AN IMPACT ASSESSMENT OF HUMAN INTERVENTIONS ON THE HYDROLOGICAL REGIME OF THE BLACK RIVER BASIN IN VIETNAM

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Cover image: Hoa Binh dam and water storage reservoir
on the Black River in Vietnam [26]

Preface

My name is Walter Winkel and I am a final year bachelor student at the University of Twente, studying Civil Engineering. I have performed my thesis at Vietnam National University of Science (VNU) in Hanoi.

I am very grateful for the opportunity to work on a project about the transboundary Black River basin in Vietnam and China. The topic of the thesis is the assessment of human interventions on the hydrological regime of the Black River by means of a hydrological model. My interests in hydrology and Civil Engineering in developing countries have driven me to choose this research topic.

The target audience of this thesis are fellow students and researchers in the hydrology field. Some background knowledge is required to fully understand the findings of this thesis.

I would like to thank my internal supervisor Martijn Booij and external supervisor Nguyen Tien Giang for their support and assistances during the research. Their contributions were very valuable to this thesis.

Secondly, I would like to thank to the staffs of Center for Environmental Fluid Dynamics – VNU University of Science, Hanoi, Vietnam, for their support and data providing. Their assistances were very important during my research study in Vietnam.

Hopefully, readers will enjoy the contents of this study and may be able to use it for future research too.

Summary

Measurements of water levels and streamflow show reduced flow in the Vietnamese part of the Black River basin from 2008 onwards. It is expected that human interventions in the Chinese part of the Black River basin play a large role in this. This study aims to assess impacts of human interventions on the hydrological regime of the Black River qualitatively by a water balance and quantitatively by using a hydrological model, the VIC-model.

Two observed streamflow timeseries were derived by using rating curves and measurement data and validated by comparison to other independent station data. A global and regional gridded precipitation data product were acquired and compared to measurement data. It was concluded that the regional data product is more accurate than the global data product, also after correction of the global data product. A water balance was created to assess impacts of climate variability on streamflow and literature research was used to identify impacts of land use and land cover changes and water storage reservoirs on streamflow. The VIC-model was used to quantify and separate the impacts of human interventions on streamflow and calibrated and validated for the Black River basin by means of a split-sample test and a proxy-basin test.

Streamflow has spontaneously reduced in 2008 in the Vietnamese part of the Black River basin by 21%. The water balance showed that a precipitation decrease could account for up to 50% of this discharge reduction. The VIC-model showed that water storage reservoirs account for 53% of this discharge decrease. Between 1992 and 2012, 5% of the basin area was subject to reforestation and the urban areas tripled during this period. The streamflow has been reduced by 3% due to changes in land use and land cover between 1992 and 2019. Between 2003 and 2018, 15 dams were constructed in the Chinese part of the Black River basin. The average streamflow has been reduced by 14% when comparing the period 1980-2007 with the period 2008-2018 due to the impacts of reservoirs. The wet season is responsible for 88% and the dry season for 12% of this average streamflow reduction. This suggests that the water storage reservoirs are mainly being filled during the wet season.

The discussion treats the potential, limitations and generalization of this project. The largest limitation of this project is the reliability on and availability of data. Much input data is uncertain or estimated, thereby increasing the degree of output uncertainty. A second limitation is the VIC-model calibration and validation part. The observed data series that are used for these processes have a certain degree of uncertainty in them as well, thereby weakening the calibration and validation of the VIC-model. Lastly, the method that is used for human intervention impact assessment. The methods that are used to assess impacts of Land Use and Land Cover changes and water storage reservoirs might not cover all aspects of these human interventions, i.e. seepage below dams is not considered.

The main conclusion from this thesis is that water storage reservoirs have a large impact on the hydrological regime in the downstream area of the Black River basin. Land use and Land cover changes also affect the streamflow, however in a small degree. Lastly, natural climate variation has a large direct impact on the hydrology of the Black River. The recommendations focus on improving the accuracy of this research by using and establishing more precise and more detailed data (series). Next to that, a module could be added to the VIC-model to represent the Black River basin better in its current state.

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1. Introduction

1.1. Background

Water is the most important resource in everyday life all around the globe. People use water for many purposes such as domestic/industrial/agricultural use, recreation and navigation. Because of these various applications of water, water management is an important area of expertise. Understanding the water cycle is fundamental in this field, especially the part between rainfall and evapotranspiration or runoff where waterflows interact with land and humans. The study of the distribution and movement of these water resources is the main objective within hydrology. Hydrological models fulfill a crucial role here in understanding, managing and predicting waterflows, and they can be applied as a tool to analyze all kinds of impacts on flows. Impacts on the water cycle are partially caused by natural phenomena, the main example of this is the impact of climate change. Next to that, also humans intervene in water systems and thereby change the hydrological regime by abstracting water from it. Examples of human actions are the construction of hydropower dams and water storage reservoirs and changes in land use and land cover as urbanization, industrialization, de- or reforestation and irrigated agricultural areas.

The topic of this study is to distinguish and quantify the impacts from different sources, but mainly human interventions, on a water system. It is explained how the impacts of human interventions and climate change are separated by means of a water balance and how the impacts of humans can be assessed by means of a hydrological model, the VIC-model. The Black River basin has been used as a case study for this research. The Black River catchment is a transboundary river basin that is shared by China and Vietnam. In both countries, a lot of human interventions take place which emphasizes the importance of having knowledge about the impacts of them, to be able to anticipate on it. As the available data on this area is minimal, also uncertainty and data validation have a large role in this study. The Black River basin is part of the Red River catchment, for which more research has been performed.

1.2. State of the art

What is already known, and which research techniques are already applied regarding attribution and quantification of impacts on water systems? And how are hydrological models constructed and applied when a basin is ungauged? This section describes the state of the art regarding these topics.

Assessment of impacts on flow regimes

It is generally known that human interventions and climate change have an impact on flow regimes and there are several studies that provide methods to distinguish between these different impacts. Some examples are the simulation of natural scenarios and their comparison to actual scenarios [1], the use of statistical analyses in combination with hydrological sensitivity and simulation [2] [3] and the performance of a wavelet analysis and statistical analyses [4]. For another river basin in China, ten quantitative methods are compared to separate effects of climate change and human activities on changes in runoff [5]. Next to those methods of separating impacts, the impacts on hydrological regimes should also be assessed, which is done by quantification of streamflow through measurements and by hydrological indicators [6].

Impacts of changes in land use and land cover should be assessed, preferably before the changes take place. There are many general methods described for land use & land cover change impact assessment [7] and reviewed [8].

Relevant for this research topic is the quantification of impacts of land use & land cover changes on the hydrological regimes, which is researched for land use in the Vietnamese Mekong river Delta [9] and for land cover in the Red River Basin in the Yunnan province, China [10]. Another method to assess these impacts is by using a flow-duration curve analysis [11]. Specifically, the VIC-model has been used to quantify impacts of land use & land cover on the hydrological regime [12].

Considering water storage reservoirs, there is less literature available on the quantification of their impacts. It is known that water storage reservoirs play a key role in regulating water during extreme weather events [13] and that the filling of reservoirs reduces the downstream flow significantly [14]. For the Mekong River basin, it is described how the effects of water storage reservoirs can be quantified by using the VIC-model [15].

The usage of hydrological models with limited data availability

In basins without measurements or known properties, also called ungauged basins, necessary model input data and basin parameters cannot directly be obtained. Recently, much research has been done to explore the prediction in ungauged basins, also called the PUB-decade [16]. To acquire meteorological forcings, remote sensing data may be used. Remote sensing data is often inaccurate, but research studies were performed that compare different remote sensing datasets [17] and create new datasets based on that [18]. For precipitation specifically, local suggestions for bias correction are provided [19].

1.3. Research gaps

Assessment of impacts on flow regimes

It is complicated to measure or capture actual evapotranspiration from remote sensing data. As land use & land cover and climate change affect the actual evapotranspiration, it becomes difficult to separate their impacts on it. Next to that, actual evapotranspiration is part of the water balance [20], making it hard to quantify the water use or change in water storage of a catchment.

Series of water storage reservoirs affect each other and have large implications on the downstream and intermediary water regimes [21]. Not much research has been done to quantify the accumulated impact of multiple reservoirs.

The usage of hydrological models with limited data availability

Representing water storage reservoirs in a model is a complicated task. Properties and parameters of the dams and reservoirs must be known, which are hard to acquire. Next to this, the construction of reservoirs affects the parametrization of the basin [22].

Due to inaccurate representations of a study area in the model, the credibility of the model outputs might be debatable. Also, inaccurate climate forcing measurements that are used as inputs might play a role in increasing uncertainty of the output. It is hard to quantify all of these uncertainties and there are few research studies that offer guidelines on how to determine a sensible uncertainty of outputs.

Modelling a basin without having access to area properties is difficult and comes along with many sophisticated methods. The VIC-model needs much data on the catchment such as meteorological forcings, soil and vegetation parameters. Remote sensing data can help to acquire this information. When the basin is modelled, it will have to be calibrated and validated. Regionalization plays a large role here. Some studies describe ways to setup [23], calibrate [24] and validate [25] catchments without known basin parameters. During the PUB-decade more attention was given to these topics.

1.4. Research framework

Problem statement

Lower water levels have been measured from 2008 onwards in the Black River at the Vietnamese gauging station Muong Te, next to the Chinese Vietnamese border. Lower water levels lead to less streamflow towards the downstream area, in this case, the Vietnamese part of the Black River catchment. Less streamflow means that less water can be used for other relevant purposes, such as irrigation and industry or storage in reservoirs. Therefore, the Vietnamese government would like to see a quantification of the difference in streamflow since 2008 and more insights on the attribution of this difference. The identified possible causes are climate change and human interventions. The expectation is that the filling process of reservoirs is the main reason for reduced streamflow from 2008 onwards.

Hydrological research is limited for the Black River basin specifically, because the measurement data availability is limited for the basin as a whole. Generalizing, it can be stated that there is a need for a robust hydrological model of the Black River basin that can be used for quantitative impact analyses of human interventions and climate change. It is important to quantify the impacts, to be able to consider them when using prediction models or when allocating future hydropower dam locations.

Research objective

The problem statement clearly points out what the goal of this research study should be: an impact study has to be performed both qualitatively and quantitatively, mainly for human interventions, by using a hydrological model. The research objective is therefore formulated in the following way:

"To assess impacts of human interventions on the hydrological regime of the Black River catchment qualitatively by a water balance and quantitatively by running experiments with the VIC-model"

Research questions

Before any analysis, the streamflow changes must be identified. This leads to the first research question:

1. *"What is the reduction in measured streamflow in the Vietnamese part of the Black River basin before 2008 and from 2008 onwards, considering the dry and wet season?"*

The streamflow changes should be attributed to a cause, which leads to the second research question:

2. *"What is the main cause of the reduced measured streamflow in the Vietnamese part of the Black River basin from 2008 onwards?"*

The VIC-model is used to analyze the impacts of human interventions. Therefore, the VIC-model should be configured, calibrated and validated for the Black River basin, leading to the third research question:

3. *"What is the performance of the VIC-model in the Chinese part of the Black River basin while using remote sensing data and coarse parameter estimations due to limited measurement data availability?"*

Finally, the impact analysis of the construction of water storage reservoirs and changes in land cover and land use is performed with the VIC-model. This leads to the fourth and final research question:

4. *"What are the differences between measured and simulated streamflow of the VIC-model in the Vietnamese part of the Black River basin from 2008 onwards, considering the dry and wet season?"*

1.5. Research scope

According to the research objective, the goal is to assess impacts of human interventions on the hydrological regime of the Black River basin. A qualitative analysis is given by means of the water balance approach and a quantitative analysis is given by using the VIC model. No impact assessment is performed for climate change. The boundaries of the research are outlined per question in this section.

Only at two locations within the catchment a discharge series is established by means of measurements and rating curves. The established streamflow timeseries will both be validated by comparison to one other streamflow timeseries from a nearby hydrological measurement station.

As possible causes for reduced streamflow, two options are considered: climate change and human interventions. Climate change is identified but its impacts are not further analyzed. For the human interventions, a qualitative analysis is performed. However, only two types of human interventions are studied: changes in land use and land cover and the construction of water storage reservoirs.

No input datasets are created manually based on measurements and interpolation techniques. Only available datasets, either based on measurements or remote sensing, are used for the VIC-model. For the selection of remote sensing data other than precipitation, no extensive comparison study is performed: widely accepted data sources are adopted. For the validation of the VIC-model, the split sample test is used. A simplified proxy basin test is used too, where the model is applied to a subbasin within the calibrated basin. The model was not validated by applying it to another basin.

Again, the human interventions that are assessed quantitatively include land use & land cover changes and water storage reservoirs, but no other types of human interventions such as increased water use due to urbanization or industrialization. The reservoir module of the VIC-model has not been used to simulate reservoirs. Only a scenario without reservoirs was simulated to compare it to reality, where reservoirs do exist and operate. LULC maps from two years are compared.

1.6. Outline

In this research, the VIC-model will be applied to the Black River basin. Chapter 2 provides information on the model and the study area. Chapter 3 and 4 are intertwined in the sense that chapter 3 describes data and methods and chapter 4 the subsequent results. To analyze any kind of impacts on a flow regime, and to calibrate and validate a model, an observed streamflow timeseries is crucial. When running a hydrological model or creating a water balance to analyze impacts of human interventions, precipitation data is the main input. In section 3.1, the derivation of two discharge timeseries and the validation of a global and regional gridded precipitation product are described. The configuration of the water balance and the attribution of streamflow changes based on this, is explained in section 3.2. To provide a quantitative analysis of impacts, the VIC-model will be used. The set-up, calibration and validation of the model for the Black River basin are described in section 3.3. The discharge changes are again attributed, but now using the model, which is explained in section 3.4. The streamflow changes that occur in the timeseries from 3.1 are analyzed in section 4.1. The water balance, land cover maps and literature on the construction of water storage reservoirs in the Black River basin are used to analyze impacts of human interventions qualitatively in section 4.2. The performance of the optimized VIC-model is shown in section 4.3. Finally, the impacts of human interventions are analyzed quantitatively with the VIC-model in section 4.4. In chapter 5, the methodology and the results will be discussed, following by conclusions and recommendations in sections 6.1 and 6.2.

2. Study area and model

2.1. Study area

In south-eastern Asia, there are many large rivers that have a significant influence on the course of human and nature life and vice versa. One example of a river with a transboundary basin that is used as a case study and therefore the study area in this thesis is the Black River, which is a tributary of the Red River. The Black River originates from the higher grounds of Yunnan, one of the southern provinces of China and merges in the Red River delta in Vietnam with two other tributaries, the Lo River and the Thao River, as can be seen in Figure 1. Eventually, the Red River flows through the capital of Vietnam, Hanoi, southeast towards the coast where its water is released into the East Sea. In China, the Black River is called the Lixian River and in Vietnam, the Black River is sometimes referred to as the Da River.

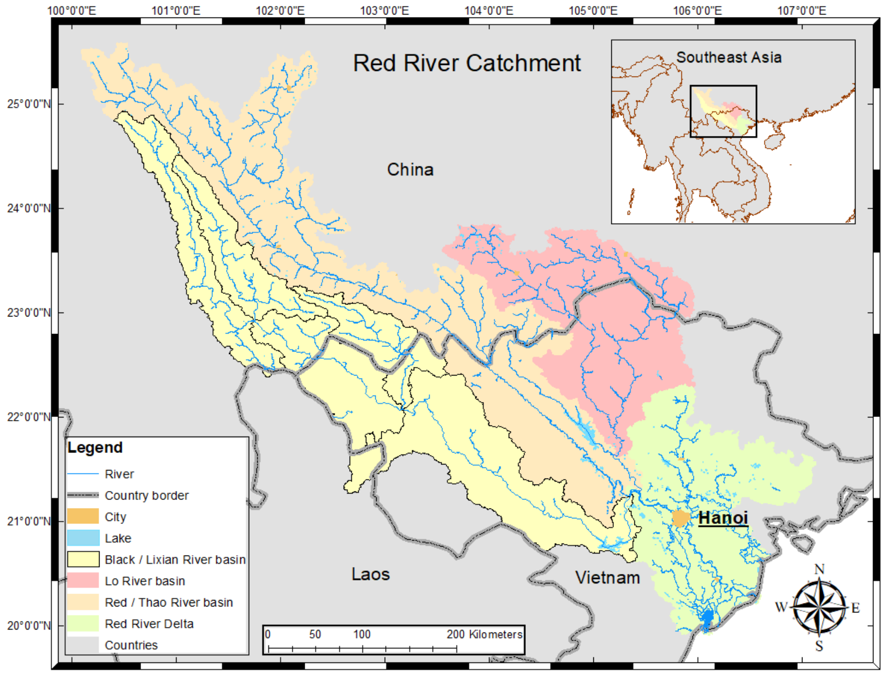


Figure 1 – Map of the study area

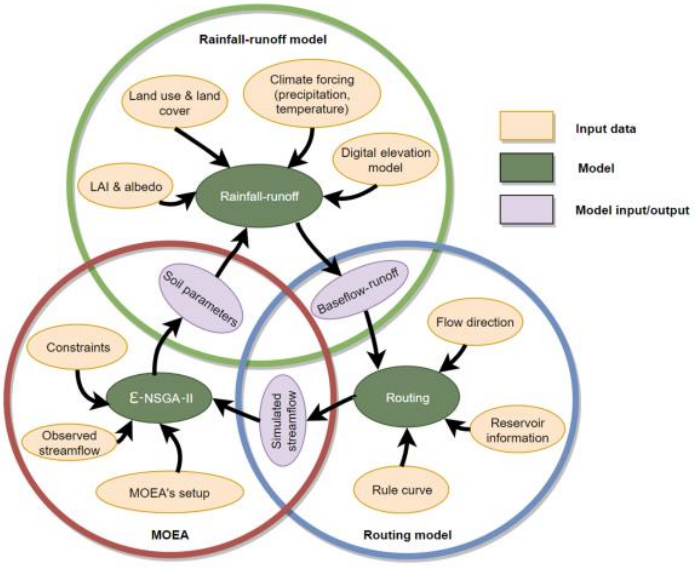
A lot of human interventions take place in and next to this river which are not always being assessed or kept track of. Changes in land use and land cover occur, but also the construction and filling of water storage reservoirs plays a large role in this catchment area. The Black River yields large amounts of hydroelectric power. In China, there is a series of 14 dams and in Vietnam, there are three large hydroelectric plants on the Black River [26]. The operating rules of the Chinese dams are not shared outside the privatized companies that deploy the dams. There are some hydrological and meteorological stations both in the Chinese and Vietnamese part of the Black River catchment, however not much of the data of these gauging stations is being shared. In this thesis, the impacts of the human interventions in the Chinese part of the basin on the streamflow in the Vietnamese part of the basin will be assessed by means of a hydrological model. Therefore, it is necessary to model only the Chinese part of the basin and a small Vietnamese part up to a location that provides reliable streamflow measurements. Subchapter 3.1 shows and explains the choice of modelling area. Since not all the necessary measurement data is available, the basin will be modelled partially with remote sensing data.

2.2. VIC-model

Before intervening in a water system, that water system should be modelled to assess impacts. The modelling of a catchment including its physical properties and its rainfall-runoff processes is called hydrological modelling [27]. Water engineers apply many models for many purposes. In this research, the VIC-model will be used to simulate the Black River basin for several reasons:

1) The VIC-model is fully distributed and physical based, meaning that it considers spatial variability of inputs highly. This is important in hydrological studies to accurately represent the study area.
2) It is a hydrological land surface model, meaning that it uses quantitative methods to simulate the exchange of water, energy and momentum fluxes between land surface and atmosphere. Again, this helps in representing the processes in the water cycle of the study area accurately.
3) Human interventions such as reservoirs and land use and land cover changes can be simulated.

The VIC-model is commonly applied by using a framework with three parts as can be seen in Figure 2 [22]. The rainfall-runoff model [28] is the basis to model the interactions between air, land and waterflows. The mechanics behind this part of the model can be seen in Figure 3 and are also explained on their website [29]. It uses climate forcings and physical properties of the area as inputs and yields gridded baseflow and runoff as output. The routing model [30] [31] is performed separately and accumulates the gridded baseflow and runoff to determine streamflow at a selected outlet. The MOEA model is a calibration algorithm to improve the performance of the rainfall-runoff and routing models by optimizing estimated parameters. This research follows the framework from Figure 2 except for that another calibration algorithm is used, namely the Shuffled Complex Evolution Method (SCEUA) [32].



