Application of SWAT Model to Assess Impacts of Soil and Water Conservation and Forest Land Restoration Measures in the Stung Sangker River Basin

Investing in Climate Change Adaptation through Agroecological Landscape Restoration: A Nature-Based Solution for Climate Resilience
(Technical Assistance 6539)

October 2023

Stung Sanger River Basin, Cambodia (photo by ICEM)

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Abbreviations

ADB	Asian Development Bank
ASL	Above Sea Level
BL	Baseline
DEM	Digital Elevation Model
FAO	The Food and Agriculture Organization of the United Nations
FRSD	Deciduous Forestry
FRSE	Evergreen Forestry
FS	Future Scenario
GCM	Global Circulation Model
GIS	Geographical Information Systems
HRUs	Hydrological Response Units
ICEM	International Centre for Environmental Management
ICRAF	World Agroforestry
LMB	Lower Mekong Basin
MOE	Ministry of Environment
MRC	Mekong River Commission
MUSLE	Modified Universal Soil Loss Equation
NSE	Nash-Sutcliffe Efficiency
RCP	Representative Concentration Pathway
SWAT	Soil and Water Assessment Tool
TA	Technical Assistance

Weights and Measures

ha	hectare
m^3	cubic meter
mm	milimeter
Mt	million tons
s	second
t	ton

Summary

The ADB project TA 6539 REG: Investing in climate change adaptation through agroecological landscape restoration works with governments and communities in Cambodia and the Philippines to restore and manage forest landscapes by following ecological principles and promoting climate-resilient agricultural livelihoods.

The project emphasizes forest restoration, agroforestry, and agroecology measures that build climate change resilience, offer improved livelihood options for communities, and enhance biodiversity. A crucial aspect of the project is to identify measures to mitigate the impacts of climate change and promote the restoration of forest ecosystems and biodiversity. In Cambodia, the project is working with local government and communities in the Sangker River basin to demonstrate restoration measures.

The Sangker River basin is the third largest tributary of the Tonle Sap Basin river system. The river is 250km long and flows through six districts and twenty-seven communes in Battambang province before draining into the Tonle Sap lake.

The lowlands of the basin are comprised chiefly of crops and rice paddy fields, about 40% of the total area. Steeper upland areas are primarily forested areas and grasslands, which have come to displace forest and orchards over the last two decades.

However, the Sangker River basin is increasingly subject to flood and drought events of increasing severity, which are projected to become more regular and intense with climate change.

An established and well-understood response to the impacts of climate change on landscapes, including flooding, is the restoration of forest land and conversion to activities such as agroforestry that minimize the effects of human activity on the land, mitigate the effects of a changing climate, and provide opportunities for local communities to improve or supplement their incomes.

However, to determine which practices will best help a landscape respond to changes in the climate, it is necessary to understand changes in rainfall patterns, how they will affect the river basin, and, in turn, farmers, businesses, and communities that are reliant on the basin.

This report describes the results of a study to assess the impact of climate change on rainfall and the flows of water and sediment (typically a result of the erosion of unprotected top soils) in the river basin. The study used a hydrology or SWAT model to test what would happen in four scenarios, with each varying in terms of the impact of climate change and the efforts to mitigate the effects of climate change.

The analysis reveals that changes in land use have already had noticeable effects on the basin's hydrology (the distribution and movement of water). Average annual water flows have decreased in the last twenty years as agricultural land replaced forested land. This has resulted in the reduced availability of water in downstream areas. Analysis of wet season flows reveals an increased tendency for flash floods and the more rapid occurrence of flood events. By contrast, the dry season is experiencing more extended periods of rain-free days.

The SWAT model also analyzed scenarios that explored the future impact of climate change on the river basin and the potential impacts of reforesting degraded land and implementing conservation measures in lowland agricultural areas.

Future Scenario 1 (FS1) adjusts the baseline rainfall in line with the Representative Concentration Pathway (RCP) 8.5, in which carbon emissions are assumed to rise at a high rate throughout the century. The scenario assesses the impact of the changes to rainfall patterns on the hydrology and sediment in the river basin. Under the scenario, monthly rainfall increases in the highest flow months of September and October, and is lower for all other months. The most significant increase is observed in October, with an increase in average monthly flows of 15%. The increase will likely cause flood damage to the basin's infrastructure, crops, and property. By contrast, the decrease in flows in the dry

season could potentially lead to drought and water supply issues for agriculture, human well-being, and ecosystems. In the scenario, sediment loads increase by 14% compared to the baseline scenario, with a 12% increase in loads entering the Treng reservoir and an increase in flows in lowland and upstream areas. Flows into the Treng reservoir may affect the reservoir's serviceability, and the increase in flows in the upland and lowland areas is also of concern.

Future Scenario 2 also adjusted the baseline rainfall in line with the Representative Concentration Pathway (RCP) 8.5 and assessed the mitigating impact of converting 30% of agricultural land in upstream areas to agroforestry. The analysis demonstrates that agroforestry will reduce the average river discharges compared to the baseline scenario and Future Scenario 1. However, while sediment loads are lower than in FS1, they are 11% higher than the baseline scenario at the Treng reservoir and 12% higher at the Sangker River outlet, implying that further measures will be needed to prevent increases in sediment loads from occurring in downstream waterways.

Future Scenario 3 tests the impact of conservation farming measures intended to prevent soil erosion, reduce soil compaction, maintain and improve soil fertility, and conserve, drain, or harvest water. The scenario extends FS2 by implementing contour farming on the remaining agricultural areas not converted to agroforestry. In the FS3 scenario, sediment loads from the lowland areas directly entering the Tonle Sap Lake are significantly lower than the FS1 scenario – 0.008 Mt/yr for FS3 compared to 0.01 Mt/yr for FS1. The reduction in sediment load is significant enough to be slightly lower than the baseline scenario despite the much higher flow rates in the FS3 scenario. When averaged across the basin, sediment yield estimates for the FS3 scenario reduce by 59% compared to the baseline. This represents an improvement on the FS2 scenario, where a 52% improvement was achieved.

The SWAT analysis invites several recommendations to mitigate the impacts of climate change on the performance of the Sangker River basin.

In upland areas reforestation of degraded areas along drainage corridors, in community forests, within protected areas, and across the agricultural landscape following allotment boundaries will help mitigate the impact of increased rainfall. In agricultural areas, converting agricultural allotments to agroforestry will also be effective.

Vegetated embankments, stream restoration works, and networks of leaky weirs will all help to reduce the increase in sediment loads in streams in upstream areas.

In lowland areas conservation farming is recommended to control erosion in agricultural areas. To reduce floods in the wet season and drought in the dry season reforestation along riparian buffer strips, tree planting in agricultural areas and restored and constructed wetlands will all be effective. Wetlands, such as shallow ponds and channels, are particularly appropriate for the lowland areas due to the flat terrain and relatively shallow water table.

1 Introduction

The ADB project *TA 6539 REG: Investing in climate change adaptation through agroecological landscape restoration* works with governments and communities in Cambodia and the Philippines to restore and manage forest landscapes by following ecological principles and promoting climate-resilient agricultural livelihoods.

The project emphasizes forest restoration, agroforestry, and agroecology measures that build climate change resilience, offer improved livelihood options for communities, and enhance biodiversity. A crucial aspect of the project is to identify measures to mitigate the impacts of climate change and promote the restoration of forest ecosystems and biodiversity.

In Cambodia, the Ministry of Environment (MOE) has identified the Sangker river basin to demonstrate restoration measures working with local government and communities. This report provides details of modelling applied to the Sangker river basin to assess the impacts of land use, land cover and climate change on the basin's hydrology and sediment transport processes. This impact assessment includes evaluation of the potential effectiveness of interventions to adapt to these hydrological and sediment transport changes.

The Sangker river basin is subject to flood and drought events of increasing severity, projected to become more significant with climate change. It is a basin undergoing a steady process of degradation. Understanding how the basin's land uses need to be managed is critical to water supply, water quality, agricultural productivity, the effective functioning of hydropower and irrigation infrastructure, including reservoirs and canals, and the protection of other strategic infrastructure such as roads, power and communications assets. The results from the modelling work described in this report are an important contribution to that understanding, and to defining the needed restoration measures that should be applied to safeguard livelihoods, infrastructure and ecosystems throughout the basin.

1.1. Background

Ecosystems, agriculture and agroforestry rely on river basins to provide their hydrological needs. However, agricultural and urban developments can significantly affect hydrology and sediment transport processes. Changes in land use and land cover can change the timing and volumes of runoff which, in turn, can change water availability in the dry season and increase the likelihood of flooding in the wet season. Furthermore, increases in flooding and the removal of native vegetation may exacerbate erosion, potentially leading to the loss of valuable topsoil, damaging crops and arable land adjacent to waterways.

Climate change can also alter the timing and volumes of runoff, affecting the capacity of river basins to sustain functioning agricultural systems and ecosystems. Durations and the timing of dry periods may change, potentially leading to more severe droughts. Changes in the timing of transitions between the wet and dry seasons may affect the timing of planting and harvesting crops.

SWAT (Soil and Water Assessment Tool) models provide useful insights into hydrologic and sediment processes and the impact of climate change and landscape change. SWAT models have been used for over 40 years in studies of rainfall-runoff and erosion processes[1], including studies in Cambodia and the Mekong River basin, including the Sangker basin.

SWAT is an open-source model that can run through its interface or with commonly used Geographical Information Systems (ARCGIS and QGIS). It can be calibrated manually or automatically and runs on a daily time step, the most common format for rainfall data inputs.

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[1] Arnold et al, 2012

1.2. Aim and Objectives

The present study developed a SWAT model to quantify and predict the impact of climate change, land use change, and the deployment of soil and water management measures on hydrological processes in the Stung Sangker river basin.

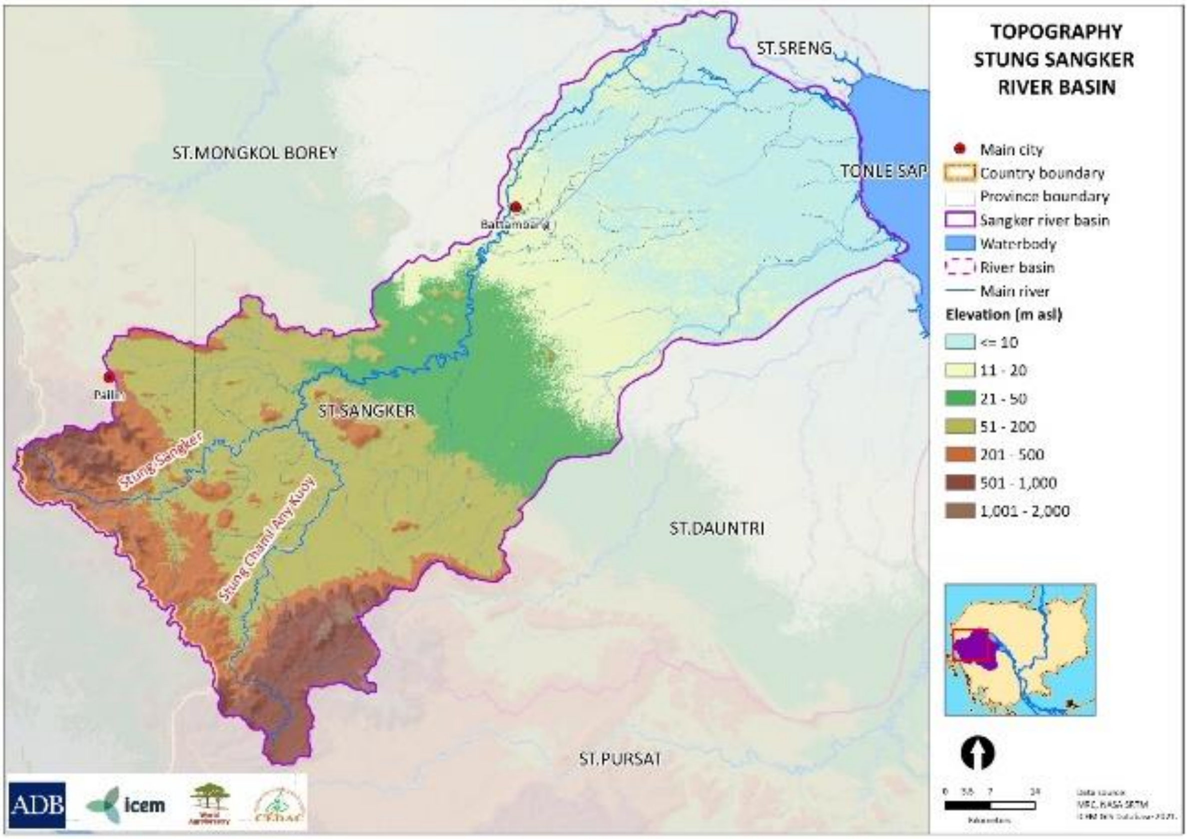
1.3. Structure of This Report

Following this introduction, Section 2 provides a description of the Stung Sangker River basin study area including its topography, soils, land use, and historical patterns of rainfall, hydrology and sediment transport on the basin. Section 3 describes the modelling approach used to apply SWAT to the basin, and the scenarios that were tested, followed by Section 4 which describes the results. Finally, Section 5 provides conclusions from the study and recommendations for future work.

2. The Stung Sangker Study River Basin

With a total drainage area of 6,051 km^{2,} the Stung Sangker river is the third-largest tributary in the Tonle Sap Basin River system. The river is 250 km long and flows through six districts and twenty-seven communes in Battambang province before draining into the Tonle Sap Lake (Figure 1).

Figure 1: Topography of the Stung Sangker River Basin



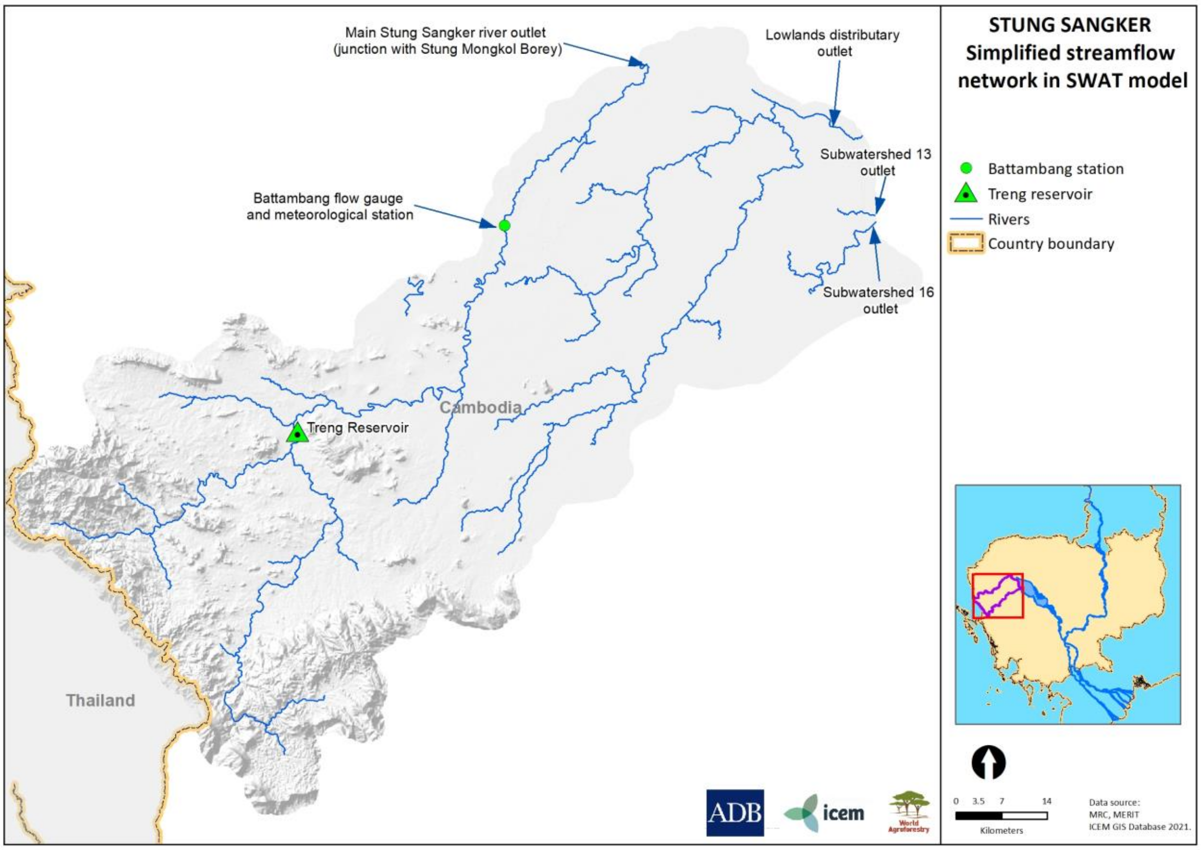
2.1. Topography, Drainage, Soils, and Land Use

The Stung Sangker river basin consists of two separate regions: a flat lowland region immediately upstream of the Tonle Sap Lake and a highland region towards the south and west of the basin where elevations extend to around 1500 m.

Drainage patterns on the Stung Sangker are complex, especially in the flat lowland region. The primary arm of the Stung Sangker river flows from the highland areas in the southwest towards the lowland regions through Battambang. The main distributary then joins the Stung Mongkol Boray River (Figure 2) and the Stung Sreng River, before discharging into the Ton Le Sap Lake.

Most of the lowland region discharge directly into the Tonle Sap Lake through a lowland distributary, separate from the main Stung Sangker river. Flows from sub-watersheds 13 and 16 also discharge directly into the lake (Figure 2).

Figure 2: Streamflow Patterns and Key Hydrological Locations on the Stung Sangker River



Crops and rice paddy fields, primarily on the lowlands, occupy about 40% of the basin's total area. The steeper upland areas consist of mostly forested areas and grasslands.

Soil types follow the general topographic pattern with distinct soil types in the lower reaches, midland soils, upland soils, and mountainous soils (Figure 3).

Land use patterns are closely linked to topography and soil types (Figure 3). Between 2001 and 2017 agriculture and grasslands displaced significant amounts of forests and orchards (Table 1 and Figure 4). Such extensive changes in land use can significantly affect runoff rates and volumes and surface water - groundwater interactions, with implications for water availability for anthropogenic and ecosystem functions.

Figure 3: Soils (above) and Landuse for the year 2017 (below) on the Stung Sangker river basin

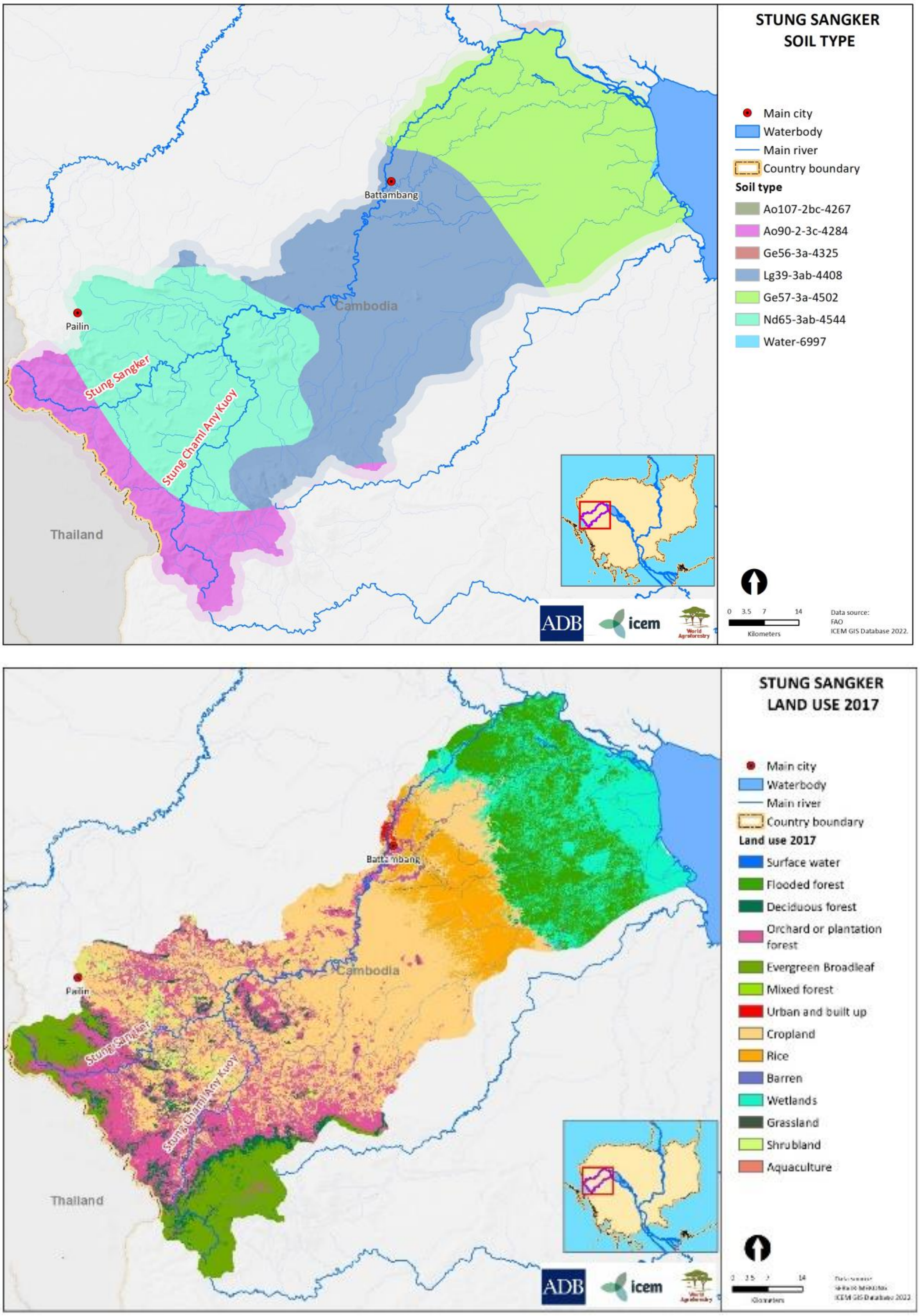


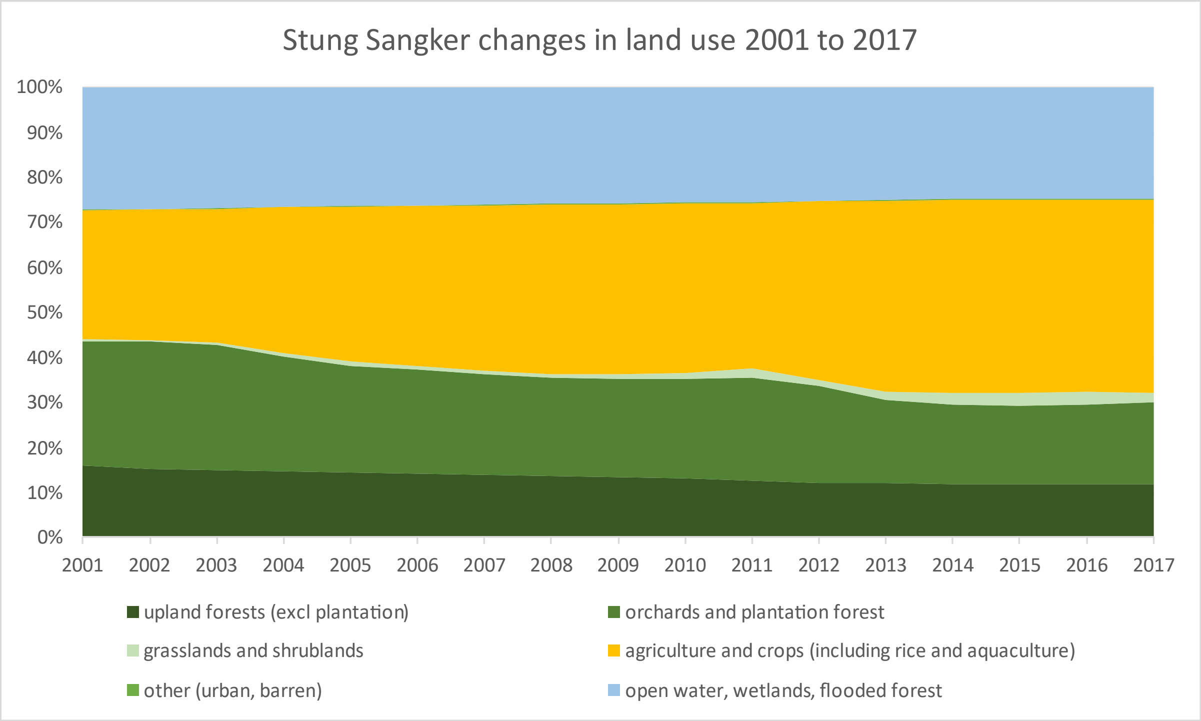
Table 1: Proportion of Forestry, Agriculture and Other Land Uses on the Stung Sangker River Basin 2001 to 2021

Year	upland forests[1]	orchards and plantation forest	grass and shrublands	agriculture and crops[2]	urban and barren areas	open water, wetlands, flooded forest
2001	16%	28%	0.4%	29%	0.1%	27%
2017	12%	18%	2.2%	43%	0.3%	25%

[1] *excluding plantation forests*

[2] *including rice and aquaculture*

Figure 4: Stung Sangker Timeline of Changes in Land Use



Although land use patterns on the basin have changed considerably, few structures have been constructed on the river itself. The only major storage is the Treng reservoir built in 2015/2016 and filled in 2017/2018. The reservoir has a dam wall 3.4 km long and a surface area of around 18 km^{2}[2]. The reservoir's full supply level is approximately 58 m ASL, the maximum depth approximately 6 m, and the volume of the reservoir at full supply level is approximately 30 million m^{3}. Distinct water color changes indicate substantial sediment load variation between the dry and wet seasons (Figure 5).

