APRIL 2023

Evaluating The Use of Sustainable Approaches for Reducing River Flooding and Erosion in The Upper Trusan River, Sarawak

YIH YOONG LIP

Thesis submitted to The University of Nottingham Malaysia for the degree of Doctor of Philosophy, School of Environmental and Geographical Science

Under the supervision of:

Prof. Christopher Gibbins

Dr. Teo Fang Yenn

Prof. Ramon J. Batalla

Prof. Damià Vericat

APRIL 2023

Acknowledgement

I would like to express my deepest gratitude to Worldwide Fund for Nature Malaysia (WWF-Malaysia) for their generous financial support, which made this PhD thesis and research possible. Their unwavering commitment to river conservation and environmental sustainability has been instrumental in the success of my research, and I am truly grateful for their invaluable contribution. I would like to say thanks specifically to Ms. Belinda, Mr. Mc Kenzie, Ms. Cindy, and Mr Andrew from WWF-Malaysia for all the supports given. The arrangement for the field visits and logistic has never been easy, I am grateful for all efforts and time spent for project planning which made every field trip successful.

I would also like to extend my heartfelt thanks to my main supervisor, Prof. Chris Gibbins, for his expert guidance, mentorship, and unwavering support throughout my research journey. His unwavering dedication to my academic and personal growth in research has been truly inspiring. During the lockdown period in 2021 and 2022, field trip was not possible, making research almost impossible to progress. Inspiring words and ideas from Prof. Chris have given me motivation to continue working and helped learning on how to adapt in situation like this. I am grateful for the time that Prof. Chris spent for the meetings and always tried to come along for field work. I appreciate the opportunity given to learn from his wisdom and experience.

I am also grateful to my co-supervisor, Dr. Teo Fang Yenn, Prof. Ramon, and Prof. Damià, for their valuable insights, constructive feedback, and encouragement. Dr Teo has always been suggesting conferences, workshop and work opportunities which help in knowledge sharing and personal development. I would like to thank him for his commitment in the project. He always tries to join me for field trip despite his busy schedule. His expertise and experience have given us much useful engineering ideas in dealing with flooding and erosion issues in the Upper Trusan River. Lastly, I would like to express thanks to Prof. Ramon and Prof. Damià for accommodating us during my visit to Spain. The experience of working with them was incredible. The ideas and constructive feedback given for the research have been invaluable in shaping the direction of research and improving the quality of work. I am truly grateful for their contributions to my work.

Acknowledgement

I am indebted to my friends and family for their unwavering support, encouragement, and understanding during the course of my PhD journey. Some supports were given silently without my knowing. Their love, patience, and belief in my abilities have been a constant source of motivation and inspiration for me to finish my work. I would like to say thanks to my parents for the financial support throughout the whole PhD journey. The encouragement from them is the most important element contributing to the completion of the thesis. I am also very grateful to Paulina Tan, for her support and help in these years. Her help in sorting out logistic for the research field trip and giving me transport to the airport have made all the trips work out smoothly. Lastly, I appreciate the help from my colleagues, Celine Chong, Zoe Lum, Kitty Chen, and Azam from Hydro Ecology Lab. Especially Azam, who travelled with me and has contributed a lot during the field work in the Trusan. They have been the source of motivation for me to keep working, giving a very healthy environment to work together. I learnt a lot from them, particularly, Celine Chong, Zoe Lum, and Azam that have contributed a lot of their skills and work experiences in my research work. I am grateful for their presence in my life.

I would like to acknowledge the support and assistance of all the individuals/villagers from Long Telingan, Puneng Trusan and Long Semadoh who have provided help and insights during my research, including Mr John, Mr Tupai, Mr Micha, and Pak Padan. Many thanks to Auntie Rumie and Pak Tadam who always ensured very safe and comfortable stay during the visits to Trusan. Their contributions, whether big or small, have been instrumental in shaping the outcome of my research, and I am grateful for their valuable inputs.

Finally, I would like to express my gratitude to all the funders, organisations, and institutions that have supported my research in various ways. Your support has been crucial in enabling me to pursue my PhD and make meaningful contributions to my field of study. In conclusion, I am deeply grateful to all those who have supported and contributed to my research journey. Your unwavering support, guidance, and encouragement have been invaluable, and I am truly honoured and privileged to have had such amazing individuals and organizations by my side throughout this process. Thank you all from the bottom of my heart.

