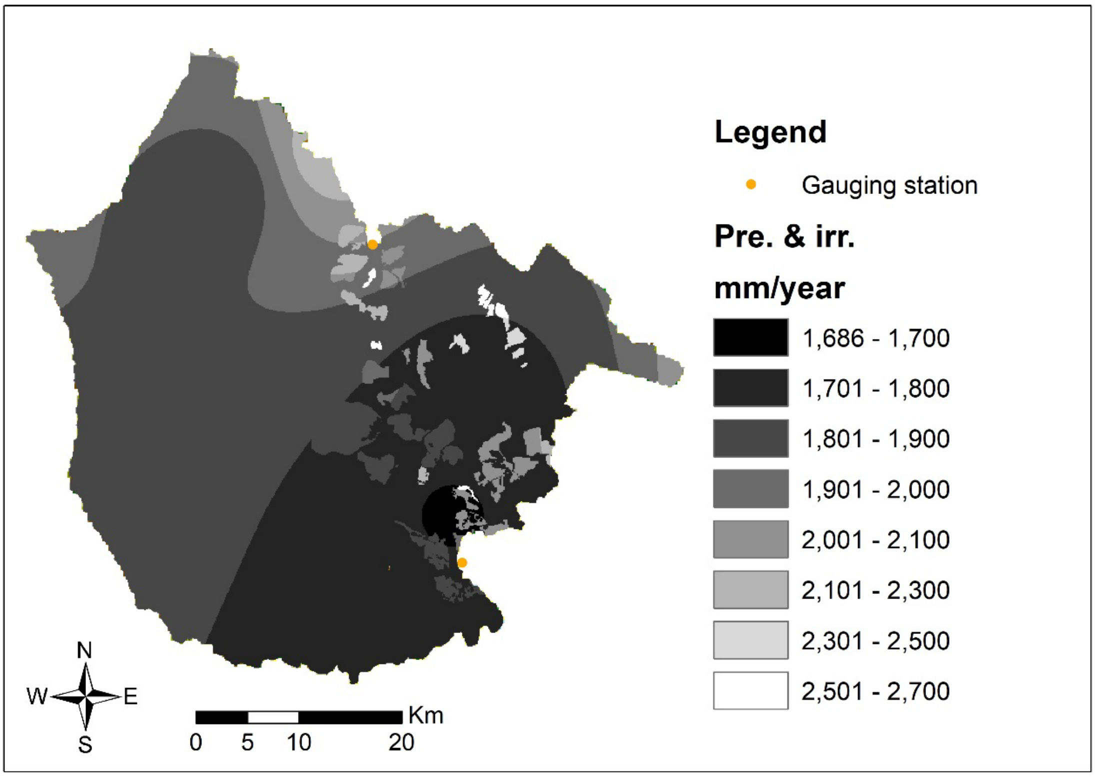


Figure 3.6. Spatially distributed precipitation for the year 2012 and irrigation water on of the command areas across the Lower NNRB

For the water table fluctuation method, a specific yield (Sy) is required. For this study, it was estimated as 13%, based on the characteristics of the coarse-grained aquifers of the N2Q1-3 unit (Perttu, 2011). The daily groundwater levels were measured using Aqua TROLL water level loggers (In-Situ Inc) from three monitoring wells, and the pressures were compensated using a barometric data logger measured nearby the well site (Baro TROLL, In-Situ). The three monitoring boreholes have similar depths and tap the same shallow unconfined aquifer; the daily groundwater levels were measured from the dry season of 2018 till 2020.

3.4 Results

3.4.1 Water balance components

Monthly water balance components including recharge, surface runoff, AET, and interception were simulated for the Lower-NNRB for 2012 till 2014 for both the non-irrigated and irrigated scenarios (Fig. 3.7). Negative groundwater recharge occurs in some dry season months when total evapotranspiration, including groundwater sustained transpiration, is higher than the infiltration (net precipitation - surface runoff).

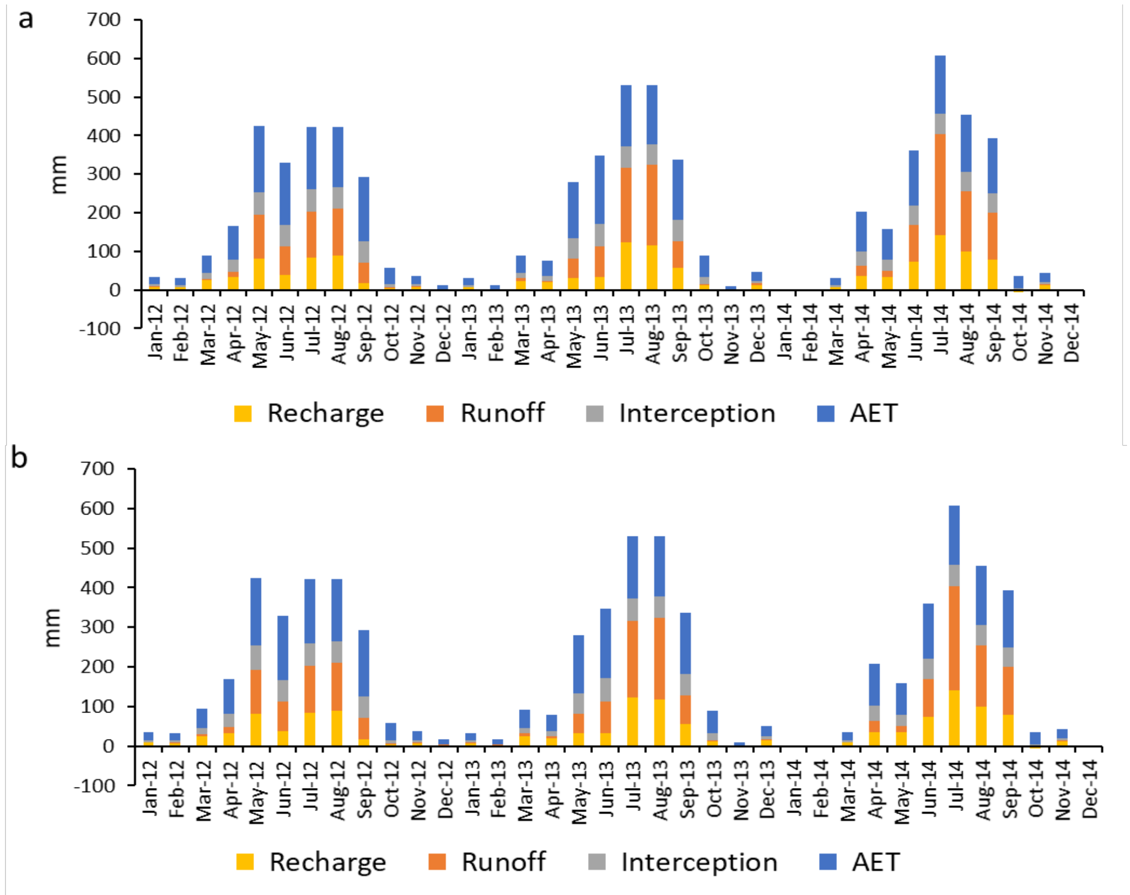


Figure 3.7. (a) Monthly water balance components average values for the Lower-NNRB : groundwater recharge; surface runoff; interception; and actual evapotranspiration for 2012-2014, scenario without irrigation; (b) scenario for monthly water balance components with irrigation.

Under irrigation conditions, the annual water balance components as a percentage of the precipitation are summarized in Table 3.3. Overall, the highest percentage is associated with

AET and surface runoff, with an average for 2012 till 2014 of 41% and 26%, respectively. In contrast, other components have lower fluxes than AET and surface runoff, particularly recharge at 19% and interception at 14% of the precipitation.

Table 3.3. Percentage of each water balance component compared to rainfall under irrigation conditions

Year	AET (%)	Runoff (%)	Interception (%)	Recharge (%)	Precipitation & irrigation (mm)
2012	46	22	15	17	2,336
2013	42	26	14	19	2,400
2014	37	30	13	21	2,295
Average	41	26	14	19	2,344

Figure 3.8 shows the yearly spatial groundwater recharge under the irrigation scenario for the years 2012 till 2014. It provides a spatial view and confirmation of the average rates of recharge shown in Table 3.2, with the highest rate (21%) for 2014, 19% for 2013 and 17% for 2012.

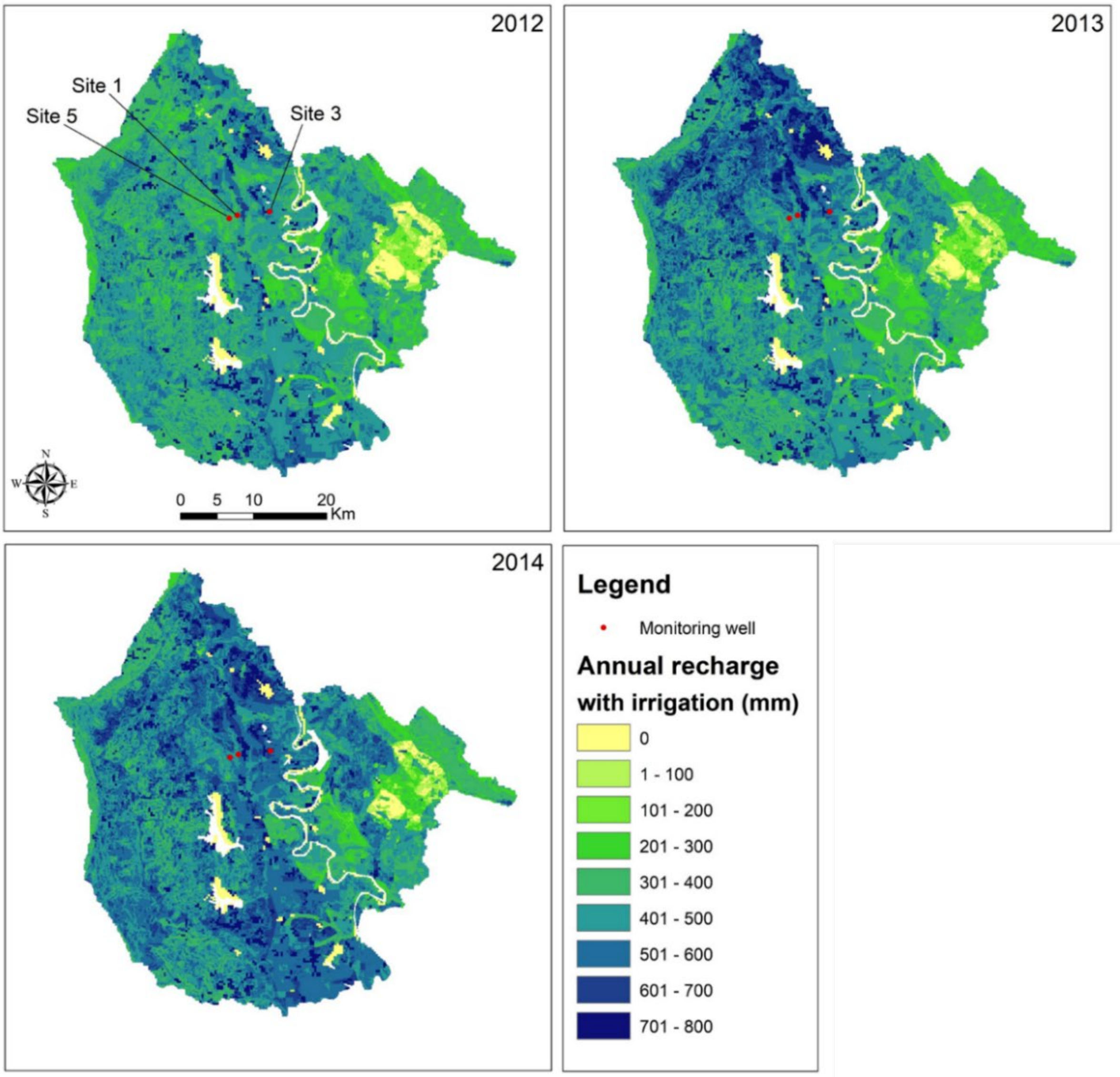


Figure 3.8. Annual spatial recharge distribution under irrigation scenario across the Lower NNRB from 2012 till 2014 and the location of monitoring wells used for the water table fluctuation method.

The monthly spatiotemporal recharge in the Lower-NNRB for the year 2012 is presented in Fig. 3.9. It shows relatively high recharge in the east and west margins of the catchment, where sandy soil, loam, and loamy sand toward the hills dominate. Lower recharge occurs in the plain areas along the Nam Ngum River. The mean monthly recharge (2012-2014) for the dry season varies from 4 to 31 mm and 5 to 116 mm for the rainy season. Overall, the temporal distribution of the recharge is determined by the precipitation taking place during the wet season months. However, the irrigation schemes make contributions in the dry season months, January, February and December, especially within the irrigation command areas (Fig. 3.9). Monthly spatial recharge within the command areas varies from 15-45 mm/month, which is comparable with the mean percolation rate provided by Phengphaengsy and Okudaira (2008); Sivanpheng and Kangrang (2015) at 1.6 mm/d, approximate 49 mm/month.