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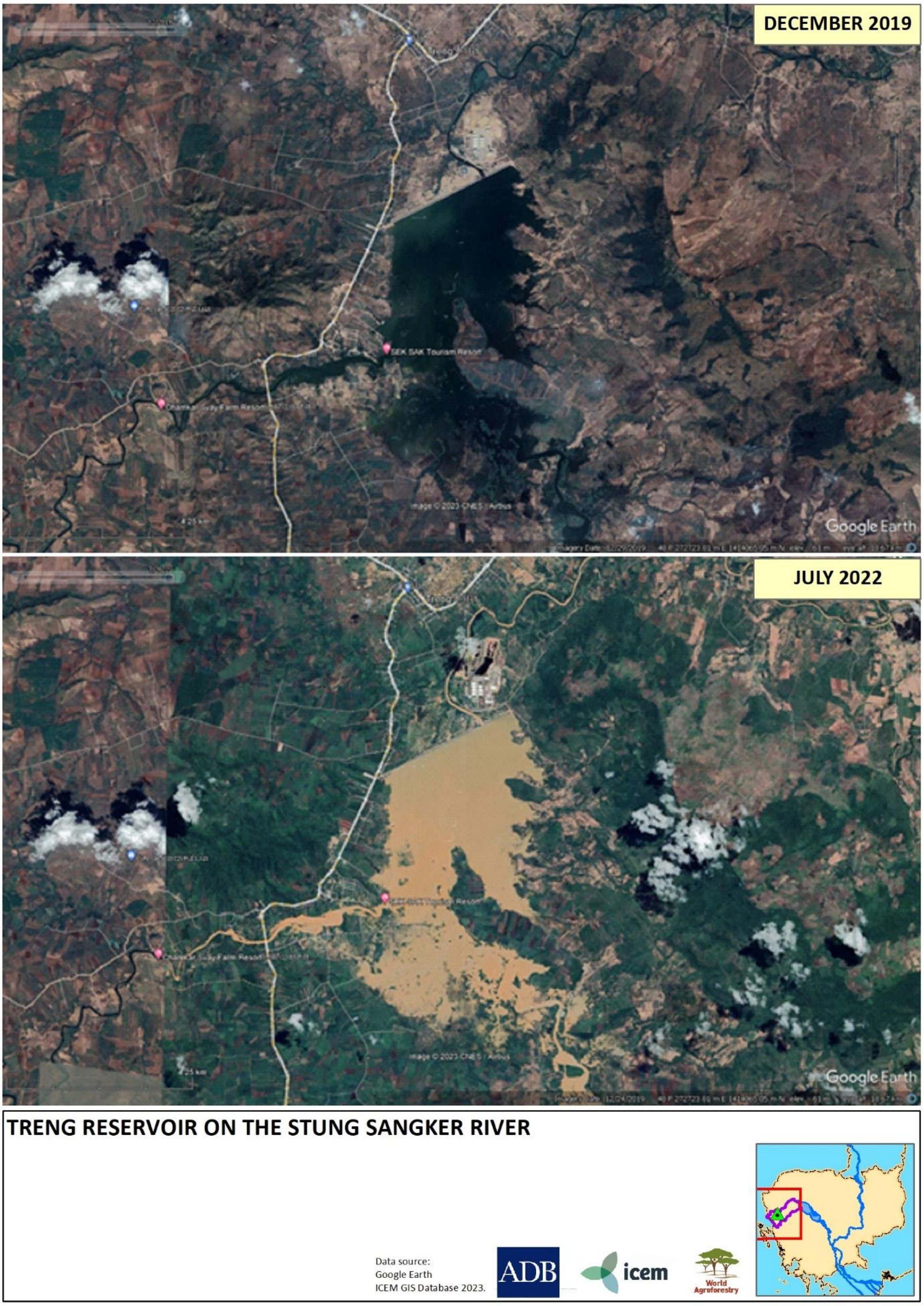
[2] Based on satellite image analysis (google earth – Copernicus/Airbus,2023).

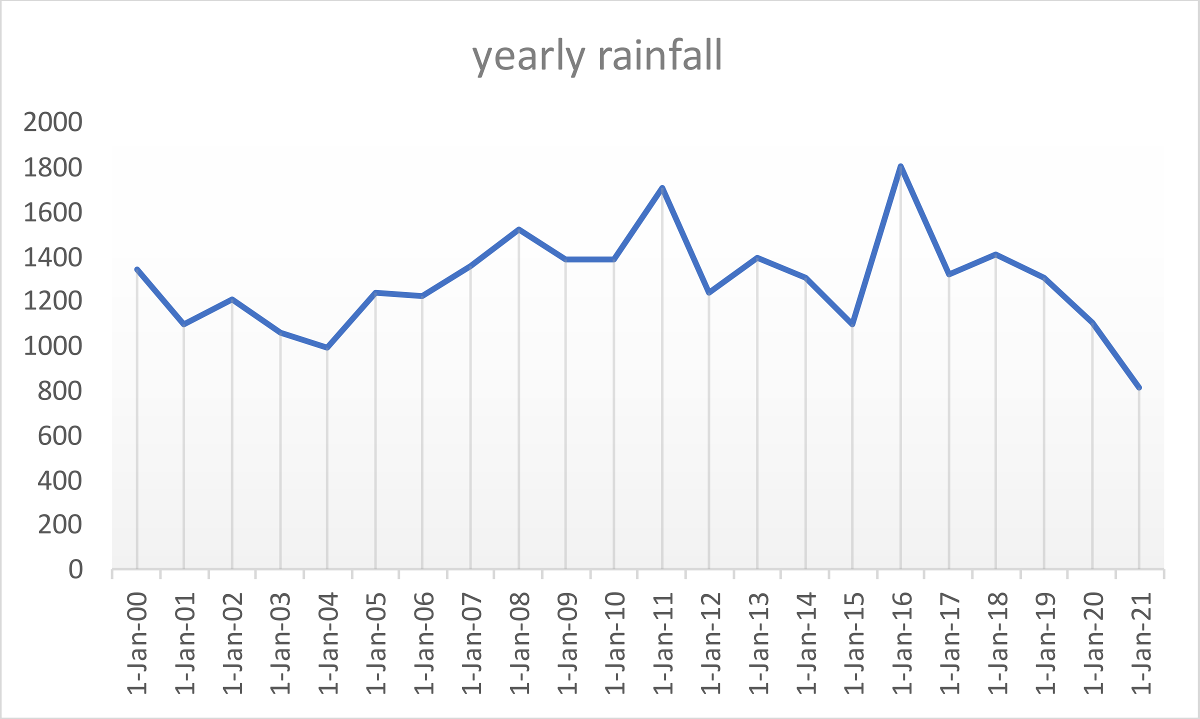
Figure 5: Treng reservoir on the Stung Sangker river in the dry season December 2019 (above) and wet season, July 2022 (below)



2.2. Rainfall

Rainfall within the Stung Sangker river basin is recorded on a number of gauges, however, only the Battambang gauge has a set of records for 20 years or more. Between 1 Jan 2000 and 31 December 2021, the average rainfall at Battambang was 1,289 mm, with a maximum of 1,810 mm and a minimum of 813 mm (Figure 6). The average disguises an increase in average rainfall between 2001 and 2016, and a decrease between 2017 and 2021.

Figure 6: Annual Rainfall at Battambang from 1997 to 2021 (mm)



Rainfall at Battambang varies significantly throughout the year (Figure 7), with a distinct dry season between December and March, a wet season that builds in strength between May and October, and transitional months in April and November. These patterns are consistent with the meteorology of the lower Mekong basin, which experiences a southwest monsoon between April and October and a weaker northeast monsoon between November and December.

While there is little evidence of any significant trend in annual rainfall from 2000 to 2021, maximum monthly and maximum daily rainfall per year do show minor upward trends (Figure 8).

Figure 7: Monthly Distribution of Rainfall at Battambang, 2000 to 2021

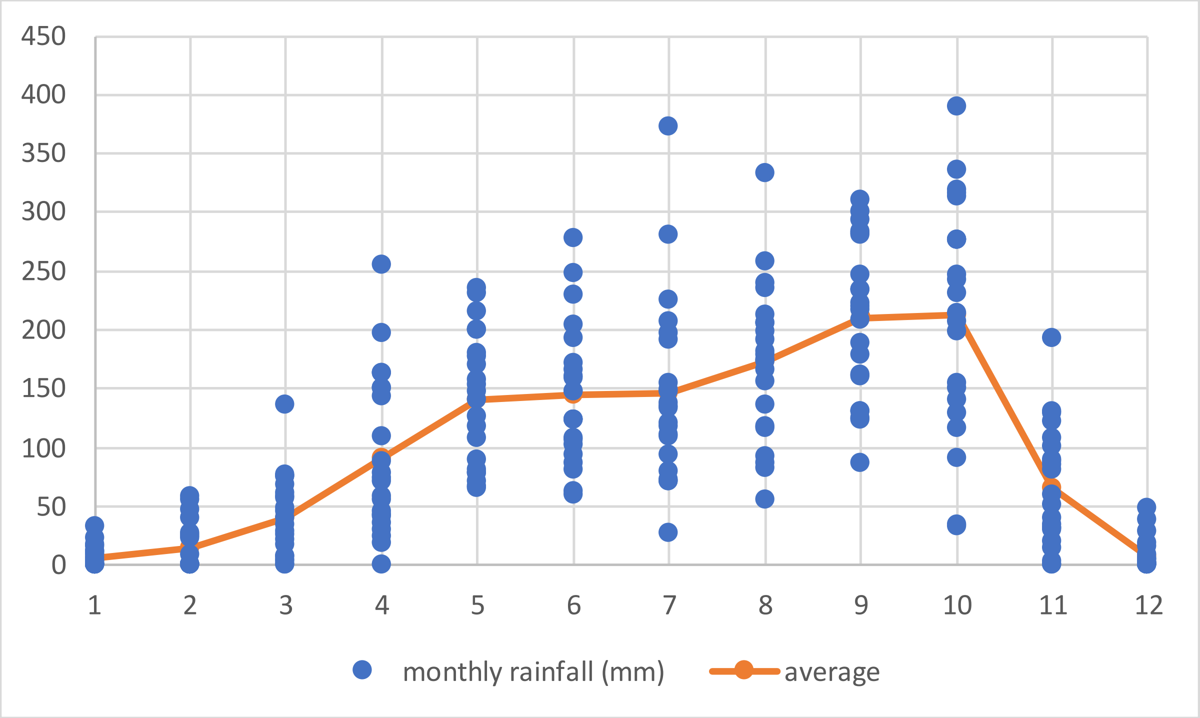
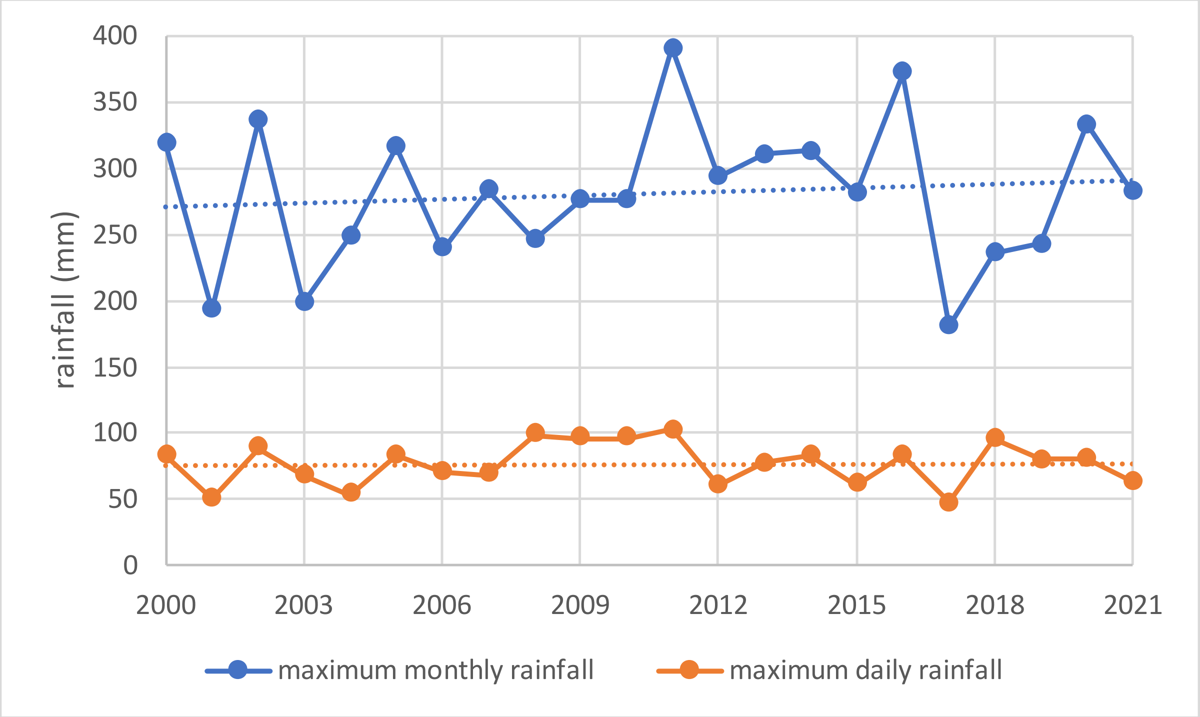
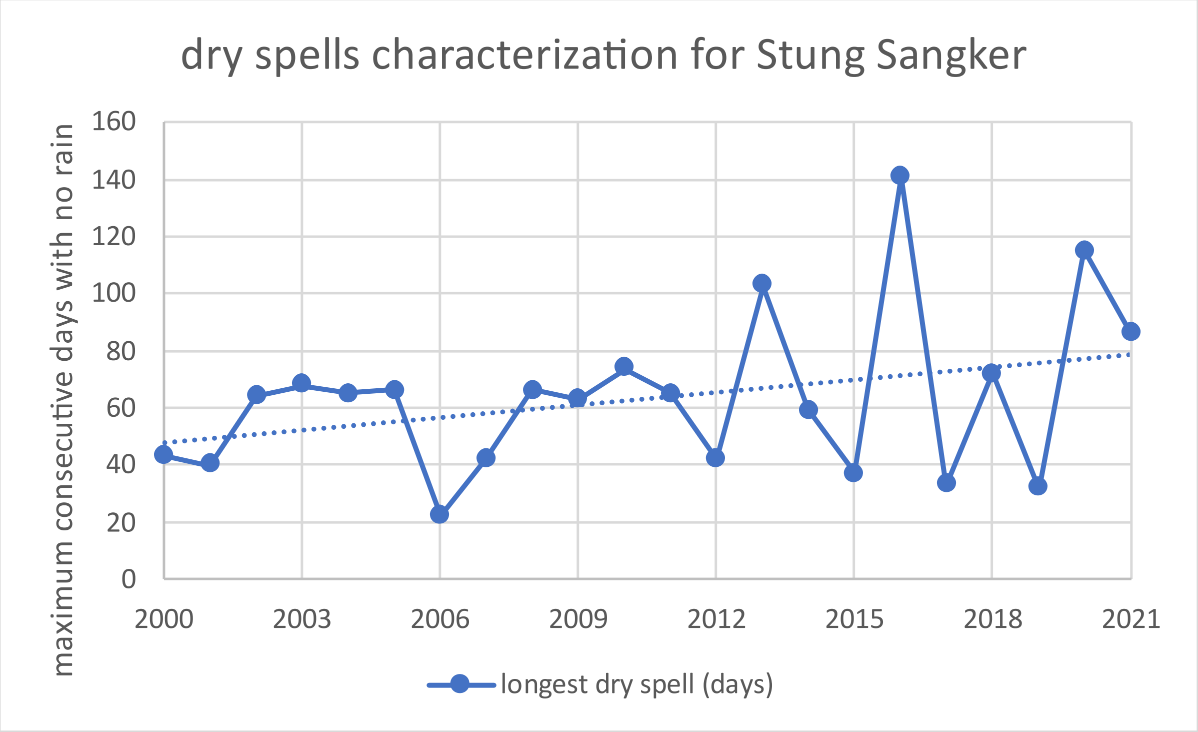


Figure 8: Trends in Maximum Rainfall over Time



Although no trends are apparent in the wet season, dry periods (consecutive days of zero rainfall) are increasing in length during dry periods (Figure 9), consistent with climate change projections of increasing severity and frequency of extreme events.

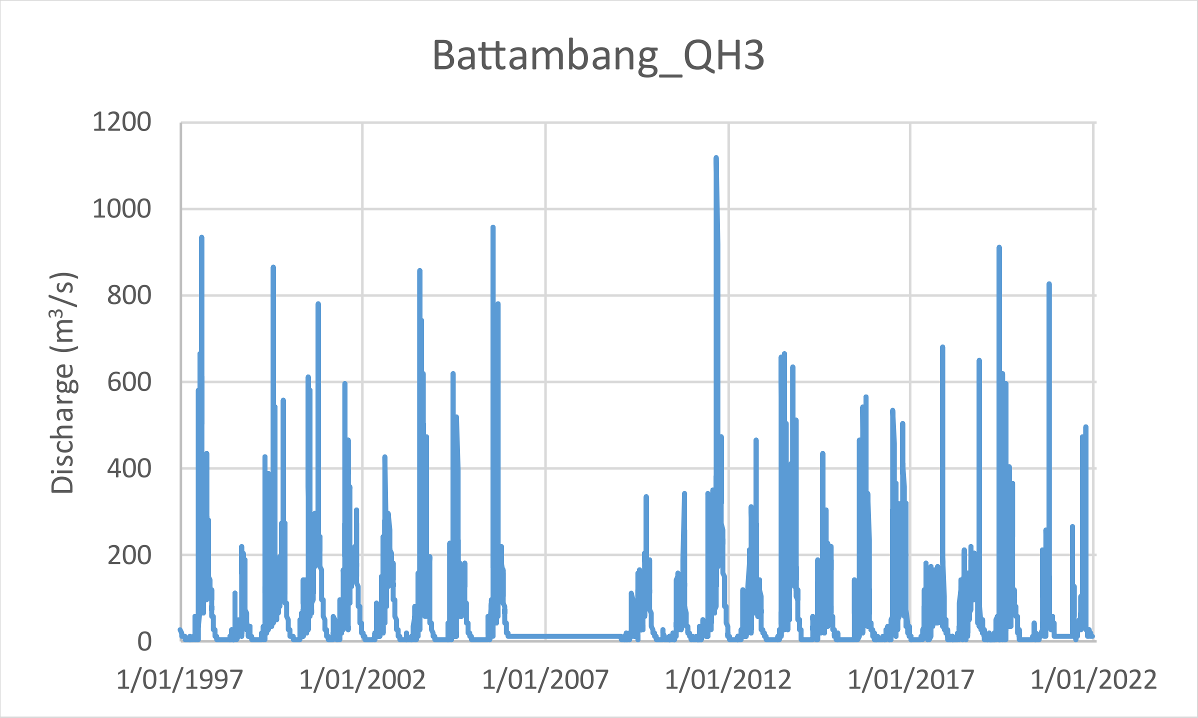
Figure 9: Maximum Consecutive Number of Days Without Rain for Each Year at Battambang



2.3. Assessment of Historical Flow Records

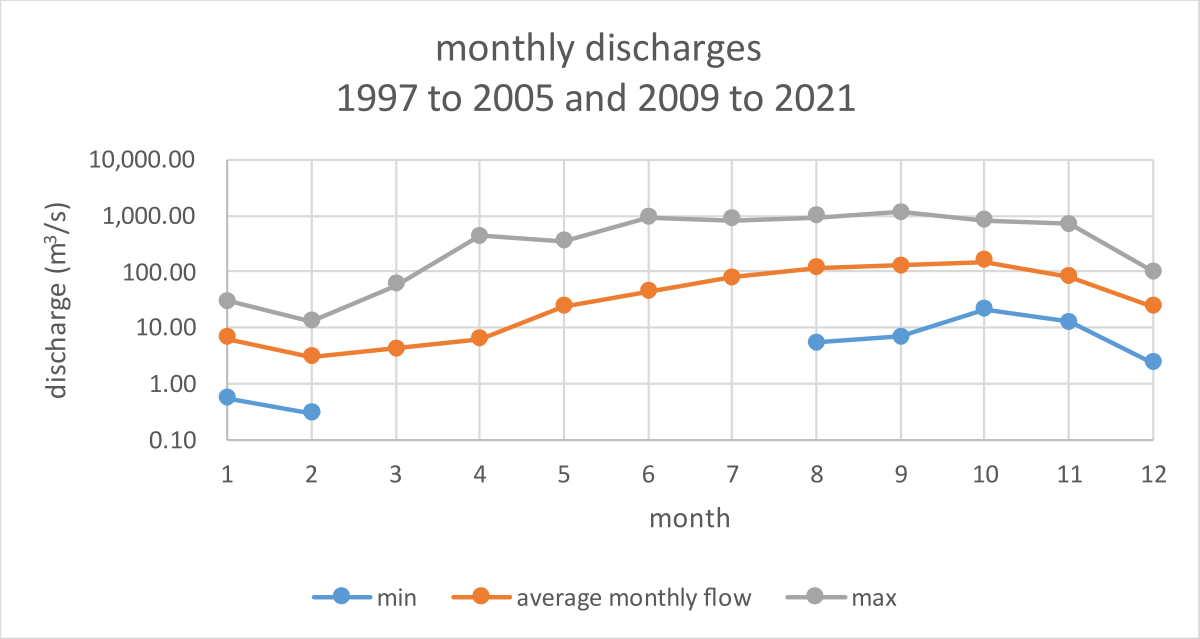
Discharge data for the Sangker river basin is only available at Battambang. Data is available for 1997 to 2021, with gaps in the data between 2006 and 2008 (Figure 10).

Figure 10: Stung Sangker Daily Historical Discharge Records at Battambang, 1997 to 2021



The monthly distribution of discharges mirrors rainfall. The dry season extends from December to April, and the wet season from June to October, with transitional months in April, May, and November (Figure 11).