Abstract

This thesis summarises work undertaken to address flooding and erosion problems in the upper part of the Trusan catchment, Sarawak, Malaysian Borneo (hereafter the 'Upper Trusan'). The Upper Trusan has been experiencing severe flooding and associated riverbank erosion, both of which affect rice production. This work aimed to identify and evaluate options for reducing the risk and impacts of these phenomena using sustainable 'green' approaches. I assessed the suitability of different types of riverbank protection measures (brush walls, brush mattresses, bamboo fencing and geotextile mattresses) as short-term measures for reducing erosion in some of the worst affected areas. In addition, we evaluated opportunities for managed flooding to help reduce flood peaks and attenuate flood waves in the downstream areas. I also assessed the contribution that land use management (especially the conservation of forest cover) could play in minimising flood risk under future land cover scenarios.

Local bank protection measures were partly successful. Brush mattresses placed on graded (sloping) banks provided the most protection, lasting longer than other measures. Because of the upland nature of the Trusan, local measures need to withstand frequent high flow forces. Consequently, non-living measures such as bamboo fencing provided only limited and temporary protection from bankfull flows. The assessments indicate that ensuring structures remain living and have adequate toe protection and regular maintenance is essential if they are to be successful. Even so, in high-energy systems such as the Trusan, local measures should not on their own be seen as a long-term solution.

Flood modelling using HEC-RAS® indicated that managed inundation of floodplain areas would have very little effect on flood peaks in the Upper Trusan. The main reason for this is that, due to the confined nature of the valley, the floodplain area is relatively small – this limits its capacity to store sufficiently large volumes of water. The models suggested that more or less the whole of the floodplain would need to be allowed to flood in order to affect any significant reduction in flood magnitude. This would defeat the objective of the exercise since the whole area that communities want to protect from flooding would need to be allowed to flood. Thus, there is limited scope for corridor scale management using managed flooding.

Satellite-based analysis of land cover in the Upper Trusan suggests that there has been limited forest loss in the last three decades. Catchment scale hydrological modelling using SWAT® indicated that this change has had very little effect on the hydrograph and has not contributed to the reported increased incidence of flooding. However, modelling future land cover change scenarios indicated that significant loss of forest – especially conversion to bare earth – would increase the number of bankfull flood events from 2 to 3 each year. Adoption of Government proposals set out in a land use Master Plan would see up to 35% of the Upper Trusan converted to agriculture. SWAT® modelling suggested that agriculture at this scale would not have a major impact on flooding unless it is accompanied by extensive road systems and built-up areas that would alter hydrological responses to rainfall.

Overall, the work suggests that there is little scope for the adoption of managed flooding in the Upper Trusan and that, in this high-energy system, local green bank protection measures should only be seen as a short-term solution to reducing bank erosion. Conservation of natural forests is key to minimising future hydrological changes. The analysis leads to a number of conclusions and recommendations: (i) Local green measures can play a role in protecting riverbanks from erosion. However, emphasis should be on using live materials and ensuring maintenance, so they do not get washed out. In flashy rivers such as the Upper Trusan, a particular challenge is finding sufficiently long-time windows so they can be built and allowed to stabilise before the next high flows. (ii) The opportunity for using floodplains to store water in upland valleys such as the Upper Trusan is constrained by space. This and the likelihood of future climate and land cover change make it imperative that a wider perspective is taken to find a way for communities to become resilient in the long-term. (iii) What is needed now is a full socioeconomic assessment to fully understand rice's contribution to local community incomes and evaluate options for diversifying income sources. This way, communities can become less reliant on the very precarious floodplain rice production. In turn, this will create opportunities for floodplain retreat and the possibility of giving land back to the river, neither of which are possible in the current livelihood model. Such approaches help to conserve the physical integrity of the channel because of how they will reduce the need for perpetual engineering intervention.