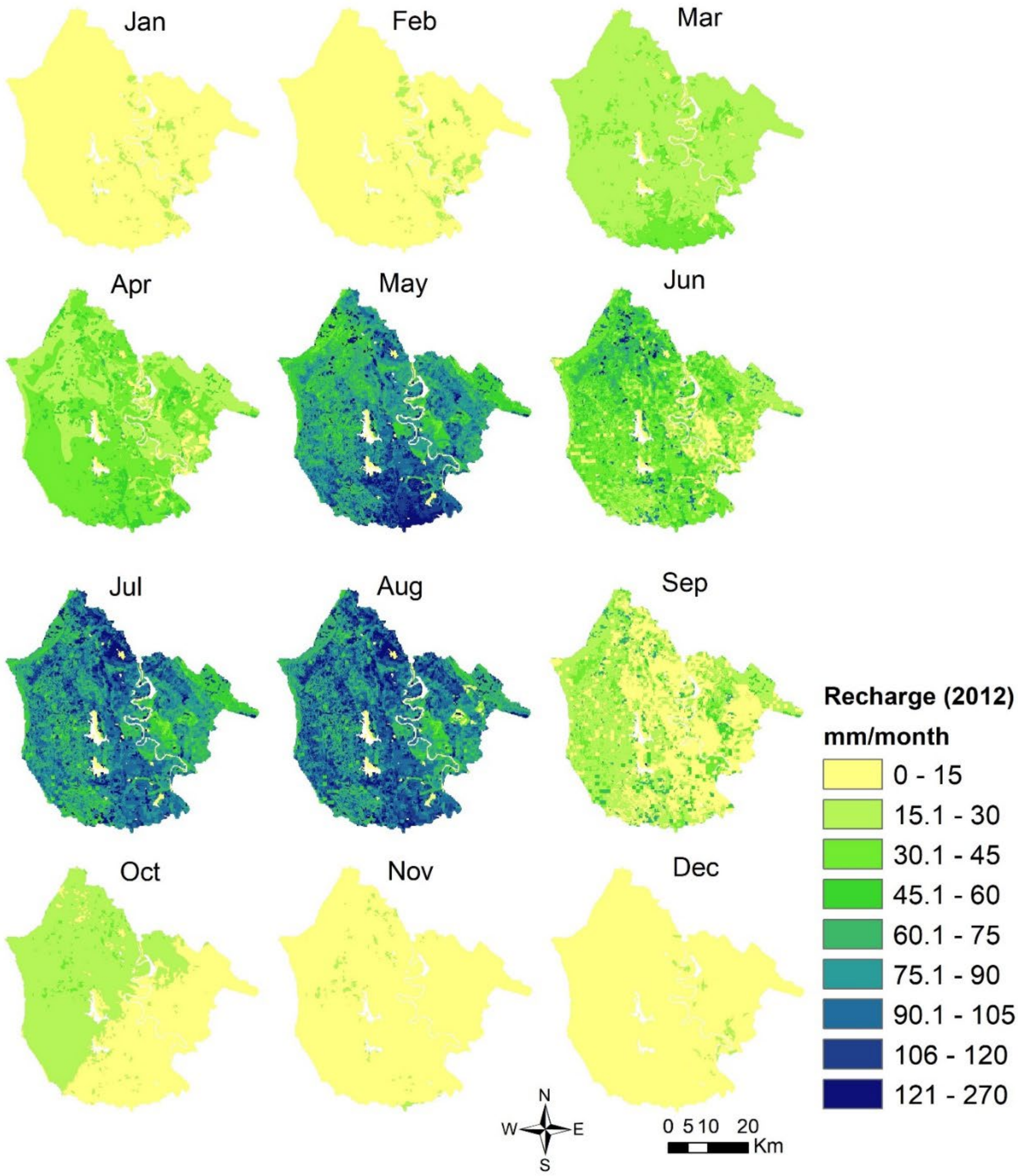


Figure 3.9. Monthly spatial groundwater recharge distributions in the Lower-NNRB for 2012 for the irrigation scenario

3.4.2 Comparison

3.4.2.1 Surface runoff plus recharge versus differential flow

The river flow is recorded at the downstream (Thangon) and upstream (Pakanhoung) gauging stations (Fig. 3.10). The differential river flow between these two stations represents the water productivity generated from the Lower-NNRB (i.e., a constitution of surface runoff and baseflow). Therefore, the annual differential flow is applicable to be compared with annual groundwater recharge plus surface runoff simulated from the WetSpass-M (Fig. 3.11). The comparison for 2012 and 2013 is very good, with a difference (WetSpass-M underprediction) of -48 x 10^6 m^3/yr (-2.5%) and 92 x 10^6 m^3/yr (4.1%) (WetSpass-M overprediction) respectively, while in 2014 the discrepancy with 18.4% is slightly higher.

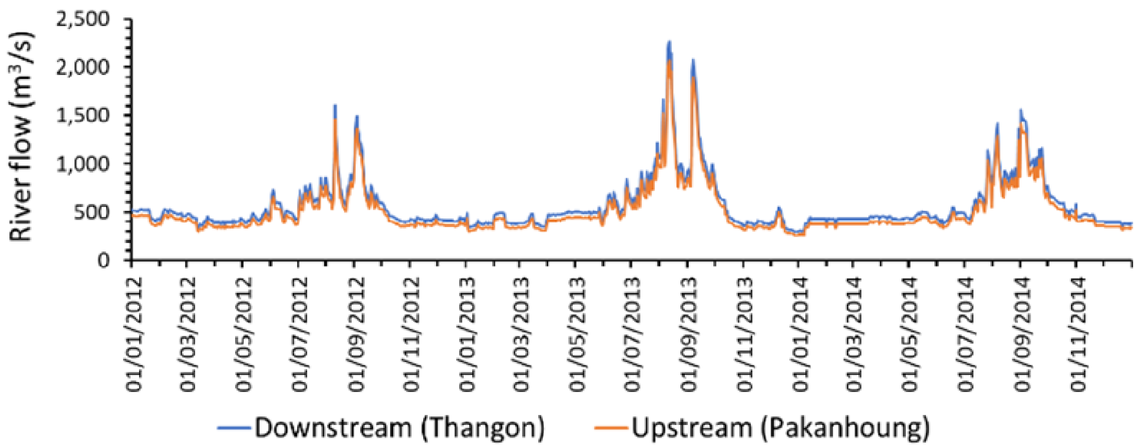


Figure 3.10. Hydrographs of daily river flow measured from the upstream and downstream gauging stations from 2012 to 2014

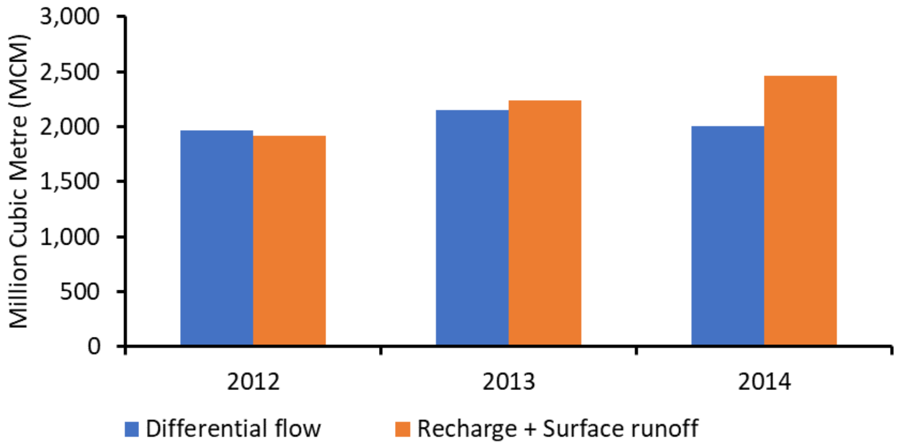


Figure 3.11. Comparison between WetSpass-M simulated sum of annual recharge and surface runoff versus measured annual differential river flow between river gauging stations Pakanhoung and Thangon for 2012-2014.

3.4.2.2 Spatial recharge distribution versus water table fluctuation (WTF) method

Annual groundwater recharge was also computed from water levels measured from the three monitoring wells in the Lower-NNRB. The daily groundwater level was observed, and the hydrographs of daily water levels for the three sites are presented in Fig. 3.12. The master recession curves are given in red-dashed lines and are the basis for the estimation of the effective water level rises used for the recharge analysis. The annual effective water level rises were assessed for the year 2019. The total effective water level rises of sites 1, 3, and 5 are not significantly different, i.e., 4.1 m, 4.2 m, and 3.1 m, respectively. Site 3 has a peak closer to the ground surface in the rainy season as it is located close to the Nam Ngum River. However, site 5 also has a peak close to the ground surface as the monitoring well is located in the paddy area with lower elevation than the surrounding areas.

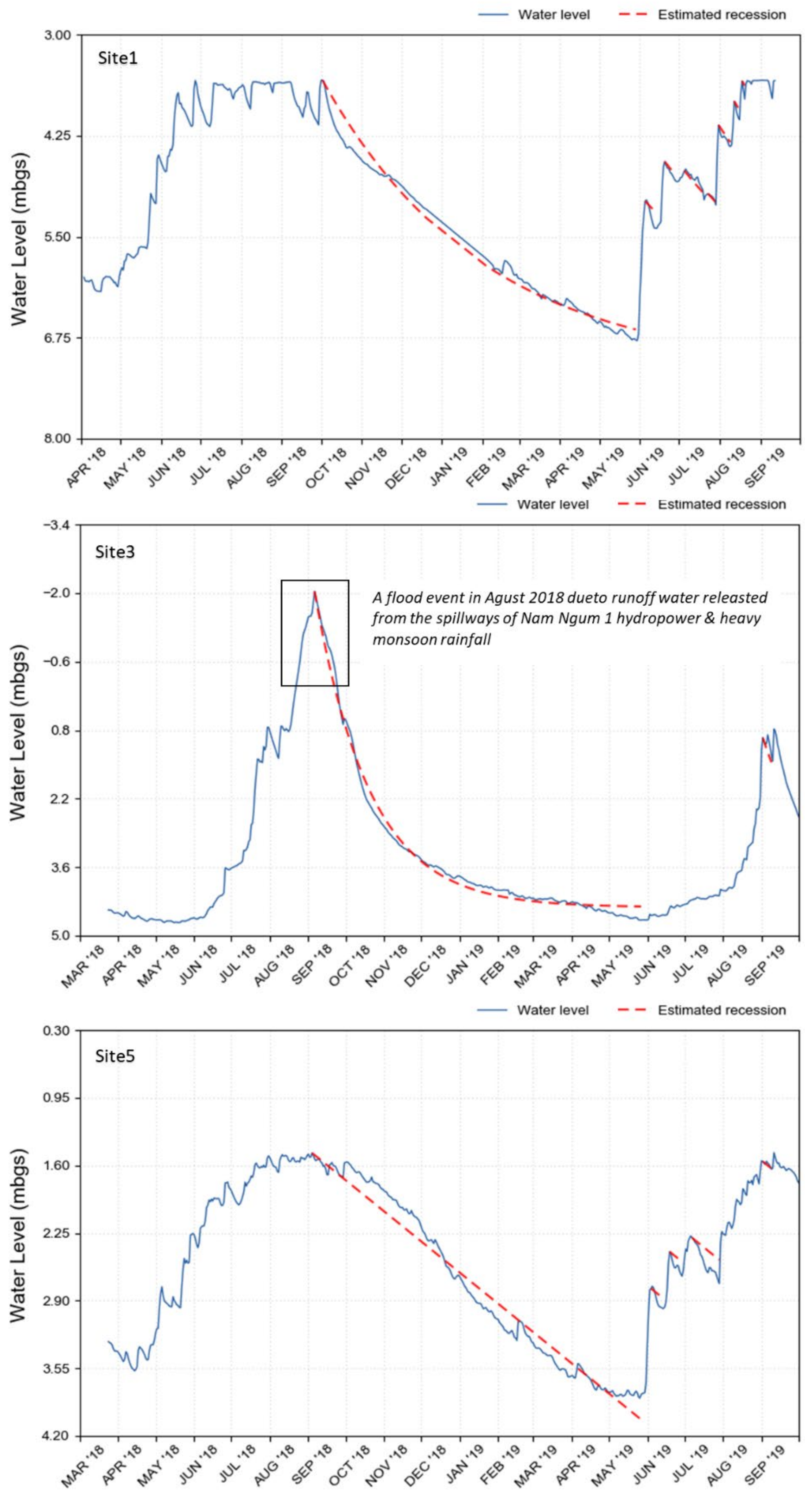
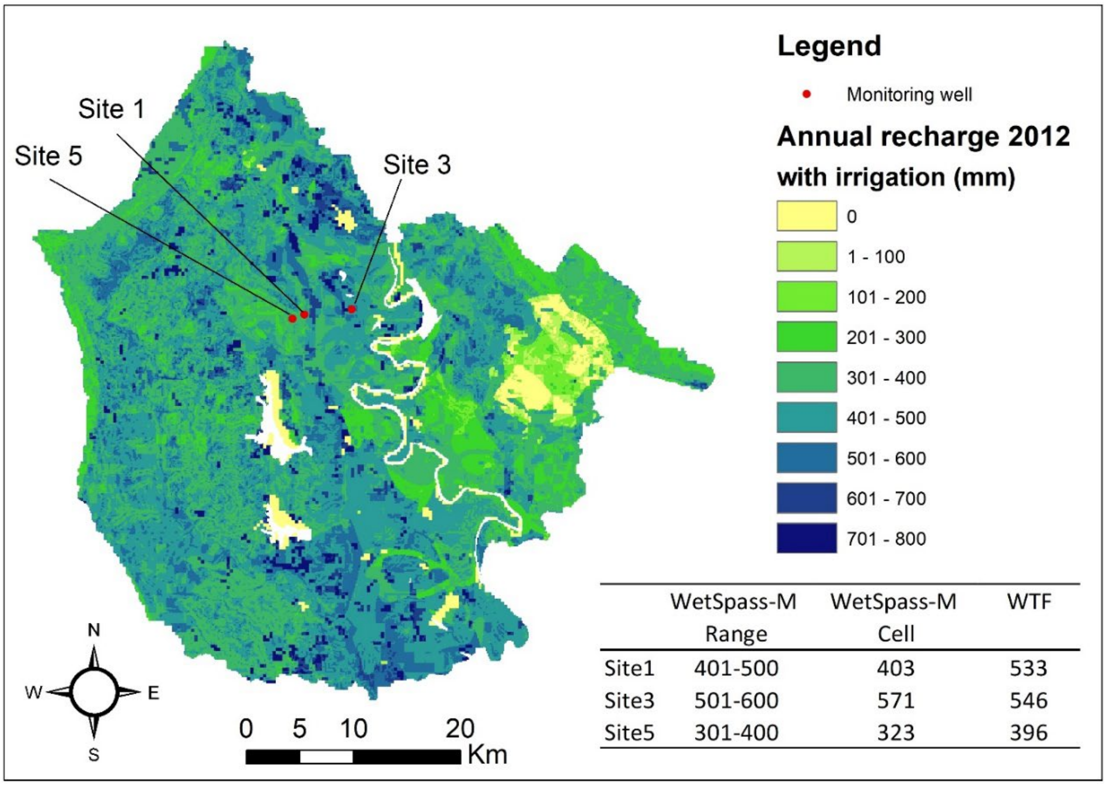


Figure 3.12. Hydrographs of groundwater table fluctuation (blue solid line) and master recession curve (red dashed line) for sites 1, 3, and 5.