Figure 11: Monthly Discharges at Battambang (Months with a Minimum Flow of Zero Not Shown)



Similarly, the basin has an evident seasonal variation in water resource availability. Approximately 73% of the total annual discharge occurs during the wet season (May to October), with October seeing over a quarter of the yearly rain flow.

The average annual flow volume at Battambang is 1,668 million m^3. The lowest average monthly discharge, 5.0 m^3/s, occurs in March, and the highest, 297m^3/s, in October. The wet season averages 1,235 million m^3, and the dry season, 433 million m^3. The maximum annual flows always occur in October, while the lowest flows occur between February and April, the three driest months.

From the start of the wet season, the average monthly flow volume at Battambang increases from 79 million m^3 in May to peak at 423 million m^3 in October and then falls to 28 million m^3 in the late dry season in March.

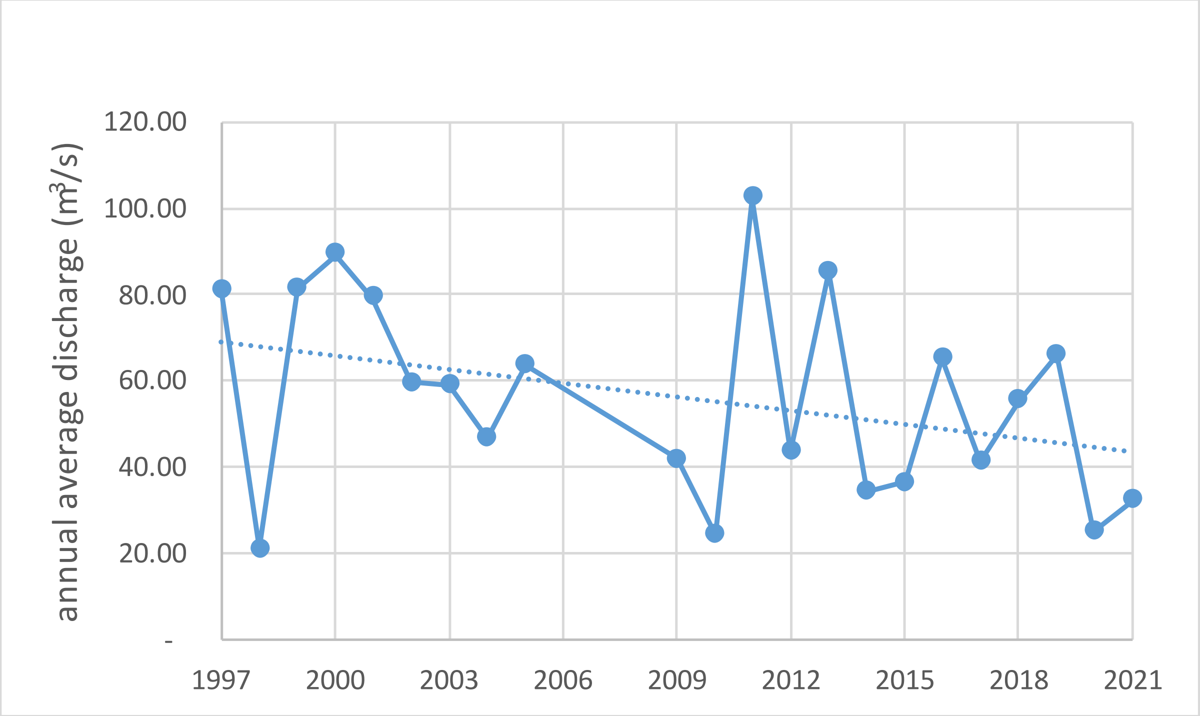
2.4. Indicators of Changes in Hydrology on the Stung Sangker Due to Upstream Developments

Analysis of key hydrological indicators can reveal where changes in land use affect surface water hydrology. The following summarises trends in annual average discharge, monthly discharge, flow duration and flow exceedance, baseflows, flood flows, and environmental flow indicators.

2.4.1 Trends in average annual discharge

Despite relatively constant rainfall, annual average flows decreased over the study period (Figure 12), consistent with the expected impact of the observed replacement of forested land with agricultural areas (Section 2.1).

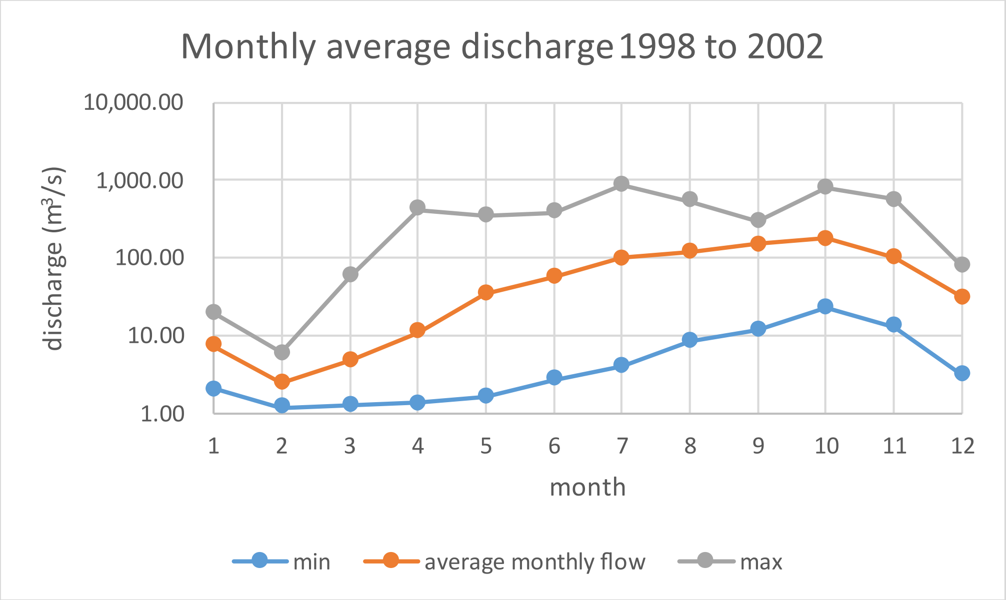
Figure 12: Annual Average Discharge for the Stung Sangker River at Battambang (Dotted Line is the Trend)

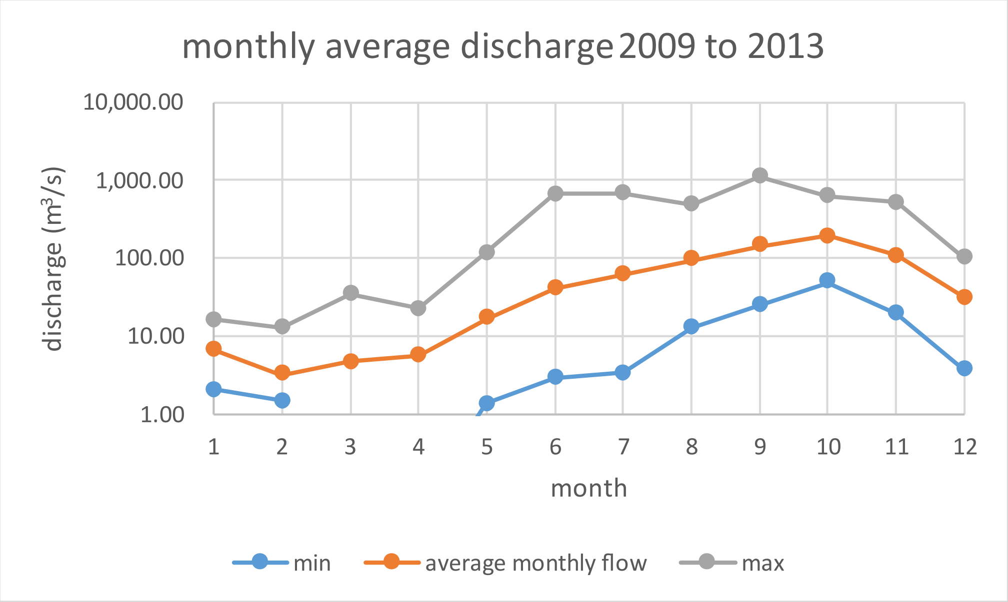


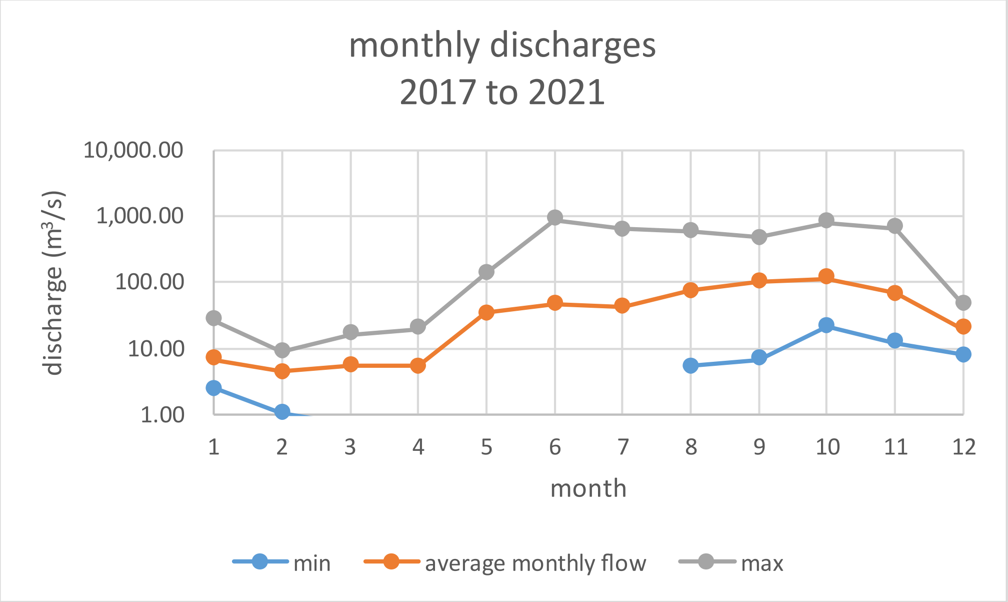
2.4.2 Trends in Average Monthly Discharge

Figure 13 shows the minimum, average, and maximum monthly discharges over the periods 1998 to 2002, 2009 to 2013, and 2017 to 2021. The monthly average and maximum discharges display no significant trend over the three periods. However, the minimum flow decreases considerably, consistent with the increasing length of dry periods (Section 2.2) and the reduction in forested areas (Section 2.1).

Figure 13: Comparison of Monthly Average Discharge Patterns from 1998 to 2002 (Upper), 2009 to 2013 (Middle) and 2017 to 2021 (Bottom)







2.4.3 *Trends in the Flow Duration Relationship*

Flow Duration Analysis is a proven method to determine the impact of upstream developments on downstream hydrology. A flow duration curve represents the proportion of flow exceeded for a particular duration at a specific location on the river. Changes in the shape of the exceedance curve indicate changes to the hydrological integrity of the river.[3]

To assess how changes in land use on the upstream watersheds on the Stung Sangker may have impacted downstream hydrology, flow duration curves for the Stung Sangker were developed for the periods 1998 to 2002, 2009 to 2013, and 2017 to 2021.

In high-flow periods, the flow duration decreases, indicating that less water is being transmitted during flood periods in more recent years (2009-2013 and 2017 to 2021) than between 1998 and 2002 (Figure 14).

Similarly, for low-flow periods, the amount of water available over extended periods (50 to 200 days) is significantly lower in recent years compared to earlier years. This is particularly concerning,

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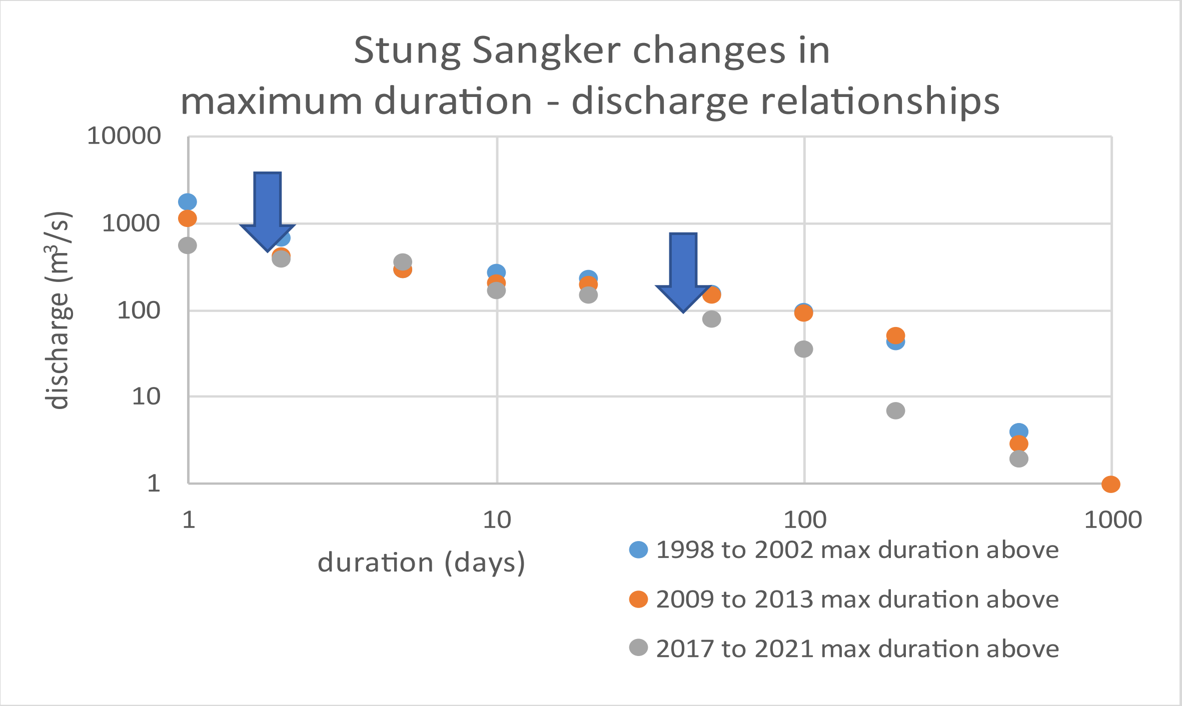
[3] See, for example, Suwal et al., 2020

indicating that over the dry season in recent years, the river has a lower capacity to maintain flows compared to previous years.

Figure 14: Changes in Flow Duration Relationships on the Stung Sangker at Battambang from 1998 to 2021



2.4.4 *Trends in Direct Runoff and Baseflows*

Trends in direct runoff and baseflows over time indicate that development predominantly in the upstream basin may significantly change the surface water and groundwater hydrological processes. Such changes may have implications for floods, droughts, and groundwater availability[4].

Direct runoff is rainfall that is directly transformed to surface flows on the overland portion of the catchment, as well as rainfall that falls directly on streams and waterways. By contrast, baseflows are water absorbed into the soil surface, transported downstream by subsurface flow, and then discharged into streams (Figure 15).

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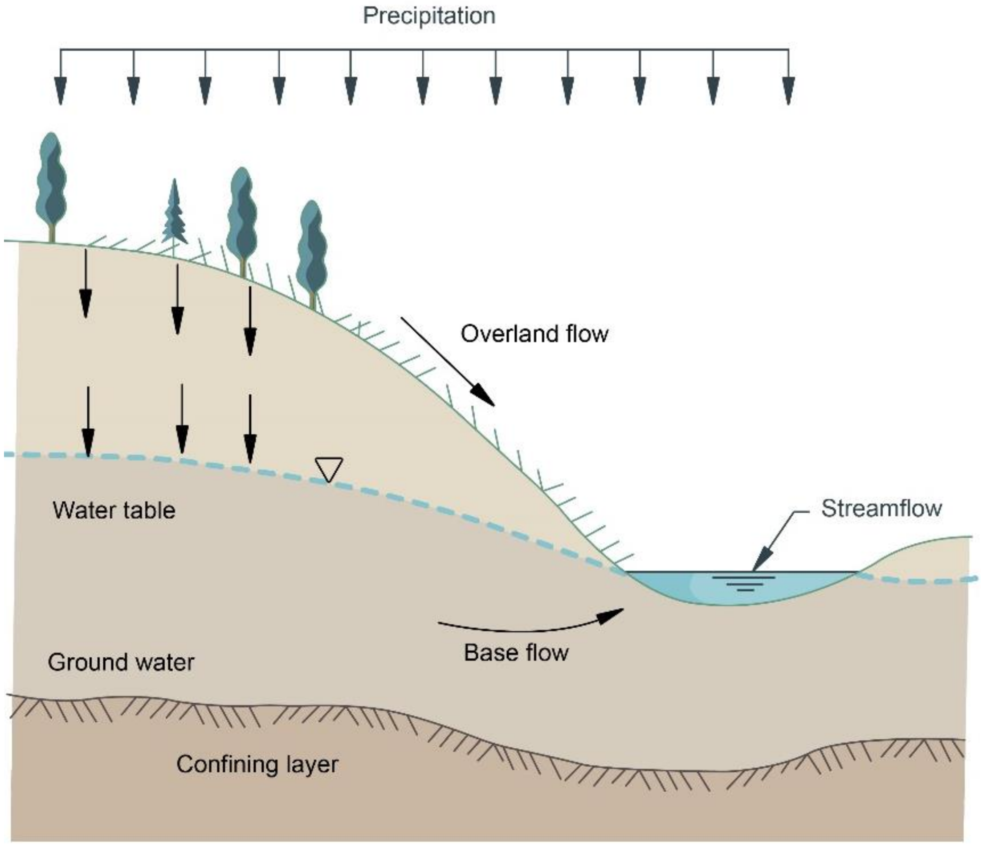
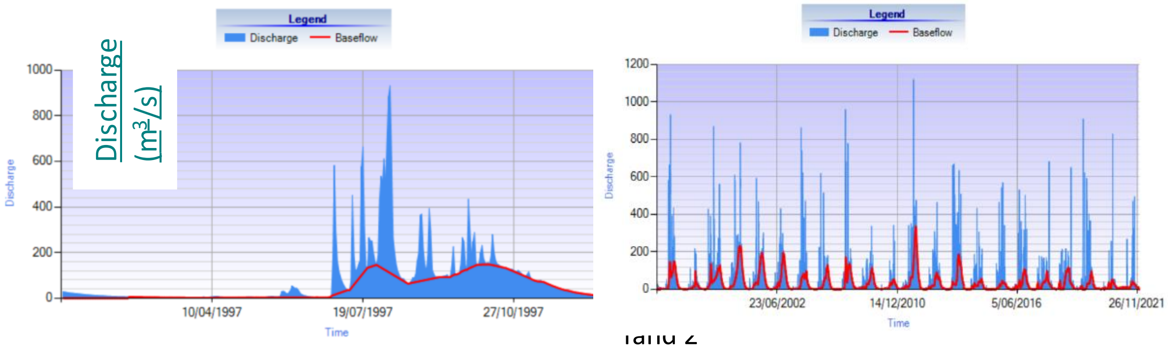
[4] See, for example, Tallaksen and Van Lenen, 2004

Figure 15: Overland Flow and Streamflow as Direct Runoff Compared with Baseflow as Delayed Runoff



Baseflow and direct runoff annual flow rates, wet season maximum flows (flood flows), and dry season minimum flows (droughts) may respond differently to land use and rainfall changes.

Figure 16: Baseflow Separation for the Year 1997 (Left) and for 1997 to 2021 (Right)[5]



2.4.5 *Average Annual Baseflow and Direct Runoff Trends*

Baseflow separation demonstrates that the annual average baseflow and direct runoff volumes decreased significantly from 1997 to 2021, consistent with the observed decreasing average annual flows (Figure 17). However, baseflows decreased more significantly than direct runoff and total flows. As a proportion of total flows, baseflow decreased from 42% in 1997 to 35% in 2021.

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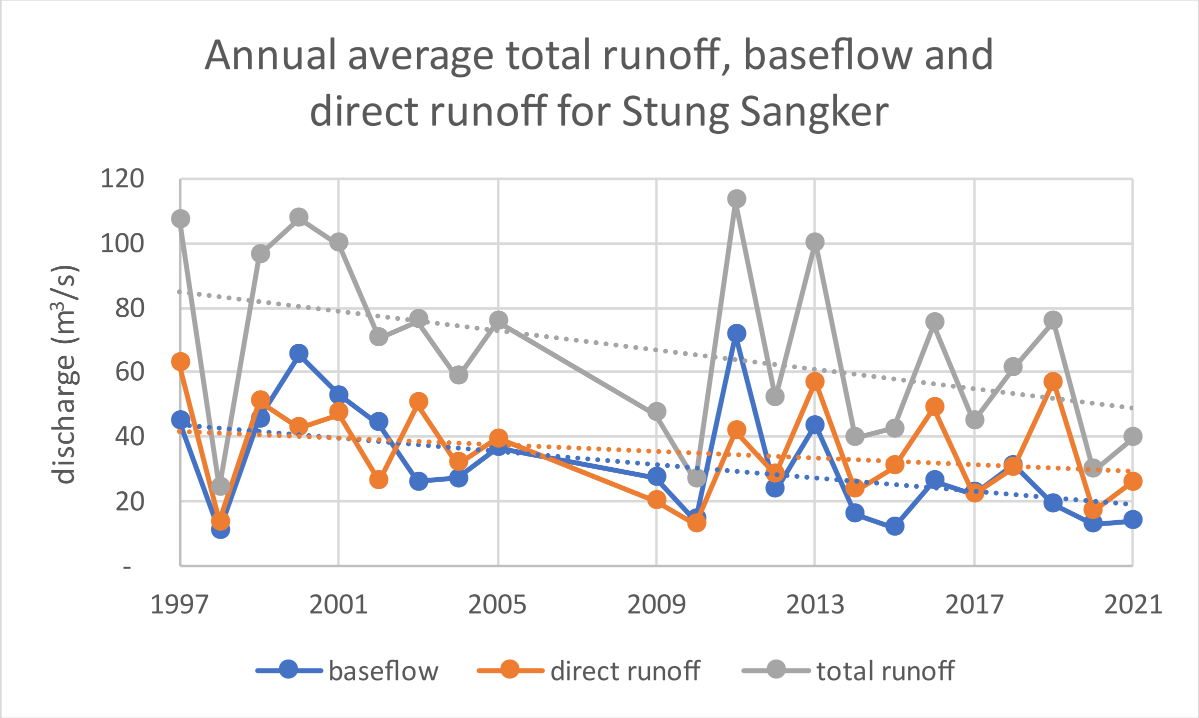
[5] Baseflow – direct runoff separation for the Stung Sangker at Battambang was performed using the software package BFI+ available from https://hydrooffice.org/.

Figure 17: Total Annual Baseflow and Direct Runoff for the Stung Sangker River Basin at Battambang



2.4.6 Wet Season Baseflow and Direct Runoff Trends

Wet season average and maximum total flows and baseflows decreased from 1997 to 2021 (Figures 18 and 19). However, average and maximum direct runoff remained more or less the same, suggesting a trend towards increasing flash floods with a more rapid onset of flood events. Rapid rising and falling flows are also associated with higher erosion rates, especially in upland areas where runoff rates tend to be faster and direct runoff is often a higher proportion of the total flow.