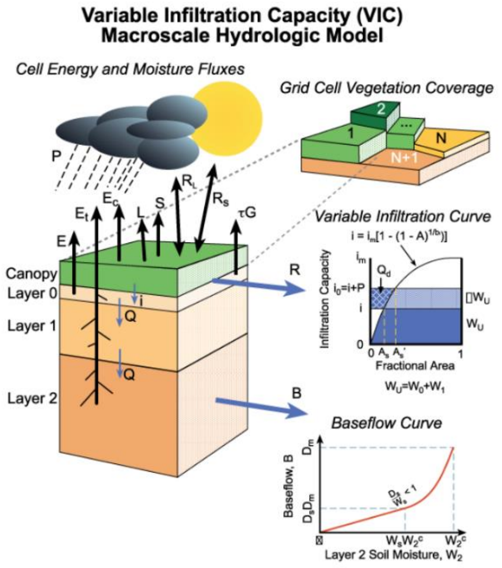


Figure 2 – Schematic overview of the VIC-model framework (left)

Figure 3 – Schematic overview of the mechanisms behind the Rainfall-runoff model (right)

The used data in this case study is a land use & land cover map, properties on vegetation amongst which LAI, albedo, global and regional meteorological forcing timeseries, a digital elevation model, a flow direction map and flow properties, a soil map including soil properties, and observed streamflow timeseries. Table A1 in appendix A shows the sources that have been used to acquire these datasets.

3. Data & Methods

3.1. Derivation and validation of hydrometeorological time series

An observed timeseries of discharge is crucial for the identification and analysis of streamflow changes, but it is also an input for the water balance and used for the calibration and validation of the VIC-model. For both the VIC-model and the water balance, precipitation is the most significant and influential input. Therefore, this section describes the derivation and validation of two discharge and precipitation timeseries. The streamflow and precipitation timeseries are shown and discussed in results section 4.1.

Derivation of discharge timeseries

In the Black River basin, there are multiple hydrological stations. Figure 4 shows the locations of the stations and Table 1 shows the unit, timespan and source of the measured data. The unit can either be discharge (Q) or water level (h). The frequency of all the Chinese data is 6-hourly, however the data is only available for the flood season from 15th of June to 15th of October. The frequency of the data is daily or aggregated to daily from 6-hourly sub daily data. The Chinese station data is obtained from the Chinese Ministry of Water Resources (MWR) and the Vietnamese station data is partially obtained from the Vietnamese Meteo Hydrological Administration (VMHA) and partially from Vietnam Electricity (EVN).

Table 1 – An overview of the hydrological stations and their data availability (left)

Stations	*Unit*	*Timespan*
Trung Ai Kieu	h	2001 - 2016
Ly Tien Do	Q, h	2002 - 2016
Tho Kha Ha	Q, h	2017 - 2021
Pac Ma	h	2019 - 2022
Muong Te	h	1962 - 2006
Po Lech	Q	2005
Lai Chau new	Q	2016 - 2020
Nam Giang	Q	1965 - 2017
Lai Chau old	Q, h	1958 - 2015

Stations	*Data (appendix A)*
Chinese stations	MWR
Pac Ma	EVN
Muong Te	VMHA
Po Lech	EVN
Lai Chau new	EVN
Nam Giang	VMHA
Lai Chau old	VMHA

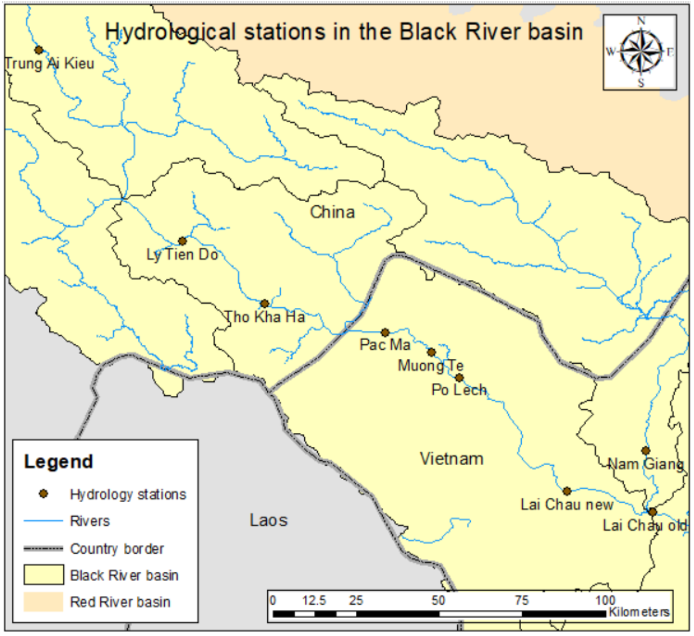


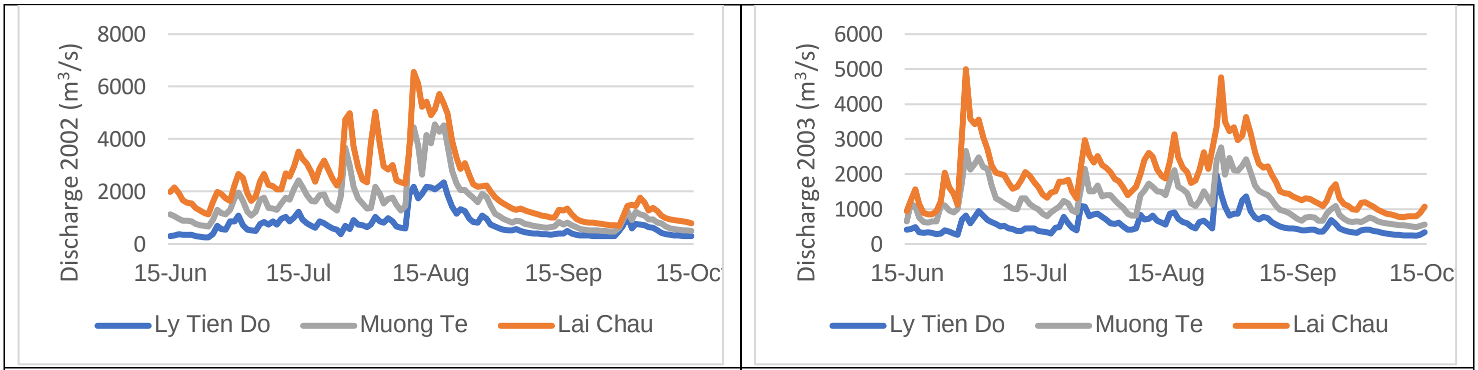
Figure 4 – Map of the hydrological stations in the Black River basin (right)

As the construction of the Lai Chau reservoir affects the streamflow from 2016 onwards, a new station was established upstream of the reservoir. In this research, this location is called Lai Chau new. The new and old Lai Chau station are located close to each other, however in Figure 4 there is a small subbasin and a large tributary that joins the Black River in between the two stations, both increasing the streamflow. By subtracting the discharge timeseries of Nam Giang (1965-2015) from the timeseries of the old Lai Chau station (1965-2015), the timeseries at the new Lai Chau station is approximated for this period, as the inflow of the large tributary is subtracted. The streamflow addition of the small subbasin is neglectable, in comparison with the total catchment size. By adding this timeseries (1965-2015) to the existing one (2016-2020), a series from 1965 to 2020 is derived for the new Lai Chau station.

Secondly, it is desired to have a discharge timeseries close to the border, as this one can be used to determine and assess impacts of human interventions in China solely. This second streamflow series can also be used for a proxy-basin validation of the VIC-model. Muong Te provides a long timeseries of water levels which can be translated to discharges by means of a rating curve. The station of Po Lech provides discharge measurements in 2005. These measurements are used with the water levels at Muong Te from the corresponding year to create a regression curve which is used as rating curve, shown in Figure B1 in appendix B. As these stations are located relatively close to each other, it is assumed that the differences in river properties between the two locations are neglectable. Subsequently, the rating curve was used to translate all water levels of Muong Te from 1962 to 2006 to streamflow.

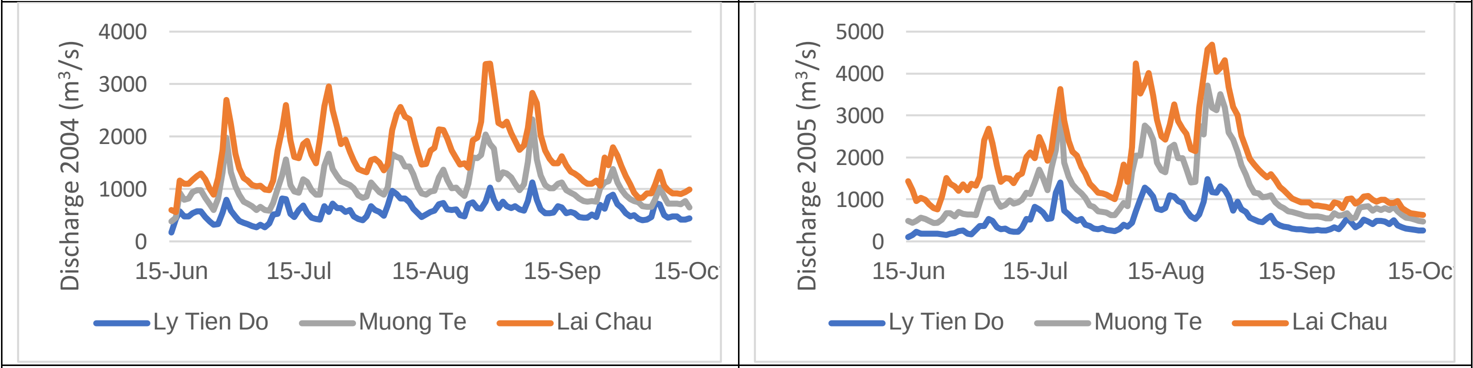
Validation of discharge timeseries

The discharge timeseries at Muong Te and at the new Lai Chau station are validated by comparison with each other and upstream discharges, measured at Ly Tien Do. Figure 5 shows magnitude and behaviour of the hydrographs that were derived from different independent sources for the years 2002-2005.



Correlation Ly Tien Do – Muong Te: 0.92207
Correlation Muong Te – Lai Chau: 0.94594

Correlation Ly Tien Do – Muong Te: 0.85725
Correlation Muong Te – Lai Chau: 0.96306



Correlation Ly Tien Do – Muong Te: 0.84953
Correlation Muong Te – Lai Chau: 0.92421

Correlation Ly Tien Do – Muong Te: 0.94230
Correlation Muong Te – Lai Chau: 0.96209

Figure 5 – Plots of the flood season hydrographs at different stations in the Black River basin

The magnitudes of discharges at Lai Chau are the highest and those at Ly Tien Do are the lowest. This is to be expected as a river increases in size the further it flows downstream. As the correlation between the different hydrographs is also good, the two derived discharge timeseries are validated successfully. As the most downstream streamflow series is measured at the (new) Lai Chau station, in the remainder of this thesis, only the catchment area up to this location will be considered for modelling and analysis.

Derivation of precipitation timeseries

For the precipitation timeseries inputs for the water balance and the VIC-model, there are two options: using measurement data or using a remote sensing data product. It is expected that measurement data is more accurate compared to remote sensing data. However, acquiring measurement data is difficult in this basin due to limited precipitation data, whereas there are many remote sensing data products. The three stations for which precipitation data was acquired are shown in Figure 6, and their data availability and sources are displayed in Table 2. The rainfall at Lai Chau is obtained from the Vietnamese Meteo Hydrological Administration (VMHA) and the Chinese rainfall is obtained from the National Oceanic and Atmospheric Administration (NOAA). Figure 6, also the locations of the streamflow timeseries and the catchment part that is considered for the remainder of this thesis is shown in red.

Table 2 - An overview of the meteorology stations and their data availability (left)

Stations	*Nature*
Kunming	Precipitation
Simao	Precipitation
Lai Chau	Precipitation
Stations	*Timespan*
Kunming	1951 - 2022
Simao	1951 - 2022
Lai Chau	1956 - 2003
Stations	*Frequency*
Kunming	Daily
Simao	Daily
Lai Chau	Daily
Stations	*Location*
Kunming	Lon: 102.7 - Lat: 25.0
Simao	Lon: 101.0 - Lat: 22.8
Lai Chau	Lon: 103.2 - Lat: 22.0
Stations	*Data (appendix A)*
Kunming	NOAA
Simao	NOAA
Lai Chau	VMHA

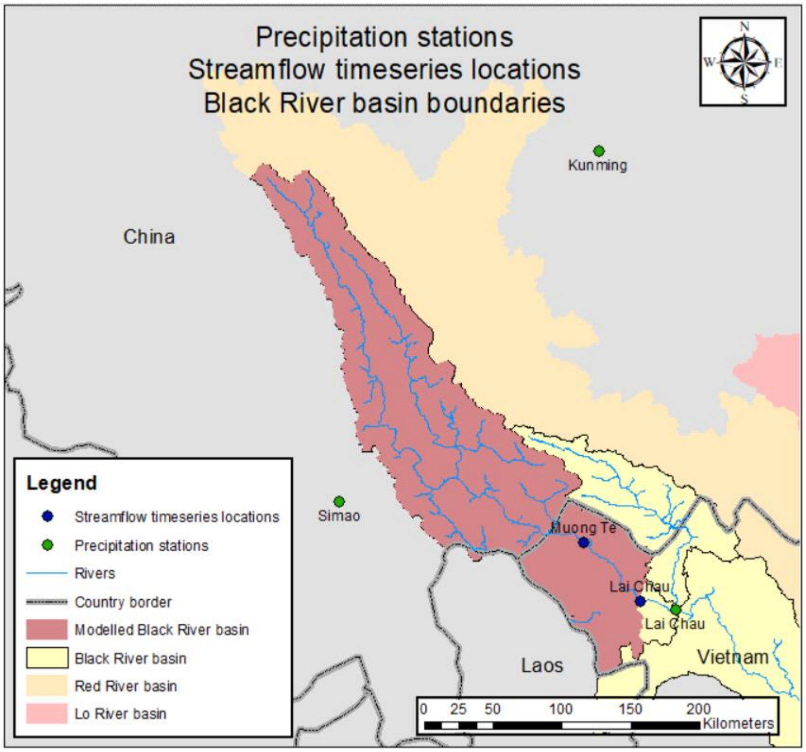
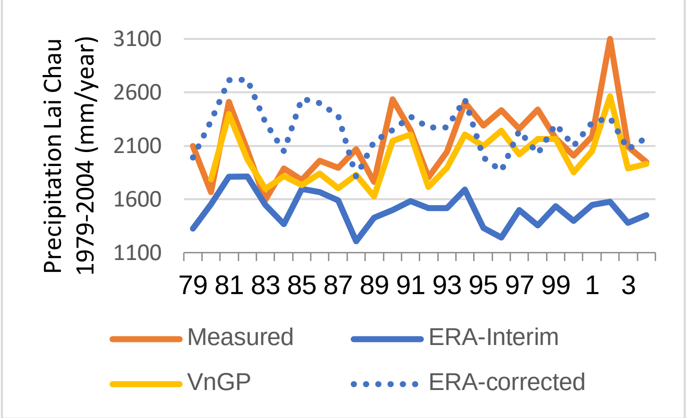


Figure 6 – Map of the meteorology stations around the Black River basin (right)

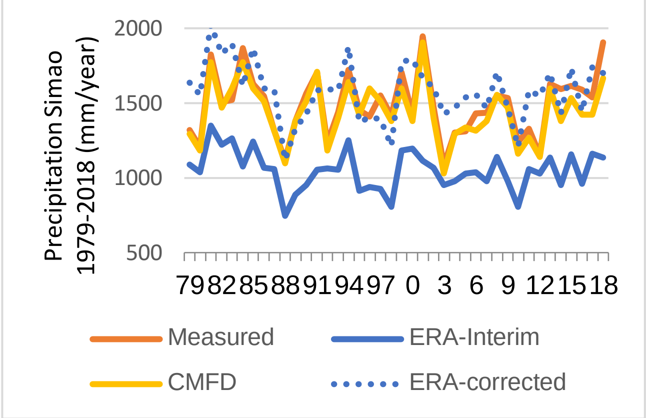
Data from three stations is too little to use interpolation techniques to create a precipitation map manually. Therefore, it was chosen to use a remote sensing data product. However, as the meteorology stations are fairly distributed over the catchment edges, they will be used for the validation of the remote sensing data products. Two (combinations of) remote sensing data products have been acquired. Firstly, the ERA-Interim global dataset [33] provides gridded precipitation, maximum and minimum temperatures and wind speed on a 0.5° resolution. The timeframe of this dataset is 1979-2019. Secondly, two regional remote sensing data products have been merged to establish a regional gridded precipitation dataset. The two products that are used are the Chinese Meteorological Forcing Dataset (CMFD) [34] and the Vietnam Gridded Precipitation dataset (VnGP) [35], which both have a spatial resolution of 0.1°. The timeframe of the CMFD dataset is 1979-2018 and the timeframe of the VnGP dataset is 1980-2018. The temporal resolutions of ERA-Interim, VnGP and CMFD are all daily.

Validation of precipitation timeseries

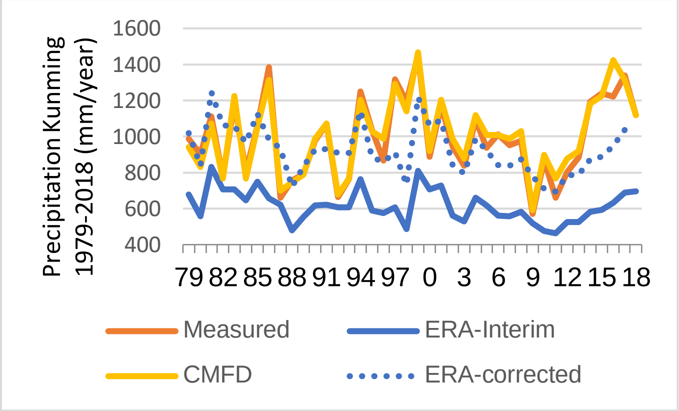
The regional and global rainfall datasets are compared in Figure 7 against the data from the stations.



Correlation VnGP – Measured: 0.93465
Correlation ERA-corrected – Measured: 0.03251



Correlation CMFD – Measured: 0.94224
Correlation ERA-corrected – Measured: 0.52671



Correlation CMFD – Measured: 0.97063
Correlation ERA-corrected – Measured: 0.51695

$$c\ (correction\ factor) = \frac{P_{obs}}{P_{ERA}}$$

$$c_{mean} = \frac{\sum c}{Number\ of\ measurements}$$

$$c_{final} = \frac{\sum c_{mean}}{Number\ of\ stations}$$

$$c_{final} = \frac{1.43 + 1.42 + 1.62}{3} = 1.5$$

Figure 7 – Annual precipitation plots from different datasets at stations around the Black River basin

It becomes clear from the three different plots that the regional dataset performs better in both the magnitude and the behaviour aspects compared to the global dataset. The regional dataset is an accurate representation of the measurements whereas the ERA-Interim dataset is underestimating at every daily timestep. The ERA-Interim dataset has therefore been corrected by using a constant correction factor. The computation of this correction factor is also shown in Figure 7. For every daily timestep of every plot, the measured value was divided by the ERA-Interim value. This yielded a single correction factor of every timestep for every station location. For every station, all the correction factors were averaged to a mean correction factor. These three mean correction factors were again averaged to obtain the final correction factor, which is equal to 1.5. In the plots, the corrected ERA-values are also displayed by dotted graphs. This correction reduced the differences in magnitude significantly, however when looking at the correlation factors of ERA-corrected and the measured data, it does not yield a good representation of the daily behaviour of the measured precipitation. Based on this data validation, it was decided to use the VnGP and CMFD dataset for the impact analyses. However, since the regional datasets may partially be based on these station measurements, the validation is not entirely valid.

3.2. Attribution of streamflow changes using a water balance approach

This chapter shows the construction of the water balance and provides the methods that are used to identify and attribute streamflow changes based on the water balance, land cover maps and literature.

Construction of the water balance

A water balance uses the principle that the inflow to a basin equals the outflow from that same basin and if not, there is a change in the water storage of the basin. Equation 1 shows this water balance:

$$Inflow\ (I) - Outflow\ (O) = Change\ in\ water\ storage\ (\Delta S) \qquad (1)$$

Inflow to a basin is usually precipitation (P), whereas outflow comprises multiple waterflows: discharge (Q) and evapo(transpi)ration (ET). Changes in water storage of a basin are i.e. caused by human interventions or by changes in the storage layers of the basin. Within the basin there are also waterflows such as capillary rise, percolation and infiltration. These are flows between different storage layers within the basin, namely surface water, soil moisture and groundwater. When considering these storage layers over a long-term period of many years, it is assumed that their storage amounts remain similar. Evapotranspiration can be divided in two types: actual and potential evapotranspiration. Actual evapotranspiration (ET_a) is hardly measurable, whereas there are many methods to calculate potential evapotranspiration (ET_p) [36]. ET_p is the maximum possible amount of evapotranspiration, and therefore ET_a should always be smaller than ET_p. In a natural system without human interventions and when assuming the ground storage does not change, Equation 2 should hold in the long term:

$$P - Q = aET \qquad ET_p > ET_a \qquad P - Q < ET_p \qquad (2)$$

The regional precipitation dataset and the discharge timeseries at Lai Chau have been established in the previous subchapter. The streamflow was converted from m^3/s to mm/year by using Equation 3 and 4. The catchment area upstream of the Lai Chau streamflow timeseries is approximately 26 700 km^2.

$$\frac{\frac{m^3}{s} * 24 * 60 * 60 * days\ in\ a\ year}{catchment\ area} * 1000 = \frac{\frac{m^3}{year}}{catchment\ area} * 1000 = \frac{m}{year} * 1000 = \frac{mm}{year} \qquad (3)$$

$$\frac{\sum_{j=1}^{grid\ cells\ basin}\left(fraction_j * \sum_{i=1}^{days\ in\ year}\left(\frac{mm}{day}_i\right)_j\right)}{\sum_{j=1}^{grid\ cells\ basin} fraction_j} = \frac{\sum_{j=1}^{grid\ cells\ basin}\left(fraction_j * \frac{mm}{year}_j\right)}{\sum_{j=1}^{grid\ cells\ basin} fraction_j} = \frac{mm}{year} \qquad (4)$$

The potential evapotranspiration has been computed for the Black River basin following various methods in other studies. The Turc and FAO-56 method were recommended and specifically for the Black River basin, their values vary between 1000 and 1200 mm/year [36]. For this water balance, a constant potential evapotranspiration of 1100 mm/year is used, as not all the necessary data for these methods is available. Results section 4.2 shows the water balance.