Table of Contents

List of Tables

List of Plates

List of Figures

CHAPTER 1: INTRODUCTION

Aerial view of village and rice paddy fields at Long Telingan
Photo: Yih Yoong Lip, September 2022

1.1 Sustainable approaches in river management: Applications and Constraints

Flooding and erosion are major issues globally. As a result of land use change and heavy development on river floodplains, the risks associated with river flooding and bank erosion have significantly increased and are now a major concern in many countries (Kundzewicz et al., 2014). Recent studies also show that climate change has induced extreme flood events, which exacerbates the impact of land cover change (Pinto et al., 2022). Flooding has caused significant damage, threatening infrastructure, human health, and livelihoods in both urban and rural areas. People who live on floodplains are often displaced (Kreienkamp et al., 2021) and in some countries (e.g. UK) there is now a presumption against further floodplain development due to flood risk.

Flooding and associated erosion have adverse impacts globally, but human effects are arguably more extreme in the tropics due to higher rainfall intensity and higher current rates of land cover change (Eccles et al., 2019; Tabari, 2020). Moreover, flood management is more rudimentary in countries in the Global South, combined with the large number of people living in flood-prone areas. In rural tropical areas, for example, floodplains are extensively used for agricultural purposes and are critical for the livelihoods of local people, while forested areas are subjected to logging and mining (Lambin et al., 2003). The rapid change in land cover has caused detrimental changes to soil infiltration capacities and increased surface runoff, contributing to higher occurrence of extreme flood events in tropical countries (Hu et al., 2020; Saadatkhah et al., 2016).

It is generally accepted that river systems must be managed to reduce flood and erosion risk (Serra-Llobet et al., 2022). In the past, hard engineering interventions were a common management tool. However, since the mid-1990s river management has shifted from an engineering-dominated approach to a more sustainable, 'green' approach (Biron et al., 2014). There is a broad agreement that sustainable approaches to river management are resilient to flooding, leading to growing interest in their use. Previous applications of sustainable approaches that work at different spatial scales have been shown to be successful in reducing flood risk without compromising the ecological and environmental aspects of rivers (Parrott et al, 2009).

The local scale bank protection measures that can be seen commonly in North America and European countries are live crib walls, live fencing, and brush walls. However, local measures to deal with the consequences of flooding do not address the root cause. Hence, sustainable approaches implemented at a larger scale (i.e. corridor and catchment scale) are needed as part of management strategies to address causes of flood and erosion risk.

In the past two decades there has been an emergence of the so-called 'hydrogeomorphological approach' to river management which emphasises 'freedom space for rivers'. This approach is commonly implemented at the corridor scale to allow rivers to flood and migrate naturally across the floodplain (Buffin-Bélanger et al., 2015; Piégay et al., 2005). Previous work has shown that the combination of mobility and flooding space helps with flood attenuation in downstream areas (Biron et al., 2014). Best practices in river and land use management that encompass both local measures and appropriate corridor and catchment scale management could potentially reduce river discharge, improve water quality and reduce economic losses associated with flooding (Parrott et al., 2009). For example, riparian forest restoration in middle and upper catchment areas tends to reduce flood peaks (Dixon et al., 2016). Most research on, and application of, these ideas has been undertaken in Europe and North America (Beechie et al., 2010; Powers et al., 2019), and there is limited evidence of their adoption in tropical regions. Moreover, where sustainable approaches to river management have taken place in the tropics (e.g. Singapore), they tend to be in areas of high population density, and so are most often located in lowland, urban or semi-urban areas.

There is now an extensive literature exploring the diverse approaches available to support sustainable river management (Provan & Murphy, 2021) but very little work has dealt explicitly with the constraints of applying these in tropical regions (Zafirah et al., 2017). There are particular challenges in rural or upland parts of tropical catchments (Abdullah, 2017). The first challenge is that identifying sustainable solutions requires good understanding of river hydrology and fluvial processes. However, many rural areas in the tropics lack adequate long-term data due to the absence of hydrometric monitoring networks and/or scientific research on river dynamics, with these limiting the fundamental knowledge-base needed by practitioners to plan and design measures (Wohl et al., 2015). Second, the remoteness of many areas limits the type of options that are practicable; remoteness constrains accessibility for machinery, materials and general project logistics (Bernhardt et al., 2005; Erős et al., 2019). Finally, for reasons related to governance and administration, in practice flood risk mitigation in remote areas is often left to the local (impacted) community. In Malaysia, for example, the Federal Government collaborates and cooperates with the State governments to create policies related to river governance (Abdullah, 2017). However, the government delegates some river management responsibilities to local stakeholders such as industrialists, entrepreneurs, local communities, and NGOs. Consequently, many river projects go ahead without the support of experts from government departments such as the National Water Research Institute of Malaysia (NAHRIM) or the Department of Irrigation and Drainage (DID).