The precipitation of 2019 is not significantly different from 2012, with a total annual precipitation of 1,870 mm and 1,687 mm, respectively. Therefore, it is reasonable to compare annual groundwater recharge computed by the WTF and WetSpass-M model for consistency of the assessment (Fig. 3.13). The recharge from the three sites compares well to the recharge obtained from WetSpass-M, especially for site 3 with 546 mm/year (WTF) versus 571 mm/yr (WetSpass-M) and for site 5 396 mm/yr (WTF) versus 323 mm/year (WetSpass-M) for the grid cells where the observed wells were located. However, the discrepancy for site 1 is more significant, WTF indicates a recharge of 533 mm/year while WetSpass-M's recharge is with 403 mm/year considerably lower.



	WetSpass-M Range	WetSpass-M Cell	WTF
Site1	401-500	403	533
Site3	501-600	571	546
Site5	301-400	323	396

Figure 3.13. Comparison of annual groundwater computed from the WetSpass-M and the Water Table Fluctuation method

3.4.3 Groundwater recharge with and without irrigation

Results for the comparison between the annual groundwater recharge for the with and without irrigation scenarios from 2012 till 2014 are summarised in Table 3.4. Overall, groundwater recharge for the two scenarios exhibits a non-significant difference at the scale of the whole Lower-NNRB, with 438 mm/yr for non-irrigation and 444 mm/yr for the irrigation scenario, which shows a basin-wide increase of 6 mm due to the irrigation. However, the recharge within the command irrigation areas increases on average 83 mm.

Table 3.4. Summary of annual recharge of the Lower-NNRB with and without irrigation water for 2012-2014

Year	Recharge without irrigation (mm)	Recharge with irrigation (mm)	Recharge increase over whole Lower NNRB (mm)	Recharge increase within irrigation command area (mm)	Recharge increase due to irrigation (10^6 m^3)
2012	397	404	7	99	15
2013	437	445	8	107	16
2014	480	483	3	44	7
Average	438	444	6	83	12

3.4.4 Change in water components

The impact of additional irrigation water on each water balance component in the Lower-NNRB was assessed (Table 3.4). Overall, irrigation water has caused AET, interception, and recharge to increase while the runoff remained unchanged, as irrigation practices took place during the dry season. The AET and recharge have increased on average 6 mm over 2012-2014, while interception has slightly gone up by 1 mm.

Table 3.5. Water balance components for the Lower-NNRB for the scenario without irrigation (components with the 1 identifier), the scenario with irrigation (components with the 2 identifier) and the difference between the scenarios (Δ identifier) for the years 2012 till 2014.

Year	AET1 (mm)	AET2 (mm)	Δ (mm)	Int. 1 (mm)	Int. 2 (mm)	Δ (mm)	Re. 1 (mm)	Re. 2 (mm)	Δ (mm)	__	Runoff (mm)
2012	1,059	1,067	8	356	358	1	397	404	7		500
2013	993	1,000	8	332	333	1	437	445	8		616
2014	835	838	3	287	287	0	480	483	3		684
Average	962	969	6	325	326	1	438	444	6		600

3.5 Discussion

The confidence in the simulated groundwater recharge was established by comparing the annual observed differential flow with the simulated groundwater recharge plus surface runoff (Fig. 3.11). The summed simulated recharge and surface runoff is conceptually equivalent to the differential flow and represents the natural water productivity in the Lower-NNRB. Because of the delay between recharge and baseflow, it is most appropriate to compare the annual recharge, as short-term groundwater recharge calculated from observed water level rises does not correspond to precipitation and baseflow over the same period (Labrecque et al., 2020). Therefore, the recharge as estimated by WetSpass-M and the WTF method is compared at an annual time scale (Fig. 3.13). The estimations are relatively similar, confirming that WetSpass-M reasonably simulates the hydrological water balance components in the Lower-NNRB.

Groundwater recharge is mainly dominated by rainfall and occurs during the rainy season. The annual spatial distributed recharge for 2012-2014 is reasonably homogenous distributed (Fig. 3.8). Lower recharge rates occur in the plain areas along the Nam Ngum River, and significant lower recharge occurs in marginal areas to the east of the basin, associated with heavier soil textures such as clay and clay loam present on those areas. As the recharge is influenced by soil texture and land cover, it is important to understand the recharge's dependence on the different soil textures and land cover classes. Figure 3.14 presents the mean and standard deviation of annual recharge simulated by WetSpass-M per soil texture and land use class, where clay and silty clay indicate a lower rate of recharge of 234 mm/yr and 300 mm/yr, respectively, while the sand loam has the highest rate of recharge of 507 mm/yr. Like the sandy loam, the land cover class of deciduous forest and meadow shows high recharge values of 662 mm/yr and 639 mm/yr, respectively. On the other hand, open water and urban area show a significantly lower rate of 33 mm/yr and 108 mm/yr, respectively.

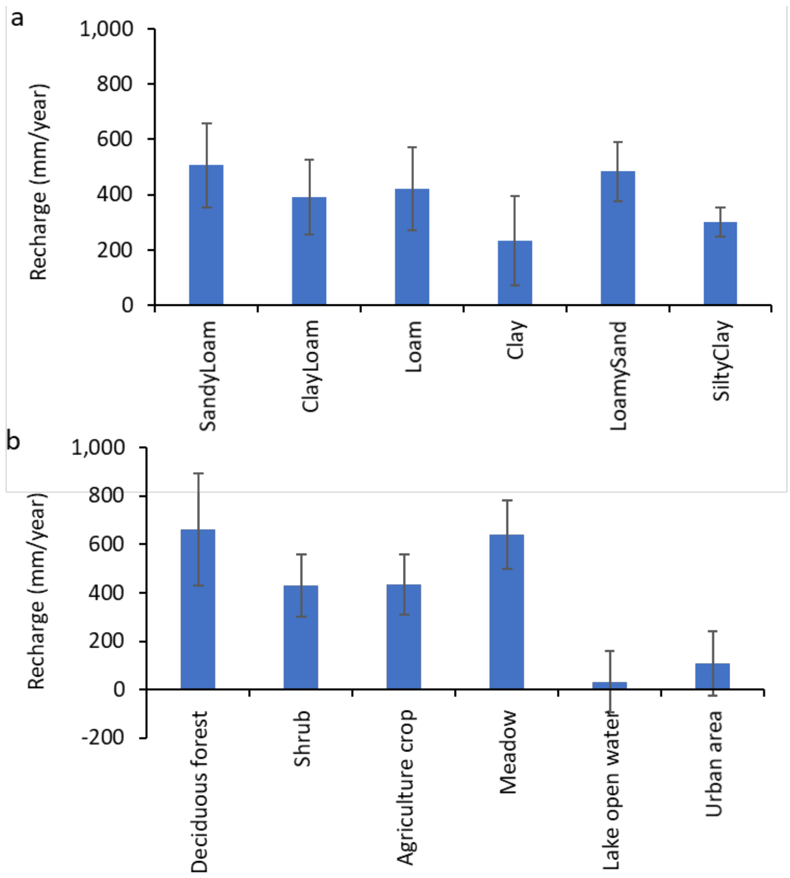


Figure 3.14. Mean and standard deviation of average recharge from 2012 till 2014 simulated by WetSpass-M per (a) soil texture; (b) and land cover class

It would also be interesting to interpret the recharge contribution per combination of different land cover classes and soil texture. Figure 3.15 shows the variation of average recharge from 2012 till 2014 per combination of land cover and soil texture class for the Lower-NNRB. This recharge assessment is important for groundwater management as it allows to determine the magnitude of the impact of changes in landscape units (land use – soil) on the recharge. Open water bodies and urban areas under any soil have very low recharge contribution, varying from 0 to 73 mm/yr, due to their high runoff and low infiltration capacity. Deciduous forests and meadows have a relatively high level of recharge even in combination with fine soils such as clay and clay loam, resulting in an average recharge of 650 mm/yr. Sandy loam with deciduous forest appears to have the highest rate of recharge, which is good for sustaining groundwater resources for the basin. The land use category appears to have a more significant influence than soil texture on the groundwater recharge in the Lower-NNRB. However, aquifer variability will not affect recharge. The recharge is most directly influenced by the soil type. Effects of groundwater storage are included in the model via the groundwater depth parameter. Deep-rooted vegetation can have therefore an impact on estimated evapotranspiration and hence on recharge.

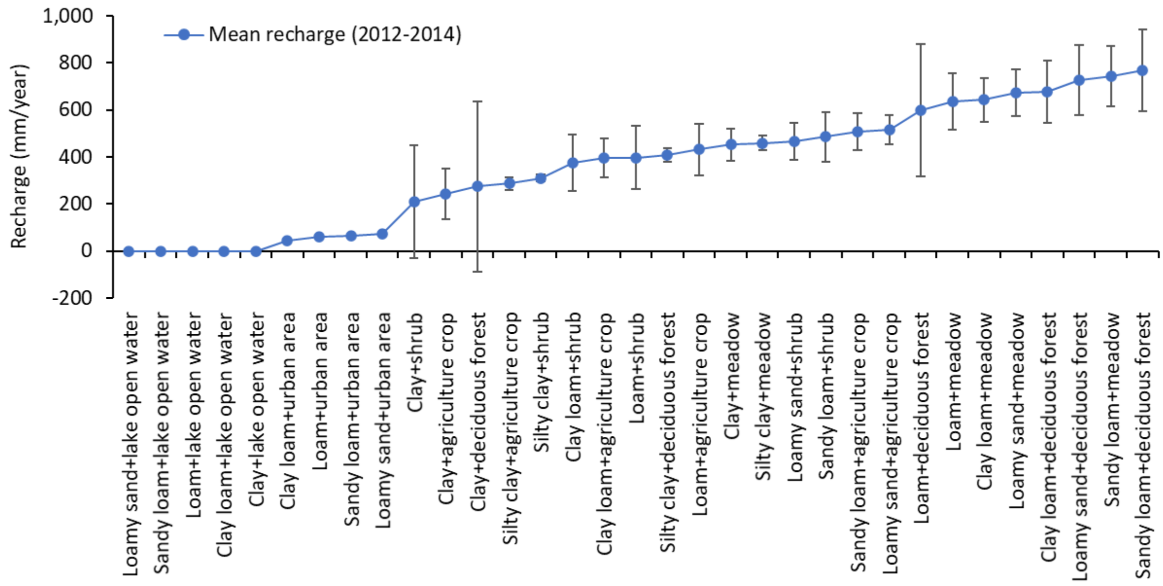


Figure 3.15. Recharge per land cover and soil texture combination for the Lower-NNRB

Irrigation water might not strongly influence groundwater recharge at the scale of the whole the Lower-NNRB, but it increases recharge within the irrigation command areas considerably, with an additional increase of 99 mm (2012); 107 mm (2013); 44 mm (2014), and an average of 83 mm. As most irrigation schemes are in the vicinity of the river, a higher irrigation return flow can discharge to the river causing changes in stream temperature, surface-groundwater interactions, increased groundwater levels, and increased nutrients discharge to the rivers. The identified increased groundwater storage and discharge to the river due to irrigation water diverted from surface water are similar to observations made in other studies (Qin et al., 2011; Essaid and Caldwell, 2017).

The irrigation water diverted from the surface water causes not only enhanced recharge but also increases other water balance components such as AET and interception. The AET for the whole Lower-NNRB increased due to more crop cultivation and optimal soil moisture conditions, allowing more evapotranspiration to occur during dry seasons. Overall, the AET increased by 8 mm in 2012 and 2013, and 3 mm in 2014, and 6 mm on average for the three years. Besides, the interception had minimal changes, with a 1 mm increase for 2012 and 2013, while in 2014, it remained unchanged. However, irrigation has not impacted the surface runoff, as irrigation is carried out during the dry season months with little or no rainfall.

3.6 Conclusions

The impact of irrigation water diverted from surface water on groundwater recharge has been assessed for the Lower-NNRB. This analysis provides useful information on water balance components under irrigated and non-irrigated conditions in the basin. The spatiotemporal recharge distributions were assessed for 2012-2014 to be on average 444 mm/yr, equivalent to 19% of annual rainfall. Irrigation has caused the recharge within the command areas to increase by 83 mm and enhance the AET and interception for the whole Lower-NNRB by 6 and 1 mm, respectively. The additional irrigation water has a significant impact on the net recharge within the command areas, but as the total irrigation area is relatively small compared to the total area of the Lower-NNRB, it has a minor impact on the entire Lower-NNRB. This study implies that irrigation water diverted from surface water enhances AET, interception, and groundwater storage, which is a positive contribution to the groundwater resources. The methodology and results of assessed recharge rate and other hydrological water balance components show a high value for informing, supporting and planning water and land management decisions in this and other basins in the Lower Mekong Basin.

Chapter 4. The impact of anthropogenically induced changes in river flow regime on connected groundwater systems: a case study of the Lower-Nam Ngum River basin, Lao PDR[3]

Abstract

Regulation of large surface water reservoirs has well-documented consequences on river flow regimes. However, the impact of change in river flow regimes and river stages as a consequence of installed reservoirs on surface water-groundwater interactions and groundwater systems more broadly is poorly understood. Our research focuses on the Nam Ngum River Basin, Lao PDR, a major tributary of the Mekong River. Here, hydropower dams were developed in the upper part of the basin, whilst the lower part is mainly undammed and intensively developed for irrigated agriculture. This study investigates the impact of river flow and river stage changes due to infrastructure development on the surface water-groundwater interactions, water budget, groundwater levels, and water balance by comparing the pre-dam to post-dam condition, using an interpretive MODFLOW model. The results indicate that the Nam Ngum River and its tributaries were losing river water in the rainy season and gaining water in the dry season in the pre-dam period. However, they have become gaining year-round, while the upstream tributaries exhibit dampened levels of change from the pre- to the post-dam period due to high topographic elevation. As a result of river stage changes, the surface water-groundwater exchange has declined in the post-dam period compared to the pre-dam condition, i.e., the annual amount of water lost and gained by the river system has reduced by 53% and 23%, respectively. Moreover, the annual amount of water entering and leaving the system also declined by 22% compared to the pre-dam period, reducing aquifer recharge and modifying the groundwater budget. In the post-dam period, the increase in river stage in the dry season has caused groundwater tables in the riparian and downstream area to increase compared to the pre-dam period.