Methods to attribute streamflow changes

There are different causes to which the streamflow changes in 2008 and onwards could be attributed. Table 3 shows four possible explanations by means of schematized water balances of the Black River.

Table 3 – Schematisation of the water balance, showing causes of reduced streamflow at Lai Chau

P decreased ⬇ ⬆ ETa equal Explanation 1: There is variability in the climate, causing a reduction in precipitation that is directly reflected in a reduced discharge. $(P - x) = ET_a + (Q - x)$ ➡ Q reduced	P equal ⬇ ⬆ ETa increased Explanation 2: Climate and/or Land Use and Land Cover have changed, causing an increase in actual evapotranspiration. $P = (ET_a + x) + (Q - x)$ ➡ Q reduced
P equal ⬇ ⬆ ETa equal Explanation 3: Reservoirs are filled and/or Land Use and Land Cover have changed, causing an increase in water storage. $P = ET_a + \Delta S + (Q - \Delta S)$ ➡ S increased ➡ Q reduced	P reduced ⬇ ⬆ ETa increased Explanation 4: There are multiple causes and flows responsible for the reduced discharge at Lai Chau from 2008 and onwards. $(P - a) = (ET_a + b) + \Delta S + (Q - x)$ ➡ S increased ➡ Q reduced

The difference between land use and land cover is that land use is about the way humans use the land (urban area, agriculture, etcetera), and land cover is about the physical land type itself (water, types of forest, shrubland, etcetera). Land cover and land use affect the evapotranspiration due to their properties (i.e., Leaf Area Index, roots) and water storage due to the abstraction of water from the cycle.

Explanation 1 is researched by taking a closer look at the exact behaviour of the precipitation and discharge. If they follow each other precisely in 2008 and later, it can be stated that changes in rainfall are directly reflected in the discharge and that natural variability in rainfall or climate change is a cause. Explanation 2 is more difficult to research: as it is hard to measure actual evapotranspiration, it cannot be visualized or analyzed. However, the possible causes of an increase in ETa can be investigated to estimate whether the ETa has increased. Using ArcGIS, land use and land cover maps [37] for 1992, 2002 and 2012 were created to observe the changes in land use and land cover for this period. Literature was used to conclude whether climate change has an impact on the actual evapotranspiration [38]. Explanation 3 cannot be quantified based on the water balance as a lack of actual evapotranspiration data prevents the estimation of water storage in the Black River catchment. Literature was used to study the changes in land use and land cover and the construction of reservoirs around 2008 in the Black River basin and their possible impacts on water storage. Explanation 4 comprises a combination of the previous explanations. The findings are discussed in subchapter 4.2

3.3. Set-up, calibration and validation of the VIC-model

This section describes how the VIC-model was set-up and which data precisely is necessary. Next to that, the calibration and validation methods are explained of which the results are shown in section 4.3.

Set-up of the VIC-model

The VIC-model requires an intensive set-up procedure before running the model. This set-up procedure consists of collecting and pre-processing data. Figure 8 shows the data components that were acquired to set-up the VIC-model. The data was pre-processed by using python scripts and ArcGIS.

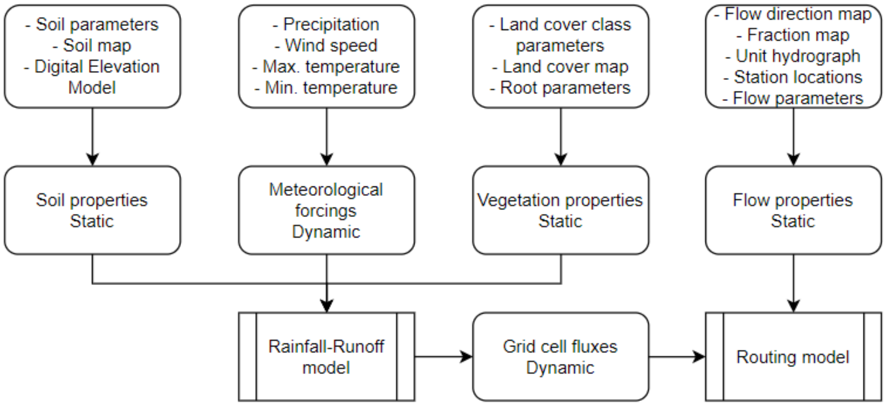


Figure 8 – Schematic overview of the necessary input data for the VIC-model setup

The Rainfall-Runoff model requires soil properties, vegetation properties and meteorological forcings. The Routing model requires grid cell flux outputs from the Rainfall-Runoff model and flow properties, such as flow speed and direction. The meteorological forcings are dynamic, meaning that they change over time and the soil, vegetation and flow properties are static, meaning that only spatial variability can be specified, but not temporal variability. There is one exception on this, the Leaf Area Index (LAI) and Albedo values can be added either to the vegetation properties, meaning that only their spatial variability is considered, or to the meteorological forcings, meaning that their spatial and temporal variability are considered. In this research, 12 monthly LAI and Albedo values for every vegetation type were provided as vegetation properties, meaning that their temporal variability throughout different years is not taken into account. Table A1 in appendix A provides detailed information on sources that were used to acquire the VIC-input data. The fraction map was established using ArcGIS and is used by the routing model to determine whether the whole grid cell is covered by the Black River basin or only a fraction of it. The station location is set at the grid cell where Lai Chau is located, to generate streamflow output at this location. The soil [39] and vegetation parameters [40] that are used for the model are shown in Table E1 and E2 of appendix E and the other parameters and settings of the model are displayed by means of the global parameter file and global routing file in appendix F.

The resolution of the regional precipitation dataset is 0.1°, and as this is the most influential input, it was chosen to set the spatial resolution of the grid cells in the VIC-model to 0.1°. This required the soil map, the digital elevation model, the flow direction map and the land use & land cover map to be aggregated to a coarser spatial resolution, which was done by using ArcGIS. At the same time, the wind speed and temperature data were acquired at a spatial resolution of 0.5°, and by applying a linear interpolation technique for the newly created cells, gridded datasets of 0.1° were constructed. The model was run using a daily timestep, as all the dynamic input data also has a daily timestep.

Calibration and validation of the VIC-model

The VIC-model has been calibrated and validated for many study areas, for example in China [41]. There are means for hydrological model calibration using water level measurements [42], which would be helpful since there are many water level measurements in the Black River basin, but not many discharge measurements. However, the routing model output is streamflow, therefore the calibration and validation will be based on the two established discharge timeseries in subchapter 3.1. As it is desired to use the VIC-model for the period starting in 2008, only the periods up to 2007 are used for calibrating and validating the model. Figure 9 shows that 14 years of the Lai Chau data are used for split-sample calibration and 14 years are used for split-sample validation. In addition, the discharge timeseries of 27 years at Muong Te is used for a partial proxy-basin validation, as the validation is not performed on another basin but on a part of the same basin. A successful partial proxy-basin validation increases the robustness of the VIC-model for the whole basin [43].

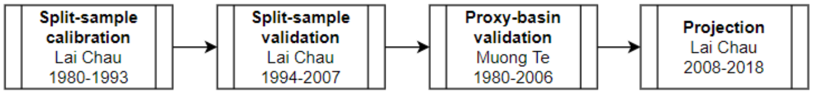


Figure 9 – Calibration and validation processes that are performed for the VIC-model

There are six soil parameters which are particularly difficult to measure as they are quite conceptual and do not correspond to actual physically observable quantities. These parameters are initially estimated but calibrated by means of an autocalibration script as they appear to be sensitive [29]. Other parameters are not optimized. The calibration procedure that is used, is shown in Figure 10. The rectangles show processes, and the ellipses display data or values. This calibration procedure follows the generally applied VIC-model framework [22], however the used optimization algorithm is different. It was decided to apply the Shuffled Complex Evaluation method as it is more suitable, with the right algorithmic parameters, to find global optima in comparison to other algorithms [32]. The physically possible ranges of the parameters have been assumed using the principle of regionalization and are obtained from the Mekong-River basin [22]. As a single run of the Rainfall-Runoff and Routing model takes 15 minutes and a good calibration requires at least 5000 function evaluations before converging to the global optimal parameter set [32], it was decided to mimic the Black River basin by aggregating the spatial resolution of the grid cells to 0.5° for running the autocalibration script. After obtaining the optimal parameter set, the model performance is measured by the key performance indicators (KPI) NSE, BIAS and RMSE, by running the VIC-model again on 0.1° spatial resolution. Results section 4.3 shows the initial and final soil parameter sets and the VIC-model performance with these.

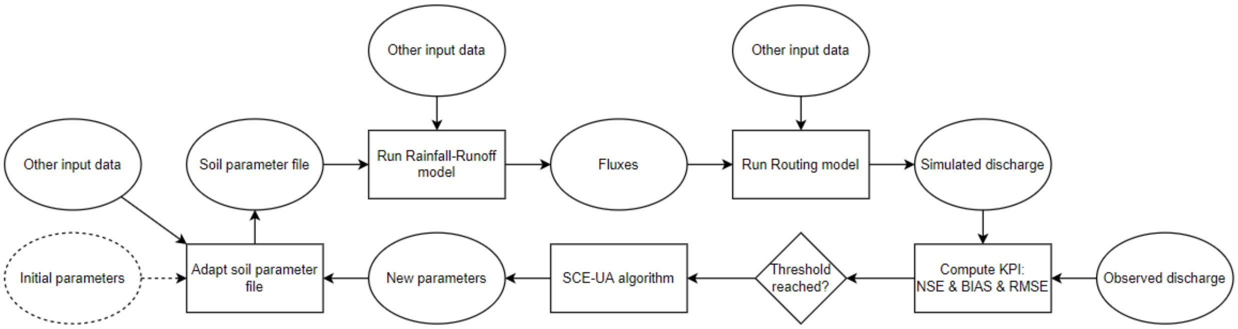


Figure 10 – Schematic overview of the autocalibration routine that was applied to the VIC-model

3.4. Attribution of streamflow changes using the VIC-model

This chapter explains how impacts of land use & land cover changes are separated from impacts of the filling process and operating rules of water storage reservoirs and how these human interventions in the Black River basin are quantified by using the VIC-model. Climate changes are not analyzed.

Separation of impacts by human interventions

The land use & land cover are considered by the VIC-model in two ways. Firstly, the LULC map shows for every grid cell what the types of land use or land cover are and what the root and vegetation properties, monthly LAI and Albedo values are within these LULC classes. Secondly, the LAI and Albedo can be supplied to the VIC-model as meteorological forcings, meaning that next to their spatial variability, also their temporal variability is considered. As mentioned before, that is not the case in this research. Therefore, changes in land use and land cover can only be considered by the VIC-model by using different LULC maps for different model runs, as the vegetation input is static and only allows for one input map per model run. All other variables should remain equal to prevent interference of other impacts with impacts of land use & land cover changes. This way of assessing land use & land cover has also been used for a sub-watershed in China [12].

To consider the changes in the flow regime due to the impact of reservoirs, a scenario with impacts of reservoirs must be compared to a scenario without impacts of reservoirs. All other variables should remain equal as their impacts may not interfere with the reservoir impacts. In this study, the observed discharge values after 2008 represent a scenario where the impacts of reservoirs are present, as it was concluded in 3.2 that reservoirs impact the flow regime from 2008 onwards. A natural scenario without impacts of reservoirs is simulated by running the VIC-model from 2008 to 2018, as it was calibrated for the basin in the period 1980-2007, when the flow regime was natural without reservoir impacts.

Quantification of impacts by human interventions

Figure 11 shows a framework for the quantification of the human interventions. The Land use and land cover changes are quantified by running the VIC-model for the Black River basin from 1980 to 2017 three times. All model settings will remain equal, however four different LULC maps (1992, 2002, 2012, 2019) from Figure C1 in appendix C are used. The streamflow outputs are compared, and the change factors are computed. Changes to the streamflow regime due to reservoirs are quantified by running the VIC-model from 2008 to 2018. The simulated streamflow reflects the natural flow regime before 2008 and is compared to observed streamflow, which reflects impacts of reservoirs. The changes between observed and simulated discharges indicate impacts of reservoirs. For the model run, a recent LULC map of 2012 was used, as the modelled scenario should, except for reservoirs, be equal to the real scenario.

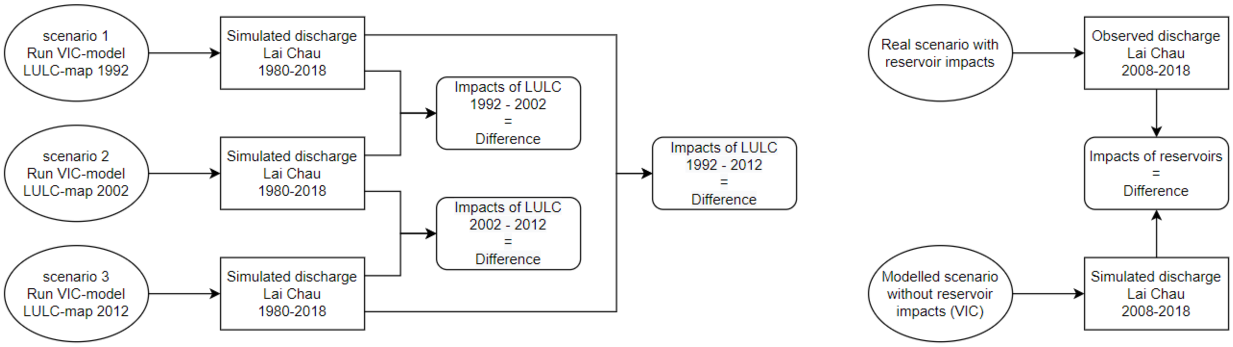


Figure 11 – Framework for the separation and quantification of human interventions

4. Results

4.1. Changes in the streamflow regime of the Black River basin

In this section, observed timeseries of Lai Chau and Muong Te are shown and the streamflow at Lai Chau is analyzed on two temporal scales. The annual averages of the daily discharges are displayed first, and then monthly averages, maxima and minima of the daily discharges before and after 2008 are shown.

Analysis of observed annual averages

The observed streamflow timeseries at Lai Chau (1965-2021) and Muong Te (1962-2005) are visualized in Figure 12. The streamflow averages before and after 2008 are displayed for the Lai Chau timeseries.

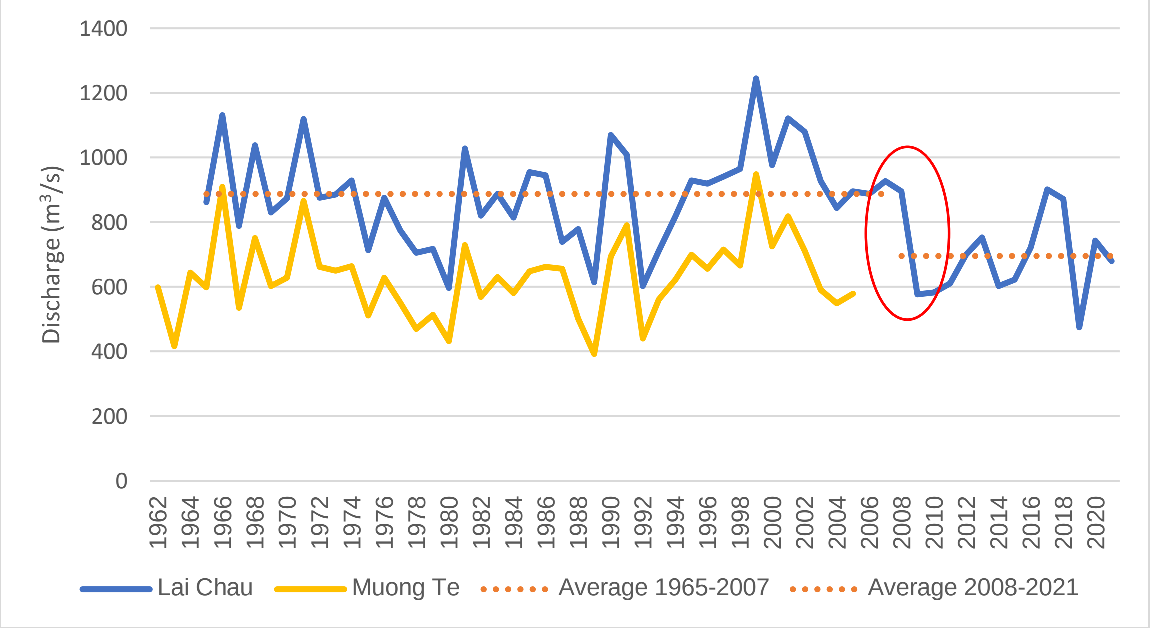


Figure 12 – Observed streamflow timeseries at Lai Chau (1965-2021) and Muong Te (1962-2006)

Considering the streamflow at Lai Chau, the average up to 2007 is 888 m^3/s, while the average after 2007 is 696 m^3/s. This is an absolute difference of 192 m^3/s and a relative difference of -21%. It is hard to base on the discharge data from the period 2008-2021 alone whether this deemed discharge decrease can be attributed to climate change or to changes in the catchment due to human interventions. Between 2007 and 2008 a large gap in discharge can be detected which seems to stabilize afterwards as well. A clear gap as marked by the red circle in Figure 12 indicates that a sudden change in discharge has occurred. This would point towards a sudden change in the catchment, likely caused by human interventions or possibly caused by natural variation between different years in climate forcings. It points less towards climate change, since this should be represented by a smoother gap, indicating a gradual change of discharge. Chapter 3.2 and 4.2 use a water balance to acknowledge this hypothesis and identifies the cause of the reduced discharges from 2008 onwards more precisely.

The streamflow timeseries of Muong Te does not give any information on the period from 2008 and onwards. Therefore, this timeseries cannot be used in further impact analyses. However, this timeseries is based on an independent source and can be used for the validation of the VIC-model in chapter 3.3.

Analysis of observed monthly averages

The monthly streamflow at Lai Chau is displayed in Figure 13 for the periods before and after the identified streamflow change in 2008. The monthly discharge values within the periods 1965-2007 and 2008-2021 were averaged over these whole periods to obtain the average monthly streamflow values. Table 4 shows the relative and absolute changes in average streamflow for the two periods.