Figure 18: Average Wet Season Discharge Trends 1997 to 2021

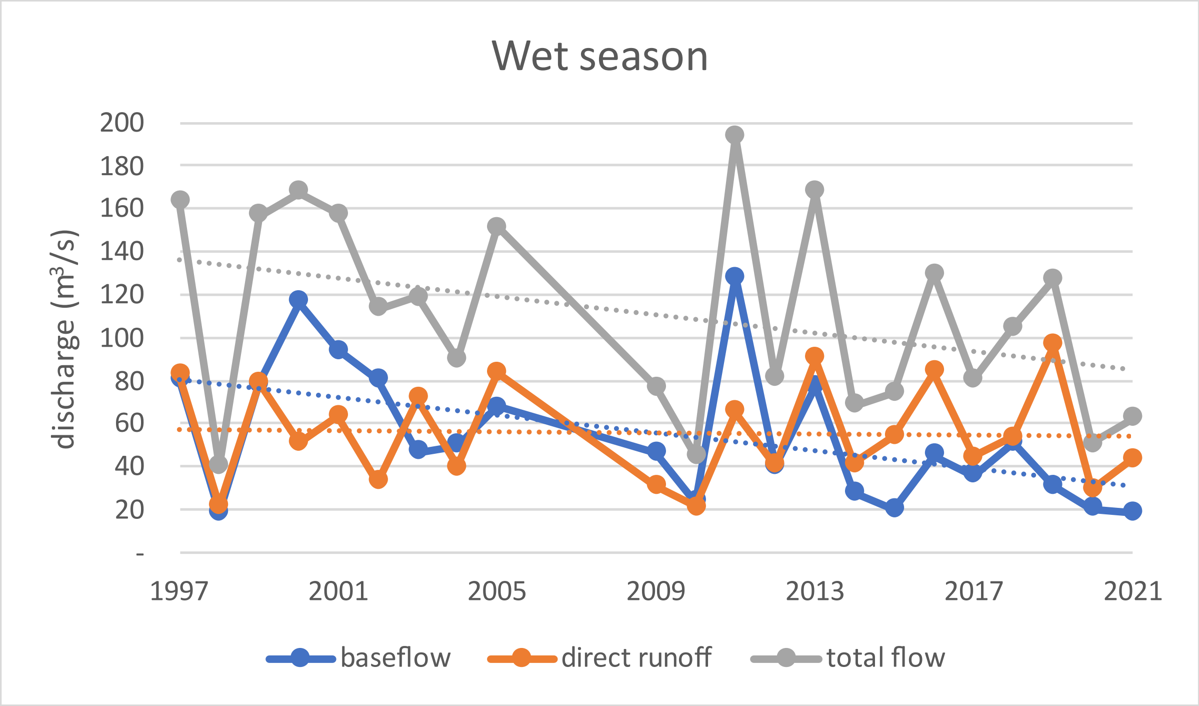
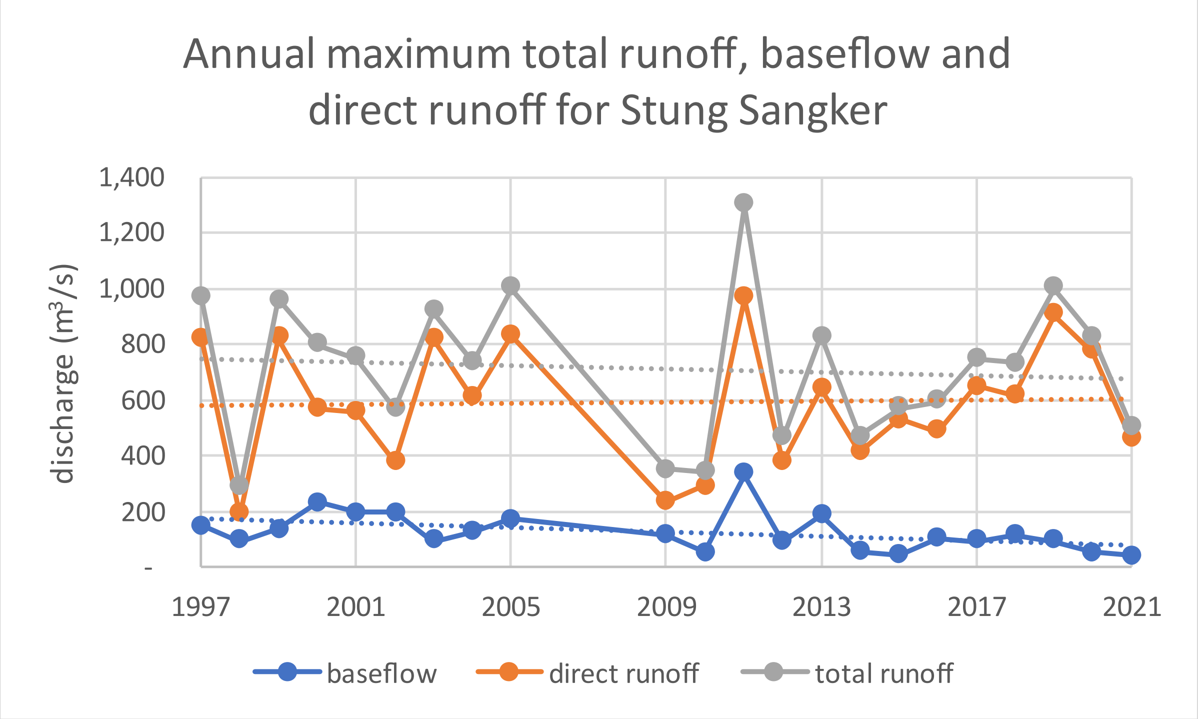


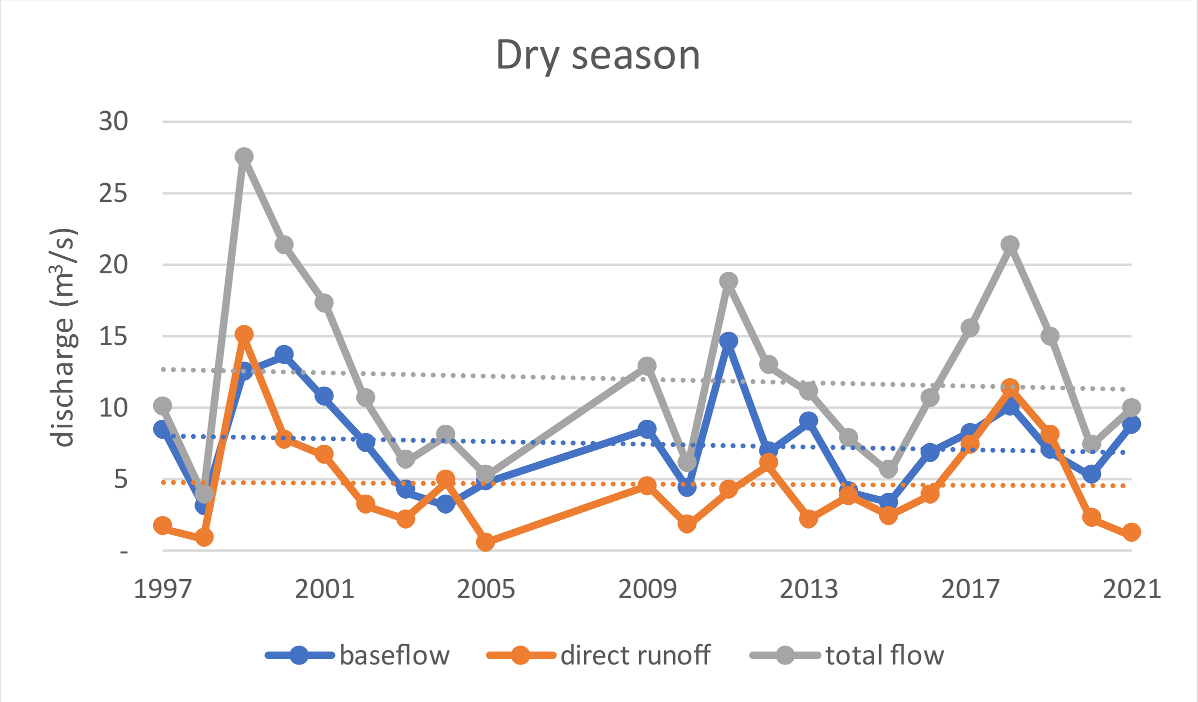
Figure 19: Trends in Annual Maximum Direct Runoff (Peak Flood Flows)



2.4.7 *Dry Season Baseflow and Direct Runoff Trends*

Average dry season flows, baseflows, and direct runoff decreased over time (Figure 20), a trend consistent with the lengthening periods of rain-free days (Section 2.2).

Figure 20: Average Dry Season Discharge Trends 1997 to 2021



2.5. Current Knowledge of Sediment Transport Processes for the Stung Sangker River Basin and Tonle Sap Basin

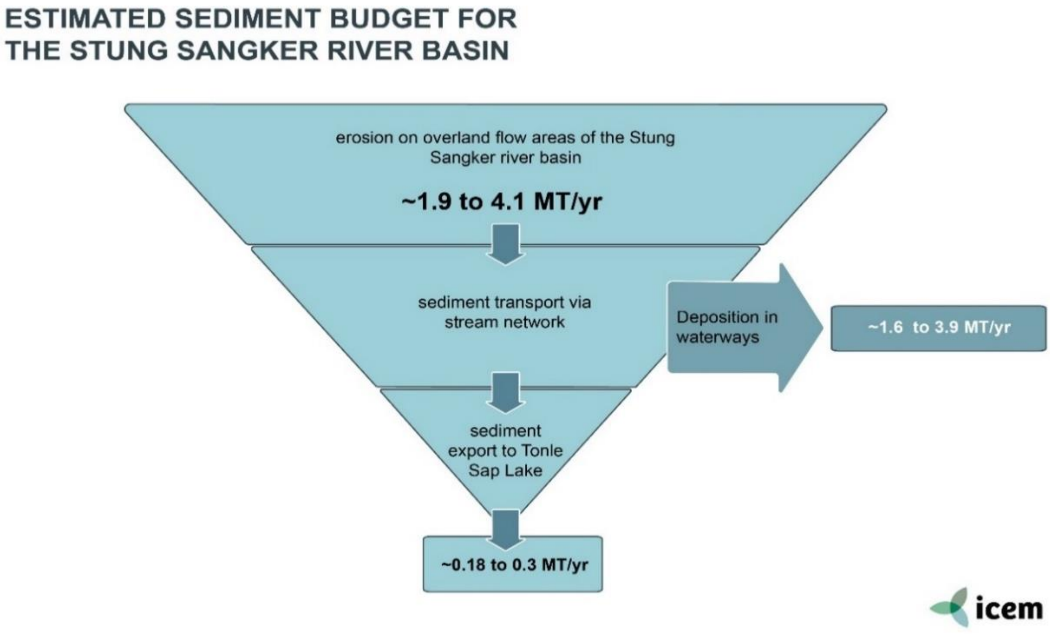
As there are no known gauging of sediment transport in the Stung Sangker River basin, sediment loads were estimated as a range of potential values based on areal sedimentation rates from other previous studies within the region and by SWAT modelling.

In the entire Sangker river basin area, an estimated 1.9 million tons of sediment were lost from overland flow areas in 2002 and 4.5 million tons in 2015[6]. Sediment loss (erosion) rates in overland flow areas are estimated as being between 0.2 t/ha/yr for forest areas and 31 t/ha/yr for upland agricultural areas.[7] The highest erosion rates are likely to occur in the high-sloped upstream watersheds in the western portion of the catchment, especially in areas converted from forest to agriculture. By contrast, the flat marshlands, shrublands, grasslands, and paddy fields in the east of the catchment are likely to have relatively low erosion rates.[8]

However, the majority of the lost sediment does not arrive at the Tonle Sap Lake. The total sediment load entering the Tonle Sap Lake from the upstream basin is estimated to be between 2 and 3.5 million t/yr[9]. As the Stung Sangker river basin accounts for only around nine percent of the Tonle Sap basin area, approximately 180,000 to 300,00 tons of sediment would be expected to reach the lake every year (assuming that sediment loads are uniform across the basin).

This difference between high sediment loss rates from the overland flow areas and lower sediment loads entering the Tonle Sap downstream indicates that around 85% to 95% of the sediments lost from overland flow areas on the Stung Sangker river basin are deposited overland and in waterways including canals, reservoirs and irrigation systems within the catchment with only around 5% to 15% of these sediments being exported by the Sangker river network to the Tonle Sap lake, as shown in Figure 21.

Figure 21: Estimated Sediment Budget for the Stung Sangker River Basin



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[6] Nut et al., 2021.

[7] Nut et al., 2021

[8] Sediment export and load rate estimates should be treated as indicative as they are based on an uncalibrated Geographical Information Sytems (GIS) model which assessed areal export rates for the catchment based on rainfall rates, soil types, land use and the topography of the catchment without accounting for hydrological processes on the catchment.

[9] Kummu et al., 2005a and MRC ISH, 2013

3. Modelling Approach

A Soil and Water Assessment Tool (SWAT) model was used to assess the impact of meteorology, topography, and land management practices on runoff rates and erosion. SWAT is a process-based watershed modeling platform developed by the USDA Agricultural Research Center. SWAT is widely accepted internationally as an effective tool to explore the impact of climate change and extreme weather conditions on hydrology and sediment transport[10]. A comprehensive review of SWAT applications highlighted the capacity of the model to assess the impact of climate change on watershed hydrology, fluctuations in river flow under different climate forecasts, and as a tool to guide decisions in flood control projects[11].

SWAT models have also proved their value in assessing the impact of land-use changes on water flows. For example, a study in the Phalico watershed in the Philippines found a reduction in forest cover reduced baseflow in dry periods by up to 17% and increased streamflow in wet periods by up to 24%[12].

SWAT models can also simulate different physical processes in a river basin, including water movement, sediment movement, crop growth, and nutrient cycling. As SWAT divides landscapes into sub-basins, further subdivided into hydrological response units (HRUs) – land parcels with homogeneous land uses, soil types, and classes of terrain slope – the model can be readily applied to both small and large river basins.

SWAT has been successfully applied to the Lower Mekong Basin (LMB), including the Tonle Sap basin; however, no previous studies are known to have addressed runoff and sediment transport on the Stung Sangker.[13]

3.1. Soil and Water Assessment Tool Model Setup and Calibration for Baseline Conditions

A typical approach to modelling hydrological systems is summarized in Figure 22.

Figure 22: Modelling Approach

Define problem	Model selection	Model set-up	Model calibration/ verification and baseline simulation	Future Scenarios simulation
Upstream Deforestation. Unsustainable agricultural management practices, Climate Change	SWAT model	Set up HRUs and assemble input data	Calibrate and verify runoff outputs from the model against observed flows to simulate baseline conditions	Change rainfall inputs to simulate climate change. Change HRU properties to simulate land use changes and adaptation responses

Topography data was extracted from the MERIT global database, land use from the Servir Mekong online database[14] for 2017, the latest year data is available, and soil types from the Food and Agriculture Organization of the United Nations (FAO) global soils database.[15] Topography and soil types have been consistent over the last two decades. Landuse, however, has changed significantly. Agricultural land and paddy rice fields accounted for almost 42% of the total land in 2017, an increase

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[10] Bressiani et al., 2015

[11] Gassman et al., 2007

[12] Briones et. al., 2016

[13] Rossi et al., 2009, Sok et al., 2020 and Ang and Oeurng, 2018

[14] https://servir.adpc.net/

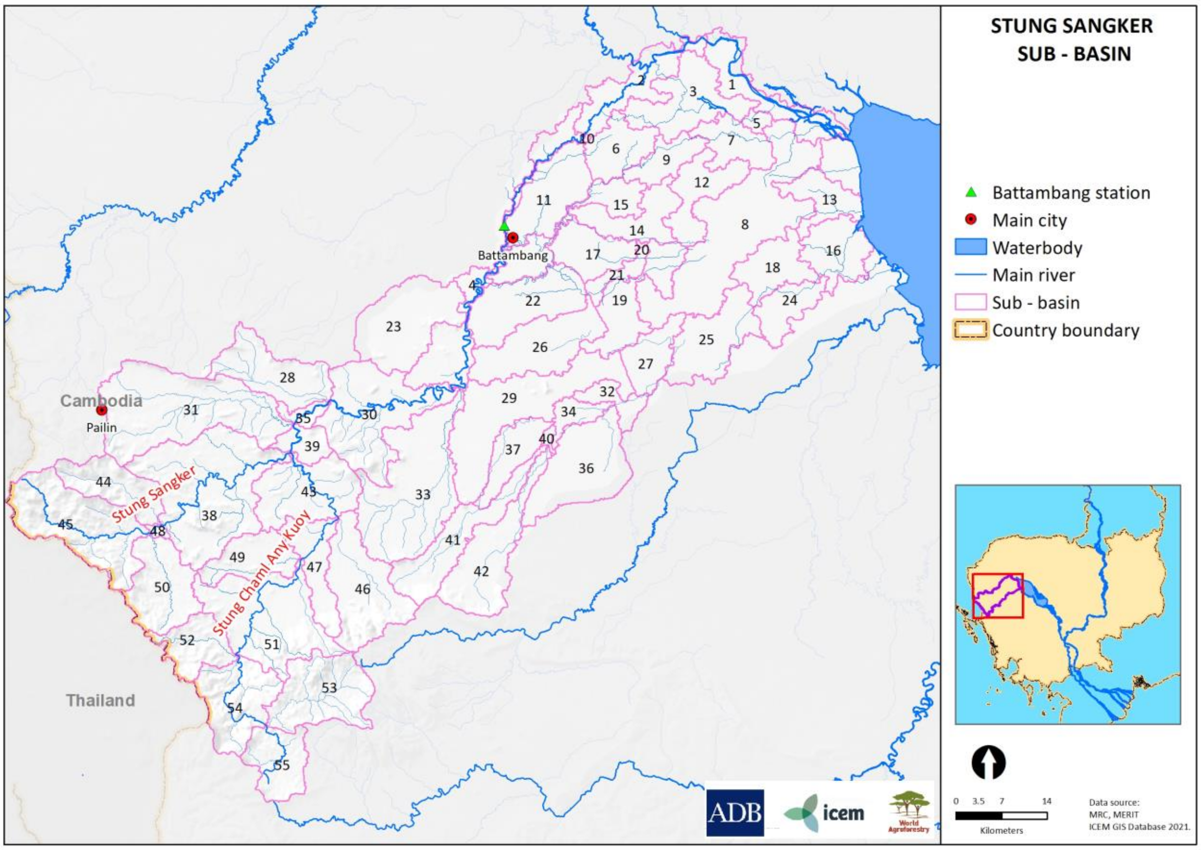
[15] https://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/en/

of 30% from 2002. Conversely, forest cover (evergreen, deciduous and mixed forest) declined by 44% in 2002 to 29% in 2017.

Based on these data sets, Sangker sub-basins were delineated (Figure 23), and over 200 Hydrological Response Units (HRUs) were automatically generated by SWAT across all sub-basins.

The only major structure in the Stung Sangker river basin is the Treng reservoir, constructed in 2016. Detailed information on the reservoir's design and operating rules is unavailable, so the reservoir has not been incorporated into the SWAT model.

Figure 23: Sangker Sub-Basins Defined for Soil and Water Assessment Tool Modeling



Data source:
MRC, MERIT
ICEM GIS Database 2021.

The SWAT model was calibrated and verified against observed river flows and rainfall at Battambang, the only gauge from which rainfall was available in the basin. The model was run through an initial "warm up" period (2007 to 2008), a calibration period (between 2009 and 2015) and a verification period (2016 to 2021). Eleven parameters in the model were adjusted to perform the calibration as described in Annex B.

The model performance showed an acceptable fit between observed and simulated stream flows in the calibration and verification periods (Figure 24).

While the model's overall fit is generally good, the simulation frequently under-estimated peak flows (Figure 24). This is most likely due to orographic effects in the catchment: larger flood events are most likely linked to high rainfall rates in the steep sloping upland areas. However, as the gauge is located downstream, rainfall is not representative of these events, and withdrawals of flow from the river upstream of Battambang are not accounted for in the model. Previous SWAT studies of climate change impacts on the hydrology of the Stung Sangker river basin using HEC-HMS and the Tonle Sap basin had similar difficulties matching peak flows.[16]

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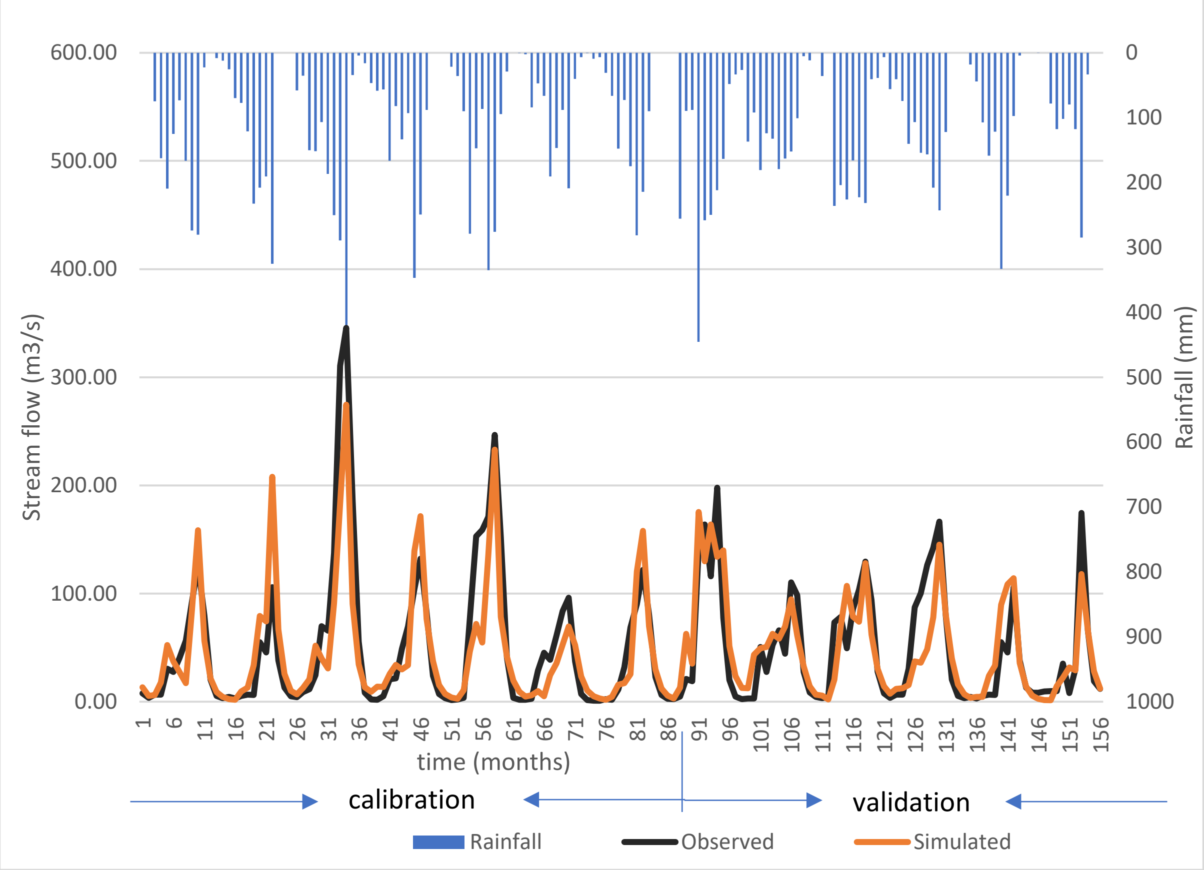
[16] Sok and Oeurng, 2016 and Oeurng et al., 2019

Figure 24: Rainfall, Observed Monthly Flows, and Simulated Monthly Flows for the Sangker River at Battambang



With no sediment gauging data available to calibrate SWAT for sediment loads, baseline sediment load rates were performed for two cases to reflect the uncertainty of the modelling: a medium erosion case and a high erosion case. In the medium erosion case, the erosion-related parameters of the Modified Universal Soil Loss Equation (MUSLE) in SWAT were set to the middle of their recommended ranges. In the high erosion case, erosion parameters were set to the maximum of their recommended ranges.

3.2. Future Scenarios

The future scenarios are designed to assess the impact of climate change on the hydrology of the Stung Sangker river basin, and how changes in land use practices and soil and water management measures can mitigate and adapt to the impacts.

For this landscape restoration project, reforestation efforts should predominantly take place in degraded areas in key locations such as along drainage corridors, in community forests, within protected areas and across the agricultural landscape following boundaries of allotments and for the replacement of agricultural allotments with agroforestry to ensure healthy hydrological and sediment processes within the watersheds.