Keywords: Impact dams, surface water-groundwater interaction, groundwater modelling, Nam Ngum River, Lao PDR

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[3] To be submitted to the *Journal of Hydrology: Regional Studies*

4.1 Introduction

Groundwater has a potentially important role in improving crop production and poverty reduction for Laos, but the development of groundwater resources is constrained by the limited understanding of the groundwater system. Groundwater development and usage in Laos have primarily been unregulated, poorly understood, and limited by lack of technical capacity, which results in ineffective water resources management (Pavelic et al., 2014; Viossanges et al., 2018). In contrast, surface water resources have been heavily exploited by human activities to boost the nation's economy, i.e., hydropower dams and irrigation schemes, causing water resources to face a major challenge to contribute to sustainable development. For instance, in the areas where river surface water is not available, farmers are increasingly irrigating their home garden and commercial crops with groundwater (Vote et al., 2015), increasing groundwater abstraction and potentially depleting aquifer due to accessive use of groundwater (Döll and Fiedler, 2008; Gleeson et al., 2012). Moreover, regulating large rivers water for energy production and river-fed irrigation have influenced free-flowing rivers, flow regimes, and river stages (Francis et al., 2010; Roy et al., 2015; Li et al., 2017a; Räsänen et al., 2017; Hecht et al., 2018; Grill et al., 2019), resulting in alteration of surface water-groundwater exchanges in the lower basins (Hucks Sawyer et al., 2009; Ferencz et al., 2019; Zhang et al., 2020). It is believed that reservoir operation of hydropower upstream causes not only a change in river flow regimes and river stages but can also influence hydraulic gradient and flow in the hyporheic zone (Roy et al., 2015; Biehler et al., 2020), affecting the ecological value of both surface and groundwater resources.

In the Nam Ngum River Basin (NNRB), Laos, a major tributary of the Mekong River, hydropower dams were developed in the upper part of the basin, whilst the lower part is undammed mainly and intensively developed for agriculture (Fig 4.1). Due to hydropower dam operations in the upper part of the NNRB, there has been a change in the seasonal river flow regime and river stages in the lower part of the basin. The consequence of this change in flow regime on the connected groundwater flow system is poorly understood. Several previous studies in the NNRB have attempted to assess surface water resource availability and discharge as a consequence of hydropower dam and irrigation development for different scenarios, i.e., without development (no dam), baseline condition of the year 2000, full proposed hydropower dams operations, irrigation expansion from 60,000 to 100,000 ha in the NNRB, and climate change using the hydrological models Soil and Water Assessment Tool (SWAT) and Integrated Quantity Quality Model (IQQM) (Sanyu Consultants Ltd, 2004; AFD & ADB, 2008; WREA, 2008a; WREA et al., 2009; Lacombe et al., 2014). Only a few studies have focused on the hydrogeology and groundwater development potential in the NNRB. In 1993, the Japan International Cooperation Agency (JICA) carried out a groundwater development project in the Vientiane Plain, which covers the lower NNRB. The aim was to drill deep wells to provide a safe water supply for rural communities, but 60% of the total 118 drilled wells could not be used due to poor water quality, i.e., high level of salinity in the water, colour, and odour issues (JICA, 2000). Perttu et al. (2011) investigated and characterized the hydrogeology of the Vientiane Plain, aiming to locate the fresh-salt water interface and distinguish freshwater from clay, using multiple geophysical measurements. Recently, a similar study also delineated groundwater potential areas in some parts of the Vientiane Plain using seismic refraction techniques (Xayavong et al., 2020). On a country scale, annual spatial groundwater recharge (Lacombe et al., 2017) and groundwater resource potential (Viossanges et al., 2018) were also assessed. Vongphachanh et al. (2017) carried out research to assess hydrogeological conditions in southern Laos; this included examining surface water-groundwater interactions by comparing groundwater levels and riverbed elevations. Most of these previous studies in Laos have focused on the development of groundwater potential to meet future requirements, but none of them has evaluated the impact of river stage changes due to human-made water infrastructure on the groundwater systems.

Due to the installation and operation of multiple cascading reservoirs in the upper Nam Ngum Basin, it is hypothesized that changes in river stages will have consequent impacts on the groundwater through changes in surface water-groundwater interactions. This hypothesis is in opposition to the statement of Smith et al. (2016): "In addition, the upstream-downstream relationships typical for surface waters, with their associated power dynamics among water users, have little to do with groundwater, and the spatial and temporal scope of groundwater is very different to surface waters". Hence, there is a need to understand better how the upstream surface water infrastructures impact the groundwater downstream. Moreover, how the groundwater system downstream changes due to the dammed river regime is further complicated by the poor knowledge of the hydrogeology of the Lower-NNRB. Hence, defining an appropriate hydrogeological conceptual model and the response of the groundwater system are open questions. The specific aims of this research are, therefore: (i) to derive a hydrogeological conceptual model capturing the essentials of the connected groundwater-surface water system during the pre- and post-dam condition; (ii) to assess the status and change in river interaction, groundwater resources (budget) and water tables in the Lower-NNRB for the pre- and post-dam period via groundwater flow modelling; and (iii) to establish the implications on the management of the groundwater resources as a consequence of the anthropogenically-induced changes in the river basin.

The entire Lower-NNRB covers a relatively large area with insufficient hydrogeological information, i.e., groundwater levels and aquifer properties, particularly at the high altitude and hilly areas to the east and west of the basin. These are unlikely zones of high groundwater potential. Therefore, the numerical groundwater flow model for this study was designed as an interpretive conceptual model. It focuses on demonstrating and improving the understanding of the groundwater system. It aims to support the testing of the hypothesis that changes in river stages due to regulation impacts groundwater systems rather than providing a predictive, calibrated-validated model (Quinn et al., 2006; Anderson et al., 2015).

4.2 Study area and data

4.2.1 Study area

The Nam Ngum River Basin (NNRB) is a sub-basin of the Mekong River Basin (Fig. 4.1a) and is located in central Laos. It comprises a total drainage area of 16,800 km^2 (Fig. 4.1b). Its elevation ranges from 155 m above mean sea level (masl) at the confluence of the Nam Ngum River with the Mekong River to 2,820 m asl on mount Phou Bia (WREA, 2008b). The NNRB generates about 4.3% of the Mekong River's mean (1962-1984) annual flow (Lacombe et al., 2014). This flow is essential for power production, urban water supply, and fisheries (WREA, 2008b). The NNRB is home to roughly 502,000 people, representing approximately 9% of the total population of Laos (WREA, 2008b). The lower NNRB was delineated from the digital elevation model (DEM) developed by MRC (Heinimann et al., 2005). It is situated between the Pakanhoung and Thangon river gauging stations and is the focus area for this study (Fig 4.1c). The lower basin is an important area for food production (WREA, 2008b; Bartlett et al., 2012; Lacombe et al., 2014), and is supported by considerable irrigation development. To meet the requirements of the population and socio-economic growth, expansion of the irrigation is expected.

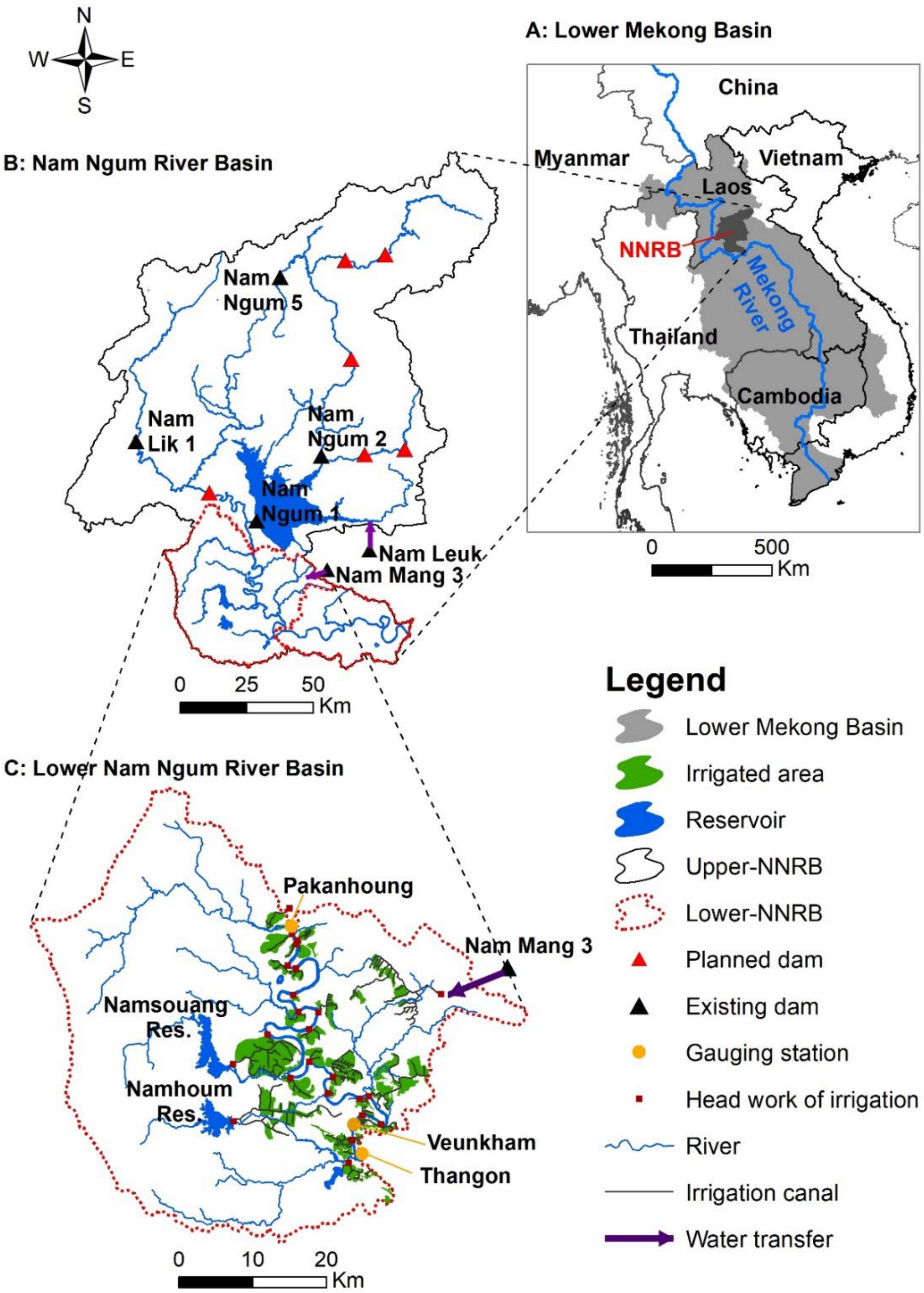

Figure 4.1. Study area: (a) The Lower Mekong Basin with highlighted Nam Ngum River Basin (NNRB). (b) The Nam Ngum River Basin with the location of existing and planned dams, reservoirs, and delineation of Lower NNRB. (c) The Lower NNRB, between gauging stations Pakanhoung and Thangon. Indicated is the location of the Nam Mang3 dam, reservoirs, major irrigation command areas with irrigation pumping stations, river gauging stations. The locations of dams are derived from the map of dams in the Mekong Basin, available from https://wle-mekong.cgiar.org/.

4.2.2 Data

4.2.2.1 Geology of the Lower-NNRB

There are six geological units present in the Lower-NNRB (Fig. 4.2). The Champa Formation (K_2cp) is Cretaceous in age, which mainly comprises sandstone, siltstone, brownish sandstone, and white arkose sandstone lying along the east and west side of the catchment. Further to the eastern and western hilly-mountainous edge of the catchment is the Phu Pha Nang Formation of Jurassic to Cretaceous age (J-Kpn), composed of sandstone bearing mica, white siltstone, and brown sandstone. The Nam Ngum River floodplain is shaped by three Quaternary depositional phases of alluvium, termed Qii-Qiv, containing sand, clay, peat, and gravel. In the southeast of the catchment occurs the Cretaceous Tha Ngon Formation (K2tn), which includes Na-salt, potash salt, claystone, siltstone, sandstone, gypsum and anhydrite, rhyolite, and tuff. In the south, the most occurring geological unit is the Vientiane Formation (N2-Q1vc), a Neogene to Quaternary unit of gravel, shingle, sandy kaolinite, and laterite (Geological and Mineral Map of Vientiane Plain, scale 1:200,000; Ministry of Energy and Mines).

The sandstone and siltstone (J-Kpn and K2cp) have low storage and groundwater yield in the hilly areas, but the alluvium such as sand, gravel, clay (Qii-iii and Qiv) located in the central part of the study area has high groundwater potential. The alluvium thickness is limited near the hills but increases toward the Nam Ngum River with a maximum thickness of 40 m, which is found in the Viengkham district north of the study area (ACIAR, 2016). The geology and the characteristic formations are summarized in Table 4.1, which was derived from the Geological and Mineral Map of Vientiane Plain, scale 1:200,000, Ministry of Energy and Mines, and Perttu et al. (2011).