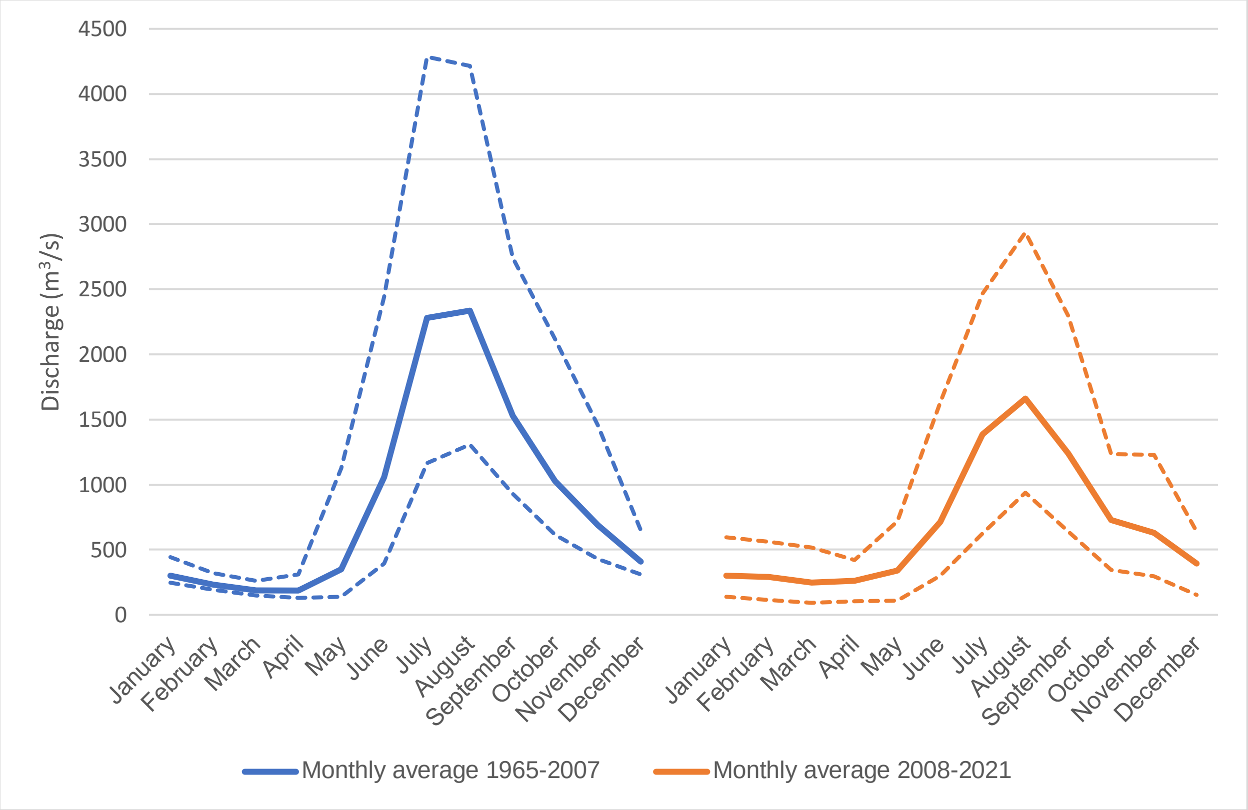


Figure 13 – Observed monthly streamflow at Lai Chau for the periods 1965-2007 and 2008-2021

Table 4 – Quantification of the average changes in streamflow per month at Lai Chau

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
(%)	+0.08	+23.3	+31.1	+40.3	-2.15	-32.7	-39.3	-28.9	-18.9	-29.4	-8.62	-3.32
(m^3/s)	+0.24	+54.5	+58.7	+75.2	-7.51	-346	-895	-675	-288	-302	-59.3	-13.5

The lengths of the dry and wet seasons are based on a set of rules and therefore differing per year. On average, the dry season lasts from November to the end of April and the wet season from May to the end of October. In Figure 13, average, minimum and maximum streamflow during the wet season is significantly lower from 2008 onwards compared to the 1965-2007 (-419 m^3/s). In the dry season, the flow regime is similar in both periods (+19 m^3/s). This suggests that the discharge change in 2008 from Figure 12 is mainly attributable to changes during the wet season and not during the dry season.

The absolute values in Table 4 support the hypothesis that the change in streamflow is less likely due to climate change, as climate change could reduce the discharge more equally throughout the whole year. In January until April, the discharge changes positively and from May until December the discharge changes negatively, which indicates that the possible changes to the basin have a dynamic impact.

4.2. Impacts of climate change and human interventions using a water balance

In this section, the results of the investigations to the different explanations for the reduced streamflow are shown and discussed. In Figure 14, the constructed water balance is displayed from 1980 to 2018.

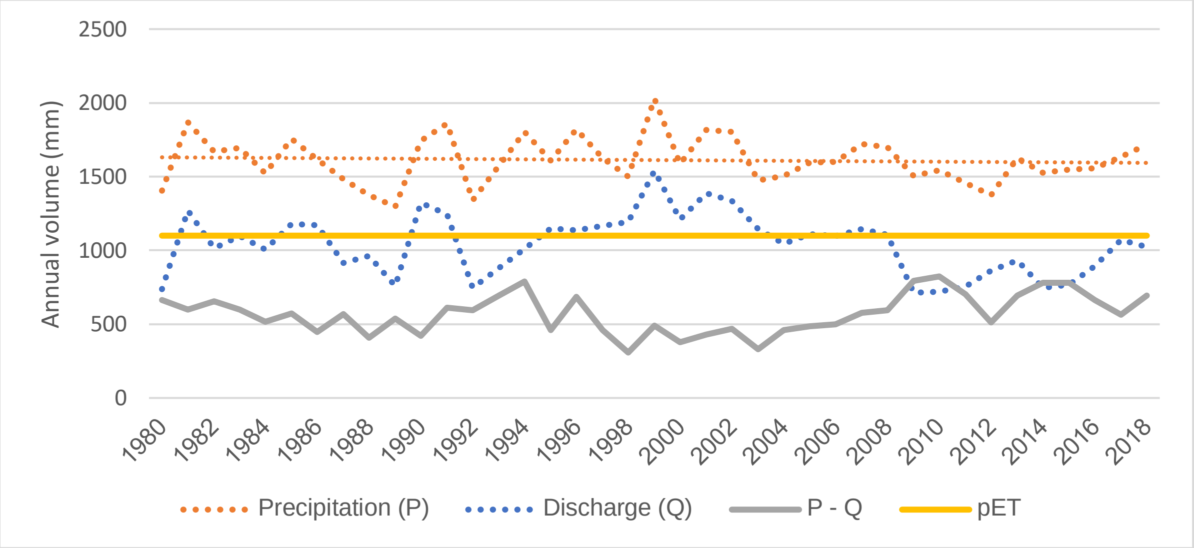


Figure 14 – Water Balance for the Black River basin (1980-2018)

The subtracted graph, which very roughly represents the actual evapotranspiration (ETa), remains below the line of the potential evapotranspiration (ETp) throughout the whole period, which means that ETa is indeed always smaller compared to ETp. This indicates that the precipitation and discharge data that are used for the Black River basin are at least valid in this respect and can be used with the VIC-model.

Climate change or climate variability as a cause of reduced streamflow

The precipitation graph in Figure 14 seems to show a trend that over 38 years, the annual precipitation has reduced with 37.6 mm, which is 2.3% relatively. However, a one tailed Mann-Kendall test with significance level α=0.05 accepted the null hypothesis that there is no trend but only natural variation. Climate change does therefore visibly seem to contribute to long term changes in the water system of the Black River. The natural fluctuation in precipitation seems to contribute to sudden streamflow changes as the precipitation graph and the discharge graph follow each other accurately throughout the period. In 2008 itself, the change in streamflow of 393.5 mm can be recognized which seems to be the start of a new trend afterwards. The precipitation only shows a sudden decrease of 195.7 mm in 2008.

Climate change and variability also affect ETa. Many studies have shown that this impact is significant. The actual evapotranspiration is partially determined by vegetation variation and meteorological forcings temperature and wind speed, but most dominantly by precipitation [38]. However, the relative impacts of those factors are dependent on the land cover type [44]. Changes to ETa due to climate variability will roughly cancel out in the water balance with changes to rainfall, as rainfall dominantly determines ETa. Climate change, however, may affect ETa independently of rainfall.

On this basis, it can be stated that climate change contributes to long term changes in streamflow through changes in precipitation and ETa. Climate variability is accepted as partial cause of the sudden flow regime change in 2008. The 195.7 mm decrease in precipitation equals 49.7% of the 393.5 mm streamflow reduction.

Land use and land cover as a cause of reduced streamflow

The land use & cover maps of 1992, 2002 and 2012 are displayed in Figure C1 in appendix C. Table 5 shows the percentage of each land cover and land use class for the three years.

Table 5 – Percentages of land use & land cover types within the basin for 1992, 2002 and 2012

Land cover and Land use class	*1992*	*2002*	*2012*
Rainfed Cropland	2.66	2.70	2.69
Herbaceous Cropland	2.08	2.11	2.11
Irrigated or Post-Flooding Cropland	0.93	0.93	0.93
Mostly Cropland in a Mosaic with Natural Vegetation	2.45	2.47	2.47
Mostly Natural Vegetation in a Mosaic with Cropland	16.88	16.90	16.72
Closed to Open Canopy Broadleaved Evergreen Tree Cover	24.03	26.09	27.11
Closed to Open Canopy Broadleaved Deciduous Tree Cover	2.37	2.33	2.37
Closed Canopy Broadleaved Deciduous Tree Cover	0.11	0.12	0.13
Closed to Open Canopy Needleleaved Evergreen Tree Cover	20.79	21.19	21.78
Mostly Trees and Shrubs in a Mosaic with Herbaceous Cover	16.73	17.06	17.81
Mostly Herbaceous Cover in a Mosaic with Trees and Shrubs	0.01	0.01	0.01
Shrubland	5.88	3.02	0.82
Evergreen Shrubland	4.85	4.84	4.79
Grassland	0.16	0.16	0.16
Saline Water Flooded Tree Cover	0.03	0.03	0.05
Urban Areas	0.02	0.02	0.05
Bodies of Water	0.00	0.00	0.00

Most changes in land use and land cover are minimal, however, two outstanding changes have been highlighted. The shrublands in the basin have almost all been replaced by tree cover between 1992 and 2012, which is around 5% of the total catchment area. Reforestation leads to higher actual ET as the density of vegetation usually increases [45] [46]. At the same time, reforestation also decreases the soil moisture content as the large tree roots absorb a lot of water from the soil [47].

Another remarkable change in land use is the increase in urban areas. Although the percentages of the total catchment area are very low, the urban areas have been increased more than twice in size between 2002 and 2012 (736 km^2), which indicates a rapid urbanization. In urban areas, the actual evaporation and infiltration to the soil are reduced and therefore disturbing the natural water balance [48] and increasing the runoff [46]. At the same time, the increase in urban areas suggests that the flows in the water cycle are changing, as new urban areas abstract water from the water cycle for, amongst others, domestic and industrial purposes.

These changes in land cover and land use according to Table 5 contribute to changes in the water system of the Black River and therefore also to changes in the streamflow regime. However, the mentioned changes as reforestation and urbanization are long-term processes, and they do not explain the sudden change in streamflow in 2008 and onwards. Therefore, land use and land cover changes are not accepted as cause of the sudden streamflow reduction in 2008 and onwards based on Table 5.

Water storage reservoirs as a cause of reduced streamflow

Dams are constructed often nowadays in rivers. Usually, the main reason behind such projects is the enormous amount of electricity that can be obtained through hydropower. There are also other advantages: hydropower is generally green energy, meaning that it is a sustainable way of gathering electricity. Another advantage is that during extreme weather events, water storage reservoirs can play a key role in regulating water: storing water in advance to minimize issues related to droughts and storing water during a heavy rain event to reduce the damage due to floods downstream [13]. Based on the equation that inflow must equal outflow in any study area, filling a reservoir with water after its construction increases the water storage of the catchment and reduces downstream flow. The filling process of a water storage reservoir can take up to multiple years, depending on the reservoir size, and takes a large amount of water resources, which affects the downstream regime significantly [14]. Once a reservoir has been filled, the operating rules of a dam have an impact on the downstream regime [15]. Operating rules are based on the objectives of the exploiting company or institute and regulations set by governments, determining how much water is being discharged through the dam and in which period of the year. In general, more water will be released during dry periods and more water will be stored in wet periods. Figure D1 in appendix D shows the hydropower dams and storage reservoirs in the Black River basin. The dams and reservoirs that are located upstream of Lai Chau and therefore relevant to this research are displayed in Table 6 [49], showing their total storage volume, date of construction and first date of operation. Not for all reservoirs, these relevant properties could be retrieved unfortunately.

Table 6 – Properties of dams and reservoirs in the Chinese part of the Black River basin

Name	*Total storage volume (m^3)*	*Start construction*	*First operation*
Ya Yang Shan	247 000 000	2003	2006
Shimenkan	197 000 000	2007	2010
Meng Ye Jiang	< 50 000 000	??	??
Longma	590 000 000	2003	2008
Xin Ping Zhai	< 50 000 000	??	??
Unknown	??	??	??
Unknown	??	??	??
Zhong Ai Qiao	< 50 000 000	??	??
Chang Tian	> 50 000 000	??	??
Pu Xi Qiao	521 000 000	??	??
Sinan Jiang	271 000 000	2003	2008
San Jiang Kou	> 50 000 000	??	??
Jufudu	174 000 000	2004	2008
Gelantan	409 000 000	2006	2008
Tukahe	88 000 000	2003	2008

It becomes clear that at least five dams have been commissioned in 2008, meaning that they have started filling their water storage reservoirs from 2008 onwards and thereby reducing the streamflow. This pattern coincides with the changes in the streamflow timeseries at Lai Chau in 2008 and later. Based on this qualitative analysis, the filling process of water storage reservoirs is accepted as partial cause of the sudden reduced streamflow in 2008. Also in other years, the commissioning of dams and reservoirs may affect the streamflow regime of the Black River basin.

4.3. Performance of the VIC-model for the Black River basin

In this section, the used key performance indicators (KPI's) are explained first. Secondly, the calibrated parameters are shown. Thirdly, the model performance is visualized by KPI-values and hydrographs.

Key performance indicators

The used key performance indicators to assess the VIC-model performance are the Nash-Sutcliffe Efficiency (NSE), the Root Mean Square Error (RMSE) and the model bias. In equation 5, 6 and 7, *t* represents the observation number and *T* represents the total number of observations. *Q* indicates the discharge, where *sim* stands for simulated and *obs* for observed. The unit of RMSE and BIAS are m^3/s.

$$NSE = 1 - \frac{\sum_{t=1}^{T}\left(Q_{sim,t} - Q_{obs,t}\right)^2}{\sum_{t=1}^{T}\left(Q_{obs,t} - Q_{obs,mean}\right)^2} \quad (5) \qquad RMSE = \sqrt{\frac{\sum_{t=1}^{T}\left(Q_{sim,t} - Q_{obs,t}\right)^2}{T}} \quad (6) \qquad BIAS = \frac{\sum_{t=1}^{T} Q_{sim,t} - Q_{obs,t}}{T} \quad (7)$$

The NSE indicates the extent to which a hydrological model can predict discharges. A NSE value of 1 suggests a perfect predicting model and a value of 0 or lower indicates that the observed mean has an equal or better variance with respect to observed values than model predictions, which is not desirable. The RMSE is the square root of the mean of squared errors, meaning that large differences between simulated and observed values have a large impact on the RMSE, and therefore it is sensitive to outliers. A lower RMSE indicates a better model performance for peaks to the point where 0 indicates a precise data fit, however the value of RMSE is dependent on the scale of the simulated and observed values. The SCE-UA algorithm generates parameter sets based on the objective function that minimizes RMSE.

Calibrated soil parameters

The initial and calibrated soil parameters and their ranges are displayed in Table 7. Calibration ranges were obtained using regionalization from the Mekong River basin [22].

Table 7 – Description and values of calibrated soil parameters

Parameter	*Description*	*Initial*	*Calibration range*	*Final*
b_{inf} (-)	Variable Infiltration Capacity curve parameter	0.2	0.002 – 0.495	0.064
Ds (-)	Part of D_{max} where nonlinear baseflow begins	0.001	0.019 – 0.875	0.077
D_{max} (mm/day)	Maximum baseflow in millimeters per day	4	2.653 – 29.983	26.543
Ws (-)	Part or fraction of maximum soil moisture where nonlinear baseflow occurs	0.9	0.1 – 0.984	0.639
$Soil_{d2}$ (m)	Thickness of second soil layer in meters	0.7	0.497 – 1.491	0.921
$Soil_{d3}$ (m)	Thickness of third soil layer in meters	0.7	0.497 – 1.491	0.760

Model performance

The calibrated values are based on the model runs with a 0.5° spatial resolution. These are inserted in the model running on a 0.1° spatial resolution. Table 8 displays the performance of these model runs.

Table 8 – VIC-model performance expressed in NSE, RMSE and BIAS

KPI	*No calibration 1980-2007*	*Split-sample calibration 1980-1993*	*Split-sample validation 1994-2007*	*Proxy-basin validation 1980-2006 (corrected)*
NSE	0.73	0.86	0.87	0.77 (0.88)
RMSE	497.79 m^3/s	332.68 m^3/s	374.32 m^3/s	336.37 (321.57) m^3/s
BIAS	-43.44 m^3/s	31.27 m^3/s	-33.25 m^3/s	-12.38 (-2.89) m^3/s

The performance of the VIC-model seems to be appropriate based on the key performance indicators, also when comparing KPI-values to other VIC-modelling studies in the Black River basin. The model bias is changingly positive and negative, showing that there is no general over- or undershooting. A 1-year warm-up period was used for simulations, based on VIC-documentation [29]. Figure 15 shows hydrographs of the split-sample test.

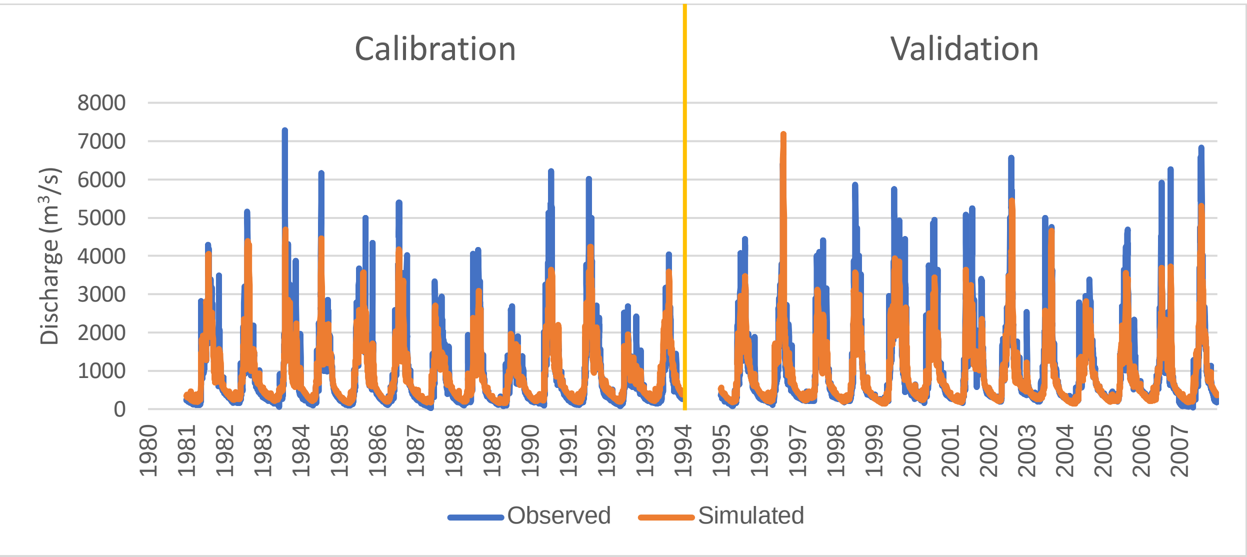


Figure 15 – Hydrograph of the split-sample test using the observed Lai Chau data (1980-2007)

Some inconsistencies in the observed data of Muong Te were noted which were eliminated by data processing: 2 missing values were added by taking the average of the previous and next timestep. Next to that, 6 values showed disproportionate higher values than the Lai Chau downstream timeseries. A regression analysis was performed for the observed values from both timeseries, visible in Figure G1 in appendix G. A linear regression line was used to correct these values. The performance after correction is shown in Figure 16 and has increased as can be seen by the KPI values in Table 8 between brackets.

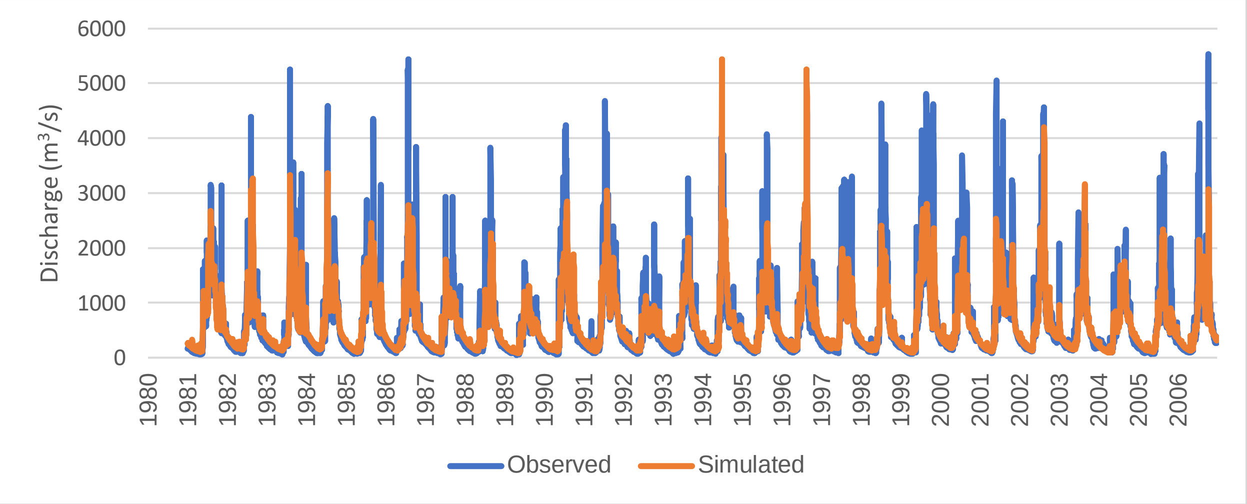


Figure 16 – Hydrograph of the proxy-basin test using the observed Muong Te data (1980-2006)

The validation hydrographs emphasize that the VIC-model is especially undershooting in the wet season.

4.4. Impacts of human interventions using the VIC-model

This chapter quantifies the impacts of human interventions on the flow regime of the Black River. First, the impacts of LULC changes are displayed and secondly the impacts of reservoirs are presented.

Impacts of land use and land cover changes

The VIC-model was run for the period 1980-2018 with three different LULC-maps from 1992, 2002, 2012 and 2019. The simulated annual streamflow at Lai Chau is shown in Figure 17 for all four scenarios.