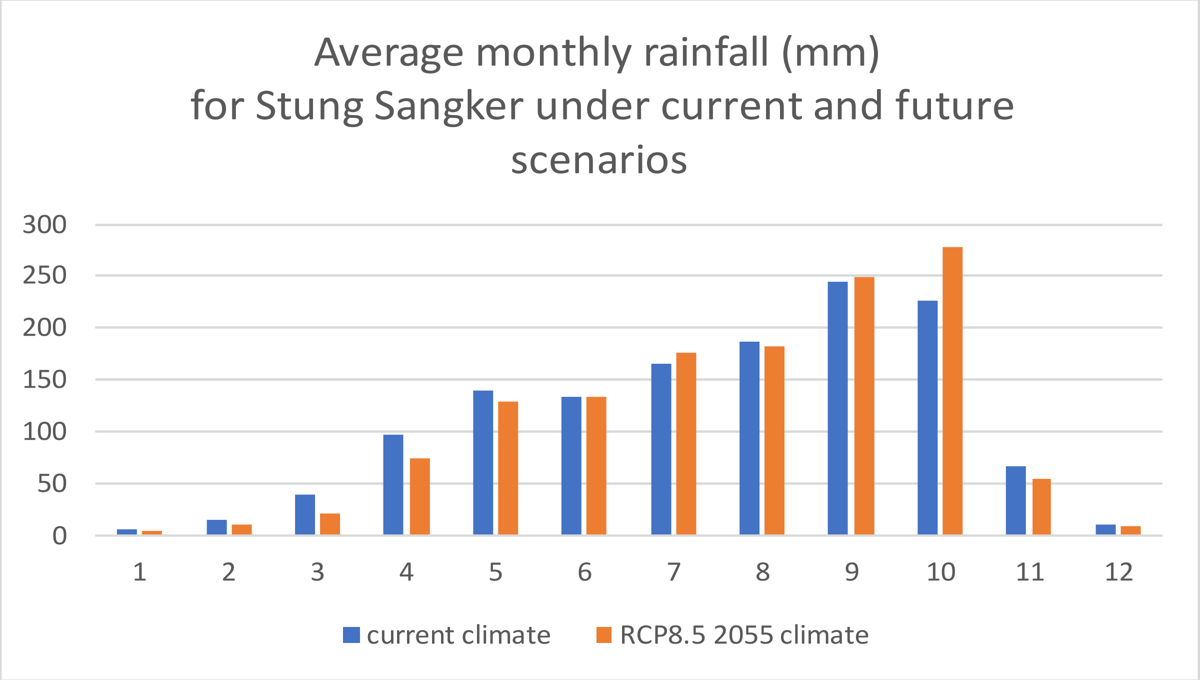
The purpose of modeling is rarely to simulate exactly processes that occur in the real world and how they may change with time. Factors that limit the ability of models to truly “simulate” the real world include limitations in accurate data for calibration, limitations in model resolution, limitations in the scientific understanding of the underlying processes and the inherently *stochastic* nature of these processes compared to the deterministic nature of most models.

Given these considerations, modelling objectives typically involve determining *what may happen* under different scenarios that represent simplified conditions and changes in conditions in the real world. Model results always need to be carefully interpreted in light of the limitations and simplifications made when modelling is performed.

3.2.1. Future Scenario 1 (FS1): Climate Change Scenario by 2055

SWAT forecasts for climate change model scenarios were based on forecast rainfall for Cambodia from the Institut Pierre Simon Laplace modelling centre fifth version (IPSL-CM5A-MR) global circulation model (GCM) under Representative Concentration Pathway (RCP) 8.5 by the year 2055. The model was chosen for its reliability in replicating interannual rainfall variability resulting from the Indian ocean monsoon [17]. Under the scenario, monthly rainfall over the Stung Sangker river basin is expected to become higher for the highest flow months of September and October, and lower for all other months (Figure 25).

Figure 25: Comparison of Average Monthly Rainfall Under Current Climatic Conditions and with Climate Change



Results for the wet season are indicative as the effects of climate change on typhoons in South East Asia remain uncertain in climate modelling[18].

Results for the dry season should also be treated with caution as no adjustment was made to account for changes in evapotranspiration in the catchment due to potential meteorological changes resulting from climate change, including temperature increases, and possible changes in relative humidity, windspeed, and cloud cover.

3.2.2. Future Scenario 2 (FS2): Upland Watersheds Land Use Change Scenario

The second scenario assessed the potential for land use change to offset climate change impacts. Under the land use change scenario, 30% of 2017 agricultural land is assumed to be converted to agroforestry, represented in SWAT as “Orchard” or ORCD land use type.

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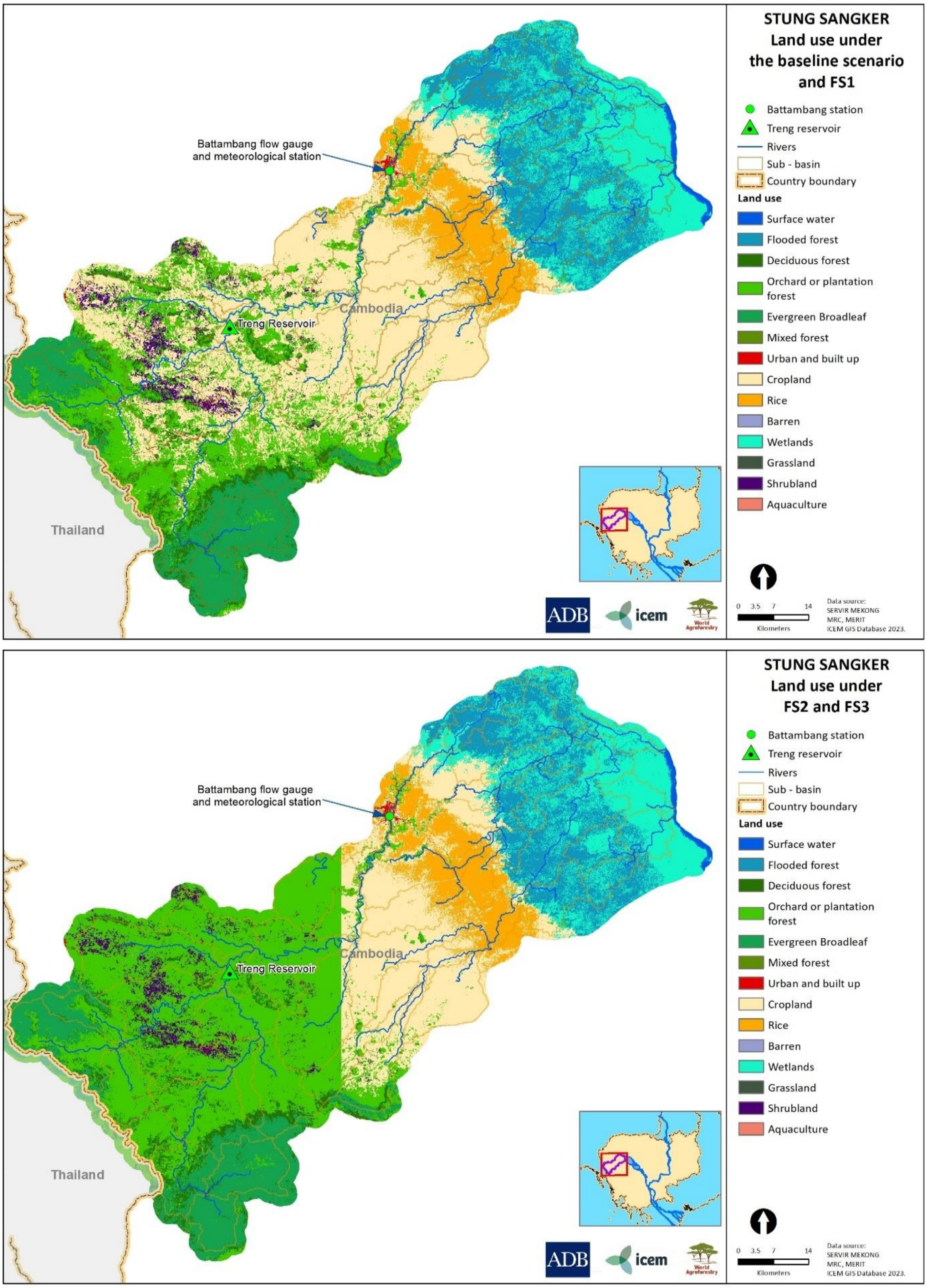
[17] MRC, 2015

[18] See for example Gallo etal, 2018

This approach is less feasible in downstream areas as the project encourages agroforestry at higher elevations. As such, the scenario implements only implements land-use changes in upstream HRUs (Figure 26).

Figure 26: Land Use Under the Baseline Scenario and FS1 (Above) and for FS2 and FS3 With Upland Agricultural Areas Converted to Agroforestry (Below)



Input rainfall for this scenario was selected as the 2055 projected rainfall under climate change RCP8.5, as used for input to FS1.

3.2.3. Future Scenario 3 (FS3): Application of Conservation Farming in Lowland Areas

Conservation farming measures are applied to prevent soil erosion, reduce soil compaction, maintain or improve soil fertility, and conserve, drain or harvest water[19]. Conservation practices can be modelled in SWAT by changing values of the land uses management practice (p) factor in the MUSLE.

To further reduce sediment losses beyond those achieved by land use change under FS2, Future scenario 3 (FS3) simulated a change in management practices by implementing contour farming on the remaining agricultural areas not converted to agroforestry under FS2. As land use change under FS2 covered only the upland watersheds with no land use changes in downstream lowland areas, FS3 can give insights into the effectiveness of interventions in the lowland areas.

The implementation of contour farming was modelled in SWAT by adopting land uses over the river basin to be the same as the FS2 case, with the land use management Practice (“p”) factor in the MUSLE sediment yield equation from its default value of 1 (which was used for the BL, FS1 and FS2 scenarios) to a value of 0.6 over all remaining agricultural areas that were not converted to agroforestry. Changing the p factor in this way will result in a 40% reduction in sediment yield from these areas.

A p factor of 0.6 can be achieved with strip cropping, whereby contoured strips of sod are laid alternatively with strips of row crops. For land sloping at 1.1% to 2% strip widths of 40 m are used with maximum slope length limits of 244 m[20].

As for FS1 and FS2, the 2055 projected rainfall was applied over the basin as the input time series.

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[19] Tidemann 1996

[20] Wischmeier and Smith, 1978

4. Simulated Scenarios Results and Analysis

Baseline (BL) scenario results, and results for future scenarios 1, 2 and 3 are described in Sections 4.1, to 4.4 below respectively. Scenario results focus mostly on the Sangker river outlet, the Treng Reservoir and the lowlands distributary outlet as key locations in the basin as shown in Figure 26.

The Sangker river outlet is considered a critical location to understand flow and sediment processes to give an improved understanding of the overall basin wide hydrology and sediment transport processes under the baseline conditions, how these may change under the three future scenarios and for implications of changes in hydrological and sediment loadings entering the Tonle Sap Lake.

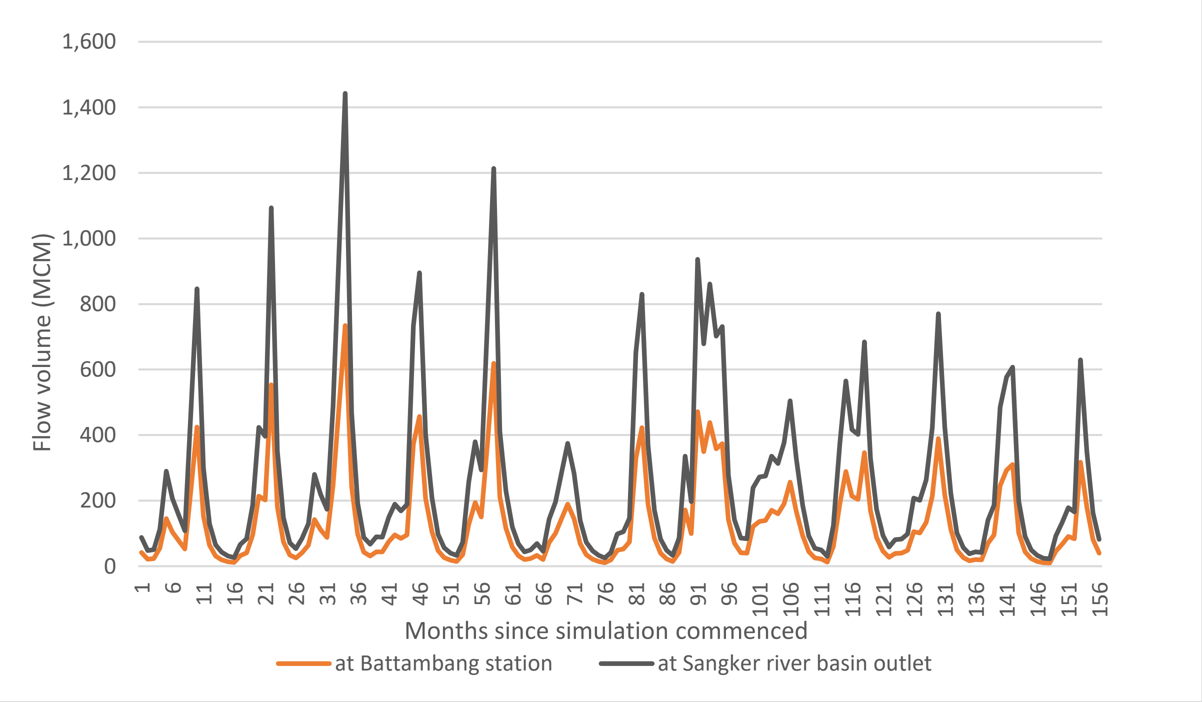
The Treng Reservoir site is considered as a key location as it is located immediately downstream of the upland watersheds in the west of the basin where sediment loads are highest. The reservoir may therefore act as a sediment trap, preventing sediments from being transported downstream which may exacerbate downstream erosion. Furthermore, there is a risk that over time the volume of sediment deposited in the reservoir may lead it to fill up, thereby disrupting its utility as an impoundment.

The lowlands distributary outlet is also an important location within the basin. This outlet only receives flows from the downstream lowland areas of the basin where slopes are low and so is not likely to experience high sediment transport rates.

4.1. Baseline Scenario Average Annual Discharges and Sediment Loads

The average annual flow volume at the Stung Sangker river basin outlet was 3,125 million m^3, equating to an annual average discharge of approximately 100 m^3/s. Of this, an average 2,313 million m^3 is discharged in the wet season and 811 million m^3 in the dry season. October contributed 793 million m^3 to annual flow, compared to a low of 52 million m^3 in March. The average monthly flow volume increased from 148 million m^3 in May to 793 million m^3 in October. A time series plot of the average monthly discharge at the outlet of the Stung Sangker river basin is shown in Figure 27 with the simulated discharge at Battambang where the calibration gauge is also shown for reference.

Figure 27: Monthly Flow Volume at Battambang Station and at the Stung Sangker River Basin Outlet in the Baseline Simulation



As expected, discharges from the upland watersheds in the Southeast of the basin are relatively high due to the high-water yields (surface water discharges) of the most upstream sub-basins where the topography is steepest (Figure 28). Stream discharges increase as the river tributaries meet through Treng and Battambang to the main Stung Sangker river outlet.

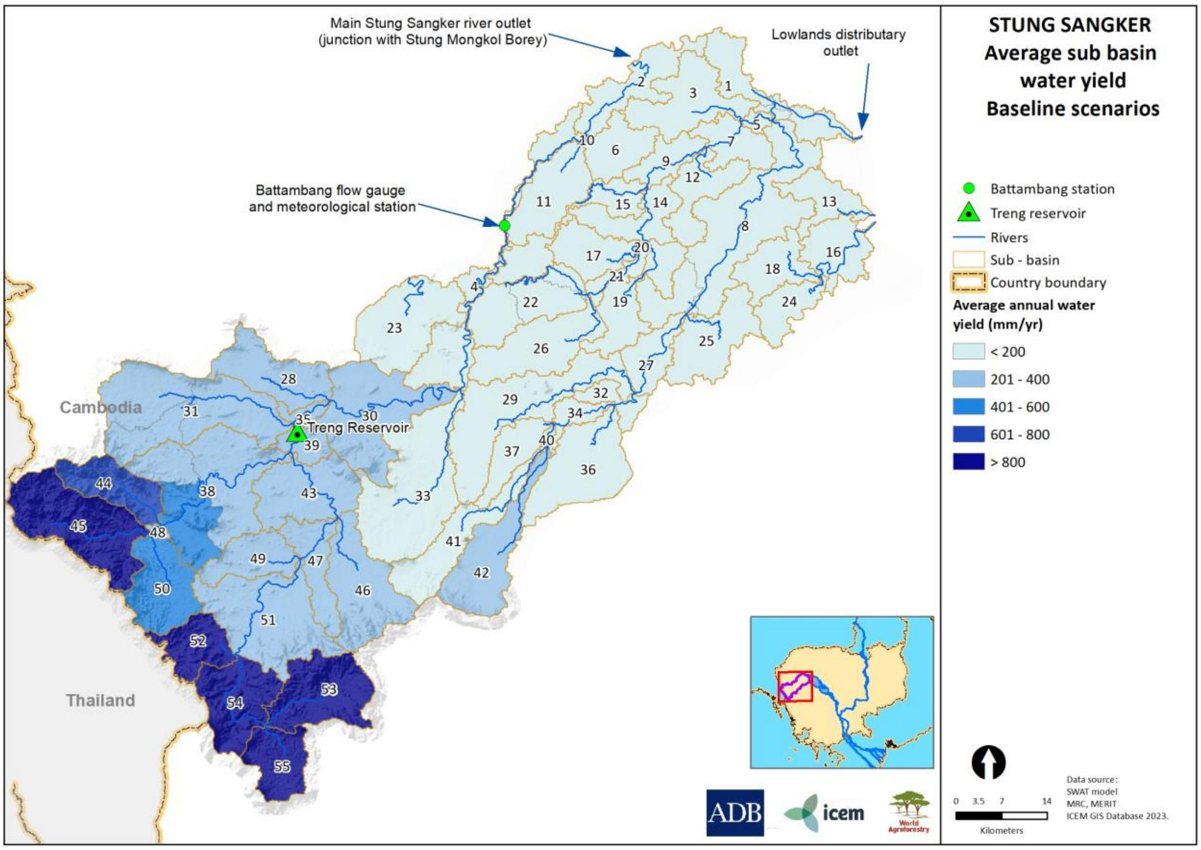
At the Treng Reservoir, the average annual river discharge is approximately 38 m^3/s. The highest flow month is October, when 26% of the annual flow occurs, and the lowest flow months are January to March, when 2% to 2.5% of the annual flow occurs.

As the volume of the Treng reservoir is estimated to be approximately 30 million m^3 (Section 2.1), the residence time of the reservoir (reservoir volume divided by discharge) is around 17 days, so reservoir operations may significantly affect peak flood hydrographs, as well as dry season flows. However, the reservoir is of insufficient size to give rise to significant inter-seasonal or interannual variations in flows.

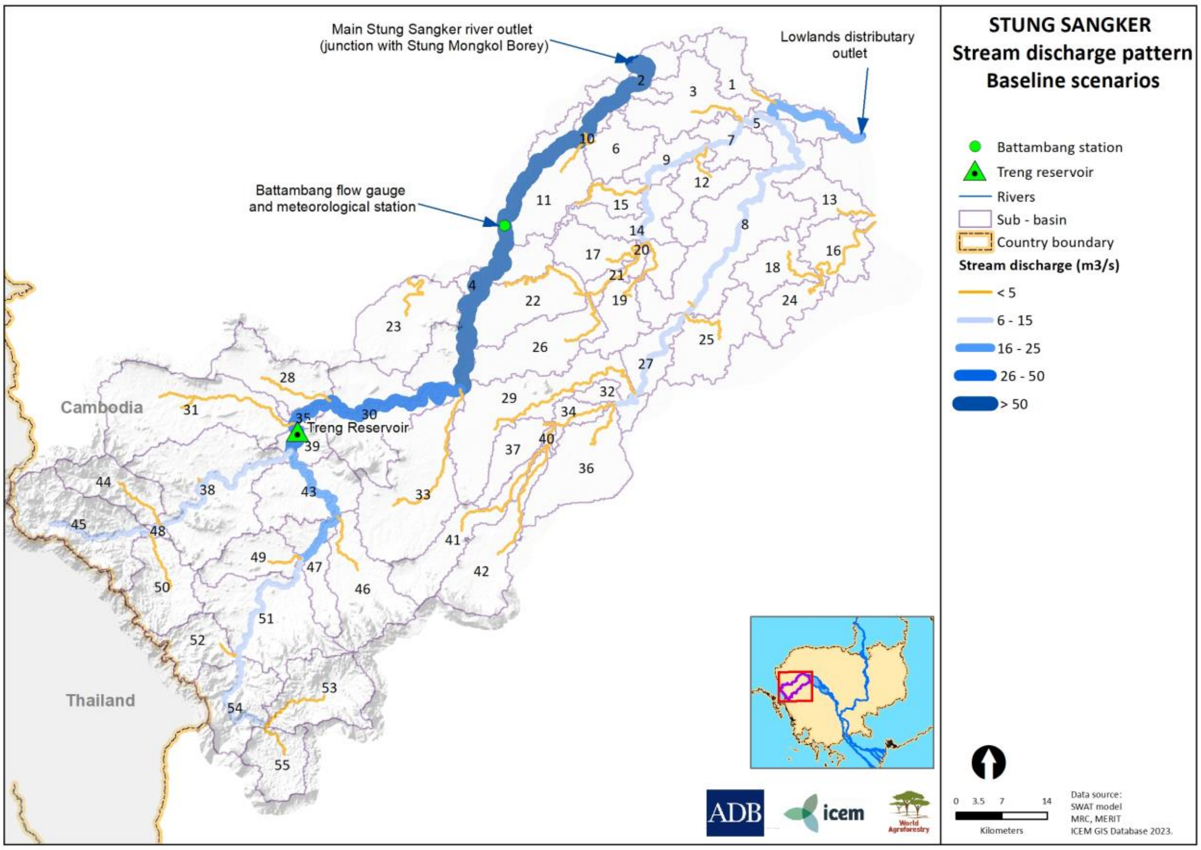
By contrast, a 17-day residence time is likely to significantly impact sediment transport, as sand to silt size sediments are likely to be trapped in the reservoir, with only fine-grained clays transported downstream.

The lowland areas occupy a significantly smaller area with much flatter terrain, so discharge rates are much lower than those from the upland areas.

Figure 28: Average Sub-Basin Water Yield (Above) Stream Discharge (Below) Patterns for the Stung Sangker River Basin, 2009-2021 Baseline Scenario



Data source:
SWAT model
MRC, MERIT
ICEM GIS Database 2023.



Default values for all sediment transport parameters were applied to estimate sediment loads for the baseline scenario. Results show a total average annual sediment load from the main Stung Sangker river and the lowlands distributary of around 256,000 t/year between 2007 and 2021. This result can be considered reasonable given the regionally estimated sediment loads range of 180,000 to 300,000 t/year (Section 2.5).

Due to the steep sloping topography in the upstream watersheds, very high sediment loads are expected at the Treng reservoir location (Figure 29 and Table 2). Downstream of Treng, the river enters a depositional phase as the river flows through the flat lowland section of the basin. The sediment load gradually reduces as the river flows past Battambang and down to the Tonle Sap lake.