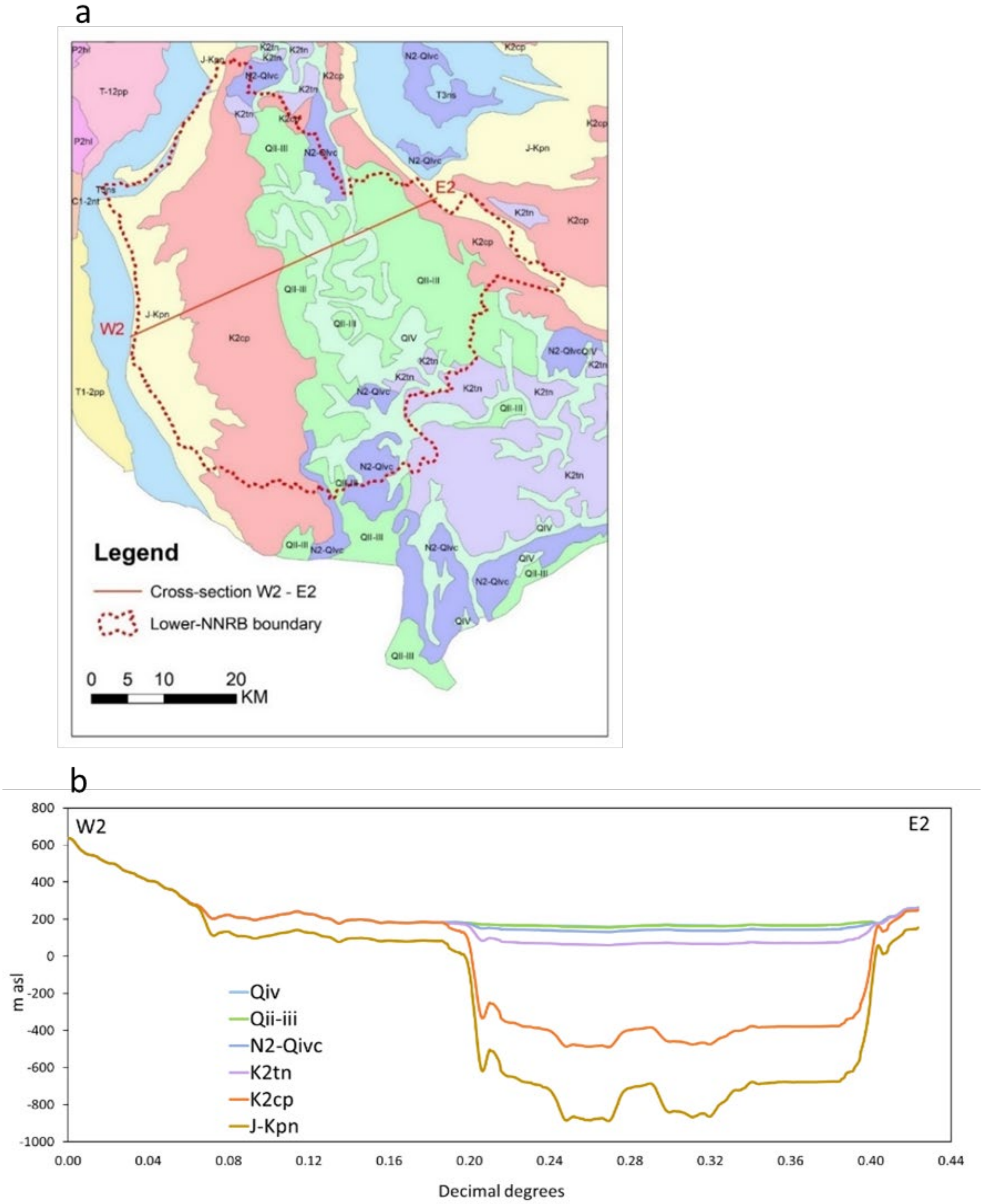

Figure 4.2. (a) Geological map of the lower-NNRB, modified from the Geological and Mineral Map of Vientiane Plain, scale 1:200,000; Ministry of Energy and Mines. (b) Geological cross-section W2-E2 of the lower-NNRB, and the Digital Elevation Model (DEM) (Heinimann et al., 2005).

Table 4.6. Stratigraphic table for the lower-NNRB

Era	Period	Epoch	Symbol	Thickness (m)	Characteristic geology	Formation
Cenozoic	Neogene-Quaternary		Qiv	<0.5	Sand, gravel, shingle, clay, and peat	
			Qii-iii	20-25	Sand and clay, shale, gravel, kaolinite	
			N2-Q1vc	<70	Gravel, shingle, sandy kaolinite, and laterite	Vientiane formation
Mesozoic	Cretaceous	Middle	K2tn	<550	Na-salt, claystone, siltstone, sandstone, potash salt, gypsum, and anhydrite	Thangon formation
			K2cp	<400	Sandstone, siltstone, brownish sandstone, white arkose, quartz-feldspar	Champa formation
	Jurassic Cretaceous		J-Kpn	<350	Sandstone bearing mica, white siltstone, brown sandstone, quartzite sandstone	Phouphanang formation

4.2.2.2 River stage

Time series of water levels are recorded at the three gauging stations (Pakanhoung, Veunkham and Thangon; Fig. 4.1c in the Lower-NNRB for the pre-dam and post-dam period. These stations are operated by the Lao Department of Hydrology and Meteorology. For the pre-dam period from 1963-1970, available water level data characterizes the relatively undeveloped river flow conditions with no reservoir hydropower dams in operation. The post-dam period started in 1971 when water infrastructure construction commenced. This study focuses on 2012 till 2017 for the post-dam period. Because the water levels at the Thangon station are only available until 2002, the water levels from the Veunkham station, which is located about 4 km upstream of Thangon, was used to estimate data for the missing period.

The average pre-dam 1963-1970 and post-dam 2012-2017 monthly water levels for the upstream and downstream stations are shown in Fig. 4.3. River stages for both the upstream and downstream stations in the Lower-NNRB during the pre-dam period were seasonally strongly varying following the seasonal precipitation regime. However, due to reservoir hydropower operations, river stages have increased in the dry season by 1.97 m for the upstream and 4.08 m for the downstream station for the driest month (April). In the rainy season, the river stages have decreased by 2.77 m for the upstream and 2.34 m for the downstream station for the wettest month of August. The monthly changes in river stages for the two periods were used in the groundwater flow model to test and evaluate the impact of river stages on the surface-groundwater exchange and groundwater balance.

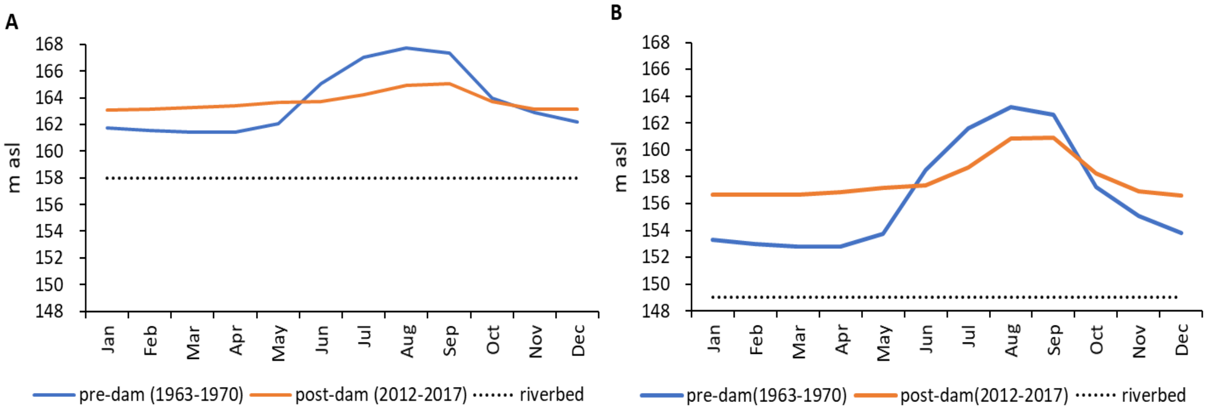

Figure 4.2. (a) Average pre-dam (1963-1970) and post-dam (2012-2017) monthly water levels at the upstream gauging station (Pakanhoung), and (b) at the downstream gauging station (Thangon)

4.2.2.3 Groundwater recharge

The recharge was defined unchanged for the pre- to post-dam period in order to evaluate the impact on the groundwater system of changing river stages. In this study, the average monthly recharge of 2012 was used as an input for the groundwater flow model for pre-dam and post-dam scenarios. The spatial distribution of monthly groundwater recharge in the Lower-NNRB was assessed by a WetSpass-M model and compared with results from the Water Table Fluctuation (WTF) method (Chapter 3). Monthly groundwater recharge is high in the rainy season and low in the dry season, with a variation of 1.4 to 87.2 mm/month, equivalent to 397 mm/year (17% of annual rainfall).

4.2.2.4 Aquifer properties

There is limited hydrogeological information available for the Lower-NNRB. However, some previous studies have indicated aquifer properties for different formations in the basin. The Thangon formation has a hydraulic conductivity (K) value between 10^{-14} to 10^{-8} m/s, the specific yield (S_y) is estimated as 10^{-7} and the specific storage (S_s) at 2 x 10^{-9} m^{-1}, which is considered as a formation with very low water storage (Srisuk, 1999). Champa (K2cp) and Phu Pha Nang (J-Kpn) formations that are mainly found in the western and eastern part of the basin have K values between 10^{-8} to 10^{-5} m/s, S_y is approximate 0.05 and S_s about 5 x 10^{-6} m^{-1}(Perttu et al., 2011). The Vientiane formation consists of coarse sediments (N2-Q1vc) mixed with younger deposits (Qii-iii and Qiv) and has K values ranging from 10^{-6} to 10^{-4} m/s, and S_y estimated from geophysics is ranging from 0.03 to 0.13 (Perttu et al., 2011), which is considered as a high potential aquifer (Takayanagi, 1993). Based on drilling logs of the groundwater development project in the Vientiane Province, conducted by JICA (1994), the Lower-NNRB is considered to be a shallow unconfined alluvium aquifer with a thickness of up to 40 m in the plain and decreasing towards the edge of the hills (Perttu et al., 2011; ACIAR, 2016).

For this study, aquifer properties in the Vientiane formation were evaluated by a pumping test conducted in March 2020. The pumping test was in the centre of the Lower-NNRB and carried out to determine the hydraulic characteristics of aquifers. The well test was implemented in the dry season with no influence of precipitation, surface water, or river nearby. It was a single-well test for both drawdown and recovery in the well. The groundwater was pumped at a constant discharge rate of 5.4 l/s for 2 hours and 30 minutes until the drawdown level becomes stable. The hydraulic properties of the aquifer were analysed from the drawdown-recovery record, well structure, and geological profile of the well by using a leaky confined aquifer solution of Neuman and Witherspoon (1969) and simulating in the AQTESOLV program. The well productivity is relatively high as the total drawdown was only about 1 m for the entire pumping period of two and half hours. The hydraulic conductivity was estimated to vary between 1.5 x 10^{-4} to 1.2 x 10^{-3} m/s.

4.3 Methods

4.3.1 Conceptual model

The conceptual model was defined based on the geological setting of the area and available field data. Since the Jurassic (J-Kpn) and Cretaceous (K2nt and K2cp) formations consist of mainly sandstone and siltstone with relatively low hydraulic conductivity and large thicknesses (Fig. 4.2b), they are considered low-water yielding formations (Srisuk, 1999). For instance, drilled wells in the Phousan village, which is located at the western margin of the basin, exhibit insufficient yield for water supply with pumping rates as low as 0.5 l/s (Vinckevleugel, 2015; ACIAR, 2016). As the sandstones in the hilly areas have low storage capacity and yield, these formations can be taken as an impervious lower boundary for the purpose of the groundwater flow model.

For this study, an interpretive conceptual model was defined to have dimensions of 20 by 28 km, which covers major parts of the Vientiane formation (N2-Qivc) and the most recent alluvial deposits (Qii-iii and Qiv) (Fig. 4.4). The model was divided into two lithological layers per hydrogeologic unit to make the model numerically robust and capture the interactions between shallow and deeper aquifers and rivers. Layer 1 has a thickness of 25 m and layer 2 of 20 m. A total of six major tributaries of the main river were selected to investigate the surface water-groundwater interaction. Each tributary, the main river, and each aquifer layer were assigned a zone number.

The interpretive model is intended to test the effect of the river stages on the groundwater level and the water balance. To test this, MODFLOW 2005 was used to simulate groundwater flow in the study area (Niswonger et al., 2011). ModelMuse, a graphical user interface for MODFLOW, was used to create input data for the model (Winston, 2009). The model grid, time, and boundary conditions are summarized in Table 4.2.

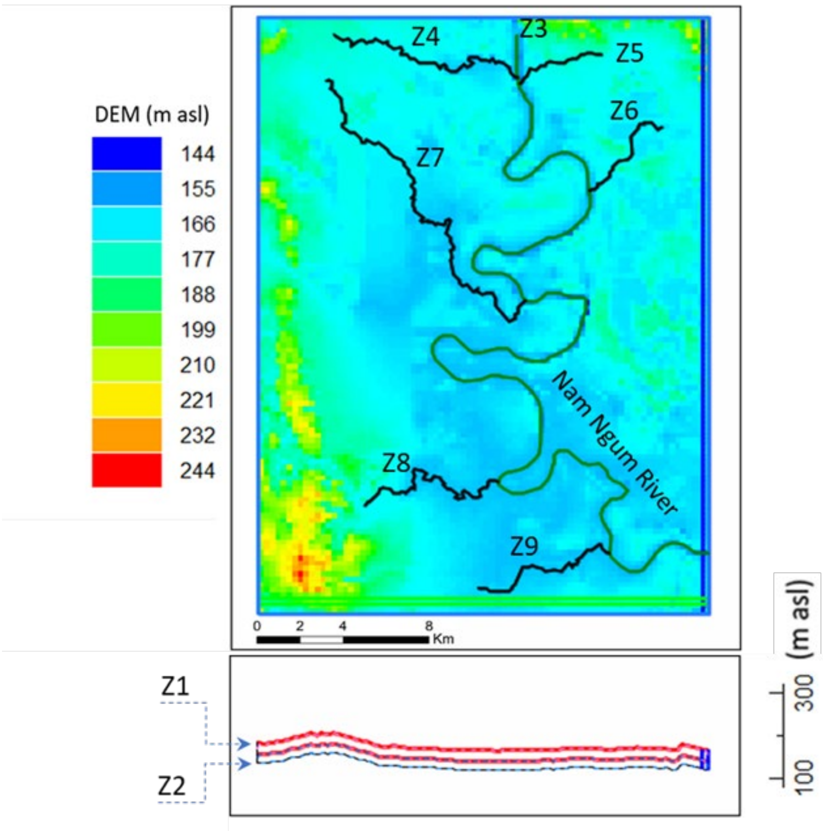

Figure 4.4. Top: Digital elevation model top boundary, the Nam Ngum River and its tributaries with corresponding zone numbers (Z3 for the Nam Ngum River, Z4 to Z9 are for tributaries numbered from the upstream to downstream respectively); below: two-layer cross-sectional front view with zone numbers (Z1 for layer one, and Z2 for layer two).