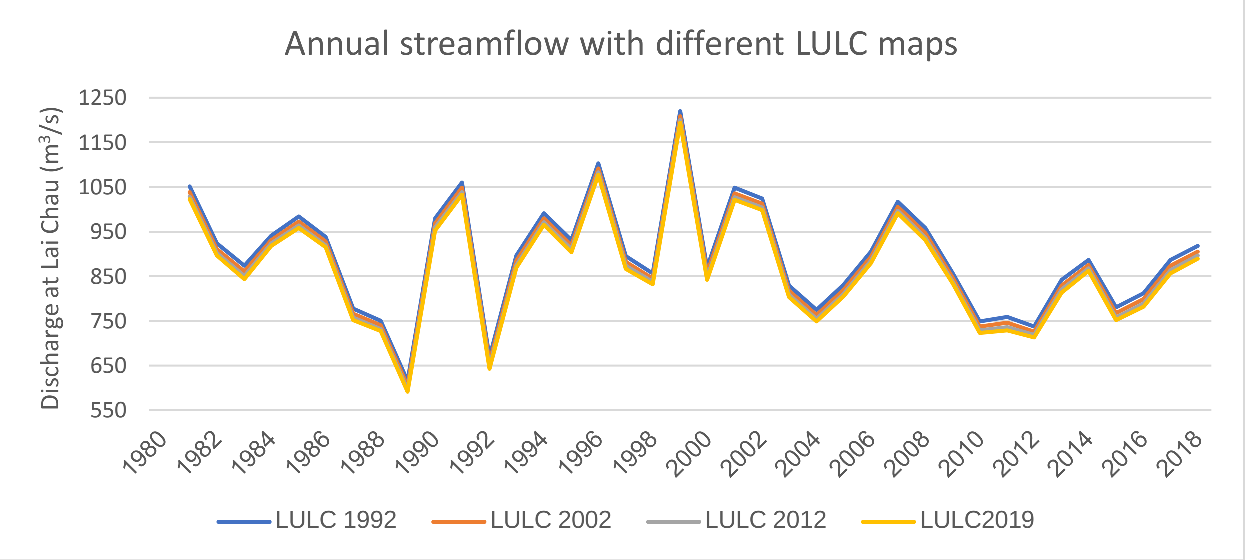


Figure 17 – Hydrographs of Lai Chau using LULC maps of 1992, 2002, 2012 and 2019

On an annual scale, the impacts of LULC changes are small but consistent. The changes in land use and land cover over time reduce the streamflow. The land use and land cover in 1992 leads to the highest streamflow, the land use and land cover in 2002 leads to smaller streamflow and the land use and land cover in 2012 leads to the lowest streamflow. The average discharges over the period 1981-2018 and the absolute and relative changes in streamflow due to LULC changes are displayed in Table 9.

Table 9 – Absolute and relative changes in streamflow due to LULC changes

Year of LULC map	*Average discharge*	*LULC impact period*	*Absolute change*	*Relative change*
1992	893.05 m^3/s	1992-2002	-11.82 m^3/s	-1.32%
2002	881.22 m^3/s	2002-2012	-8.67 m^3/s	-0.98%
2012	872.55 m^3/s	2012-2019	-5.96 m^3/s	-0.68%
2019	866.59 m^3/s	1992-2019	-26.46 m^3/s	-2.96%

Impacts of water storage reservoirs

To resemble the real scenario as described in method section 3.4, the VIC-model is run for the period 1980-2018 with the LULC map from 2012. Figure 18 displays the simulated hydrograph at Lai Chau, representing the annual average natural flow without reservoir impacts, and the observed streamflow timeseries at Lai Chau, representing the annual average flow from the real scenario which is impacted by reservoirs. For the impacts of the reservoirs, the period from 2008 and onwards is analyzed. Figure 19 displays the monthly averaged streamflow for the period 2008-2018 to show the seasonal impacts. The wet season lasts from 01-05 to the 31-10 and the dry season lasts from the 01-11 to the 31-04.

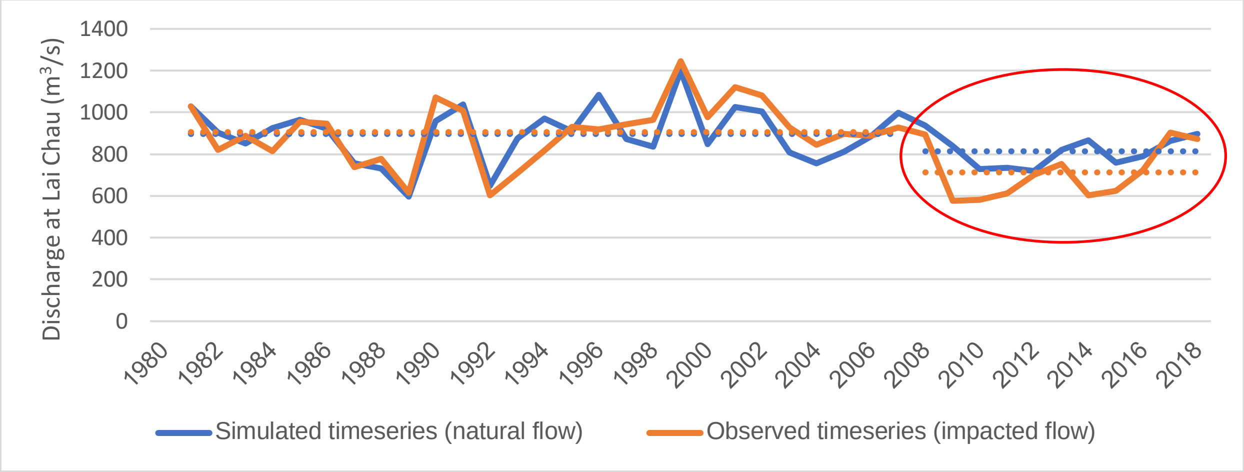


Figure 18 – Hydrograph showing naturalized (simulated) and impacted (observed) flow (1980-2018)

The graphs show that the simulated and real scenario are similar in the period up to 2007 and that the average observed impacted flow from 2008 onwards is significantly lower, 712.65 m^3/s, than the average simulated natural flow, 813.75 m^3/s. The impacts of reservoirs are quantified by subtracting the observed impacted flow from the simulated natural flow. The reservoirs cause an absolute streamflow reduction of 101.1 m^3/s after 2008, which is a relative reduction of 12.42%. Next to that, the impacts of reservoirs are accountable for 52.66% of the average streamflow reduction in the period before and after 2008 (192 m^3/s) from the results in 4.1. In 2017, the flow regimes seem to be similar again, possibly indicating that the reservoirs have been filled. Based on this quantitative analysis, reservoir impacts are accepted as partial cause of the streamflow change in 2008.

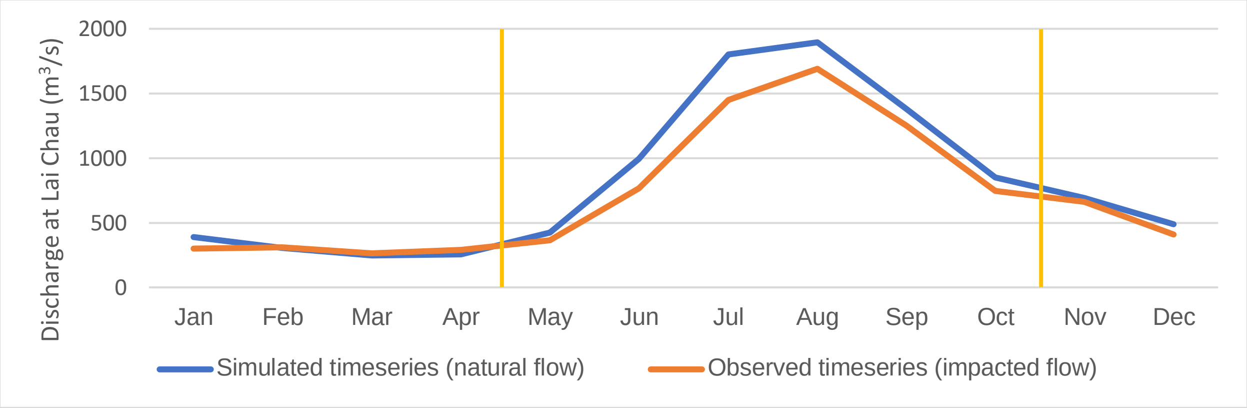


Figure 19 – Hydrographs showing natural and impacted monthly average streamflow (2008-2018)

The observed flow during the wet season has overall reduced significantly from 2008, compared to the simulated flow. This indicates that the impacts of reservoirs are significant in the wet season. Changes in the dry season are relatively small, meaning that the reservoirs are mainly filled during the wet season. The changes in dry and wet months were averaged separately, to quantify the changes in Table 10. The wet season is responsible for 88% of the annual streamflow reduction and the dry season for 12%.

Table 10 – Absolute and relative changes in streamflow due to reservoir impacts

Season	*Simulated discharge*	*Observed discharge*	*Absolute change*	*Relative change*
Wet	1224.33 m^3/s	1044.88 m^3/s	-179.44 m^3/s	-14.66%
Dry	395.33 m^3/s	371.98 m^3/s	-23.35 m^3/s	-5.91%

5. Discussion

This chapter reviews the performed research study on human interventions in the Black River basin. First, the potential is described by connecting key findings to the research questions. Secondly, the limitations of this research study are acknowledged. Finally, a generalization is provided, suggesting possible general applications of the methods and general usage of the results from this research.

5.1. Potential

The research objective of this study was to assess the impacts of human interventions on the hydrological regime of the Black River catchment qualitatively and quantitatively by running experiments with the VIC-model. These impacts have been assessed in results sections 4.2 and 4.4.

"What are the differences in measured streamflow in the Vietnamese part of the Black River basin before 2008 and from 2008 onwards, considering the dry and wet season?"

According to the problem statement, the discharges in the Black River basin have been reduced from 2008 onwards. Results chapter 4.1 shows that this is indeed the case. The derived streamflow timeseries at Lai Chau show an average annual discharge reduction of 21% from 888 m^3/s in the period 1965-2007 to 696 m^3/s in the period 2008-2021. On a seasonal scale, the streamflow has reduced in the wet seasonal months by averagely 419 m^3/s and has increased in the dry seasonal months by 19.3 m^3/s.

"What is the main cause of the reduced measured streamflow in the Vietnamese part of the Black River basin from 2008 onwards?"

From the water balance in chapter 4.2, it appeared that variability in climate seems to be accountable for a precipitation decrease of 195.7 mm in 2008, which is 49.7% of the 393.5 mm streamflow reduction. Climate variability therefore has a significant share in the reduced streamflow at Lai Chau in 2008.

The land use and land cover maps of 1992 and 2012 showed that 5% of the area in the Black River basin has been transformed from shrublands to forests. The urban areas in the Black River basin have tripled from 0.016% to 0.052% of the total catchment area, which is 961 km^2. Reforestation increases evaporation and reduce streamflow in the long term [45]. Urbanization increases streamflow as the evaporation and infiltration flows reduce [48]. LULC changes are generally long-term processes, that do not cause sudden changes in streamflow.

There are 15 water storage reservoirs in the Black River basin presently, of which at least 5 have been commissioned in 2008. The filling process of these reservoirs increases the water storage of the basin and thereby reduces the downstream discharge [13]. As these reservoirs have a significant storage volume, their filling process seems to play a large role in the streamflow reduction.

"What is the performance of the VIC-model in the Chinese part of the Black River basin while using remote sensing data and parameter estimations due to limited measurement data availability?"

The model performance at Lai Chau in terms of the key performance indicators NSE and RMSE is shown in 4.3 and is respectively 0.86 and 332.68 during the calibration and respectively 0.87 and 374.32 during the split-sample validation. The model performed properly at Muong Te as well, with a NS-value of 0.77 and RMSE-value of 336.37 before data correction and 0.88 and 321.57 after data correction.

“What are the differences between measured and simulated streamflow of the VIC-model in the Vietnamese part of the Black River basin from 2008 onwards, considering the dry and wet season?”

The differences in simulated streamflow with different LULC maps are small according to 4.4. With the LULC map from 1992, the average annual discharge is 893.05 m^3/s and with the LULC map from 2019, the average annual discharge is 866.59 m^3/s, which is a reduction of 3% over 27 years of LULC changes.

The average annual measured flow from 2008 to 2018, which is real and impacted by reservoirs, is 712.65 m^3/s. The average annual simulated flow from 2008 to 2018, which is natural and not impacted by reservoirs, is 813.75 m^3/s. The average discharge is reduced by 101.1 m^3/s, equal to 12.42%. During the wet season, the decrease is much larger, 179.44 m^3/s, than in the dry season, 23.35 m^3/s. The impacts of reservoirs are accountable for 52.67% of the total sudden streamflow reduction in 2008.

5.2. Limitations

The largest limitation in this research is the reliability on available data. In order to properly model the Black River basin, a lot of data is required, especially for a fully distributed model as the VIC-model. When the input data is uncertain or estimated, the outputs also have a certain degree of uncertainty. In this research, there are many inputs that contain uncertainty or are inaccurate:

- The meteorological forcings wind speed and minimum and maximum temperature are obtained from a global reanalysis product, which are not accurate as was shown for precipitation in 3.1.
- The soil map is detailed in China, however for the Vietnamese part of the considered basin, only one soil type is identified. This reduces the accuracy of the soil parameters and properties.
- A limited amount of land use and land cover classes is considered. Multiple types of forests are included, however for agriculture, only one general type is used by the LULC classification.
- Soil layer depths and variable infiltration curve parameters are not physically measurable, therefore they are estimated and optimized. Optimizing is a way to increase the model performance for a specific case study, but it is still uncertain if these parameters reflect reality.
- The routing model accepts uniform and spatially distributed flow parameters. In this study, the flow speed and flow diffusion were uniformly assumed for the whole basin due to a lack of data. These variables are spatially distributed in reality and have different values throughout the basin. The use of uniform flow parameters reduces the accuracy of the streamflow output.

Normally, the calibration and validation are used to correct parameters that are estimated by comparing it to reliable observed data. Unfortunately, in this research, also the observed streamflow timeseries are derived, and not directly measured, meaning that the evaluation materials for the model also contain uncertainty. The regression analysis in appendix G shows that there is a systematic error in the method of deriving the discharge timeseries or in the measurement data. Since Lai Chau is located downstream of Muong Te, at every timestep all the discharges at Lai Chau should be larger than the discharges at Muong Te. There are many datapoints above the orange line, indicating that at that timestep, the discharge is larger at Muong Te than at Lai Chau, which should not be possible. The rating curve from 2005 might not be applicable to the whole Muong Te water level timeseries as there are changes in the river profile and flow regime over time. Furthermore, the subtraction of the discharges at the old Lai Chau station and the Nam Giang station might not reflect the discharge at the new Lai Chau station properly. Possible reasons for this are the neglection of the sub basin in between these stations and the impacts of reservoirs on the flow regime at Nam Giang and the old Lai Chau station.

A second limitation in this research is the calibration and validation process. The hydrographs in section 4.3 show that the model is undershooting in the wet season. Figure 18 confirms this model behaviour when looking at the period 1980-2007. The simulated annual discharges are, with a few exceptions, a bit lower than the observed annual discharges. Some assumptions were made in the used methods that are debatable and could decrease the trustworthiness and reliability of the model:

- As explained, the observed discharge timeseries contains errors. By using these timeseries to improve the reflection of the basin in the model by calibrating and validating, the basin representation might instead become worse. This reduces the quality of the model outputs.
- In the auto calibration process, a coarse spatial resolution of 0.5° for the grid cells of the Black River basin was used instead of the 0.1° grid cells to reduce the model run time. Although this is suggested by the VIC-documentation, it is questionable whether the basin representation is still accurate and to what degree the optimized soil parameters represent the basin when running the model for the Black River basin with the fine spatial resolution of 0.1° grid cells.
- The optimized parameters are assumed and optimized uniformly, however in reality they might be spatially distributed, which can be considered by the VIC-model. Including the spatial distribution of these soil parameters in the auto calibration process could increase the possible parameter sets exponentially. It would take much more model runs, and thereby time, before finding a global optimum of parameter sets. Therefore, it was chosen to use uniform parameters in this research, but it reduces the quality of the model representation of the Black River basin.

The last important limitation is the method that is used for assessing impacts of human interventions.

The land use and land cover changes are assessed by running the VIC-model with LULC maps from different years. To quantify the changes in land use and land cover, a comparison of values must be done. The value that is compared in Table 9 is the average streamflow of all the annual streamflow values between 1980 and 2018. However, the land use and land cover in a particular year only affect the streamflow in that same year. Therefore, the annual streamflow in any other year besides 1992 may not represent the impacts of land use and land cover in 1992 and similar for 2002, 2012 and 2019.

The impacts of water storage reservoirs are quantified by comparing the natural flow to the impacted flow in results section 4.4. The possible impacts of reservoirs are expressed as the total storage volume of the reservoirs in results section 4.2. However, there are more factors that contribute to the impacts of the reservoirs than the storage volume solely, as the construction of water storage reservoirs interacts with more flows than the water storage of the basin. The presence of water storage reservoirs affects the microclimate, thereby significantly increasing the actual evaporation in their proximity [50], and reducing the downstream flow. Seepage of water into surrounding soil and seepage through dam foundations lead to water losses that are not incorporated in the storage volume of reservoirs. These impacts of reservoirs are not considered in this study.

Assessing impacts of human interventions and climate change by means of a water balance can be a powerful tool. In this study, the full potential of the water balance has not been used. If the actual evapotranspiration was estimated accurately for the Black River basin, the water balance could have been used to display the changes in water storage of the basin. These could help to make stronger claims about the impacts of land use and land cover changes and the construction of reservoirs. Furthermore, the changes in water storage of the basin according to the water balance could support the quantitative impacts of human interventions that are obtained by using the VIC-model.

5.3. Generalization

This research used a water balance approach to assess the impacts of human interventions qualitatively and the VIC-model to assess impacts of human interventions quantitatively. General application of these methods is discussed here. Next to that, the usability of the results from this research are discussed.

The water balance approach uses precipitation, potential or actual evapotranspiration and streamflow timeseries to estimate the changes in water storage of a basin. It is a very powerful, yet relatively simple tool that can be applied to any study area. A requirement for the use of the water balance is that the timeseries must be accurate. When using inaccurate datasets with the water balance, it will yield a wrong reflection of the water storage changes in a catchment, as the order of magnitude of the precipitation, evaporation and streamflow is generally larger than the order of magnitude of the water storage changes in a basin. Small inaccuracies in these datasets lead to large errors in the representation of the water storage changes. It is difficult to separate impacts of human interventions by means of a water balance alone. Impacts of climate change and variability on streamflow are separatable from those of human interventions as the water storage change is based on a subtraction of climate forcings.

The VIC-model seems to be a sophisticated model that requires a lot of input data. If these can be acquired for a particular basin, and the user understands the functionality of the model, it might give an accurate representation of the streamflow in that basin. Results section 4.3 showed high NSE-values, indicating that the simulated data is a good representation of the observed data. As some parameters are not measurable, they will have to be estimated and could be different for any basin. By calibrating and validating the model, the accuracy of these parameter estimations might increase. When applying the VIC-model to another basin, a reanalysis climate forcing dataset may be used. However, initial VIC-model runs with the ERA-interim dataset did not yield NSE values larger than 0.6. It seems that the model outputs are sensitive to meteorological datasets, therefore these should be selected carefully.

The VIC-model offers many options for many practical applications. In this research, the VIC-model is used to estimate natural streamflow by using the rainfall-runoff and the routing model. The VIC-model gives many output fluxes for every grid cell, which can be used for various hydrological purposes such as water and energy balance calculations, streamflow simulation and forecasting, reservoir water management and climate change studies. Lastly, the VIC-model community offers anthropogenic impact modules to represent specific phenomena, such as water storage reservoirs, irrigation areas, industry areas and domestic areas [51]. Again, if a user would like to use these modules, a lot of data on the location and water demand of these areas is required.

Assessing LULC changes by using different LULC maps in VIC-model runs is possible, but the results would be more accurate by using the mentioned modules, as they include specific land uses which are not captured by LULC maps. As the land cover classification is coarse and methods of assessing LULC changes involve a lot of uncertainty, the results may not be accurate. Therefore, it is not recommended to use them in further research. The method to assess water storage reservoirs with the VIC-model is also used by other studies and the quantified impacts are in line with the expectations. Therefore, this method could be applicable in other case studies and the reservoir impact results could be used for future research.

6. Conclusions and Recommendations

In this chapter, conclusions about the research are drawn based on the results and the discussion. Lastly, recommendations for improvement of this research and future research are provided.

6.1. Conclusions

Climate change and human interventions affect the hydrological regime of the Black River basin. It was found that climate variation and the construction of water storage reservoirs have instantaneous impacts on the flow regime, while climate change and land use and land cover changes cause gradual changes in the flow regime over time. The VIC-model and water balance seem appropriate tools for impact assessments, however accurate datasets of meteorological forcings are a prerequisite.