Figure 29: Average Annual Sediment Transport Rates on Stung Sangker River Basin, 2009-2021 Baseline Scenario

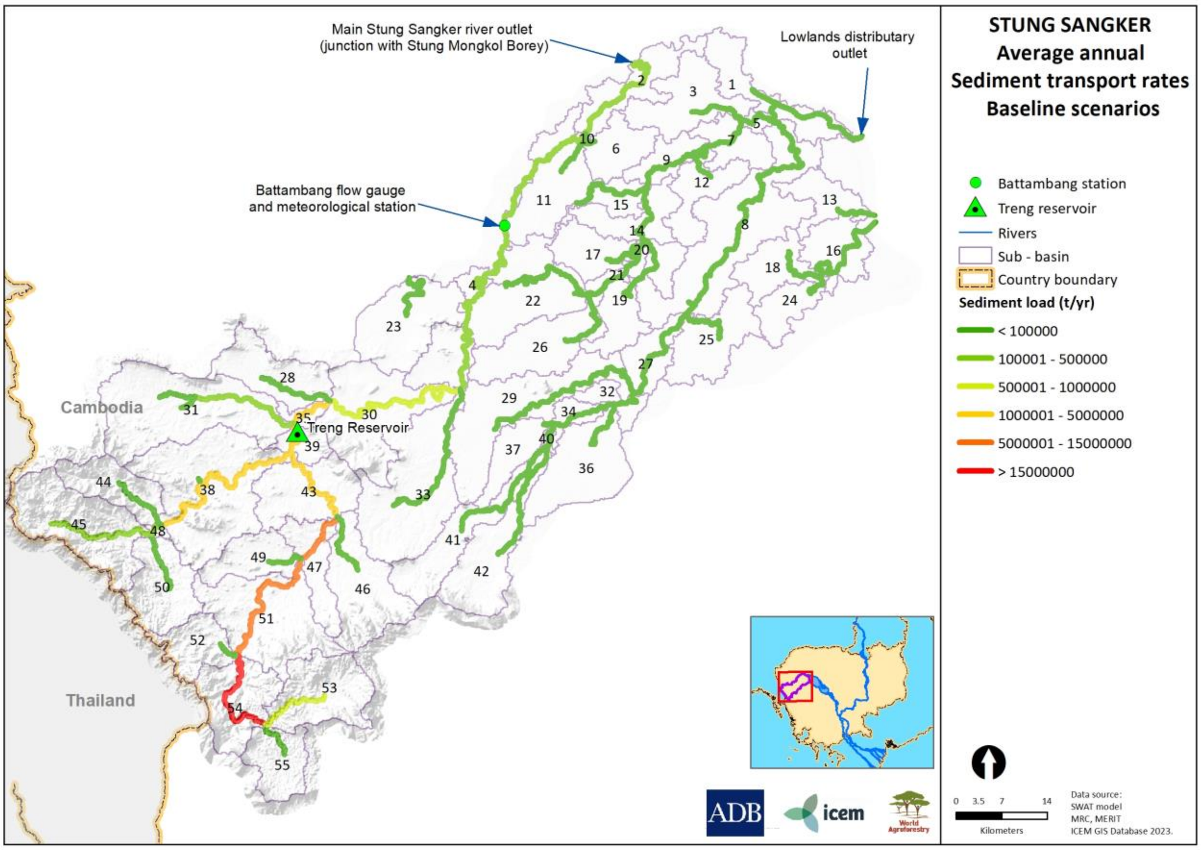


Table 2: Annual Average Outflows, Peak Outflows and Average Annual Sediment Loads at Key Locations in the Stung Sangker River Basin for the Baseline Scenario

Location	Flow out m³/s	Sediment load Mt/yr
Treng Reservoir	38	2.37
Sangker River main outlet	54	0.25
Sangker lowlands distributary outlet	18	0.008
Total outflow from the Stung Sangker river basin to the Tonle Sap lake	**72**	**0.26**

Sediment loads at the Treng reservoir site are a concern. With an annual average incoming load of about 2.4 Mt/yr, and assuming a bulk density of sediments of 1 t/m^3[21], the average volume of sediment deposited into the reservoir is expected to be of the order of 2.4 million m^3. The estimated storage volume of the reservoir is 30 million. Under current hydrological conditions and land use management strategies, if the total incoming sediment load is trapped in the reservoir, it could lose as much as 8% to 9% of its storage capacity per year to sediment buildup unless action is taken to manage the situation.

Plotting sediment (erosion) yield rates across the sub-basins reveals the origins of the sediment flows (Figure 30). Erosion rates are highest in the watersheds immediately above the Treng reservoir, where there is a higher proportion of agricultural land use and erosion rates are higher.

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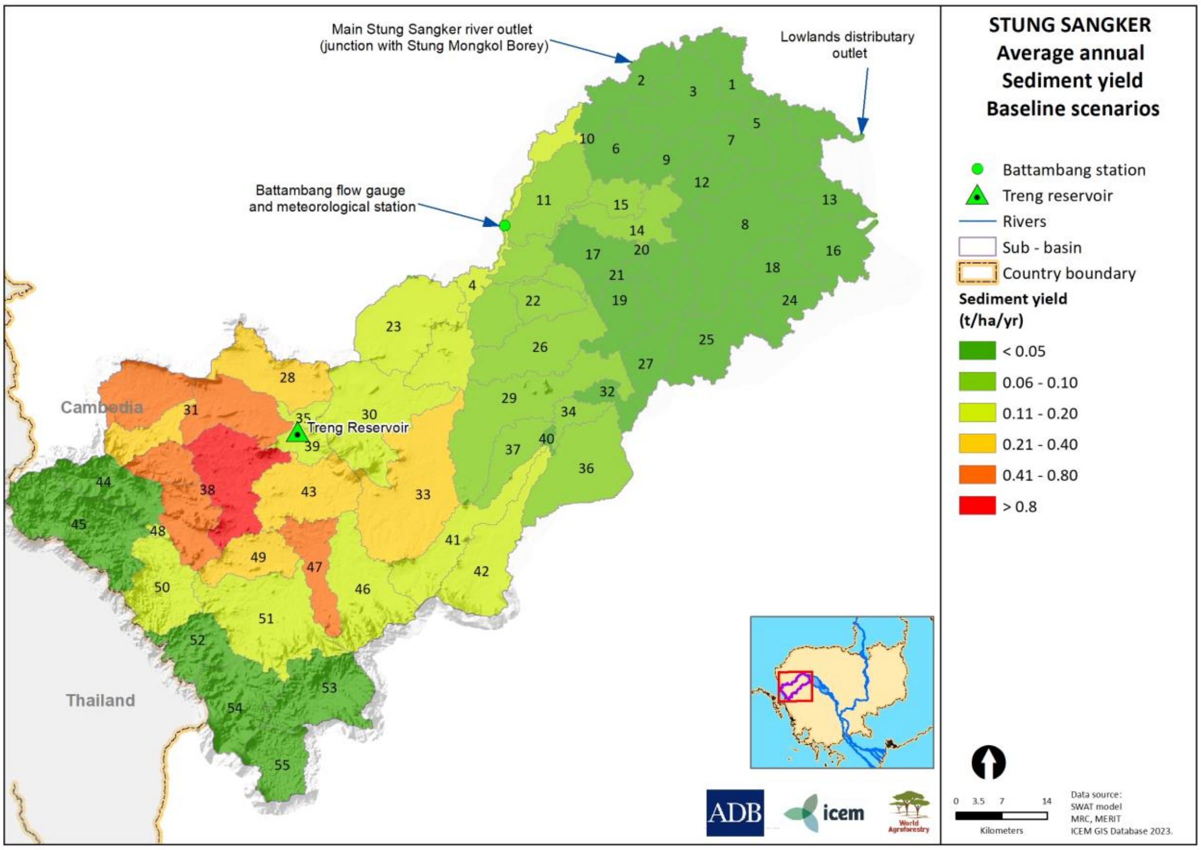
[21] Das, 2009

Figure 30: Sediment Yield from Catchment Areas for Baseline Scenario

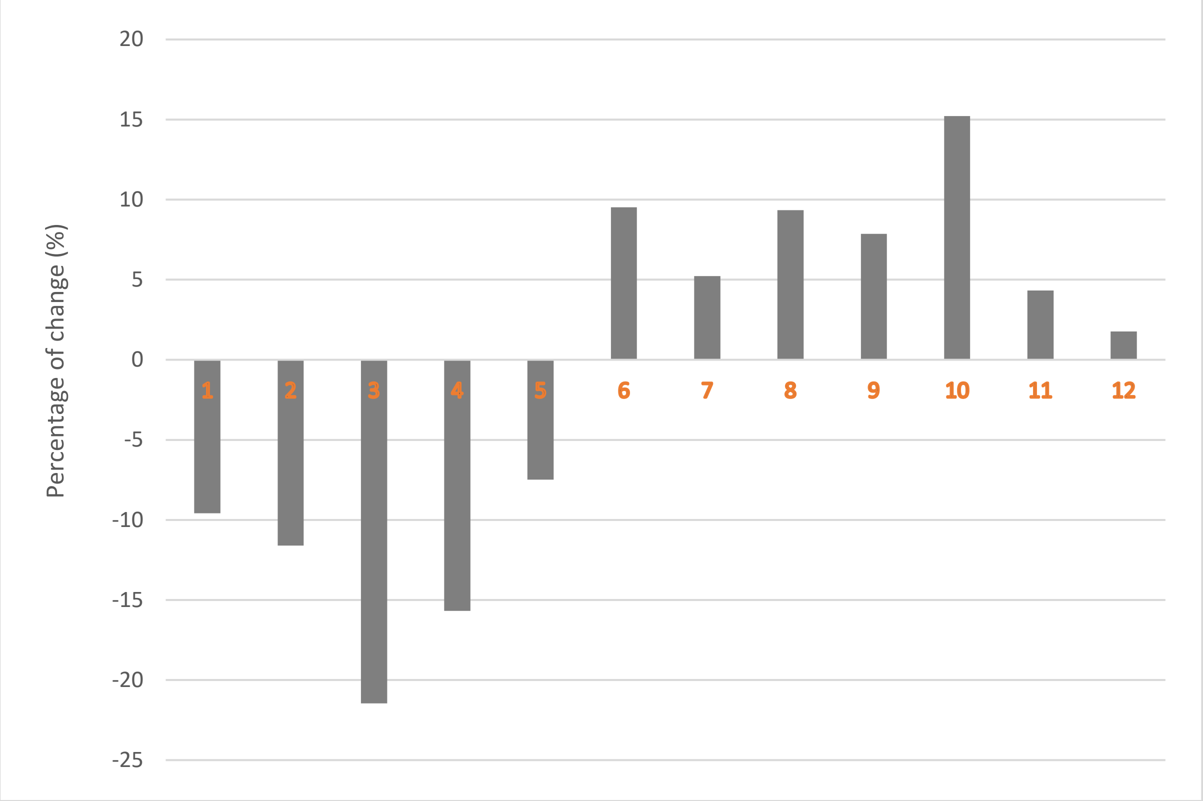


4.2. Future Scenario 1: Climate Change Under RCP8.5 for 2055, Average Annual Discharges and Sediment Loads

The purpose of FS1 is to assess the impact of changes to rainfall patterns that result from climate change on hydrological conditions and sediment transport processes in the Stung Sangker river basin by 2055 under the RCP8.5 climate change scenario. As expected, the model shows an increase in flows in the wet season and a decrease in the dry season, following the pattern of changes in rainfall under FS1 (Figure 25). The average wet season discharge increased by 6.6% and decreased by 8.7% in the dry season compared to the baseline at Battambang (Figure 31).

The magnitude of change varied, depending on the month. The most significant increase in monthly discharge was observed in October, with an increase in average monthly flows of 15% at Battambang. The increase is likely to cause flood damage to infrastructure, crops, economic assets, houses, and other property in the basin. By contrast, the decrease in flows in the dry season could potentially lead to drought and water supply issues for agriculture, human wellbeing, and ecosystems.

Figure 31: Percentage of Change in Average Monthly River Flow for Future Scenario 1 at Battambang



Patterns of average annual water yield and stream discharges across the basin appear similar under FS1 to the baseline scenario (Figure 32 and Table 3), with five to six percent increases in flow rates in the upper basin and the main Sangker River. Changes in discharge rates in the lowland areas of the basin are smaller in magnitude, although the relative change is greater (a nine percent increase in discharges from the lowlands distributary outlet occurring in FS1).

Figure 32: Annual Average Water Yield from Sub-Basins (Above) and Discharge in Streams (Below) of the Stung Sangker River Basin under Future Scenario 1

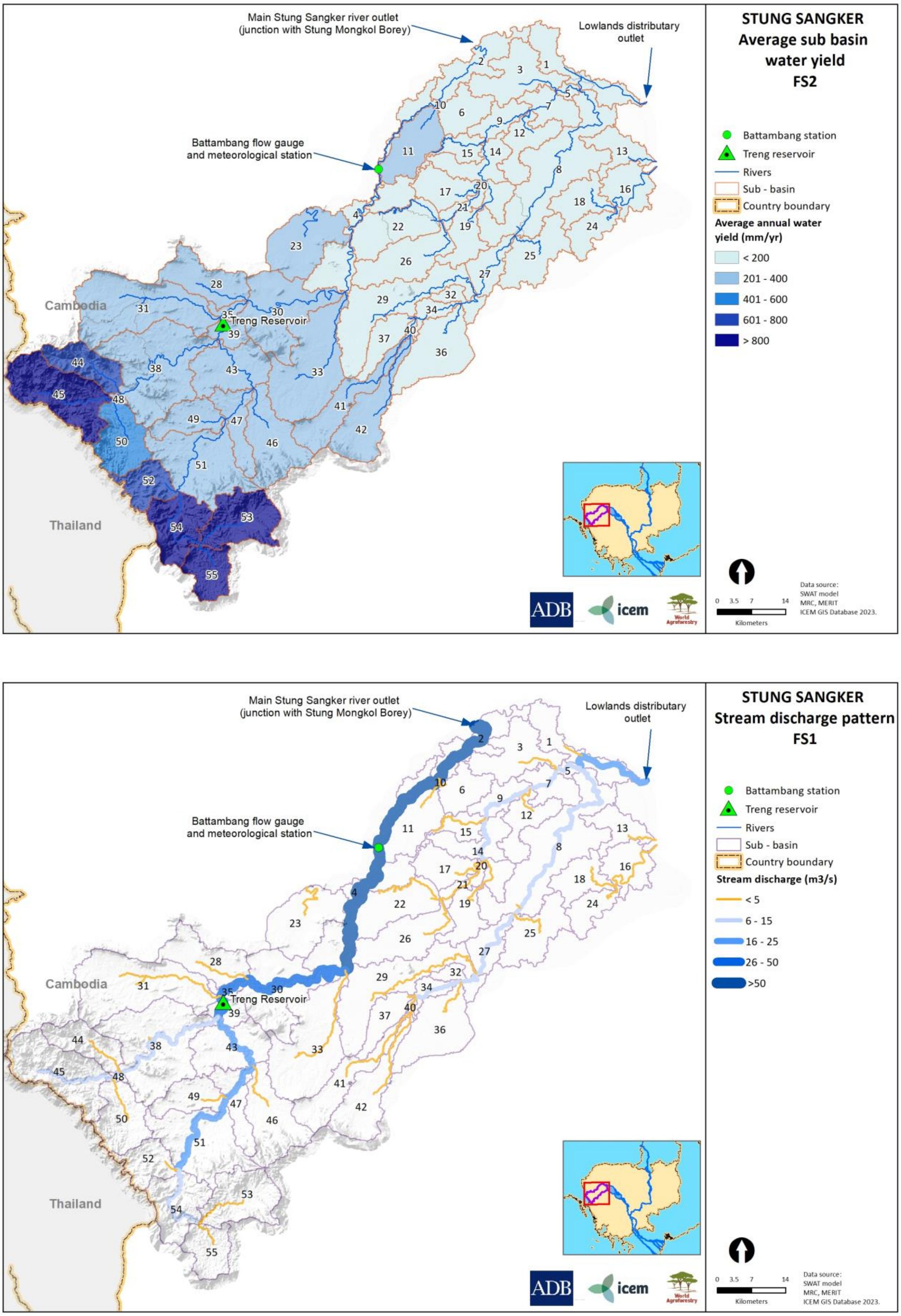


Table 3: Average Annual Discharge for the Baseline and Future Scenario 1

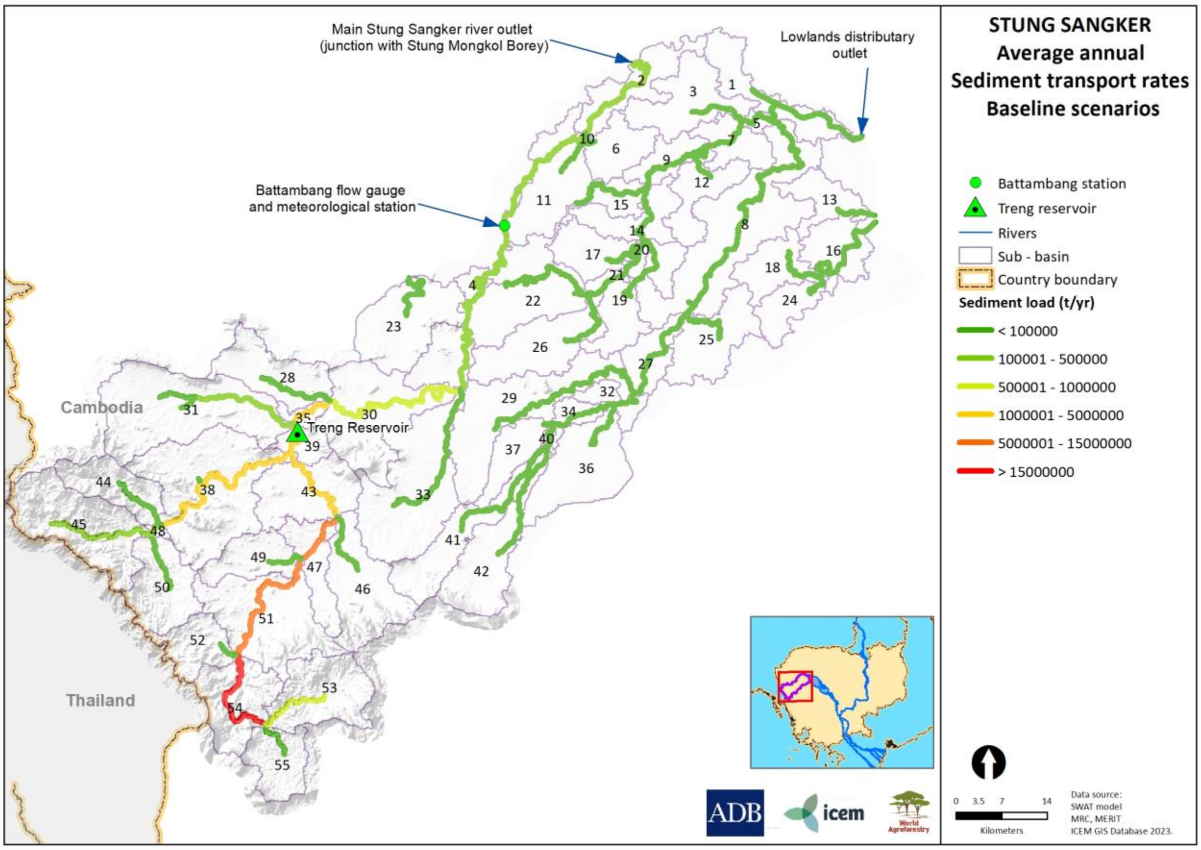
	Baseline discharge (m3/s)	Future Scenario 1 discharge (m3/s)	Change
Treng reservoir	38	40	5%
Main Stung Sangker river outlet	54	57	6%
Lowlands distributary outlet	18	20	9%
Total basin outflow	72	77	6%

For average annual sediment loads, the SWAT model predicts that under FS1 a 14% increase in sediment load will occur compared to the baseline scenario (Table 4 and Figure 33). Further upstream, sediment loads entering the Treng reservoir increase by 12%. Sediment loads from the lowland areas increase by 25%, reflecting the greater increase (32%) in wet season flows in lowland areas compared to flows above Treng (20%).

Table 4: Average Annual Sediment Transport Rates for Future Scenario 1 and Change from Baseline

	Baseline sediment load (Mt/yr)	Future Scenario 1 sediment load (Mt/yr)	% Change
Treng reservoir	2.37	2.64	12%
Main Stung Sangker river outlet	0.25	0.280	13%
Lowlands distributary outlet	0.008	0.010	25%
Total basin outflow	0.26	0.29	14%

Figure 33: Sediment Loads on the Stung Sangker River Basin under Future Scenario 1



Increases in sediment loads for waterways in the upper watersheds under climate change are, therefore, of significant concern as the overall magnitude of these loads is much higher than in the lowland areas. With a 12% higher sediment load at the Treng reservoir in the FS1 scenario compared to the baseline scenario, the reservoir's infilling rate may also increase by 12%, which may affect the reservoir's serviceability. There are still significant concerns for sediment loads in the lowland areas, given the greater proportional change in load.

Similar to sediment loads, sediment yields[22] increase across the Stung Sangker basin under FS1 compared to the baseline scenario by 26% (Figure 34 and Table 5).

Figure 34: Sediment Yield from Catchment Areas for the Baseline (Left) and Future Scenario 1 (Right)

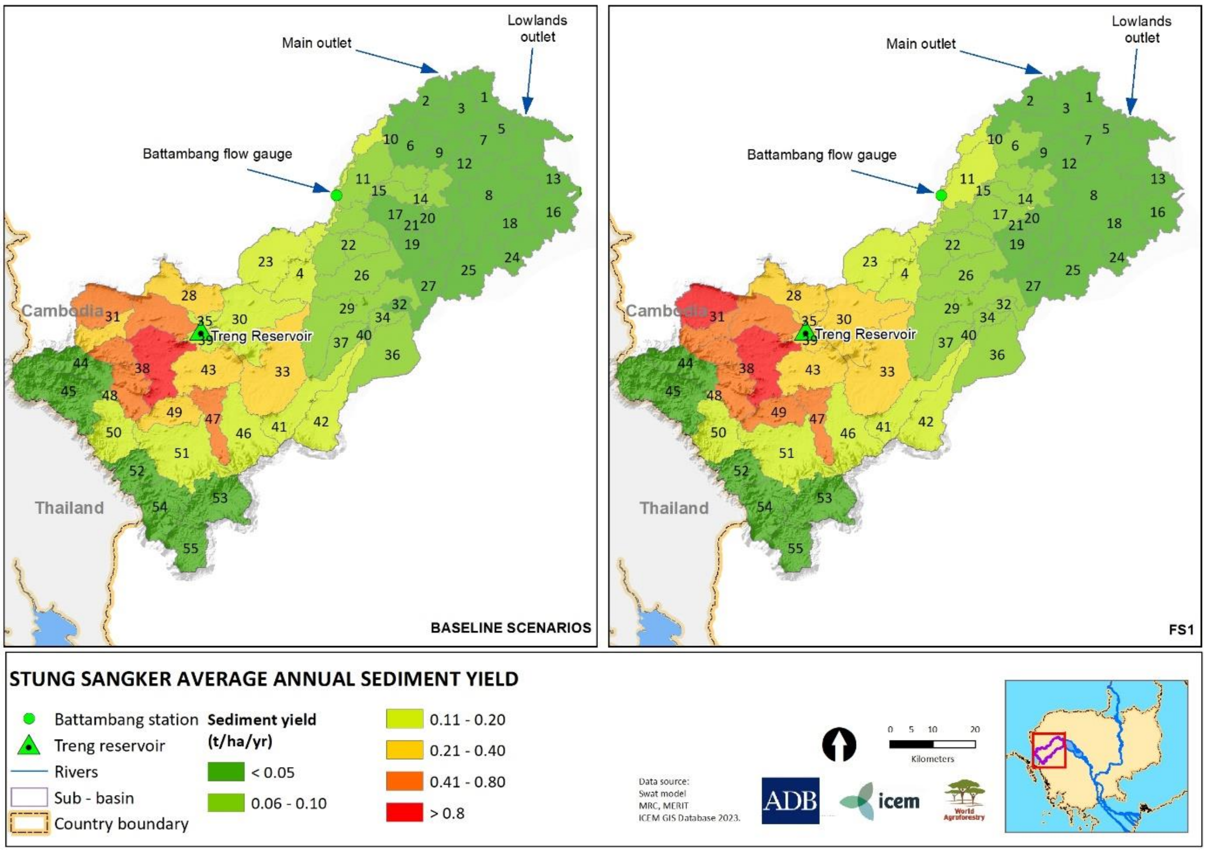


Table 5: Sediment Loss Rates from Catchment Areas for the Baseline and Future Scenario 1

	Baseline	Future Scenario 1
Basin-wide annual average sediment yield (t/ha/yr)	0.13	0.16
% Change from baseline		23%

4.3. Future Scenario 2 – Reforestation of Upland Areas as a Climate Adaptation Intervention, Effects on Average Annual Discharges and Sediment Loads

To simulate the impact of reforestation and conversion of agricultural land to agroforestry, 30% of agricultural areas in the basin were assumed to be converted to agroforestry (Section 3.2). The selected regions are in upland areas (Figure 26), as agroforestry is expected to be more appropriate in upland watersheds. The high sediment loads in the baseline scenario support the approach, indicating that the highest sediment loads and more extensive erosion occur in upstream areas.