Table 4.7. Summary of groundwater flow model grid, time, and boundary conditions

Model configuration	**Model packages**	**Details**
Model grid	Grid cell size	250 x 250 m
	Number of rows	112
	Number of columns	80
	Number of layers	2
Model time	Simulation type	Transient
	Stress period	Monthly
	Timestep	Daily
	Length of simulation	1-year (9 years of warm-up)
Package and Boundary conditions	Flow package	Upstream weighting package (UPW)
	Specified flux	Recharge package (RCH)
	Head dependent flux	River package (RIV)
	Post-processors	ZONEBUDGET package
	Solver	Newton solver (NWT)

4.3.2 Model configuration and simulation

For both the pre- and post-dam conditions, a transient MODFLOW 2005 model with RIVER package assigned water levels for the Nam Ngum River was set up. Monthly observed river stages and riverbed elevations at the upstream and downstream stations for the pre-dam (1963-1970) and post-dam (2012-2017) conditions were assigned in ModelMuse. They were linearly interpolated to assign values to the unknown river stages and riverbed along the mainstream. Next, six major tributaries were connected to the mainstream with corresponding river stages and riverbed elevations for each tributary. At the downstream end of a tributary, the river stage and riverbed elevation were extracted from the cell at the confluence with the Nam Ngum River. Monthly average recharge was defined based WetSpass-M simulation results for 2012 (Chapter 3). To reduce the impacts of the initial head conditions on the simulated results, nine years of warm-up, with the same conditions as the final 10^{th} year, were defined. The groundwater flow model was run with a daily time step, and results for the 10^{th} year were selected to evaluate the groundwater flows, levels, and budget.

The monthly groundwater recharge and other parameters were kept unchanged for the pre- and post-dam scenarios. The river and groundwater exchanges were then compared for the pre- and post-dam conditions.

The Zonebudget package was used for the pre- and post-dam models to assess of each subregion the water budget using the results from MODFLOW. Each subregion was designated by a zone number, i.e., zone 1 and zone 2 for layer 1 and 2, respectively; zone 3 for the main river, and zone 4 to zone 9 for the six tributaries (numbered from up- to downstream, respectively). The water budget was estimated for each zone and the entire composite zone, consisting of the whole modelling area.

The model also simulated groundwater levels for the pre- and post-dam periods. The results were exported to ArcGIS in raster format for visualization and further analysis. The water table difference between the wettest (August) and driest (March) months was compared for both the pre- and post-dam periods. Also, the difference in groundwater level between the pre- and post-dam periods for August and March were investigated. The spatial distribution of water level differences was visualized as classified rasters identifying areas with more than ± 1 m differences.

Specific river leakage to the system is defined as the surface water-groundwater interaction (m^2/s) per unit length of the river. It is estimated as the cumulative simulated volumetric interaction flow divided by the length of the river. The specific river leakage reveals the gaining and losing river conditions with respect to the groundwater system for both the pre- and post-dam period. The monthly river gaining (G) and losing (L) specific discharges were further examined for their relationship by simple statistical analysis such as (i) the ratio of gaining and losing specific discharge (Ratio G/L) (Eq. 4.1); (ii) percentage of seasonality index for gaining and losing conditions (SI G and SI L) (Eq. 4.2a and 4.2b); and (iii) the ratio between the number of gaining versus losing months (Mnth G/Mnth L) (Eq. 4.3).

$$\text{Ratio G/L} = \frac{\text{Avg G}}{\text{Avg L}} \qquad \text{(Eq. 4.1)}$$

$$\text{SI G} = 100 * \left(\max\left(\frac{\text{Gj}}{\text{Avg G}}\right) - \min\left(\frac{\text{Gj}}{\text{Avg G}}\right)\right) \qquad \text{(Eq. 4.2a)}$$

$$\text{SI L} = 100 * \left(\max\left(\frac{\text{Lj}}{\text{Avg L}}\right) - \min\left(\frac{\text{Lj}}{\text{Avg L}}\right)\right) \qquad \text{(Eq.4.2b)}$$

$$\text{Mnth G/Mnth L} = \frac{\sum_{j}^{n} \text{Months of G}}{\sum_{j}^{n} \text{Months of L}} \qquad \text{(Eq. 4.3)}$$

Where Avg G is the average gaining specific discharge for a river zone; Avg L is the average losing specific discharge for a river zone; SI G and SI L (%) are respectively the seasonality index for the gaining and losing specific discharges; Gj and Lj are respectively the gaining and losing specific discharges for month j, with n=12 months; $\sum_{j}^{n}$ Months of G is the total number of months with gaining conditions; $\sum_{j}^{n}$ Months of L is the total number of months with losing conditions.

The groundwater balance of layer 1 (Z1) for the pre- and post-dam period was assessed monthly (Eq. 4.4a and 4.4b). A conceptual diagram of water balance assessment with variables description is shown in Fig. 4.5, which defines the total water flux entering (Z1_In, Eq. 4.4a) and the total water flux leaving (Z1_Out, Eq. 4.4b) the upper aquifer (Z1).

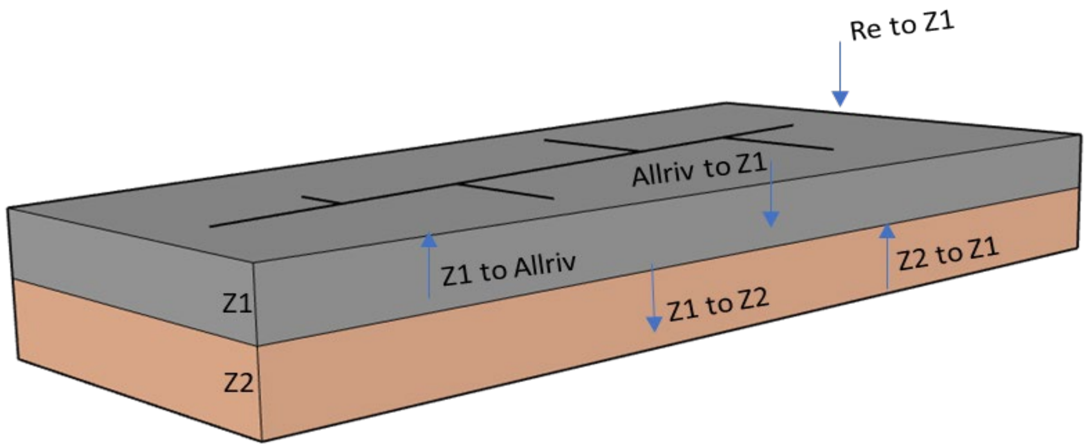

Figure 4.5. A conceptual diagram of the groundwater balance calculation for layer 1 (Z1). Black solid lines represent the river and tributaries; the grey and dark yellow layer are respectively layer1 and 2; the arrows indicate the exchanges.

Z1_In = (Allriv to Z1) + (Re to Z1) + (Z2 to Z1) (Eq. 4.4a)

Z1_Out = (Z1 to Allriv) + (Z1 to Z2) (Eq. 4.4b)

Where Allriv to Z1 is water leakage from all tributaries and river to Z1 (the upper aquifer); Re to Z1 is groundwater recharge to Z1; Z1 to Allriv is groundwater discharge to the river (gaining), Allriv to Z1 is losing river water to the top aquifer Z1; Z1 to Z2 is the water flux from Z1 to Z2, and vice versa.

4.4 Results

4.4.1 Status and change in river and groundwater interactions

The impact of altering river stages was evaluated with the MODFLOW RIVER package for the pre- and post-dam periods. Figure 4.6 shows the monthly specific river discharge in and out of the groundwater system, which refers to losing and gaining conditions for the two periods. The graphs show how the status and interaction between the surface river and groundwater system have changed from the pre- (left figures) to the post-dam (right figures) period for the main Nam Ngum River (Z3) and the six tributaries (Z4 to Z9). The graphs also indicate seasonality, i.e., monthly variations, of the losing (solid blue line) and gaining (solid orange line) conditions for the two different periods. The graph inset indices provide summarizing characteristic values for comparison for the period of one year of the pre-dam versus the post-dam conditions. The ratio of gaining month over losing month (Mnth G/Mnth L) with the value of "infinity" indicates that the gaining rate is for every month greater than the losing rate in the post-dam period, which occurs in the mainstream Z3, and the tributaries Z6, Z7, Z8, and Z9. In opposite, the tributary Z5 shows that losing conditions prevail every month in the post-dam period. Hence, its index Mnth G/Mnth L is 0. For the tributary, Z4 Mnth G/Mnth L = 2 for the post-dam period, indicating that net gaining conditions occur twice as much (8 months) compared to net losing conditions (4 months).

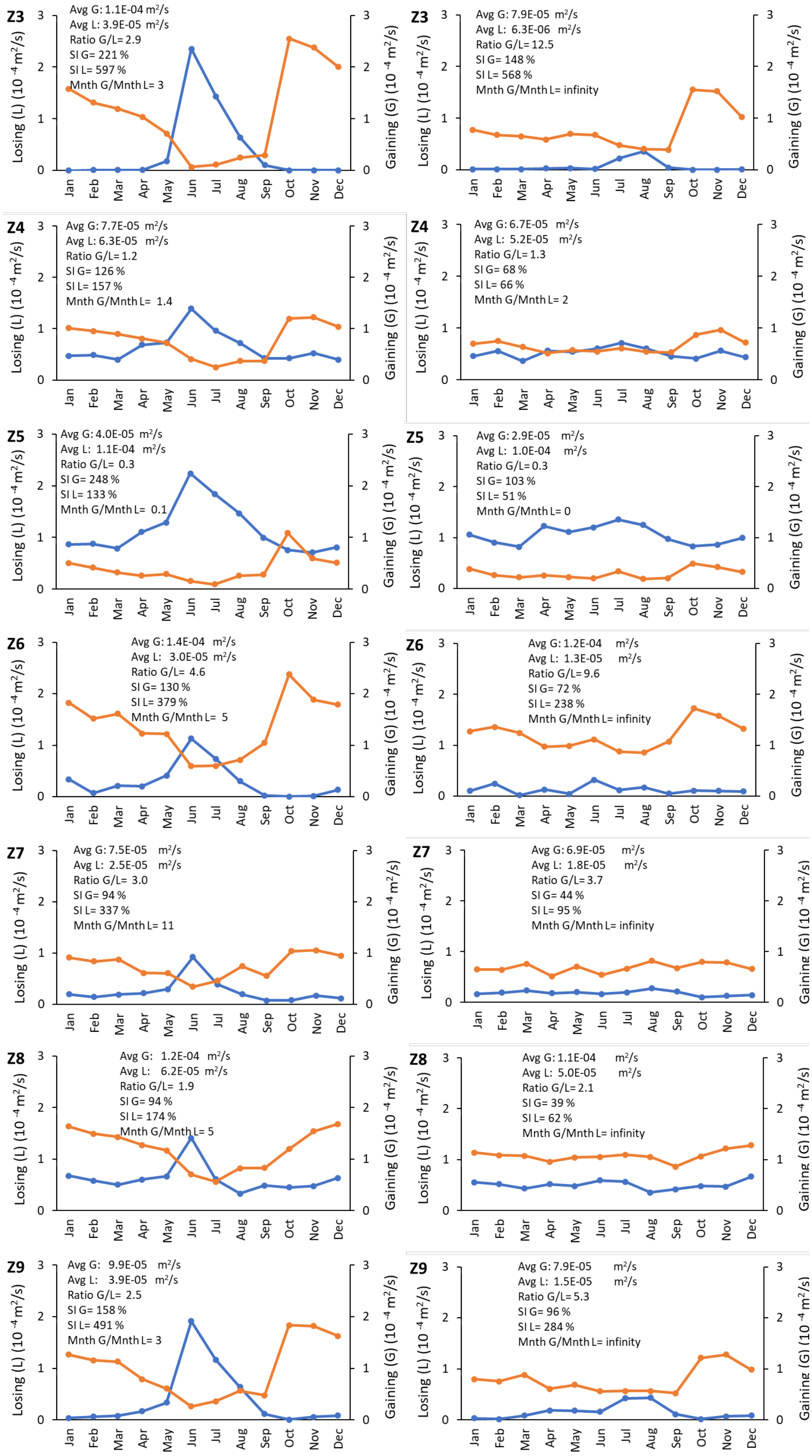

Figure 4.6. Specific river leakage during the pre-dam (left graphs) and the post-dam (right graphs) periods. The solid blue line shows the losing river conditions, while the solid orange line refers to gaining river conditions. Avg G and Avg L are the averages of the gaining and losing conditions; Ratio G/L is the ratio of the total gained over the total lost interaction flow; SI G and SI L are seasonality indexes for gaining and losing; Mnth G/Mnth L is the ratio of the months with gaining vs losing conditions.

4.4.2 *Zone budget*

The water budget was calculated from the groundwater flow model for each subregion and the entire river network. Table 4.3 shows the annual budget for the Nam Ngum River (NNR) and the entire river networks in million cubic meters per year (10^6 m^3/yr) for the pre-and post-dam period. For the Nam Ngum River (zone 3), the annual losing component reduced from the pre- to post-dam from 80 to 13 x 10^6 m^3/yr, equivalent to an 84% reduction. Similarly, the annual gaining also declined by 30% from the pre- to post-dam period. Moreover, the entire river network also shows a similar pattern to the NNR budget, with a 53% reduction in the losing budget and a 23% reduction in the gaining water budget.