Streamflow has reduced in 2008 in the Vietnamese part of the Black River basin by 21%. A water balance showed that a precipitation reduction in the same year could account for up to 50% of this discharge reduction, depending on the amount of actual evapotranspiration. The VIC-model showed that the commissioning of water storage reservoirs accounts for 53% of the total streamflow reduction in 2008.

Over 40 years, the precipitation has been reduced by 2.3%, which suggests a small impact of climate change, however according to the Mann-Kendall test, this is not a trend but only natural variation.

Human interventions seem to play a large role in the Black River basin. Between 1992 and 2012, 5% of the basin area was subject to reforestation and the urban areas tripled during this period, thereby affecting the water storage of the catchment and affecting the hydrological regime. The streamflow has been reduced by 3% due to changes in land use and land cover between 1992 and 2019.

Between 2003 and 2018, 15 dams and water storage reservoirs were constructed in the Chinese part of the Black River basin. Their filling processes increase the water storage of the basin and affect the flow regime. The operation of these reservoirs mainly affects the hydrological regime. In the period 2008-2018, the average streamflow has been reduced by 12.4% due to the impacts of reservoirs compared to the average streamflow in the period before 2008. The wet season from May to October is responsible for 88% of this streamflow reduction and the dry season from November to April is responsible for 12% of the streamflow reduction. This suggests that the water storage reservoirs are mainly being filled during the wet season. The natural and impacted flow are similar from 2017 onwards, possibly indicating that the water storage reservoirs have been filled totally.

Using the VIC-model while having limited availability to data seems a difficult task, however, a model performance with a NSE value of 0.87 was reached during the calibration. It is of utmost importance to select accurate meteorological forcing datasets as they have a large sensitivity to the model output. The VIC-model heavily relies on calibration as some parameters are not physically measurable. Therefore, an accurate observed dataset is necessary to be able to quantify these parameters properly for the Black River basin by calibration. In general, the VIC-model undershoots peak discharges during wet seasons. The potential of the water balance is high, but to use it, accurate actual evapotranspiration and precipitation datasets are required. For the Black River basin, good actual evapotranspiration datasets are hard to acquire. For precipitation, the CMFD and VnGP datasets provide a very good fit.

6.2. Recommendations

The performance of the VIC-model is sensitive to the precipitation dataset. For this research, accurate regional datasets for China (CMFD) and Vietnam (VnGP) have been used. However, these datasets only provide timeseries from 1979-2018 and 1980-2018. For future research in the Black River basin, it is recommended to find or establish gridded precipitation datasets with larger timespans. This could be accomplished by using measurement station data and interpolation techniques or by finding an accurate global data product and applying correction to it. It is not recommended to use the ERA-Interim data product, as its performance is inaccurate in the Black River basin.

It is recommended to use a water balance approach to quantify changes in water storage. An accurate actual evapotranspiration timeseries and precipitation timeseries should be established in order to properly estimate changes in water storage. This timeseries can also be used to calibrate and validate the VIC-model (in absence of observed streamflow data), as one of the rainfall-runoff model flux outputs is actual evapotranspiration. Based on the simulated and observed actual evapotranspiration, parameters can be optimized, thereby increasing the credibility of the VIC-model.

Some of the parameters of the VIC-model have been assumed uniformly for the whole basin in this research. In order to increase the accuracy of model outputs, it is recommended to consider the spatial variability of flow speed, flow diffusion and maximum baseflow. Next to that, the spatial variability of elevation in the Black River basin could be specified more by using elevation bands. Currently, grid cells are assumed to be flat, however in reality, there is a lot of elevation variability within grid cells as the upstream part of the Black River basin is a mountainous area.

The calibration and validation of the VIC-model is important. In this research, the best parameter set from the auto calibration procedure has been chosen to represent unmeasurable soil parameters. However, there is still a large uncertainty in the validity of these values. It is recommended to quantify this uncertainty by creating confidence intervals for the model output. This could be done by picking a number of appropriate parameter sets from the auto calibration procedure and by running the model with all of these parameter sets. This will give some insights on uncertainties in the streamflow output.

The changes in land use and land cover could be estimated better by representing them better in the VIC-model experiments. Instead of only using different land use and land cover maps for the model runs, also the temporal variability in Albedo and Leaf Area Index values could be included. Modules for specific land use types as irrigation, domestic and industry areas could be implemented in the VIC-model too. In order to do so, data on the locations and water demand of these purposes should be acquired.

In this research, the VIC-model has been used to simulate natural flow by representing the Black River basin in the past. Future research regarding forecasting of streamflow with climate forcing predictions would need a representation of the Black River basin in its current state. A module to represent water storage reservoirs could be included in the VIC-model to display the current Black River basin. This will also allow to estimate and analyze impacts of different operating rules of upstream hydropower dams.

References

[1] X. Wei, S. Sauvage, T. P. Q. Le, S. Ouillon, D. Orange, V. D. Vinh and J. Sanchez-Perez, "A Modeling Approach to Diagnose the Impacts of Global Changes on Discharge and Suspended Sediment Concentration within the Red River Basin," *Water,* pp. 958-983, 2019.

[2] Y. Li, D. L. X. He, Y. Zhang and L. Yang, "Contributions of Climate Variability and Human Activities to Runoff Changes in the Upper Catchment of the Red River Basin, China," *water,* pp. 1-16, 2016.

[3] J. Wang, H. Ishidaira and Z. X. Xu, “Effects of climate change and human activities on inflow into the Hoabinh Reservoir in the Red River basin,” *Procedia Environmental Sciences,* pp. 1688-1698, 2012.

[4] J. Gao, Z. Dai, X. G. Z. Mei, W. Wei and H. L. S. Xie, "Interference of natural and anthropogenic forcings on variations in continental freshwater discharge from the Red River (Vietnam) to sea," *Quaternary International,* pp. 1-10, 2015.

[5] J. Wu, C. Miao, X. Zhang, T. Yang and Q. Duan, "Detecting the quantitative hydrological response to changes in climate change and human activities," *Science of Total Environment,* 2017.

[6] B. D. Richter, J. V. Baumgartner, J. Powell and D. P. Braun, "A Method for Assessing Hydrologic Alteration within Ecosystems," *Conservation Biology,* pp. 1163-1174, 1996.

[7] D. A. Stonestrom, B. R. Scanlon and L. Zhang, "Introduction to special section on Impacts of Land Use Change on Water Resources," *Water Resources Research,* pp. 1-3, 2009.

[8] T. Perminova, N. Sirina, B. Laratte, N. Baranovskaya and L. Rikhvanov, "Methods for land use impact assessment: A review," *Environmental Impact Assessment Review,* pp. 64-74, 2016.

[9] T. N. Le, A. K. Bregt, G. E. van Halsema, P. J. G. J. Hellegers and L.-D. Nguyen, "Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta," *Land Use Policy,* pp. 269-280, 2018.

[10] Y. Li, D. He and C. Ye, "Spatial and temporal variation of runoff of Red River Basin in Yunnan," *Journal of Geographical Sciences,* pp. 308-318, 2008.

[11] N. C. Q. Truong, H. Q. Nguyen and A. Kondoh, "Land Use and Land Cover Changes and Their Effect on the Flow Regime in the Upstream Dong Nai River Basin, Vietnam," *water,* pp. 1-15, 2018.

[12] X. Yang, L. Ren, Y. Liu, D. Jiao and S. Jiang, "Hydrological response to land use and land cover changes in a sub-watershed of West Liaohe River Basin, China," *Journal of Arid land,* pp. 678-689, 2014.

[13] B. Đorđević and T. Dašić, "Water storage reservoirs and their role in the development, utilization and protection of catchment," *Spatium,* pp. 9-15, 2011.

[14] D. H. Cuong, N. L. Dan, B. T. B. Anh, N. T. Nhan, N. X. Tung, P. D. Hung and N. T. Linh, "Assessment of impacts of utilization on water resources in the basin of trans-boundary Red river system," *Vietnam Journal of Marine Science and Technology,* pp. 497-505, 2019.

[15] X. Yun, Q. Tang, J. Wang, X. Liu, Y. Zhang, H. Lu, Y. Wang, L. Zhang and D. Chen, "Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin," *Journal of Hydrology,* pp. 1-11, 2020.

[16] M. Hrachowitz, H. H. G. Savenije, G. Blöschl, J. J. McDonnell, M. Sivapalan, J. W. Pomeroy, B. Arheimer, T. Blume, M. P. Clark, U. Ehret, F. Fenicia, J. E. Freer, A. Gelfan, H. V. Gupta, D. A. Hughes, R. W. Hut, A. Montanari, S. Pande and D. Tetzlaff, "A decade of Predictions in Ungauged Baisns (PUB) - a review," *Hydrological Sciences Journal,* pp. 1-51, 2013.

[17] X. Guo, Z. Wu, H. He and Z. Xu, "Evaluating the Potential of Different Evapotranspiration Datasets for Distributed Hydrological model Calibration," *remote sensing,* pp. 1-21, 2022.

[18] G. Simons, W. Bastiaanssen, L. A. Ngô, C. R. Hain, M. Anderson and G. Senay, "Available ET products for the Red Rver Basin and the construction of an ensemble ET product," *remote sensing,* pp. 1-28, 2016.

[19] M. Cucchi, G. P. Weedon, A. Amici, N. Bellouin, S. Lange, H. M. Schmied, H. Hersbach and C. Buontempo, "WFDE5: bias adjusted ERA5 reanlysis data for impact studies," *Earth System Science Data,* pp. 1-32, 2020.

[20] G. Falalakis and A. Gemitzi, "A simple method for water balance estimation based on the empirical method and remotely sensed evapotranspiration estimates," *Journal of Hydroinformatics,* pp. 440-451, 2020.

[21] E. Vonk, Y. P. Xu, M. J. Booij, X. Zhang and D. C. M. Augustijn, "Adapting Multireservoir Operation to Shifting Patterns of Water Supply and Demand," *Water Resources Management,* pp. 625-643, 2014.

[22] T. D. Dang, A. F. M. K. Chowdhury and S. Galelli, "On the representation of water reservoir storage and operations in large-scale hydrological models: implications on model parameterization and climate change impact assessments," *Hydrology and Earth System Sciences,* pp. 397-416, 2020.

[23] S. Foppes, "Regionalisation Based on Basin Characteristics Applied to Flood Forecasting in the Da River," Enschede, 2005.

[24] A. E. Odusanya, K. Schulz and B. Mehdi-Schulz, "Using a regionalisation approach to evaluate streamflow simulated by an ecohydrological model calibrated with global land surface evaporation from remote sensing," *Journal of Hydrology: Regional Studies,* pp. 1-29, 2022.

[25] A. E. Odusanya, B. Mehdi, C. Schürz, A. O. Oke, O. S. Awokola, J. A. Awomeso, J. O. Adejuwon and K. Schulz, "Multi-site calibration and validation of SWAT with satellite-based evapotranspiration in

a data-sparse catchment in southwestern Nigeria," *Hydrology and Earth System Sciences,* pp. 1113-1144, 2019.

[26] Vietnam Electricity (EVN).

[27] M. T. Anees, K. Abdullah, M. N. M. Nawawi, N. N. N. A. Rahman, A. R. M. Piah, N. A. Zakaria, M. I. Syakir and A. K. M. Omar, "Numerical modeling techniques for flood analysis," *African Earth Sciences,* pp. 478-486, 2016.

[28] X. Liang, D. P. Lettenmaier, E. F. Wood and J. S. Burges, "A Simple hydrologically Based Model of Land Surface Water and Energy Fluxes for GSMs," *Journal of Geophysical Research,* pp. 14415-14428, 1994.

[29] University of Washington Computational Hydrology Group, "VIC Model Overview," 2021. [Online]. Available: https://vic.readthedocs.io/en/master/Overview/ModelOverview/.

[30] D. Lohmann, R. Nolte-Holube and E. Raschke, "A large-scale horizontal routing model to be coupled to land surface parametrization schemes," *Tellus,* pp. 708-721, 1996.

[31] D. Lohmann, E. Raschke, B. Nijssen and D. P. Lettenmaier, "Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model," *Hydrological Sciences Journal,* pp. 131-141, 1998.

[32] Q. Duan, S. Sorooshian and V. K. Gupta, "Optimal use of the SCE-UA global optimization method for calibrating watershed models," *Journal of Hydrology,* pp. 265-284, 1994.

[33] ECMWF, "The ERA-Interim reanalysis dataset - European Center for Medium-Range Weather Forecasts," *Copernicus Climate Change Service (C3S),* 2011.

[34] K. Yang and J. He, "China meteorological forcing dataset (1979-2018)," *Natonal Tibetan Plateau Data Center,* 2019.

[35] T. Nguyen-Xuan, T. Ngo-Duc, H. Kamimera, L. Trinh-Tuan, J. Matsumoto, T. Inoue and T. Phan-Van, "The Vietnam Gridded Precipitation (VnGP) Dataset: Construction and Validation," *SOLA (Scientific Online Letters on the Atmosphere),* pp. 291-296, 2016.

[36] T. P. Q. Le, C. Seidler, M. Kändler and B. N. T. Tran, "Proposed methods for potential evapotranspiration calculation of the Red River basin (North Vietnam)," *Hydrological processes,* pp. 1-9, 2011.

[37] ESA, "Land Cover CCI Product User Guide Version 2," 2017.

[38] T. Li, J. Xia, D. She, L. Cheng, L. Zou and B. Liu, "Quantifying the Impacts of Climate Change and Vegetation Variation on Actual Evapotranspiration Based on the Budyko Hypothesis in North and South Panjiang Basin, China," *water,* pp. 1-18, 2020.

[39] FAO - Unesco, "Soil map of the world," *Food and Agriculture Organization of the United Nations,* 1974.

[40] European Commission, "Global Land Cover 2000 database," *Joint Research Centre,* 2003.

[41] G. Q. Wang, J. Y. Zhang, J. L. Jin, T. C. Pagano, R. Calow, Z. X. Bao, C. S. Liu, Y. L. Liu and X. L. Yan, "Assessing water resources in China using PRECIS projections and a VIC model," *Hydrology and Earth System Sciences,* pp. 231-240, 2012.

[42] J. Jian, D. Ryu, J. F. Costeloe and C. Su, "Towards hydrological model calibration using river level measurements," *Journal of Hydrology: Regional Studies,* pp. 95-109, 2017.

[43] V. KLEMEŠ, "Operational testing of hydrological simulation models," *Hydrological Sciences Journal,* pp. 13-24, 1986.

[44] L. Yang, Q. Feng, M. Zhu, L. Wang, M. R. Alizadeh, J. F. Adamowski, X. Wen and Z. Yin, "Variation in actual evapotranspiration and its ties to climate change and vegetation dynamics in northwest China," *Journal of Hydrology,* 2022.

[45] S. Filoso, M. O. Bezerra, K. C. B. Weiss and M. A. Palmer, "Impacts of forest restoration on water yield: A systematic review," *PLoS ONE,* pp. 1-26, 2017.

[46] T. S. Ngo, D. B. Nguyen and P. S. Rajendra, "Effect of land use change on runoff and sediment yield in Da River Basin of Hoa Binh province, Northwest Vietnam," *Journal of Mountain Science,* pp. 1051-1064, 2015.

[47] Y. Yao, X. Wang, Z. Zeng, Y. Liu, S. Peng, Z. Zhu and S. Piao, "The Effect of Afforestation on Soil Moisture Content in Northeastern China," *PLoS ONE,* pp. 1-14, 2016.

[48] P. Starke, P. Göbel and W. G. Coldewey, "Urban evaporation rates for water-permeable pavements," *Water Science and Technology,* pp. 1161-1169, 2010.

[49] WLE Greater Mekong, "Dams in the Red River Basin: Commissioned, Under Construction and Planned Dams in April 2016," *CGIAR Research Program on Water, Land and Ecosystems - Greater Mekong,* 2016.

[50] G. Manteghi, L. Hasanudin and D. R. Ossen, "Water Bodies an Urban Microclimate: A Revew," *Modern Applied Science,* pp. 1-11, 2015.

[51] B. Droppers, W. H. P. Franssen, M. T. H. van Vliet, B. Nijssen and F. Ludwig, "Simulating human impacts on global water resources using VIC-5," *Geoscientific Model Development,* pp. 1-40, 2019.

[52] VMHA, "National Centre for Hydro-Meteorological Forecasting," *Vietnam Meteorological and Hydrological Administration.*

[53] MWR, "Ministry of Water Resources China".

[54] NOAA, "National Centers for Environmental Inormation," *National Oceanic and Atmospheri Administration.*

[55] B. Lehner, K. Verdin and J. A., "New global hydrography derived from spaceborne elevation data," *Eos, Transactions, American Geophysial Union,* pp. 98-94, 2008.

[56] J. Spruce, J. Bolten, I. Mohammed, R. Srinivasan and V. Lakshmi, "Mapping Land use Land Cover Change in the Lower Mekong Basin From 1997 to 2010," *Frontiers in Environmental Science,* pp. 1-18, 19 March 2020.

[57] N. D. Luong, "Application of VIC Hydrologcal Model for Simulating River Flow of Red Rver System to Support Water Resource Management," *Journal of Science and Technology in Civil Engineering,* pp. 198-204, 2017.

[58] N. T. Giang and T. A. Phuong, "Calibration and verification o fa hydrological model using event data," *VNU Journal of Science, Earth Sciences,* pp. 64-74, 2010.

Appendices

Appendix A – Data sources

Table A1 – Overview of the used datasets and their sources

Datasets	*Purpose*	*Source*
Station streamflow and water levels Vietnam	Discharge timeseries	EVN, VMHA [26] [52]
Station streamflow and water levels China	Validation discharge	MWR [53]
Grid precipitation Vietnam (VnGP)	VIC-model input	[35]
Grid precipitation China (CMFD)	VIC-model input	[34]
Grid wind speed and min/max temperature	VIC-model input	[33]
Station precipitation China	Validation rainfall	[54]
Station precipitation Vietnam	Validation rainfall	[52]
Station locations	ArcGIS maps	[26] [52] [53] [54]
Dam locations	ArcGIS maps	[49]
Basin and reservoir shapefiles (HydroSHEDS)	ArcGIS maps	[55]
Digital Elevation Model (HydroSHEDS)	VIC-model input	[55]
Soil map & Soil properties	VIC-model input	[39]
Land Use & Land Cover maps	VIC-model input	[37]
Vegetation properties (GLC2000)	VIC-model input	[40]
Flow Direction map (HydroSHEDS)	VIC-model input	[55]