In the past decade, Worldwide Fund for Nature Malaysia (WWF-Malaysia) has been working closely with the local community in the Trusan catchment, Sarawak (Figure 1.1) under the auspices of Forum Masyarakat Adat Dataran Tinggi Borneo (FORMADAT). The partnership encompasses a wide range of initiatives related to preserving the natural environment and conserving important flora and fauna. One of the FORMADAT projects involves work to reduce flooding and erosion in the Upper Trusan River, an area that has been experiencing frequent flooding and increased riverbank erosion in recent years. In 2018, the University of Nottingham Malaysia (UNM) was invited to collaborate on this project, to provide guidance and explore the potential of applying sustainable approaches to help resolve these problems. The first phase of the collaboration involved an assessment of the magnitude and causes of the flooding and erosion and resulted in a set of general recommendations (Marteau et al., 2018). These recommendations involved improved catchment management (e.g. presumption against further forest clearance) and adoption of corridor scale measures such as the use of floodplain retention, supported by some local green bank engineering to provide short-term protection against erosion in areas where problems were considered most acute. The current thesis follows on from this initial work and involves development of more specific and detailed recommendations for catchment and corridor scale management, and assessment of the success of local bank protection measures installed to reduce erosion. The following sections provide details of the study area and the issues in the Upper Trusan, and then set out the aims and objectives of the thesis.

1.2 Study area, aims and objectives

1.2.1 Catchment

The study area is located in Northern Sarawak, immediately below the Sabah border and close to the Indonesia border (Figure 1.1). It sits within the uppermost sub-catchment of the main Trusan catchment. At its downstream end the study area is delimited by the village of Long Semadoh; the area upstream from here has a catchment size of approximately 140 km^2, and includes most of the headwater sources of the Trusan. The Upper Trusan River flows south-westward for a total length of 14 km, extending from the headwaters down to Long Semadoh. It then flows westward, passing through Long Beruyu and Long Kerebangan for a distance of 14.2 km and eventually joins the main stem of Batang Trusan. This sub-catchment (i.e. upstream from the Batang Trusan confluence) is henceforth referred to as the Upper Trusan, while the main (whole) catchment is referred to as the Trusan Catchment. The Trusan drains a total catchment of 2515 km^2, and finally discharges to the sea in Brunei Bay.

The Upper Trusan is a gravel-cobble bed river (Marteau et al., 2018), with median sediment in the coarse gravel size fraction. It has a steep gradient with high precipitation throughout the year (see section 1.2.4), creating a high energy river. The river floodplains are 400 – 500 meter wide and play an essential role in sustaining human livelihoods via rice cultivation.