Table 4.8. Water budget (losing – L and gaining – G) for the Nam Ngum River and the entire river network for the pre-and post-dam period

		L (10^6 m^3/yr)	G (10^6 m^3/yr)
Zone 3 (NNR)	Pre-dam	80	227
	Post-dam	13	159
Reduction from pre- to post-dam		84%	30%
NNR+all tributaries	Pre-dam	170	394
	Post-dam	80	305
Reduction from pre- to post-dam		53%	23%

4.4.3 *Groundwater tables for the pre-and post-dam period*

The differences in groundwater tables from the pre- to post-dam period were investigated as it indicates the magnitude of the spatial distribution of the impact of the changed river water level regimes. Figure 4.7 shows the difference between the highest water table month (August) and the lowest water table month (March), for both the pre-dam and the post-dam period.

The differences in groundwater tables for the same month but the different periods (pre- vs post-dam) were also compared, i.e., August pre-dam minus August post-dam and March pre-dam minus March post-dam (Fig. 4.8). The average water table difference in March for the pre- and post-dam period (Fig. 4.8b) is almost 2-fold greater than in August (Fig. 4.8a), with average water table differences of -0.83 m 0.45 m respectively. The negative value refers to a higher water table in March during the post-dam period, while the positive value indicates a lower water table in the rainy season of August for the post-dam condition.

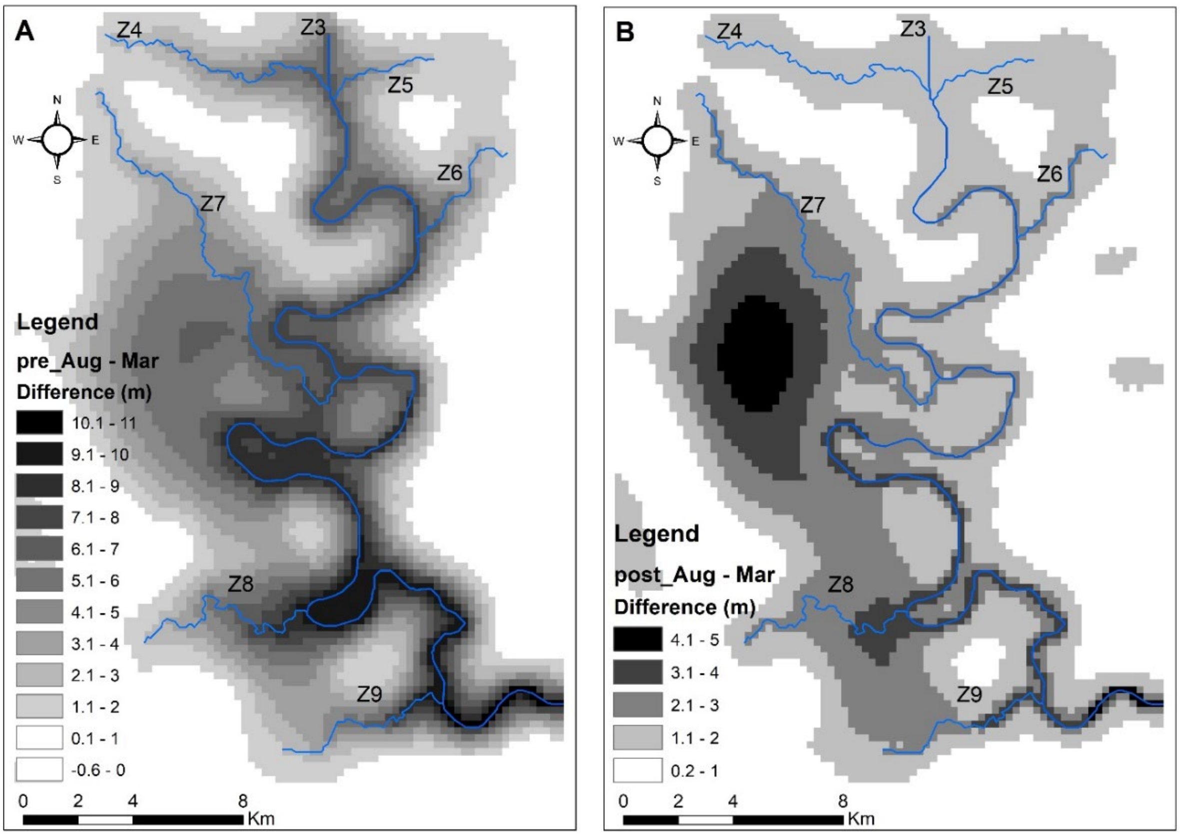

Figure 4.7. (a) Differences in groundwater table between August and March for the pre-dam and (b) for the post-dam period. The differences that have values greater than ± 1 m are in grey and black, while the classes smaller than ± 1 m are the white area.

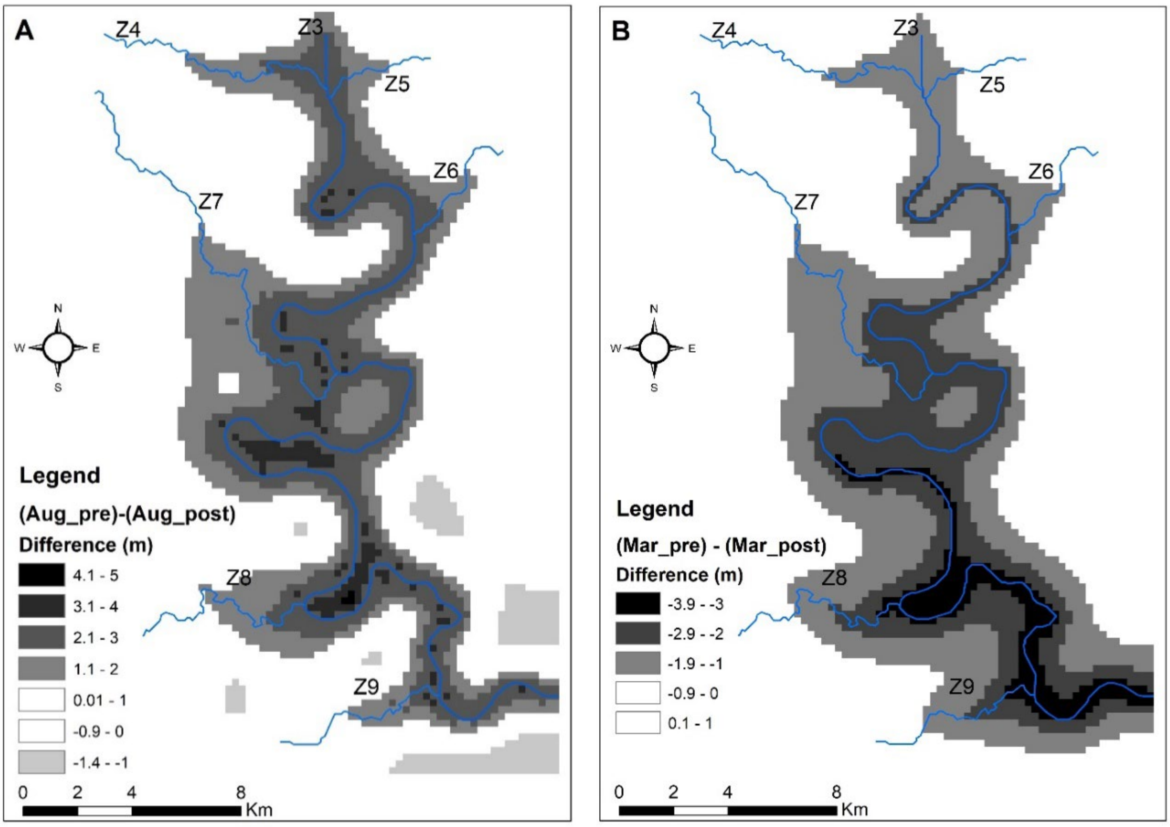

Figure 4.8. (a) Groundwater tables differences in the same month for different periods, August water tables in the pre-dam versus August water table in the post-dam period; and (b) March versus March water tables for the pre- and post-dam period. The differences that have values greater than ± 1 m are in grey and black areas, while the values that are smaller than ± 1 m are in the white area.

4.4.4 Water balance

The groundwater balance of layer 1, which is the most accessible aquifer and with the highest potential for development, was investigated for the two periods. The groundwater flows in and out of the aquifer for the pre- and post-dam conditions were assessed using Eq. 4.4a and 4.4b. Figure 4.9 shows the results of water flow in and out of the system on a monthly basis for the two different periods. The amount of water entering the system (In Z1) for the pre- and post-dam is displayed with a black dashed line and solid line, respectively. It is relatively similar for the dry season, particularly from January to May and September to December. However, it declines in the rainy season for the post-dam condition, especially from June to August. On the other hand, comparing the amount of water leaving the aquifer (Out Z1) for the two different periods shows an inverse trend to the incoming water; the water discharging from Z1 for the post-dam, highlighted in the red solid line, increases for the rainy season and decreases for the dry season for the change from the pre- to post-dam period.

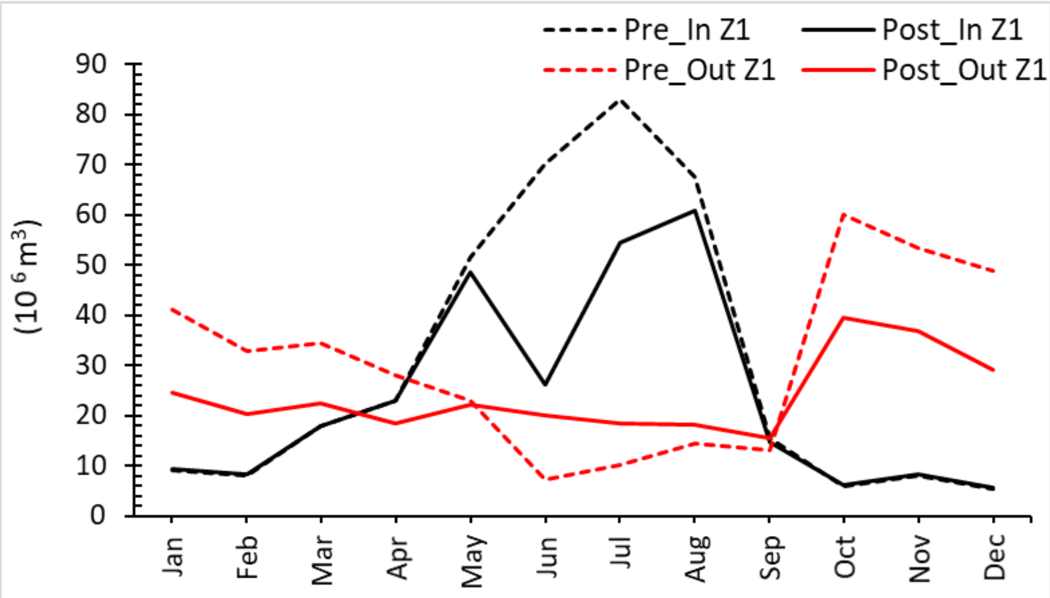

Figure 4.9. Comparison of groundwater budget for layer 1 (Z1) for the water entering the system in the pre-dam (black dashed line) and post-dam (black solid line), and the water leaving the system in the pre-dam (red dashed line) and post-dam period (red solid line).

4.5 Discussion

4.5.1 River and groundwater interactions

In the pre-dam period, most tributaries (Z4, Z6, Z7, Z8, Z9) were mainly gaining in the dry season months and at the end of the rainy season, particularly from January-May and August-December and losing in the rainy season, especially from June-July (Fig. 4.6). However, Z5 showed a different pattern than the other tributaries. It was losing most of the year (January to September and November to December) and showed minimal gaining conditions in October. The different pattern for the Z5 tributary is most likely due to topographical differences, more than half of the length of the Z5 tributary (upstream) is located on a relatively high-altitude area, ranging from 170-180 m asl (Fig 4.10). This results in higher surface runoff and lesser interaction between river and aquifer systems (Cai et al., 2016; Ward et al., 2019).

Most tributaries located in the downstream part of the basin (Z6, Z7, Z8, Z9) and the NNR (Z3) have become year-round gaining in the post-dam period. However, the Z5 tributary has become losing year-round, while the Z4 tributary remained the same pattern as it had in the pre-dam situation, but its fluctuation has gone down significantly. This can be explained by the fact that the pre-dam to post-dam change in river stages in the upstream section of the NNR is much smaller than downstream. This results in small changes for the surface water-groundwater interaction for Z4. Overall, the post-dam conditions show that there has been a shift to strongly gaining conditions and a significant reduction in river and groundwater exchange, which confirm results from studies conducted by Ferencz et al. (2019) and Zhang et al. (2020).

An interesting observation is that the post-dam water table fluctuations for the NNR and all tributaries for the entire model area have decreased, while in the pre-dam period, they were highly seasonal and dependant on rainfall dominance. The seasonality index (SI) illustrates this well, with higher values in the pre-dam period than in the post-dam period (Fig. 4.6).