Appendix B – Regression analysis of measured water heights and discharges

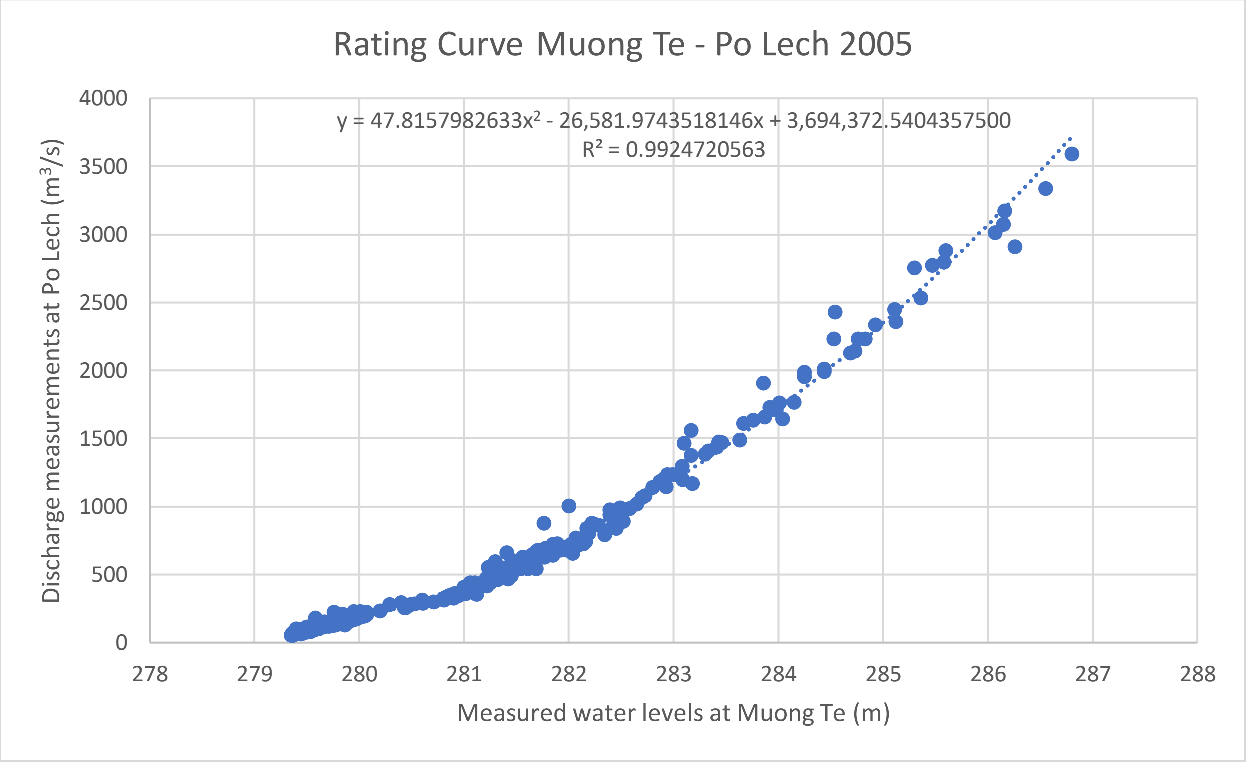


Figure B1 – Regression curve based on measurements at Muong Te and Po Lech

Appendix C – Land Cover and Land Use maps of the Black River basin

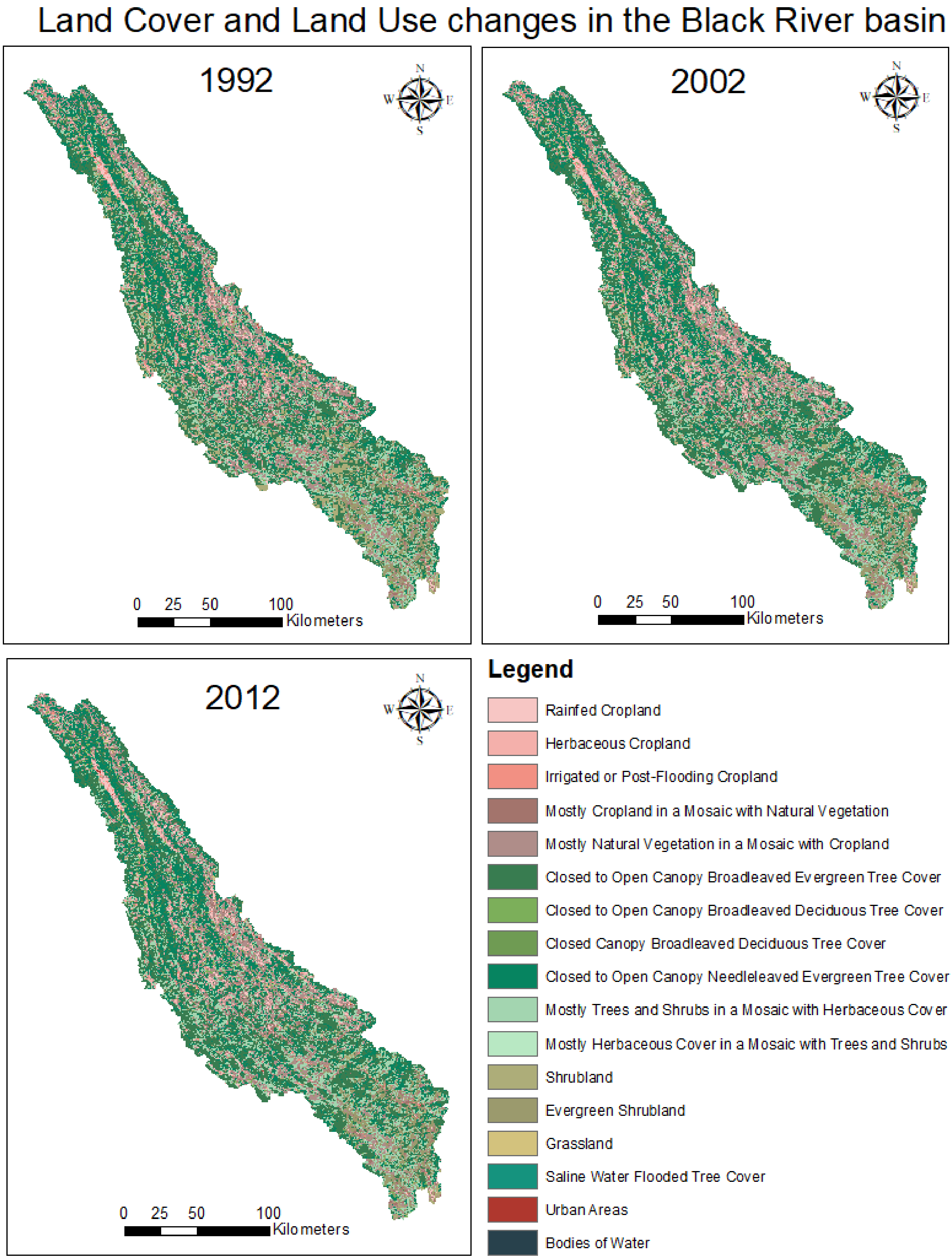


Figure C1 – Land Use & Land Cover maps for 1992, 2002 and 2012 on a 300-meter spatial resolution

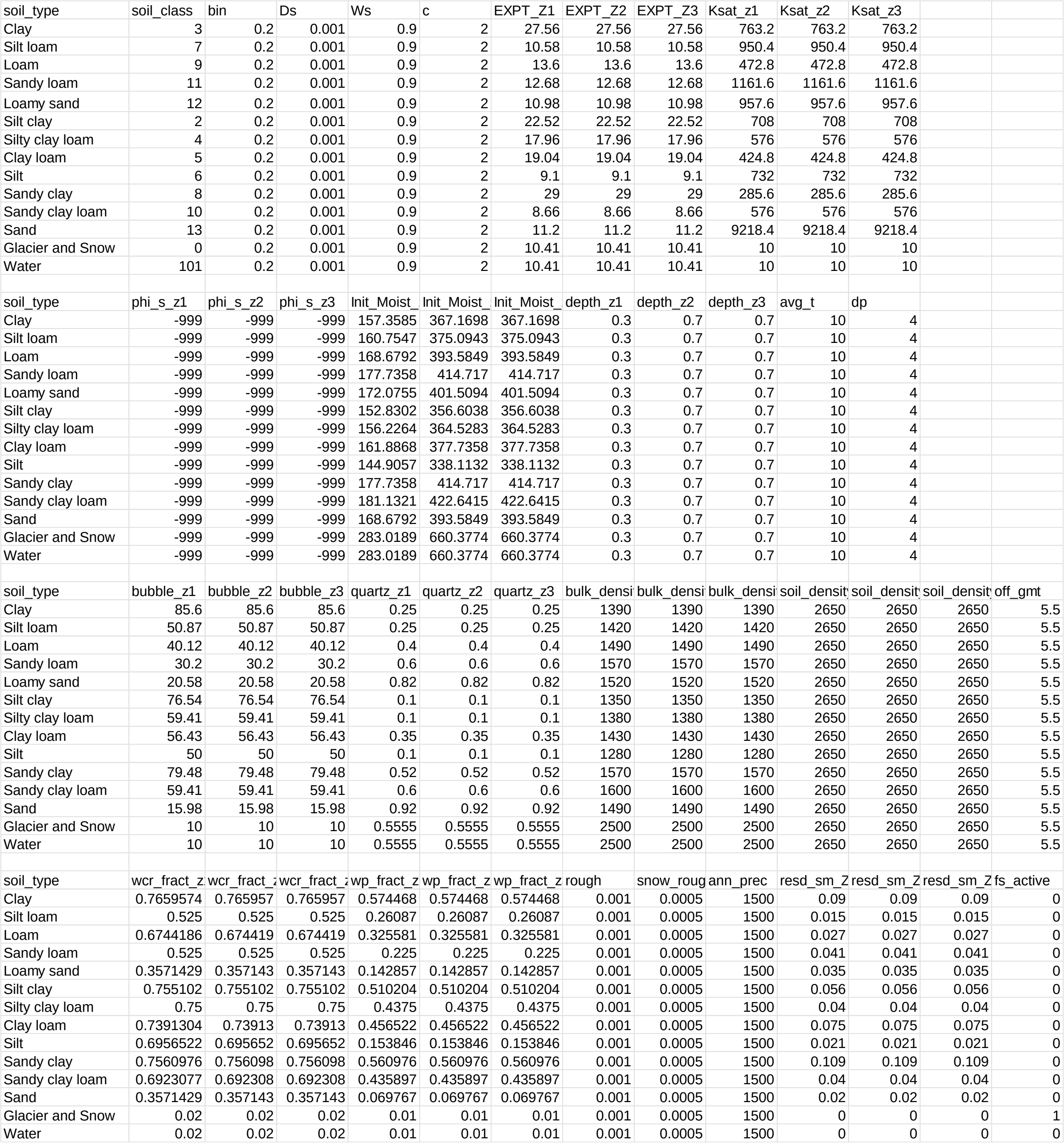
Appendix D – Map of the dams and reservoirs in the Black River basin

Figure D1 – Map of the dams and reservoirs in the Black River basin

Appendix E – Parameters of the Black River basin in the VIC-model

The soil parameter Dsmax is necessary for the VIC-model but was not provided by the FAO soil properties. The initial estimated Dsmax values were added to the soil parameter file manually. Table shows the used soil parameters for every soil type [39] and Table shows the used vegetation parameters for every vegetation type [40].

Table E1 – Overview of soil parameters and their values for the VIC-model



soil_type	soil_class	bin	Ds	Ws	c	EXPT_Z1	EXPT_Z2	EXPT_Z3	Ksat_z1	Ksat_z2	Ksat_z3			
Clay	3	0.2	0.001	0.9	2	27.56	27.56	27.56	763.2	763.2	763.2			
Silt loam	7	0.2	0.001	0.9	2	10.58	10.58	10.58	950.4	950.4	950.4			
Loam	9	0.2	0.001	0.9	2	13.6	13.6	13.6	472.8	472.8	472.8			
Sandy loam	11	0.2	0.001	0.9	2	12.68	12.68	12.68	1161.6	1161.6	1161.6			
Loamy sand	12	0.2	0.001	0.9	2	10.98	10.98	10.98	957.6	957.6	957.6			
Silt clay	2	0.2	0.001	0.9	2	22.52	22.52	22.52	708	708	708			
Silty clay loam	4	0.2	0.001	0.9	2	17.96	17.96	17.96	576	576	576			
Clay loam	5	0.2	0.001	0.9	2	19.04	19.04	19.04	424.8	424.8	424.8			
Silt	6	0.2	0.001	0.9	2	9.1	9.1	9.1	732	732	732			
Sandy clay	8	0.2	0.001	0.9	2	29	29	29	285.6	285.6	285.6			
Sandy clay loam	10	0.2	0.001	0.9	2	8.66	8.66	8.66	576	576	576			
Sand	13	0.2	0.001	0.9	2	11.2	11.2	11.2	9218.4	9218.4	9218.4			
Glacier and Snow	0	0.2	0.001	0.9	2	10.41	10.41	10.41	10	10	10			
Water	101	0.2	0.001	0.9	2	10.41	10.41	10.41	10	10	10			
soil_type	phi_s_z1	phi_s_z2	phi_s_z3	Init_Moist_	Init_Moist_	Init_Moist_	depth_z1	depth_z2	depth_z3	avg_t	dp			
Clay	-999	-999	-999	157.3585	367.1698	367.1698	0.3	0.7	0.7	10	4			
Silt loam	-999	-999	-999	160.7547	375.0943	375.0943	0.3	0.7	0.7	10	4			
Loam	-999	-999	-999	168.6792	393.5849	393.5849	0.3	0.7	0.7	10	4			
Sandy loam	-999	-999	-999	177.7358	414.717	414.717	0.3	0.7	0.7	10	4			
Loamy sand	-999	-999	-999	172.0755	401.5094	401.5094	0.3	0.7	0.7	10	4			
Silt clay	-999	-999	-999	152.8302	356.6038	356.6038	0.3	0.7	0.7	10	4			
Silty clay loam	-999	-999	-999	156.2264	364.5283	364.5283	0.3	0.7	0.7	10	4			
Clay loam	-999	-999	-999	161.8868	377.7358	377.7358	0.3	0.7	0.7	10	4			
Silt	-999	-999	-999	144.9057	338.1132	338.1132	0.3	0.7	0.7	10	4			
Sandy clay	-999	-999	-999	177.7358	414.717	414.717	0.3	0.7	0.7	10	4			
Sandy clay loam	-999	-999	-999	181.1321	422.6415	422.6415	0.3	0.7	0.7	10	4			
Sand	-999	-999	-999	168.6792	393.5849	393.5849	0.3	0.7	0.7	10	4			
Glacier and Snow	-999	-999	-999	283.0189	660.3774	660.3774	0.3	0.7	0.7	10	4			
Water	-999	-999	-999	283.0189	660.3774	660.3774	0.3	0.7	0.7	10	4			
soil_type	bubble_z1	bubble_z2	bubble_z3	quartz_z1	quartz_z2	quartz_z3	bulk_densi	bulk_densi	bulk_densi	soil_densit	soil_densit	soil_densit	off_gmt	
Clay	85.6	85.6	85.6	0.25	0.25	0.25	1390	1390	1390	2650	2650	2650	5.5	
Silt loam	50.87	50.87	50.87	0.25	0.25	0.25	1420	1420	1420	2650	2650	2650	5.5	
Loam	40.12	40.12	40.12	0.4	0.4	0.4	1490	1490	1490	2650	2650	2650	5.5	
Sandy loam	30.2	30.2	30.2	0.6	0.6	0.6	1570	1570	1570	2650	2650	2650	5.5	
Loamy sand	20.58	20.58	20.58	0.82	0.82	0.82	1520	1520	1520	2650	2650	2650	5.5	
Silt clay	76.54	76.54	76.54	0.1	0.1	0.1	1350	1350	1350	2650	2650	2650	5.5	
Silty clay loam	59.41	59.41	59.41	0.1	0.1	0.1	1380	1380	1380	2650	2650	2650	5.5	
Clay loam	56.43	56.43	56.43	0.35	0.35	0.35	1430	1430	1430	2650	2650	2650	5.5	
Silt	50	50	50	0.1	0.1	0.1	1280	1280	1280	2650	2650	2650	5.5	
Sandy clay	79.48	79.48	79.48	0.52	0.52	0.52	1570	1570	1570	2650	2650	2650	5.5	
Sandy clay loam	59.41	59.41	59.41	0.6	0.6	0.6	1600	1600	1600	2650	2650	2650	5.5	
Sand	15.98	15.98	15.98	0.92	0.92	0.92	1490	1490	1490	2650	2650	2650	5.5	
Glacier and Snow	10	10	10	0.5555	0.5555	0.5555	2500	2500	2500	2650	2650	2650	5.5	
Water	10	10	10	0.5555	0.5555	0.5555	2500	2500	2500	2650	2650	2650	5.5	
soil_type	wcr_fract_z	wcr_fract_z	wcr_fract_z	wp_fract_z	wp_fract_z	wp_fract_z	rough	snow_roug	ann_prec	resd_sm_Z	resd_sm_Z	resd_sm_Z	fs_active	
Clay	0.7659574	0.765957	0.765957	0.574468	0.574468	0.574468	0.001	0.0005	1500	0.09	0.09	0.09	0	
Silt loam	0.525	0.525	0.525	0.26087	0.26087	0.26087	0.001	0.0005	1500	0.015	0.015	0.015	0	
Loam	0.6744186	0.674419	0.674419	0.325581	0.325581	0.325581	0.001	0.0005	1500	0.027	0.027	0.027	0	
Sandy loam	0.525	0.525	0.525	0.225	0.225	0.225	0.001	0.0005	1500	0.041	0.041	0.041	0	
Loamy sand	0.3571429	0.357143	0.357143	0.142857	0.142857	0.142857	0.001	0.0005	1500	0.035	0.035	0.035	0	
Silt clay	0.755102	0.755102	0.755102	0.510204	0.510204	0.510204	0.001	0.0005	1500	0.056	0.056	0.056	0	
Silty clay loam	0.75	0.75	0.75	0.4375	0.4375	0.4375	0.001	0.0005	1500	0.04	0.04	0.04	0	
Clay loam	0.7391304	0.73913	0.73913	0.456522	0.456522	0.456522	0.001	0.0005	1500	0.075	0.075	0.075	0	
Silt	0.6956522	0.695652	0.695652	0.153846	0.153846	0.153846	0.001	0.0005	1500	0.021	0.021	0.021	0	
Sandy clay	0.7560976	0.756098	0.756098	0.560976	0.560976	0.560976	0.001	0.0005	1500	0.109	0.109	0.109	0	
Sandy clay loam	0.6923077	0.692308	0.692308	0.435897	0.435897	0.435897	0.001	0.0005	1500	0.04	0.04	0.04	0	
Sand	0.3571429	0.357143	0.357143	0.069767	0.069767	0.069767	0.001	0.0005	1500	0.02	0.02	0.02	0	
Glacier and Snow	0.02	0.02	0.02	0.01	0.01	0.01	0.001	0.0005	1500	0	0	0	1	
Water	0.02	0.02	0.02	0.01	0.01	0.01	0.001	0.0005	1500	0	0	0	0	

Table E2 – Overview of vegetation parameters and their values for the VIC-model

#veg_class	overstory	rarc	rmin	WIND_H	RGL	rad_atten	wind_atter	trunk_ratio	root_depth	Rooting Fr	root_depth	Rooting Fr	root_depth	Rooting Fr
Crop_Land	0	2	117	3	100	0.5	0.5	0.16	0.1	0.133	1	0.867	0.5	0
Evergreen_Broad_Leaf_Forest	1	25	150	37	30	0.5	0.5	0.8	0.1	0.08	1	0.8	0.5	0.12
Deciduous_Broad_Leaf_Forest	1	40	175	22	30	0.5	0.5	0.35	0.1	0.08	1	0.8	0.5	0.12
Evergreen_Needle_Leaf_Forest	1	50	175	19	30	0.5	0.5	0.5	0.1	0.1	1	0.9	0.5	0
Mixed_Forest	1	40	175	21	30	0.5	0.5	0.5	0.1	0.089	1	0.889	0.5	0.022
Shrub_land	0	2.5	178	3	30	0.5	0.5	0.121	0.1	0.173	1	0.827	0.5	0
Grassland	0	2	165	3	100	0.5	0.5	0.017	0.1	0.133	1	0.867	0.5	0
Mangrove_Forest	0	30	175	36	30	0.5	0.5	0.8	0.1	0.08	1	0.8	0.5	0.12
Permanent_Wetland	0	2	175	3	65	0.5	0.5	0.1	0.1	1	1	0	0.5	0
Built-up_(urban_and_rural)	0	15	154	10	30	0.5	0.5	0.5	0.1	0.125	1	0.875	0.5	0
Water_Bodies	0	0	175	3	30	0.5	0.5	0	0.1	1	1	0	0.5	0

#veg_class	JAN-LAI	FEB-LAI	MAR-LAI	APL-LAI	MAY-LAI	JUNE-LAI	JULY-LAI	AUG-LAI	SEP-LAI	OCT-LAI	NOV-LAI	DEC-LAI
Crop_Land	0.782	0.893	1.004	1.116	1.782	3.671	4.782	4.227	2.004	1.227	1.004	0.893
Evergreen_Broad_Leaf_Forest	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117
Deciduous_Broad_Leaf_Forest	0.52	0.52	0.867	2.107	4.507	6.773	7.173	6.507	5.04	2.173	0.867	0.52
Evergreen_Needle_Leaf_Forest	8.76	9.16	9.827	10.093	10.36	10.76	10.493	10.227	10.093	9.827	9.16	8.76
Mixed_Forest	4.64	4.84	5.347	6.1	7.434	8.767	8.833	8.367	7.567	6	5.014	4.64
Shrub_land	0.4	0.404	0.314	0.223	0.25	0.33	0.432	0.8	1.167	0.798	0.504	0.404
Grassland	0.782	0.893	1.004	1.116	1.782	3.671	4.782	4.227	2.004	1.227	1.004	0.893
Mangrove_Forest	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117	5.117
Permanent_Wetland	0.4	0.404	0.314	0.223	0.25	0.33	0.432	0.8	1.167	0.798	0.504	0.404
Built-up_(urban_and_rural)	1.287	1.395	1.551	1.773	2.519	4.137	5.021	4.58	2.848	1.886	1.518	1.366
Water_Bodies	0	0	0	0	0	0	0	0	0	0	0	0

#veg_class	JAN-ALB	FEB-ALB	MAR-ALB	APL-ALB	MAY-ALB	JUNE-ALB	JULY-ALB	AUG-ALB	SEP-ALB	OCT-ALB	NOV-ALB	DEC-ALB
Crop_Land	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Evergreen_Broad_Leaf_Forest	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Deciduous_Broad_Leaf_Forest	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Evergreen_Needle_Leaf_Forest	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Mixed_Forest	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Shrub_land	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Grassland	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Mangrove_Forest	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
Permanent_Wetland	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09	0.09
Built-up_(urban_and_rural)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Water_Bodies	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07