The SWAT modelling shows that, from a hydrological perspective, agroforestry is likely to represent a mostly positive intervention for climate adaptation, leading annual average river discharges to deviate less from the baseline scenario than in the FS1 scenario (Table 6 and Figure 35).

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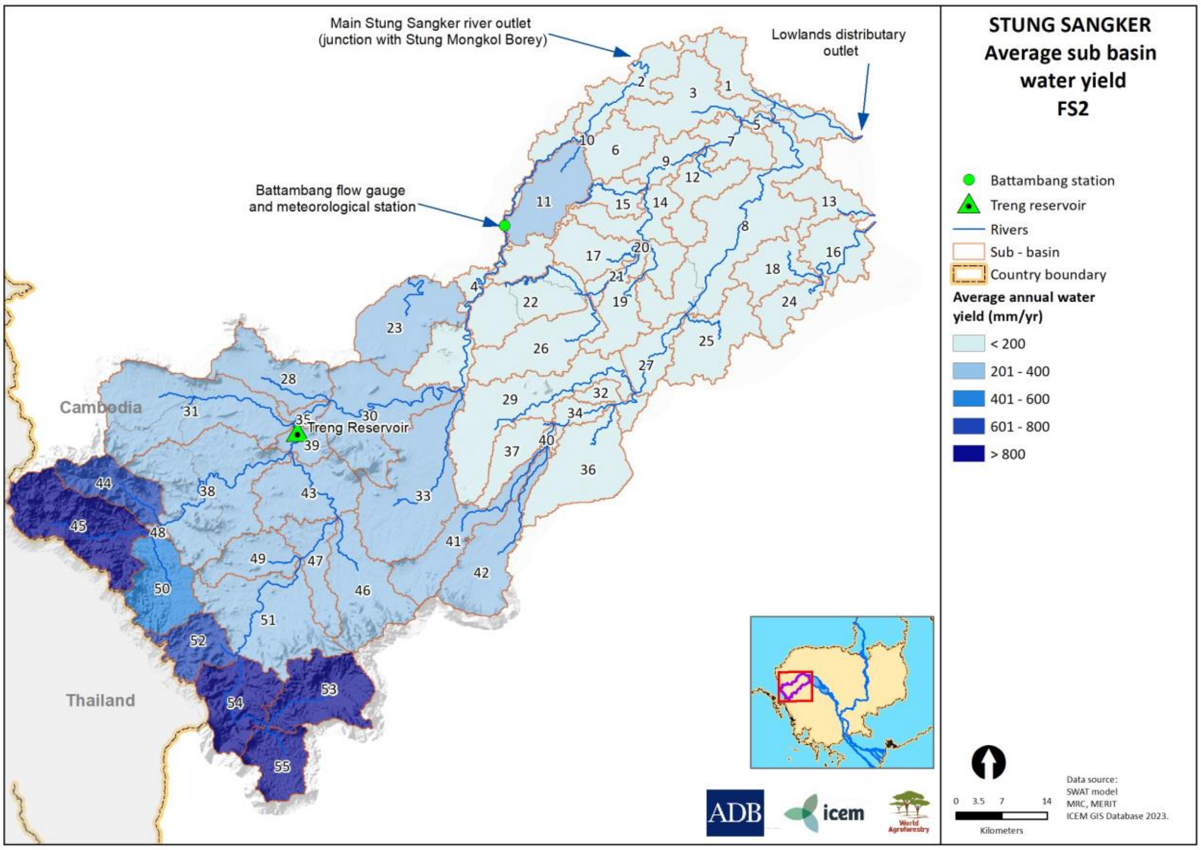
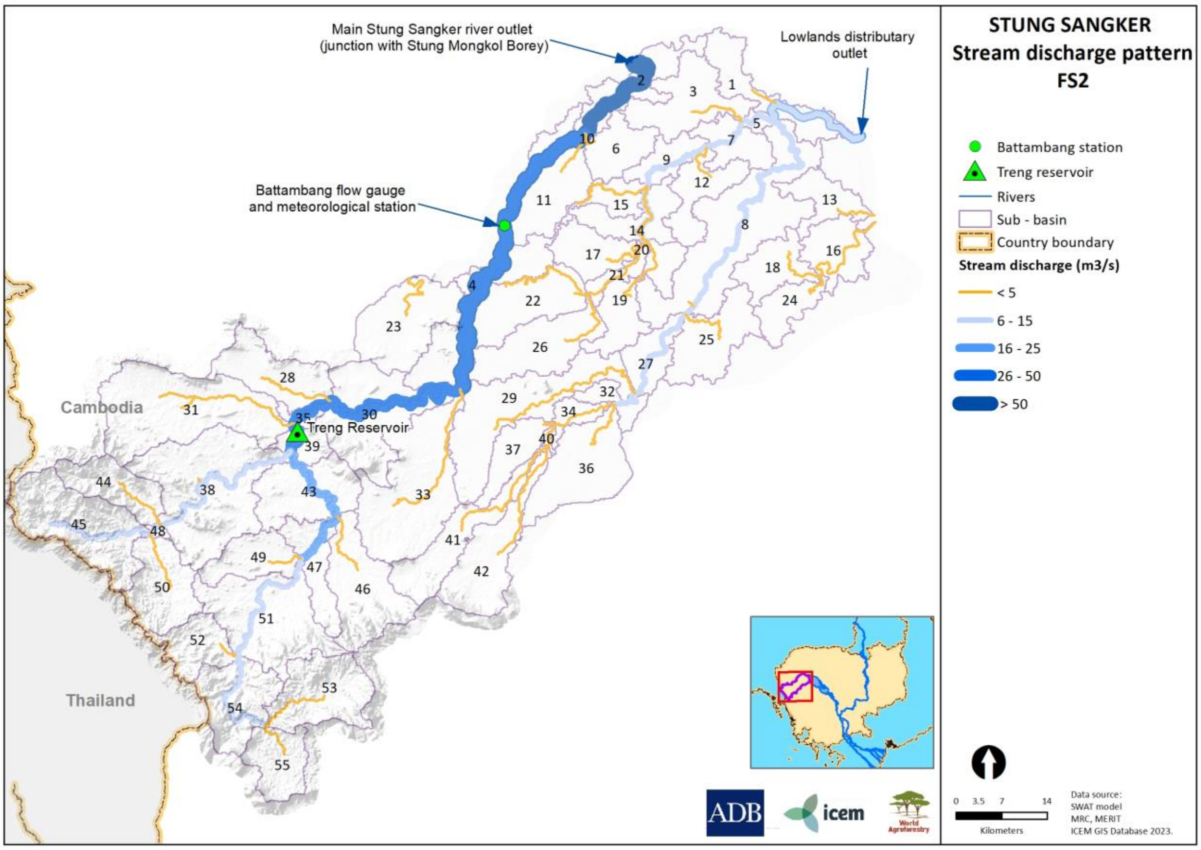
[22] Sediment load is the amount of sediment that is transported through a stream cross section over one year. Sediment yield is the amount of sediment per unit area removed from a watershed by flowing water during a specified period of time.

Table 6: Average Annual Discharge for the Baseline, Future Scenario 1 and Future Scenario 2

		Baseline	Future Scenario 1	Future Scenario 2
Treng reservoir location	Discharge (m3/s)	38	40	37
	Change from BL	-	5%	-4%
Main Stung Sangker river outlet	Discharge (m3/s)	54	57	52
	Change from BL	-	6%	-4%

Figure 35: Water Yield (Above) and Stream Discharge Patterns (Below) for Future Scenario 2





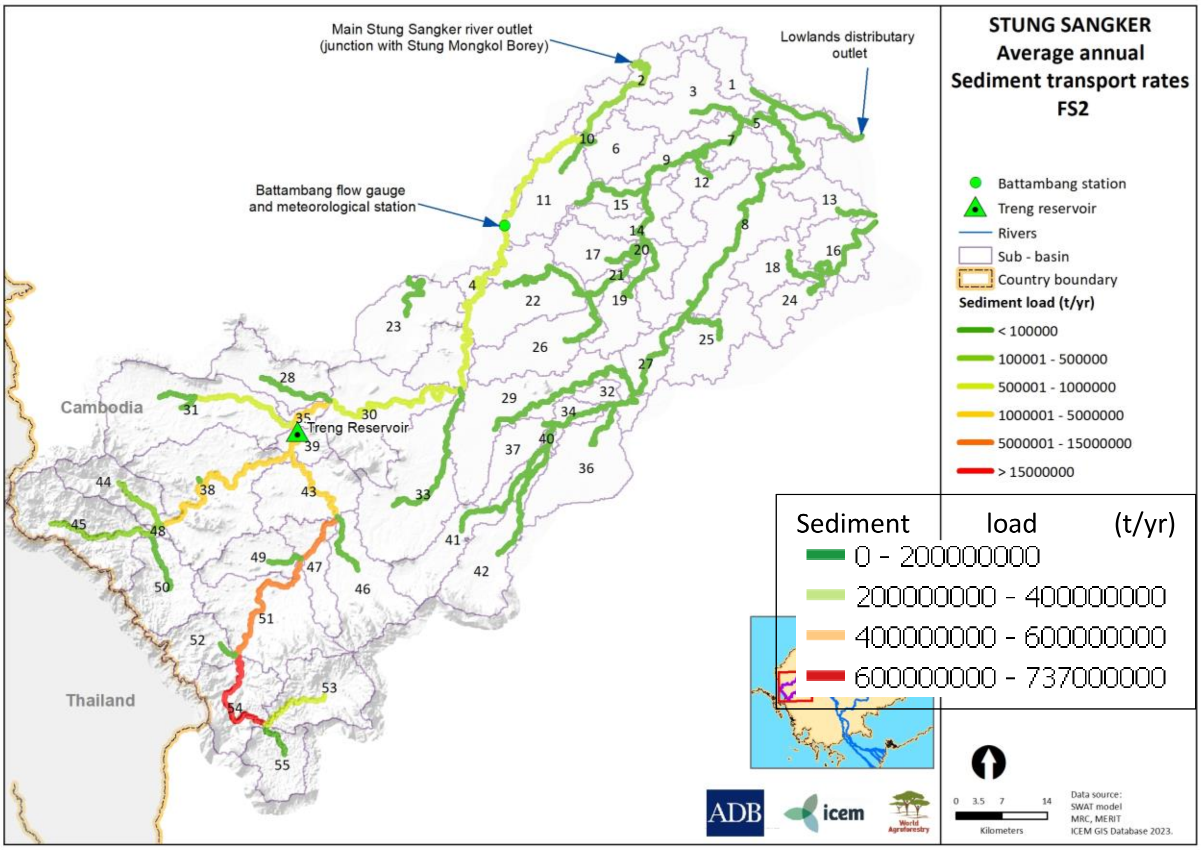
Annual average sediment loads under the FS2 scenario are also slightly improved compared to the FS1 scenario (Table 7 and Figure 36). However, even with agroforestry initiatives in FS2, the sediment load is 11% higher than the baseline scenario at the Treng reservoir and 12% higher at the main Stung Sangker river outlet. This indicates that while agroforestry initiatives will positively impact erosion compared to the FS1 scenario, further measures will be needed to prevent dramatic increases in sediment loads from occurring in downstream waterways.

Table 7: Average Annual Sediment Load Estimates for the Baseline, Future Scenario 1 and Future Scenario 2

		Baseline	Future Scenario 1	Future Scenario 2
Treng reservoir location	Sediment load (Mt/year)	2.37	2.64	2.63
	Change from Baseline		12%	11%
Main Stung Sangker river outlet	Sediment load (Mt/year)	0.25	0.280	0.280
	Change from Baseline		13%	12%

Waterways upstream of the Treng reservoir are of particular concern, as the increase in sediment loads may significantly lower the storage capacity, potentially requiring additional sediment control measures.

Figure 36: Sediment Loads in the Stung Sangker Basin under the Future Scenario 2



Although sediment load rates in streams do not improve dramatically under FS2 compared to FS1, there is a clear improvement in erosion across catchment areas for the FS2 scenario (Figure 37). Sediment yield rates under FS2 are reduced by 52% on the baseline scenario, compared to a 26% increase on the BL under FS1.

Figure 37: Sediment Yield from Catchment Areas for Baseline (Upper Left), Future Scenario 1 (Upper Right) and Future Scenario 2 (Lower Left)

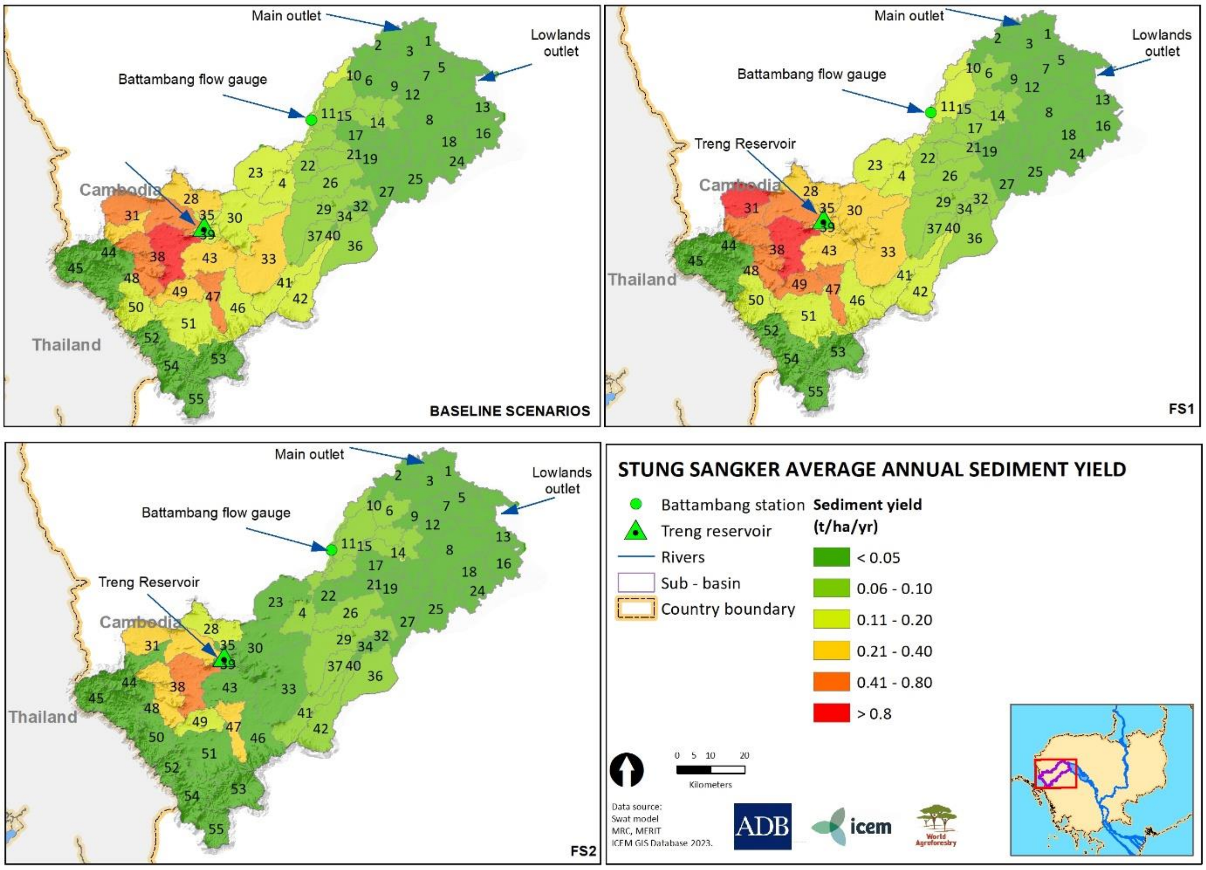


Table 8: Sediment Loss Rates from Catchment Areas for the Baseline and Future Scenarios 1 and 2

	Baseline	Future Scenario 1	Future Scenario 2
Basin-wide annual average sediment yield (t/ha/yr)	0.13	0.16	0.065
% change from baseline		23%	-52%

4.4. Comparison of Dry Season and Wet Season Flows under the Baseline, Future Scenario 1 and Future Scenario 2

Wet season flows under FS1 increased significantly more than annual average discharges, with a basin-wide increase of 26% in October, the peak wet season month (Table 9). The proportional flow increase is highest in the lowland areas, where a 32% increase in wet season flows is projected.

Table 9: Average October Discharge for the Baseline and Future Scenario 1

	Baseline discharge (m^3/s)	Future Scenario 1 discharge (m^3/s)	Change
Treng reservoir	110	133	20%
Main Stung Sangker river outlet	164	202	23%
Lowlands distributary outlet	65	86	32%
Total basin outflow	229	287	26%

By contrast, dry season flows in FS1 become significantly lower due to climate change, with average basin discharges decreasing by 19% (Table 10). The most noticeable decreases in discharge rates are in upstream areas above the Treng reservoir, where a 32% decrease in dry season flows are expected.

Table 10: Average March Discharge for the Baseline and Future Scenario 1

	Baseline discharge (m^3/s)	Future Scenario 1 discharge (m^3/s)	Change
Treng reservoir	6.2	4.2	-32%
Main Stung Sangker river outlet	10.5	8.0	-24%
Lowlands distributary outlet	6.4	5.8	-9%
Total basin outflow	16.9	13.8	-19%

The conversion of agricultural areas to agroforestry in FS2 significantly reduces flood risks. Average discharge in the highest flow month of October shows a 17% increase for the FS2 scenario against the baseline at the main river outlet (Table 11).[23] This represents a significant improvement compared to the FS1 scenario.

Table 11: Average October Discharge for the Baseline, Future Scenario 1 and Future Scenario 2 on the Upper Watersheds and Main River

		Baseline	Future Scenario 1	Future Scenario 2
Treng reservoir	Discharge (m^3/s)	110	133	128
	Change from Baseline		20%	16%
Main Stung Sangker river outlet	Discharge (m^3/s)	164	202	192
	Change from Baseline		23%	17%

During the dry season, however, results were less encouraging. Average discharge march, the lowest flow month, decreases significantly in the FS2 scenario compared with the baseline and FS1 scenarios (Table 12). A similar trend was found for average discharge in the dry season from December to March. Results consistently show lower dry season discharges under the agroforestry scenario compared with the baseline and FS1 scenarios at both the Treng Reservoir and the main river outlet.

However, these results should be treated with caution as they contradict the results of historical flow gaugings showing dry season flows decreased as forest areas were converted to agriculture. International experience also suggests that agroforestry initiatives can reduce drought risk.[24] However, the results are consistent with recent studies that indicate that climate-induced droughts can be intensified in forest areas due to increased physiological requirements for water that some forest types have under drought conditions.[25]

To confirm definitively whether the conversion of upland agricultural areas to agroforestry could exacerbate droughts in the Stung Sangker basin would require that the hydrology model account for soil moisture-plant transpiration feedback loops for different forest and crop types.[26] This is beyond the capacity of the current SWAT model, and therefore is beyond the scope of this study.

A simpler approach within the capacity of SWAT was therefore performed using three different land use types to represent agroforestry efforts in SWAT: orchards (ORCD) to represent agroforestry options that would involve significant community interactions with the landscape, deciduous forestry (FRSD) and evergreen forestry (FRSE) to represent full reforestation efforts. All three agroforestry options showed similar results with dry season discharges significantly reduced (Table 12).

The results suggest that drought-tolerant trees with low water dry-season water demands should be preferred to minimize the risk of drought intensification in areas where agroecology projects are proposed. Evergreen forests show the least decline in discharge compared to the baseline and FS1

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[23] Note that flood and drought analyses only covered the upland watersheds for FS2 as land use changes were only considered for the upper watersheds. Furthermore, land use management practices (p factor) under SWAT which were implemented on the lowland watersheds under FS3 only affect sediment yield and sediment transport. P factor changes have no impact on hydrology under SWAT

[24] See, for example, van Noordwijk et al, 2019.

[25] Anderegg et al., 2019

[26] Xu et al, 2016.

scenarios, and so appear to be the most promising form of landscape restoration. By contrast, deciduous forests showed the lowest discharges under dry season conditions.

Table 12: Minimum and Average Dry Season Discharge for the Baseline, Future Scenario 1 and Future Scenario 2 with Three Agroforestry Options

		Baseline	Future Scenario 1	Future Scenario 2 (Orchards)	Future Scenario 2 (Deciduous)	Future Scenario 2 (Evergreen)
Treng reservoir	Minimum month discharge (m^3/s)	6.2	4.2	2.8	2.5	2.9
	Average dry season discharge (m^3/s)	12.8	12.3	9.9	6.4	10.3
Main Stung Sangker river outlet	Minimum month discharge (m^3/s)	10.5	8.0	5.0	4.9	5.5
	Average dry season discharge (m^3/s)	18.8	18.1	13.4	10.4	14.6

Given these results other nature-based solutions for drought management should be implemented in conjunction with agroforestry and reforestation measures. Options include leaky weirs and restored or constructed wetlands.

4.5. Future Scenario 3 – Conservation Farming as a Climate Adaptation Intervention for Lowland Areas to Reduce Erosion

Future Scenario 3 (FS3) simulates the implementation of soil and water conservation measures, such as contour farming in lowland areas, under climate change RCP8.5 rainfall by 2055. Conservation measures are represented in the model by changing the USLE "p" factor for agricultural areas from 1 (no interventions) to 0.6. As such, the FS3 scenario gives insights into potential improvements in sediment loads and sediment yields and does not represent any change in hydrology compared to the FS2 scenario.

In the FS3 scenario, sediment loads from the lowland areas directly entering the Tonle Sap Lake are significantly lower than the FS1 scenario – 0.008 Mt/yr for FS3 compared to 0.01 Mt/yr for FS1. The reduction in sediment load is significant enough to be slightly lower than the baseline scenario, despite the much higher flow rates in the FS3 scenario (Table 13).

Table 13: Annual Average Sediment Load Estimates for Baseline, Future Scenario 1 and Future Scenario 3 on Lowland Areas of the Basin

		Baseline	Future Scenario 1	Future Scenario 3
Lowlands distributary outlet	Sediment load (Mt/year)	0.008	0.010	0.008
	Change from Baseline	-	25%	-1%
Total basin outflow	Sediment load (Mt/year)	0.26	0.29	0.28
	Change from Baseline	-	11%	7%

When averaged across the basin, sediment yield estimates for the FS3 scenario reduce by 59% compared to the baseline. This represents a modest improvement on the FS2 scenario, where a 52% improvement was achieved (Figure 38 and Table 14).