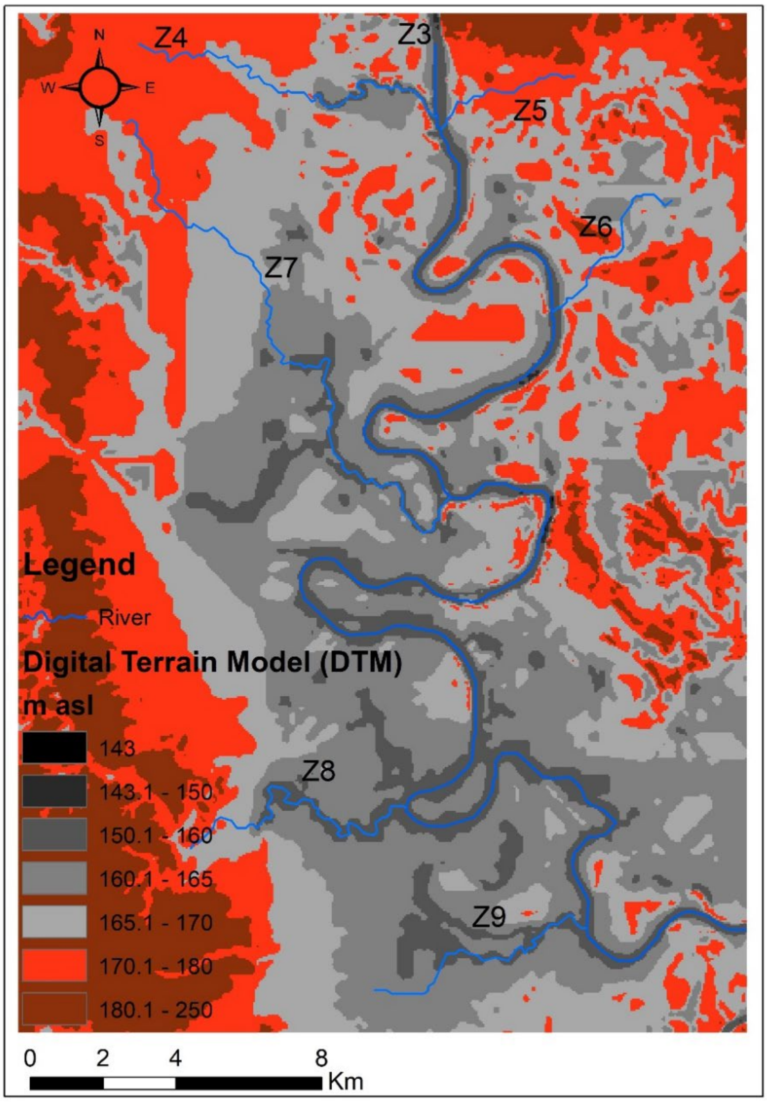

Figure 4.10. Classification of digital terrain model (DTM) and river networks with the zone numbers (Z3 to Z9)

4.5.2 Water budget

The water budget for the entire river network has been reduced from the pre- to post-dam period. The annual losing and gaining volume declined by 53% and 23%, respectively. This means that the groundwater system gains less recharge from the rivers in the post-dam period compared to the pre-dam period. In the post-dam period, the river has become gaining year-round with minor fluctuations. In contrast, under the pre-dam conditions, the rivers intensely interacted with the aquifer system, i.e., the river stages were relatively high in the rainy season, which allowed more recharge from the rivers into the groundwater system (Woessner, 2020). While in the dry season, river water levels were so low that they significantly drained the aquifers. Hence, the river has become more disconnected from the aquifer in the post-dam period, with much smaller exchanges between the river and the aquifer.

4.5.3 Groundwater table

The differences between groundwater levels in August and March during the pre-dam period is approximately twice as large as in the post-dam period. The differences vary from 0 to 10 m for the pre-dam period (Fig. 4.7a), while the variation in the post-dam period ranges from 0 to 5 m (Fig. 4.7b). The more significant differences occur along the main river. The differences become minimal toward the east and west of the Lower-NNRB boundary. Although the differences between March and August of the two periods have a significant difference, the spatially distributed areas with differences larger or smaller than 1 m are very similar. As the spatially distributed areas are similar for the pre-and post-dam period, and as the river stages have increased in the dry season for the post-dam period, the hydraulic head gradients in the post-dam period are relatively lower than during the pre-dam period. This reduces the groundwater-surface water interaction due to dam-regulated reduced river stage fluctuations (Francis et al., 2010).

Comparing the groundwater table at the same month for different periods shows a significant spatially distributed area affected (Fig. 4.8). The comparison sheds light on the magnitude of the groundwater table change in March and August for the pre- to post-dam period. In the post-dam period, the wet-season groundwater tables are lower, while the dry-season water tables are higher than in the pre-dam period. The groundwater system follows the reduced river water level regime as a consequence of the dam regulation. The spatially distributed water table difference in March exhibits a larger area than in August, especially downstream. This might be explained by the fact that the average water table difference in March for the entire model area is approximately twice that of August, with an absolute value of 0.83 m and 0.45 m, respectively. In March of the post-dam period, the higher river stage has caused the water table difference to be more widely distributed in the lower downstream area (Fig. 4.8b) than the August difference. This illustrates the estimated extension of dams influencing and elevating groundwater tables in riparian and downstream areas (Hucks Sawyer et al., 2009).

4.5.4 Groundwater balance

The monthly amount of water entering the groundwater system for the post-dam condition significantly decreases in the rainy season. The noticeable decrease in June (Fig. 4.9) is most likely due to the significant low recharge in that particular month of 2012 compared to 2013 and 2014 (see Chapter 2 for more details of recharge analysis). Overall, the total annual water entering the system in the pre-dam period is higher (365 x 10^6 m^3/yr) than in the post-dam period (284 x 10^6 m^3/yr), equivalent to a 22% reduction in the post-dam period.

The monthly amount of water leaving the system in the pre-dam period is also higher than in the post-dam, particularly in the dry season. However, it decreases in the rainy season. Overall, the annual water leaving the system in the pre-dam period is larger (367 x 10^6 m^3/yr) than in the post-dam period (285 x 10^6 m^3/yr). From the water balance analysis can be inferred that in the post-dam period, total water volume entering and leaving the system is approximately 22% lower compared to the pre-dam period, showing a great impact of hydropower dam induced river stage modification on the groundwater budget. As hydropower reservoirs elevate river stages in the dry season, the river has become gaining year-round and reduced interaction with the aquifer, resulting in a budget decline in the post-dam conditions. Apart from power grid production, the reservoir hydropower dams traditionally generate additional benefits in helping to mitigate flash flooding and drought and to sustain surface irrigation downstream areas (Westbrook et al., 2006; Bartlett et al., 2012; Lacombe et al., 2014). Little or no attention has been paid to groundwater management in the downstream areas. This study indicates that the effect on groundwater resources may be important.

4.5.5 Recommendations

Apart from the positive sides of regulating large surface rivers for electricity production, flood and drought prevention, and surface irrigation downstream with a total of 26 irrigation schemes in the study developed between 1996 and 2005, this study shows groundwater budget implications due to surface waters being dammed upstream. Regulating large rivers by reservoir hydropower dams will directly affect hydrological flow regimes and river stages downstream. This chapter discusses how surface water could affect the groundwater system due to the changes in river stages associated with hydropower development. The results demonstrated that key decision-making to sustain water resources management and development without disturbing shallow groundwater systems in the lower basin is required. To evaluate the long-term changes in groundwater resource conditions and sustain groundwater management in this basin, groundwater level monitoring networks should be established across the Lower-NNRB.

4.6 Conclusions

This study has examined the geological setting, river and groundwater exchange, groundwater levels, and water balance for pre- to post-dam conditions across the Lower-NNRB. The top two stratigraphic units Qii-iv and N2-Q1vc were analysed, particularly the top layer (Z1), which interacts most strongly with the surface water system. The Nam Ngum River and its tributaries, which are located downstream (Z6 to Z9), were losing in the rainy season and gaining in the dry season in the pre-dam period. However, they have become gaining year-round in the post-dam period. The tributaries (Z4 and Z5), which are situated in the upstream part of the Lower-NNRB, exhibit slight changes from the pre-dam period to the post-dam period, but their fluctuations have significantly reduced in the post-dam period. As the surface water and groundwater interaction has diminished considerably, the groundwater budget has declined in the post-dam period compared to the pre-dam condition, i.e., annual river losing and gaining have reduced by 53% and 23%, respectively. The groundwater table difference between rainy and dry seasons is approximately two times higher in the pre-dam period than in the post-dam period. But their spatially distributed water table differences, which are defined as greater than ±1 m, are not significantly different. However, the spatially distributed water table differences in the dry season (March) are relatively larger than in the rainy season (August), showing an impact of river stages caused by reservoir operations on groundwater tables in riparian and downstream areas in the dry season during the post-dam period.

Regulated large rivers might benefit irrigation schemes in downstream areas and provide flood and droughts mitigation, but these interventions also modify the groundwater budget. In the lower-NNRB, the surface water-groundwater exchange has been reduced, making the river more disconnected from the groundwater. This phenomenon potentially can impact vulnerable ecosystem productivity, reduce the hyporheic zone's self-cleaning capacity, and modify the ecological functioning of the lower basin.

Chapter 5. Thesis conclusions

5.1 Summary of findings

Altered river flow regimes caused by hydropower dams and irrigation schemes can affect the state of connection between surface water and groundwater, resulting in, for the case of the Lower-NNRB, gaining rivers year-round, increasing dry season and annual water yield in the post-dam period. By examining observed differential river flow from the pre- to post-dam, insights are provided into the importance and dynamics of change in groundwater-surface water interactions as it alters the hydraulic gradient between the river and aquifer, and storage conditions. The phenomenon of changes during the post-dam period shows clearly that human activities outweigh climatic drivers, as precipitation is comparable for the two periods. Irrigation practices in the post-dam period also have caused soil moisture and actual evapotranspiration to increase compared to the pre-dam period.

The groundwater recharge assessment for the two scenarios: with and without irrigation, shed light on the magnitude of the impacts on hydrological water balance components caused by irrigation. Based on current use, irrigation water appears to have a minimal influence on the recharge for the entire basin compared to within the localised irrigated command area. The additional proportion of groundwater recharge that comes from irrigation water is relatively small compared to natural recharge by precipitation, and most recharge events occur during the wet season months. The spatially distributed groundwater recharge on a yearly basis calculated by the WetSpass-M is comparable and consistent with the recharge derived by the groundwater table fluctuation method. Similarly, the observed annual differential flow between the two evaluated gauging stations shows an excellent agreement to the calculated volume of recharge and surface runoff computed from the model, suggesting that the WetSpass-M modelling generates reasonable estimates for the groundwater recharge in the Lower-NNRB.

Although the spatial and temporal scale of groundwater flow is different from surface water, this study shows that the change in river stage significantly impacts the adjacent aquifer systems as a consequence of regulated rivers. The study also demonstrates that altered river flow regimes and river stages can significantly impact river-groundwater exchange, water tables, and water balances in downstream basins. These findings are important for the effective development and management of surface water in the basin without disrupting the hydraulic gradients and flow directions within the aquifer that may lead to lowering of water tables (and therefore increased cost due to deeper pumps) or raised water tables (resulting in waterlogged conditions). The consequence of such changes would also likely deteriorate vulnerable ecosystem productivity and modify ecological habitats in the lower basin. This study's findings would apply to other downstream areas in the Mekong Basin, where rivers are regulated by upstream infrastructure. By analysing historical river flow data, anthropogenic indicators (i.e., dams, irrigation, soil moisture, land cover, total water storage, groundwater levels) and climatic data (i.e., precipitation, actual evapotranspiration), this thesis demonstrated that human-made water infrastructure has a very large influence on the river flow and connected groundwater regimes.

Combining all the results, this research sheds light on the magnitude of the impacts of anthropogenic and natural climatic drivers on river flow regimes and connected groundwater systems. It provides key evidence and useful messages from both scientific and management perspectives. From a scientific point of view, this study illustrates the importance of river-groundwater exchange dynamics before and after installed hydropower dams on groundwater systems in terms of interactions, stages, water balance, and groundwater table fluctuations. The hydrological and meteorological data are limited in this study area. However, a simple method of differential river flow is highly applicable to use, allowing the capture of temporal river losing and gaining conditions and water yield varying from the pre-dam to post-dam period.

The results are in excellent agreement with observed river-groundwater levels and the global remote sensing-based data.

Moreover, it is reasonable to compare the annual differential river flow with the hydrological water balance components (i.e., recharge plus surface runoff) derived by the WetSpass-M model. From the management perspective, this research reflects the consequences of hydropower dam development and irrigation schemes on groundwater systems from the pristine river to the dammed river condition. The research findings are important evidence and provide food for thought for policymakers and surface water and groundwater management in the NNRB.

5.2 Challenges and future work

This study makes use of historical river flow observation data from upstream and downstream gauging stations. Unfortunately, the rating curves for those gauging stations were unavailable for analysis and therefore the uncertainty associated with river flow data could not be determined. Volumetric daily river flow time series are derived via river stage-discharge rating curves, which control the uncertainty of the flow data. This is especially true when the river bed becomes mobile during flood events, potentially altering the base levels between observations. The uncertainty in data from flow gauging stations also affects the magnitude of the absolute volume of water yield assessment determined from the differential flow calculation between the up and downstream gauging stations. Hence, there is a level of unquantified uncertainty in the differential flow calculations. Despite these shortcomings, the consistency of the results with respect to our understanding of the changes in the basin climatic and hydrological conditions and the assessed trends in different hydrological parameters provides confidence in the direction of the differential flow changes that were observed.

Based on the major findings of this research, river flow analysis at a daily time interval would provide a rigorous assessment of river stage fluctuations due to hydropower dam operations (i.e., peak and off-peak electric generation depending on the power demand) and its effects on groundwater-surface water interaction. It is hypothesised that frequent river fluctuations would force river water into and out of the riverbanks. However, the extent of the river water penetration into the adjacent aquifers and its impacts on the hyporheic exchange by dam operations remains unclear. Such research could be assessed by installing piezometers along a transect perpendicular to the Nam Ngum River downstream of the Nam Ngum 1 hydropower dam. Monitoring of temperature variations recorded from piezometers would also capture the change to the groundwater flow direction relative to the river stage. Further research opportunities investigating river flow and groundwater in Laos would benefit from assessing the impacts on water quality (groundwater and surface water) in response to changed surface water-groundwater interaction and likely increases in irrigation return flows.

It would also be important to investigate further the water quality implications of the intensive irrigation return flow, which is likely to localise water circulation and influence shallow groundwater quality, particularly major irons in groundwater. (Brindha et al., 2017) identified in the Vientiane Plain concentration of lead and iron above the permissible limits, while other parameters such as arsenic, copper, zinc, mercury, and uranium were within the safe limits. Hence, it is important to investigate further anthropogenic sources such as irrigation and the use of fertilizers in agriculture that potentially impact on geochemical processes in groundwater in this area.

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