#veg_class	JAN-ROU	FEB-ROU	MAR-ROU	APL-ROU	MAY-ROU	JUN-ROU	JUL-ROU	AUG-ROU	SEP-ROU	OCT-ROU	NOV-ROU	DEC-ROU
Crop_Land	0.078	0.078	0.078	0.077	0.06	0.065	0.072	0.077	0.078	0.078	0.078	0.078
Evergreen_Broad_Leaf_Forest	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653
Deciduous_Broad_Leaf_Forest	0.52	0.52	0.666	0.91	1.031	1.044	1.042	1.037	1.036	0.917	0.666	0.52
Evergreen_Needle_Leaf_Forest	1.112	1.103	1.088	1.082	1.076	1.068	1.073	1.079	1.082	1.088	1.103	1.112
Mixed_Forest	0.816	0.812	0.877	0.996	1.054	1.056	1.058	1.058	1.059	1.003	0.885	0.816
Shrub_land	0.037	0.037	0.035	0.033	0.033	0.033	0.033	0.039	0.041	0.04	0.038	0.037
Grassland	0.072	0.077	0.078	0.02	0.01	0.065	0.072	0.077	0.078	0.078	0.065	0.07
Mangrove_Forest	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653	2.653
Permanent_Wetland	0.037	0.037	0.035	0.033	0.033	0.033	0.033	0.039	0.041	0.04	0.038	0.037
Built-up_(urban_and_rural)	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.23
Water_Bodies	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012	0.0012

#veg_class	JAN-DIS	FEB-DIS	MAR-DIS	APL-DIS	MAY-DIS	JUN-DIS	JUL-DIS	AUG-DIS	SEP-DIS	OCT-DIS	NOV-DIS	DEC-DIS
Crop_Land	0.427206	0.427206	0.427206	0.421729	0.32862	0.356005	0.394344	0.421729	0.427206	0.427206	0.427206	0.427206
Evergreen_Broad_Leaf_Forest	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333	23.33333
Deciduous_Broad_Leaf_Forest	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333	13.33333
Evergreen_Needle_Leaf_Forest	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333	11.33333
Mixed_Forest	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333	12.83333
Shrub_land	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667
Grassland	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38	0.38
Mangrove_Forest	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667	22.66667
Permanent_Wetland	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667	0.346667
Built-up_(urban_and_rural)	1.25281	2.624	2.733	2.85	2.933	2.994	3.017	3.005	2.951	2.861	2.73	2.621
Water_Bodies	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572	0.006572

Appendix F – VIC-model settings

Global parameter file (rainfall-runoff model)

```
#######################################################################
# VIC Model Parameters - 4.1.x
#######################################################################
# $Id$
#######################################################################
# Simulation Parameters
#######################################################################
NLAYER        3               # number of soil layers
NODES                         10              # number of soil thermal nodes
TIME_STEP   12                # model time step in hours (set to 24 if FULL_ENERGY = FALSE, set to < 24 if FULL_ENERGY = TRUE)
SNOW_STEP12                   # time step in hours for which to solve the snow model (should = TIME_STEP if TIME_STEP < 24)
STARTYEAR  1980               # year model simulation starts
STARTMONTH                    01              # month model simulation starts
STARTDAY   01                 # day model simulation starts
STARTHOUR00                   # hour model simulation starts
ENDYEAR     2018              # year model simulation ends
ENDMONTH12                    # month model simulation ends
ENDDAY      31                # day model simulation ends
#######################################################################
# Energy Balance Parameters
#######################################################################
FULL_ENERGY                   FALSE           # TRUE = calculate full energy balance; FALSE = compute water balance only.  Default = FALSE.
CLOSE_ENERGY                  FALSE           # TRUE = all energy balance calculations (canopy air, canopy snow, ground snow,
                # and ground surface) are iterated to minimize the total column error.  Default = FALSE.
#######################################################################
# Soil Temperature Parameters
# VIC will choose appropriate value for QUICK_FLUX depending on values of FULL_ENERGY and FROZEN_SOIL; the user should only need to override VIC's choices in
special cases.
# The other options in this section are only applicable when FROZEN_SOIL is TRUE and their values depend on the application.
#######################################################################
FROZEN_SOIL                   TRUE            # TRUE = calculate frozen soils.  Default = FALSE.
QUICK_FLUX                    FALSE           # TRUE = use simplified ground heat flux method of Liang et al (1999); FALSE = use finite element method of Cherkauer et al
(1999)
IMPLICIT      TRUE            # TRUE = use implicit solution for soil heat flux equation of Cherkauer et al (1999), otherwise uses original explicit solution.  Default = TRUE.
QUICK_SOLVE                   FALSE           # TRUE = Use Liang et al., 1999 formulation for iteration, but explicit finite difference method for final step.
NO_FLUX     FALSE             # TRUE = use no flux lower boundary for ground heat flux computation; FALSE = use constant flux lower boundary condition.  If NO_FLUX =
TRUE, QUICK_FLUX MUST = FALSE.  Default = FALSE.
EXP_TRANS  TRUE               # TRUE = exponentially distributes the thermal nodes in the Cherkauer et al. (1999) finite difference algorithm, otherwise uses linear
distribution.  Default = TRUE.
GRND_FLUX_TYPE                GF_410          # Options for ground flux:
#                                             # GF_406 = use (flawed) formulas for ground flux, deltaH, and fusion from VIC 4.0.6 and earlier;
#                                             # GF_410 = use formulas from VIC 4.1.0 (ground flux, deltaH, and fusion are correct; deltaH and fusion ignore surf_atten);
#                                             # Default = GF_410
TFALLBACK  TRUE               # TRUE = when temperature iteration fails to converge, use previous time step's T value
SPATIAL_FROST                 FALSE           (Nfrost)        # TRUE = use a uniform distribution to simulate the spatial distribution of soil frost; FALSE = assume that the
entire grid cell is frozen uniformly.  If TRUE, then replace (Nfrost) with the number of frost subareas, i.e., number of points on the spatial distribution curve to
simulate.  Default = FALSE.

#######################################################################
# Precip (Rain and Snow) Parameters
# Generally these default values do not need to be overridden
#######################################################################
SNOW_DENSITY                  DENS_BRAS # DENS_BRAS = use traditional VIC algorithm taken from Bras, 1990; DENS_SNTHRM = use algorithm taken from SNTHRM
model.
BLOWING                       FALSE           # TRUE = compute evaporative fluxes due to blowing snow
COMPUTE_TREELINE              FALSE           # Can be either FALSE or the id number of an understory veg class; FALSE = turn treeline computation off; VEG_CLASS_ID =
replace any overstory veg types with the this understory veg type in all snow bands for which the average July Temperature <= 10 C (e.g. "COMPUTE_TREELINE 10"
replaces any overstory veg cover with class 10)
CORRPREC   FALSE              # TRUE = correct precipitation for gauge undercatch
MAX_SNOW_TEMP                 0.5             # maximum temperature (C) at which snow can fall
MIN_RAIN_TEMP                 -0.5            # minimum temperature (C) at which rain can fall
SPATIAL_SNOW                  FALSE           # TRUE = use a uniform distribution to simulate the partial coverage of the
                # surface by a thin snowpack.  Coverage is assumed to be uniform after snowfall
                # until the pack begins to melt.  If TRUE, VIC will expect an additional column
                # in the soil paramter file containing the snow distibution slope parameter
                # (= 2 * snow depth below which coverage < 1).
```

```
#######################################################################
# Turbulent Flux Parameters
# Generally these default values do not need to be overridden
#######################################################################
MIN_WIND_SPEED          0.1         # minimum allowable wind speed (m/s)
AERO_RESIST_CANSNOW                 AR_406_FULL             # Options for aerodynamic resistance in snow-filled canopy:
#                                   # AR_406     = multiply by 10 for latent heat but do NOT multiply by 10 for sensible heat and do NOT apply stability correction
(as in VIC 4.0.6); when no snow in canopy, use surface aero_resist for ET.
#                                   # AR_406_LS             = multiply by 10 for latent heat AND sensible heat and do NOT apply stability correction; when no
snow in canopy, use surface aero_resist for ET.
#                                   # AR_406_FULL           = multiply by 10 for latent heat AND sensible heat and do NOT apply stability correction; additionally,
always use overstory aero_resist for ET (as in 4.1.0).
#                                   # AR_410     = apply stability correction but do NOT multiply by 10 (as in VIC 4.1.0); additionally, always use overstory
aero_resist for ET (as in 4.1.0).

#######################################################################
# Meteorological Forcing Disaggregation Parameters
# Generally these default values do not need to be overridden
#######################################################################
OUTPUT_FORCE            FALSE       # TRUE = perform disaggregation of forcings, skip the simulation, and output the disaggregated forcings.
PLAPSE                  TRUE        # This controls how VIC computes air pressure when air pressure is not supplied as an input forcing: TRUE = set air pressure to
sea level pressure, lapsed to grid cell average elevation; FALSE = set air pressure to constant 95.5 kPa (as in all versions of VIC pre-4.1.1)
SW_PREC_THRESH                      0           # Minimum daily precip [mm] that can cause dimming of incoming shortwave; default = 0.
MTCLIM_SWE_CORR         TRUE   # This controls VIC's estimates of incoming shortwave in the presence of snow; TRUE = adjust incoming shortwave for snow albedo
effect; FALSE = do not adjust shortwave; default = TRUE
VP_ITER                 VP_ITER_ANNUAL          # This controls VIC's iteration between estimates of shortwave and vapor pressure:
#                                   # VP_ITER_NEVER = never iterate; make estimates separately
#                                   # VP_ITER_ALWAYS = always iterate once
#                                   # VP_ITER_ANNUAL = iterate once for arid climates based on annual Precip/ETP ratio
#                                   # VP_ITER_CONVERGE = iterate until shortwave and vp stabilize
#                                   # default = VP_ITER_ALWAYS
VP_INTERP   TRUE        # This controls sub-daily humidity estimates; TRUE = interpolate daily VP estimates linearly between sunrise of one day to the next; FALSE
= hold VP constant for entire day
LW_TYPE                 LW_PRATA    # This controls the algorithm used to estimate clear-sky longwave radiation:
#                                   # LW_TVA = Tennessee Valley Authority algorithm (1972) (this was traditional VIC algorithm)
#                                   # other options listed in vicNl_def.h
#                                   # default = LW_PRATA
LW_CLOUD  LW_CLOUD_DEARDORFF # This controls the algorithm used to estimate the influence of clouds on total longwave:
#                                   # LW_CLOUD_BRAS = method from Bras textbook (this was the traditional VIC algorithm)
#                                   # LW_CLOUD_DEARDORFF = method of Deardorff (1978)
#                                   # default = LW_CLOUD_DEARDORFF

#######################################################################
# Carbon Cycle Parameters
#######################################################################
CARBON                  FALSE                   # TRUE = simulate carbon cycle; FALSE = do not simulate carbon cycle.  Default = FALSE.
VEGLIB_PHOTO            FALSE                   # TRUE = photosynthesis parameters are included in the veg library file.  Default = FALSE.
RC_MODE    RC_JARVIS    # RC_JARVIS = canopy resistance computed by applying resistance factors to the veg class's minimum resistance, listed in the veg library
                        # RC_PHOTO = canopy resistance computed by applying resistance factors to the minimum resistance required by current photosynthetic
demand.  Default = RC_JARVIS.

#######################################################################
# Miscellaneous Simulation Parameters
# Generally these default values do not need to be overridden
#######################################################################
CONTINUEONERROR         TRUE        # TRUE = if simulation aborts on one grid cell, continue to next grid cell

#######################################################################
# Forcing Files and Parameters
#     All FORCING filenames are actually the pathname, and prefix
#         for gridded data types: ex. DATA/forcing_
#         Latitude and longitude index suffix is added by VIC
#            There must be 1 FORCE_TYPE entry for each variable (column) in the forcing file
#            If FORCE_TYPE is BINARY, each FORCE_TYPE must be followed by:
#                                   SIGNED/UNSIGNED         SCALE_FACTOR
#                       For example (BINARY):
#                                   FORCE_TYPE              PREC        UNSIGNED    40
#                       or (ASCII):
#                                   FORCE_TYPE              PREC
```

```
################################################################################
FORCING1    /work/users/std/wwinkel/Model-files/Forcings-CMFD/data_     # Forcing file path and prefix, ending in "_"
FORCE_FORMAT            ASCII           # BINARY or ASCII
FORCE_ENDIAN            LITTLE          # LITTLE (PC/Linux) or BIG (SUN)
N_TYPES                 4               # Number of variables (columns)
FORCE_TYPE              PREC
FORCE_TYPE              WIND
FORCE_TYPE              TMAX
FORCE_TYPE              TMIN
FORCE_DT    24          # Forcing time step length (hours)
FORCEYEAR  1980         # Year of first forcing record
FORCEMONTH              01              # Month of first forcing record
FORCEDAY   01           # Day of first forcing record
FORCEHOUR               00              # Hour of first forcing record
GRID_DECIMAL            2               # Number of digits after decimal point in forcing file names
WIND_H        10.0   # height of wind speed measurement (m)
MEASURE_H      2.0    # height of humidity measurement (m)
ALMA_INPUT              FALSE           # TRUE = ALMA-compliant input variable units; FALSE = standard VIC units

################################################################################
# Land Surface Files and Parameters
################################################################################
SOIL      /work/users/std/wwinkel/calibrationHQ/Parameters_Rainfall_Runoff/soil_parameter_file.txt                  # Soil parameter path/file
BASEFLOW   ARNO         # ARNO = columns 5-8 are the standard VIC baseflow parameters; NIJSSEN2001 = columns 5-8 of soil file are baseflow parameters from Nijssen et al (2001)
JULY_TAVG_SUPPLIED      FALSE           # TRUE = final column of the soil parameter file will contain average July air temperature, for computing treeline; this will be ignored if COMPUTE_TREELINE is FALSE; FALSE = compute the treeline based on the average July air temperature of the forcings over the simulation period
ORGANIC_FRACT           FALSE           # TRUE = simulate organic soils; soil param file contains 3*Nlayer extra columns, listing for each layer the organic fraction, and the bulk density and soil particle density of the organic matter in the soil layer; FALSE = soil param file does not contain any information about organic soil, and organic fraction should be assumed to be 0
VEGLIB         /work/users/std/wwinkel/forecast/Parameters_Rainfall_Runoff/vegetation_library_file.txt              # Veg library path/file
VEGPARAM     /work/users/std/wwinkel/forecast/Parameters_Rainfall_Runoff/vegetation_parameter_file_2012.txt                 # Veg parameter path/file
ROOT_ZONES      3       # Number of root zones (must match format of veg param file)
VEGLIB_VEGCOVER         FALSE           # TRUE = veg lib file contains 12 monthly values of partial vegcover fraction for each veg class, between the LAI and albedo values
VEGPARAM_LAI            FALSE    # TRUE = veg param file contains LAI information; FALSE = veg param file does NOT contain LAI information
VEGPARAM_ALB            FALSE    # TRUE = veg param file contains albedo information; FALSE = veg param file does NOT contain albedo information
VEGPARAM_VEGCOVER  FALSE    # TRUE = veg param file contains veg_cover information; FALSE = veg param file does NOT contain veg_cover information
LAI_SRC       FROM_VEGLIB    # FROM_VEGPARAM = read LAI from veg param file; FROM_VEGLIB = read LAI from veg library file
ALB_SRC       FROM_VEGLIB    # FROM_VEGPARAM = read albedo from veg param file; FROM_VEGLIB = read albedo from veg library file
VEGCOVER_SRC            FROM_VEGLIB    # FROM_VEGPARAM = read veg_cover from veg param file; FROM_VEGLIB = read veg_cover from veg library file
SNOW_BAND               1               # Number of snow bands; if number of snow bands > 1, you must insert the snow band path/file after the number of bands (e.g. SNOW_BAND 5 my_path/my_snow_band_file)

################################################################################
# Lake Simulation Parameters
# These need to be un-commented and set to correct values only when running lake model (LAKES is not FALSE)
################################################################################
#LAKES                  (put lake parameter path/file here)     # Lake parameter path/file
#LAKE_PROFILE           FALSE           # TRUE = User-specified depth-area parameters in lake parameter file; FALSE = VIC computes a parabolic depth-area profile
#EQUAL_AREA             FALSE           # TRUE = grid cells are from an equal-area projection; FALSE = grid cells are on a regular lat-lon grid
#RESOLUTION             0.125           # Grid cell resolution (degrees if EQUAL_AREA is FALSE, km^2 if EQUAL_AREA is TRUE); ignored if LAKES is FALSE

################################################################################
# Output Files and Parameters
################################################################################
RESULT_DIR  /work/users/std/wwinkel/forecast/Outputs_RR_CMFD            # Results directory path
OUT_STEP       24      # Output interval (hours); if 0, OUT_STEP = TIME_STEP
SKIPYEAR     0          # Number of years of output to omit from the output files
COMPRESS   FALSE        # TRUE = compress input and output files when done
BINARY_OUTPUT           FALSE           # TRUE = binary output files
ALMA_OUTPUT             FALSE           # TRUE = ALMA-format output files; FALSE = standard VIC units
MOISTFRACT              FALSE           # TRUE = output soil moisture as volumetric fraction; FALSE = standard VIC units
PRT_HEADER              TRUE   # TRUE = insert a header at the beginning of each output file; FALSE = no header
PRT_SNOW_BAND   TRUE   # TRUE = write a "snowband" output file, containing band-specific values of snow variables; NOTE: this is ignored if N_OUTFILES is specified below.
```

Global parameter file (routing model)

```
# Routing main file
# NAME OF FLOW DIRECTION FILE
/work/users/std/wwinkel/forecast/Parameters_Routing/direction.txt
# NAME OF VELOCITY FILE
.false.
1.2
# NAME OF DIFF FILE
.false.
800
# NAME OF XMASK FILE
.false.
12500
# NAME OF FRACTION FILE
.true.
/work/users/std/wwinkel/forecast/Parameters_Routing/fraction.txt
# NAME OF STATION FILE
/work/users/std/wwinkel/forecast/Parameters_Routing/stations.txt
# PATH OF INPUT FILES AND PRECISION
/work/users/std/wwinkel/forecast/Outputs_RR_CMFD/fluxes_
2
# PATH OF OUTPUT FILES
/work/users/std/wwinkel/forecast/Outputs_Routing_CMFD/
# YEAR AND MONTH OF MODEL OUTPUT TO ROUTE & ROUTED OUTPUT TO WRITE
1980 1 2018 12
1980 1 2018 12
# NAME OF UNIT HYDROGRAPH FILE
/work/users/std/wwinkel/forecast/Parameters_Routing/UH.all
```

Appendix G – Regression analysis of the observed streamflow timeseries

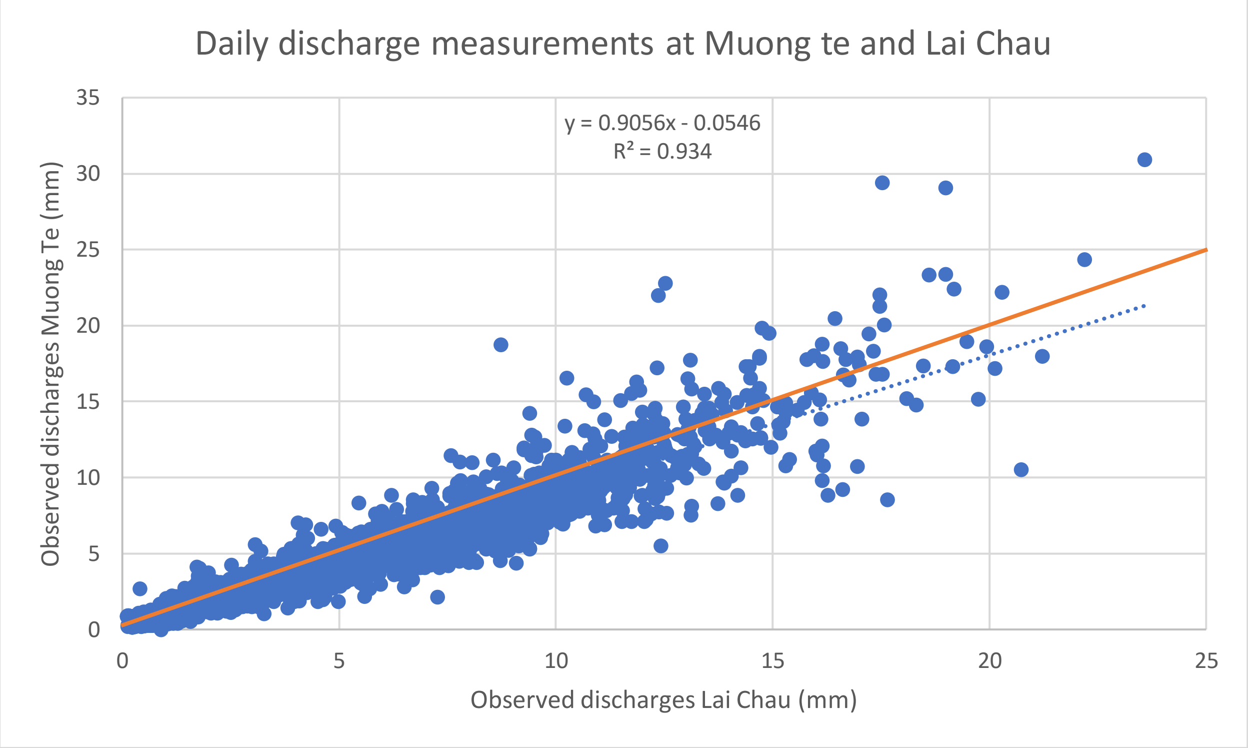


Figure G1 – Scatter plot and regression line of the observed discharges at Lai Chau and Muong Te