Figure 38: Sediment Yield from Catchment Areas for Baseline (Upper Left), Future Scenario 1 (Upper Right), Future Scenario 2 (Lower Left) and Future Scenario 3 (Lower Right)

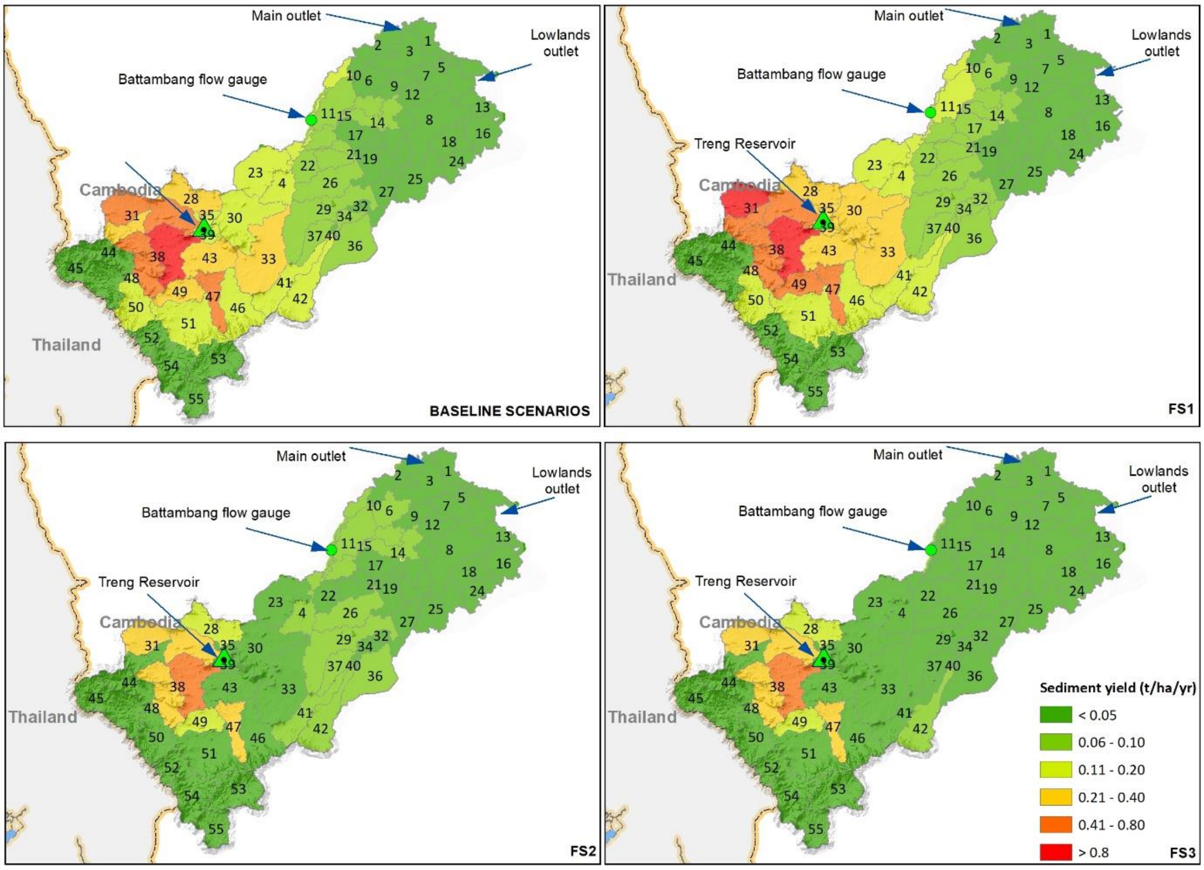

Table 14: Sediment Loss Rates from Catchment Areas for the Baseline, Future Scenario 1, Future Scenario 2 and Future Scenario 3

	Baseline	Future Scenario 1	Future Scenario 2	Future Scenario 3
Basin wide annual average sediment yield (t/ha/yr)	0.13	0.16	0.065	0.055
% Change from baseline		23%	-52%	-59%

5. Conclusions and Recommendations

The Stung Sangker River Basin consists of two largely separate areas: A flat lowland region immediately upstream of Tonle Sap Lake dominated by agriculture and wetlands and an upland area in which historically forested areas have been converted to agricultural land.

There has been no discernible long-term trend in average annual rainfall or wet season rainfall between 2000 and 2021, the period data is available. However, the length of zero rainfall periods has increased in the dry season, indicating that droughts are becoming more severe and more frequent, consistent with climate change projections for Cambodia.

Although trends in rainfall are unclear, hydrological gaugings on the Stung Sangker river show that average annual flows, wet season flows, and dry season flows have all decreased over time. The decrease in average annual flows and wet season flows is consistent with the conversion of forest to agriculture. Similarly, declining dry season flows are compatible with land use changes and the increase in days with zero rainfall.

Despite the overall pattern of decreasing flow trends, direct runoff during the dry season is not decreasing over time, indicating that the risk of flash flooding is not reducing and may even increase as upland areas are converted from forest to agriculture.

No sediment gaugings are available for the Stung Sangker basin. However, erosion rates for catchment areas of the basin are estimated at 1.9 to 4.5 Mt/year. By contrast, the total sediment load from the basin to the Tonle Sap Lake is estimated at 0.18 to 0.30 Mt/year, suggesting that between 1.5 and 4.3 million tons of sediments are deposited in the basin waterways every year.

To determine how climate change may affect the hydrology and sediment transport processes of the Stung Sangker river basin, a SWAT model was calibrated and verified to simulate the impacts of land use change, climate change, and soil and water conservation measures.

Applying the SWAT model to the historical baseline scenario showed that high levels of runoff and very high sediment loads enter the river from the upland watersheds in the southwest of basin. These enter the main Stung Sangker river with the discharge of the river gradually increasing as tributaries add more flow until the main Stung Sangker river outlet is reached. The lower parts of the basin discharge directly to the Tonle Sap by a separate distributary which derives from a relatively smaller area and consequently discharges into this distributary are relatively lower.

As for runoff, sediment loads entering the river are highest in the steep sloping upland watersheds; however, the sediment load carried by the river tends to decrease as the river flows downstream and away from these upland areas as flow velocities in the river decrease and much of the sediment load is dropped, even before the Treng reservoir is reached. Still, sediment loads reaching the Treng reservoir are relatively high, around 2.4 to 2.6 Mt/year. There is therefore some concern that sediments retained in the reservoir may reduce the available storage of the reservoir at a rate of 8% to 9% per year.[27]

Three future scenarios were also developed which depict the incremental impacts of climate change (FS1), climate change combined with land use change from agriculture to agroforestry/reforestation (FS2) and climate change combined with land use change and implementation of conservation farming measures on lowland areas of the basin (FS3).

FS1 demonstrated that climate change and resulting changes to annual rainfall patterns could increase average annual flows, increase erosion, increase the risk of flooding in the wet season and drought in the dry season.

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[27] Assuming the reservoir has a storage volume of 30 million m^3

FS2 revealed that converting agricultural areas to agroforestry in upland watersheds of the basin would decrease the risks of flooding in the wet season and decrease erosion rates. These results indicate that agroforestry and reforestation would be highly effective for climate change adaptation.

By contrast, dry season flow rates and annual sediment load rates estimated by the SWAT model under FS2 were not significantly improved compared to FS1 possibly due to the overriding influence of climate changes. Additional adaptation means to promote the retention of water in streams during the dry season, and measures to reduce sediment loads in waterways should be considered. The introduction of reforestation and agroforestry efforts to the upper watersheds of the Stung Sangker river basin is therefore recommended to overcome the potential negative impacts of climate change on the hydrology of the basin.

From FS3 it was seen that employing conservation farming practices in the lowland agricultural areas was effective in significantly reducing sediment loads entering the Tonle Sap Lake. However, SWAT models the effects of conservation farming on sediment loads only by modifying sediment loss rates from land areas without considering any hydrological changes that may occur. Consequently, the effectiveness of conservation farming alone in addressing flood and drought risks needs to be further studied, and additional climate adaptation measures should be considered.

5.1. Recommendations for Climate Change Adaptation Measures in Upland Watersheds

Based on the hydrological and land use data, reforestation and agroforestry efforts are highly recommended as climate change adaptation measures to restore the hydrological functioning of the basin.

Reforestation efforts should focus on degraded areas along drainage corridors, in community forests, within protected areas, and across the agricultural landscape following boundaries of allotments. Land use changes from agricultural allotments to agroforestry are likely to be highly effective.

Given that the results of the modelling under FS2 showed little improvement in reducing sediment loads in streams in upstream watersheds under FS1, additional measures to reduce sediment loads should be considered. These could include vegetated embankments; stream restoration works and networks of leaky weirs.

Leaky weirs are particularly favoured for steep sloping streams. These are engineered structures built from locally available natural materials that are placed in waterways to reduce stream discharge rates, mimicking natural obstructions within a river such as treefalls (Figure 39). Over time, sediments and other debris become trapped behind the leaky weir, thereby also leading the structure to act as a water storage which discharges stored water at increasingly slower rates, thereby reducing wet season flows and increasing dry season flows.

For the upper watersheds of the Stung Sangker river basin, in order for leaky weirs to be effective in reducing drought, they would need to be constructed as a series of cascading structures along the water courses of the upland watersheds in order to ensure that the combined capacity of the leaky weirs together is effective in maintaining flow through the dry season.

Figure 39: Example of a Small-Scale Leaky Weir

Source: https://rescue.earth/water-weather-initiatives/

Other positive functions of leaky weirs include reducing downstream flooding, reducing sediment discharge rates, increasing groundwater recharge rates and providing riparian habitat (Wilson, 2019). As they are sourced from local materials and can be constructed with local labour, the costs of construction and maintenance of leaky weirs are relatively low.

It is difficult to estimate the effectiveness of leaky weirs as climate adaptation measures to reduce sediment loads in the upland watersheds, due to the lack of sediment transport data on the Stung Sangker basin. Pilot trials are therefore recommended to determine their effectiveness and to allow data collection to be conducted and replication planned.

5.2. Recommendations for Climate Change Adaptation Measures in Lowland Areas

Based on the SWAT modelling, conservation farming is highly recommended as climate adaptations for erosion control from agricultural areas of the lowlands; however, conservation farming is not expected to significantly improve hydrological functioning in these areas – ie to reduce floods in the wet season and reduce droughts in the dry season. Additional measures would be needed to ensure that climate adaptation measures for the lowlands are effective, such as reforestation along riparian buffer strips, incorporating tree plantings into agricultural areas as well as restored and constructed wetlands.

Wetlands are particularly appropriate for the lowland areas due to the flat terrain and relatively shallow water table. Wetland may be shallow ponds, channels or porous beds that form habitat areas for aquatic plants. They are effective for drought reduction as water storage areas with low flow outlet and aquatic vegetation providing additional flow resistance so that water is retained for extended periods of time.

Wetlands can also be used to improve water quality, prevent flooding, recharge groundwater and to improve aquatic biodiversity. They have many livelihoods and subsistence uses. They support primary industries, provide flood and storm mitigation, act as a carbon sink, and provide communities with recreation and tourism. Wetlands may also contribute to the aesthetics and educational values of an area.

Annex A: Description of the Soil and Water Assessment Tool Model

SWAT models organize river basin hydrology into a land phase and a routing phase. The land phase is composed of the land areas that transport water together with sediment, nutrients and pesticides to the channels. The routing phase describes the progress of the water in the channels, typically from tributaries to the river basin outlet.

The hydrology cycle is simulated by the SWAT model is described in the following water balance equation:

$$SW_t = SW_o + \sum_{i=1}^{t} \left(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw} \right)$$

where, SW_t is the final soil water content (mm H_2O), SW_0 is the initial soil water content on day i (mmH_2O), t is the time (days), R_{day} is the amount of precipitation on day i (mm H_2O), Q_{surf} is the amount of surface runoff on day i (mm H_2O), E_a is the amount of evapotranspiration on day i (mm H_2O), W_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mm H_2O) and Q_{gw} is the amount of groundwater exfiltration on day i (mm H_2O).

SWAT simulates runoff by using the SCS (Soil Conservation Service) curve number method, in which the curve number varies non-linearly with the moisture content of the soil. The peak runoff rate is estimated by using a modification of the Rational Method. Water is routed through the channel network using the variable storage routing method, or the Muskingum routing method. The groundwater flow contribution to the total river flow is simulated by creating a shallow aquifer storage area, whereby percolation from the root zone is recharged to the shallow aquifer. Three methods for estimating potential evapotranspiration are used in SWAT: Priestley–Taylor, Penman–Monteith and ET–Hargreaves. This study used the SCS curve number and Muskingum routing methods for surface runoff and flow computations and the Penman method for potential evapotranspiration estimation.

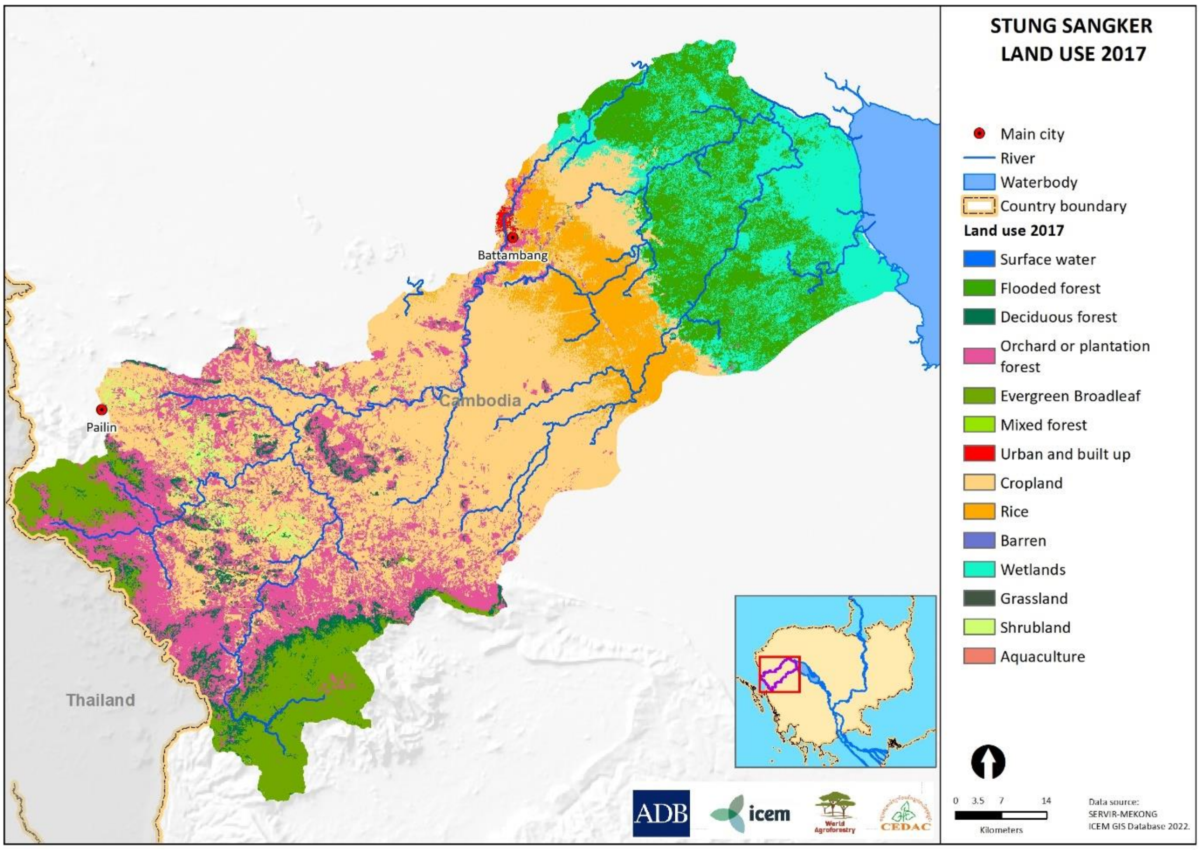
Annex B: Model Calibration and Validation

Stream flow is used for model calibration. A digital elevation model (MERIT-DEM) with 90m spatial resolution was used in this study. The DEM was projected with WGS84 UTM zone 48N and land use at 30m spatial resolution was retrieved from Servir Mekong 2017 (Figure 40). Cultivated lands, including agricultural crops and rice fields occupied about 40% of total land area in the region.

Soils are the determining factors for hydrological processes such as surface runoff, infiltration, percolation, lateral subsurface flow, plant water availability, etc. In this study, the soil map from the FAO's global soil database was used. The main soil types in the study area are categorized into: Gleysols (26%); Luvisols (33%); Nitisols (25%); and Acrisols (14%).

The SWAT model requires daily data for precipitation, temperature, wind speed, relative humidity, and solar radiation. The observed weather data and daily observed stream flow in the period 2007 - 2021 at Battambang station was obtained from the MRC data portal.

Figure 40: Land Use in Sangker Basin (2017)



Data source:
SERVIR-MEKONG
ICEM GIS Database 2022.

1. Model development

The delineation of the basin area used ground level data and a 90x90 m grid. The basin was delineated using a global digital elevation model (DEM). Before the DEM data was loaded into SWAT interface, it was projected into the UTM Zone 48N coordinate system. The DEM file, the base topographic input into the SWAT model, is used to calculate the slope and contours of the river basin. Once the DEM was added, the model then used the contours and river basin slope, calculated during the delineation, to determine flow direction and accumulation. Once flow direction and accumulation were established, the model generated a stream network in which each reach drains a sub-basin, all of which drain into a major reach. Each reach has a node or outlet. Basin delineation was further defined by identifying the outlet point of discharge for the sub-basin and the whole river basin. Sub-river basin outlets are the points in the drainage network of a sub-river basin where the stream flow exits the sub-river basin area. The outlet points for the whole river basin drain to Tonle Sap Lake. It is useful for comparison of measured and computed flows and concentrations. The outlet for each of the river basins was defined manually. It is convenient to select the most down-stream outlet of each target river basin to determine the sub-basin. For the study, the model computational domain was delineated into 56 sub-basins.

HRUs were then created with unique combinations of land use, soil type and slope. Each HRU features class-specific parameters that can be manually adjusted. Defining the number of HRUs was a three-step process. First, the land use was chosen and secondly, different types of soil for each of the land uses were assigned. Finally, land slopes were assigned to the combined land use and soil classes. In the first step, the number of land use was defined for all sub-basins in order to generate the HRU units. The number is controlled by a threshold value given for each sub-basin. The river basins were divided using five slope classes (<1%, 1–5%, 5–8%, 8-15%, and >15%). Subbasin area thresholds were used to eliminate minor land uses, minor soils for each land use, and minor slope ranges for each land use/soil combination, using values of 5% for land use, 20% for soils, and 20% for slopes.

Observed weather data, including rainfall, temperature, relative humidity, solar radiation and wind speed were prepared in text format and were added to SWAT. Calculation methods for runoff simulation, potential evapotranspiration, routing method, etc were specified in SWAT.

2. Model calibration and validation

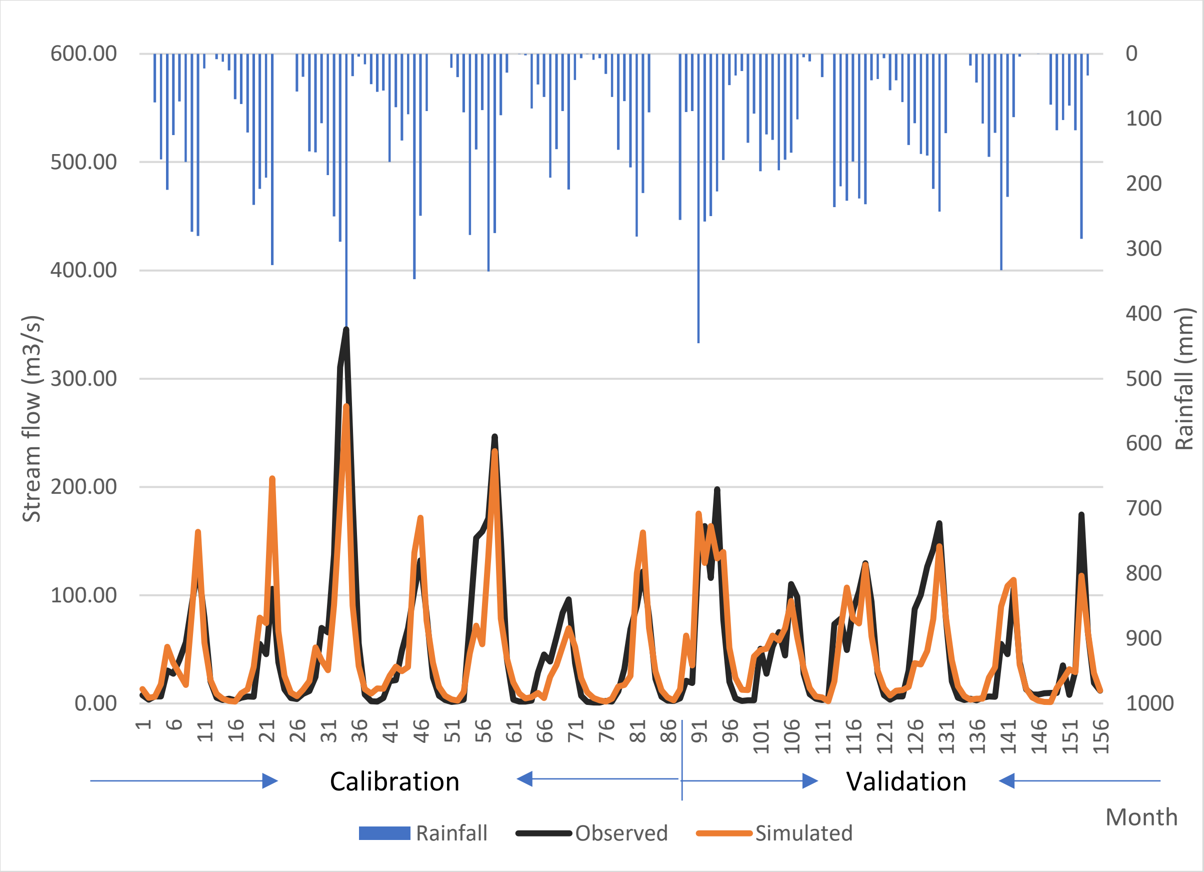
The SWAT model was calibrated and verified for river flow. The daily flows were calibrated (2007–2015) and verified (2016–2021) at Battambang river flow monitoring stations. The performance of the model in stream flow was evaluated graphically and by the Nash-Sutcliffe efficiency (NSE), the coefficient of determination (R2), the percent bias (PBIAS). Table 15 presents the range of calibrated parameters used in the SWAT model across all the watersheds. Streamflow calibration in the Stung Sangker river basin is presented in Figure 41.

Model performance showed good-fit between observed and simulated stream flow. This was indicated by NSE values of 0.76 and 0.69 in calibration and validation respectively. The PBIAS simulation of 0.10 and 0.01 also indicated a good model fit. Figure 41 shows a clear response of stream flow to rainfall, extreme rainfall events resulting in high stream flow.

Table 15: Range of Soil and Water Assessment Tool Calibrated Parameters Used in the Sangker Model

Parameters	Parameters definition	Minimum	Maximum
cn2	SCS curve number	35	95
esco	Soil evaporation compensation factor	0.01	1
epco	Plant uptake compensation factor	0.01	1
alpha	baseflow alpha factor	0	1
revap_co	Groundwater “revap” coefficient, when revap approach 0 movement of water from shallow aquifer to root zone is restricted. When revap approach 1, rate of transfer from shallow aquifer to root zone approached rate of potential evapotranspiration	0.02	0.2
revap_min	Threshold depth of water in the shallow aquifer required to return flow to occur	0	50
flo_min	Minimum storage to allow return flow	0	50
bf_max	Groundwater delay	0.1	2
bd	Bulk density	0.9	2.5
awc	Available water capacity of soil layer (mm H_2O/mm soil)	0.01	1
k	Saturated hydraulic conductivity	0	2,000

Figure 41: Observed and Simulated Rainfall and River Flow Time Series in the Sangker River at Battambang, 2007 to 2021



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