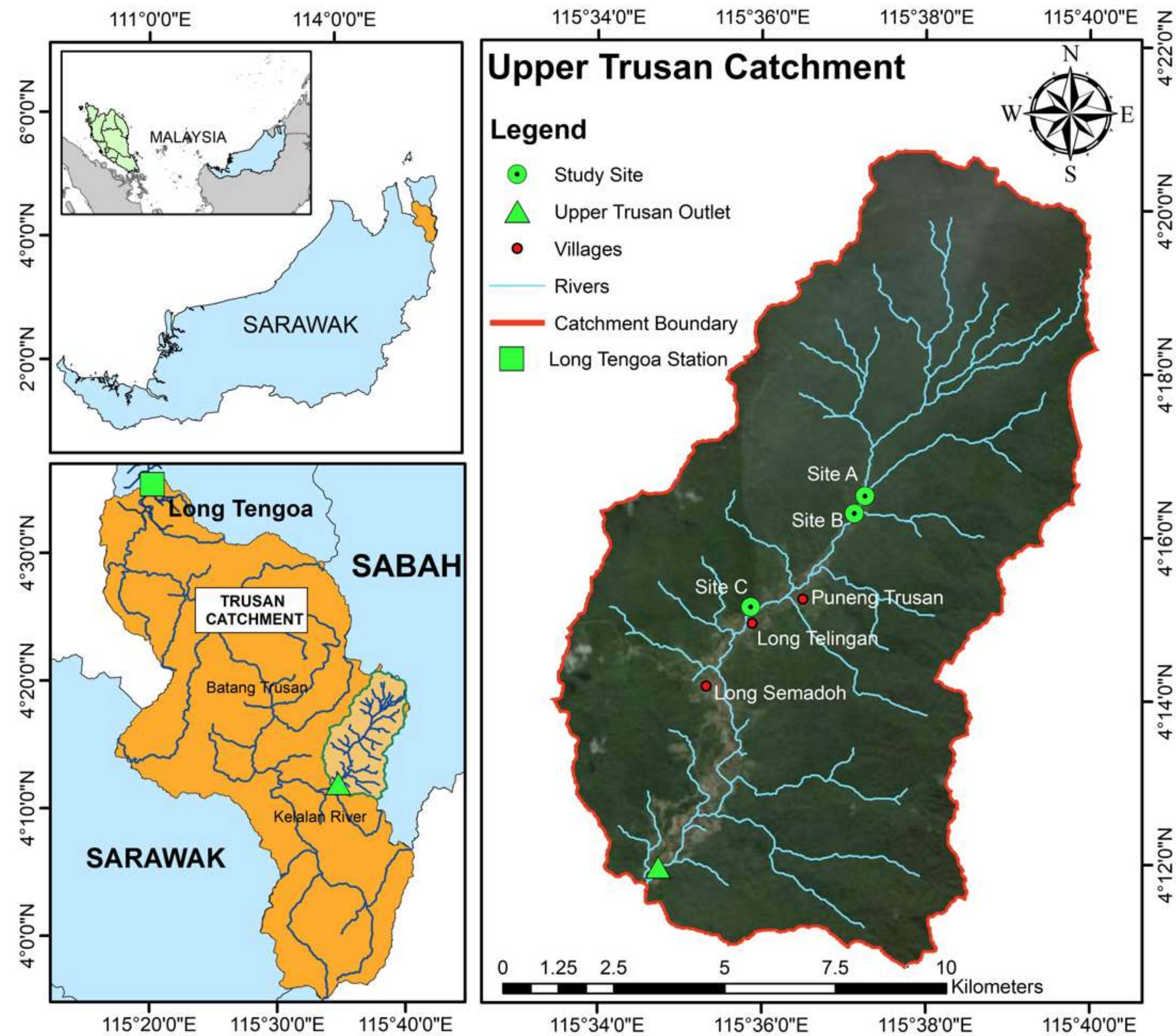

Figure 1.1: Study area. The upper left shows the location of the Trusan catchment, while the lower left shows the Upper Trusan (red border). The right-hand figure shows the detail of the Upper Trusan, including the location of villages.

1.2.2 Land cover and Land use

The Upper Trusan catchment is a forested, mountainous area with an elevation of approximately 800 - 900 meters above sea level. The catchment is subjected to multiple land uses and land covers, mainly for agricultural purposes, livestock grazing, and some rural villages (Figure 1.2). Much of the catchment has a dense forest cover, with most areas undisturbed despite small-scale logging. Most human activities are focussed near the river floodplains, which are used for rice production and livestock grazing. A small portion of the hilly areas are used as agricultural land (e.g. pineapple farms). Tracks and roads are most dense near the river floodplains as these are the main route for the local community to access the paddy field areas. There are no metalled roads in the catchment, and access via the tracks is limited during rains. Villages occupied by the indigenous people are located on higher river terraces or on lower hillslopes.

Small-scale logging activities have occurred in the past decades, resulting in a small percentage of forest loss in localised areas. However, the forest cover still accounts for 95% of the entire land cover (Marteau et al., 2018). Between 2007 and 2009, deforestation was visible near the river, and there were numerous isolated occurrences of forest disturbance on the western edge of the basin. These disturbances occurred near tracks and were likely facilitated by the accessibility created by tracks. Between 2009 and 2014, there was no significant deforestation, though there were some logging activities near the river (i.e. within the floodplain). Between 2014 and 2017, the most intense logging activity was concentrated on the western half of the basin along the river floodplain.

An estimated 25 percent of the floodplain areas are rice paddies (some used and some abandoned), while 5 percent are used as livestock grazing land. The remaining floodplain areas are grasslands, built-up areas or bare earth which together account for 62% of the entire floodplain.

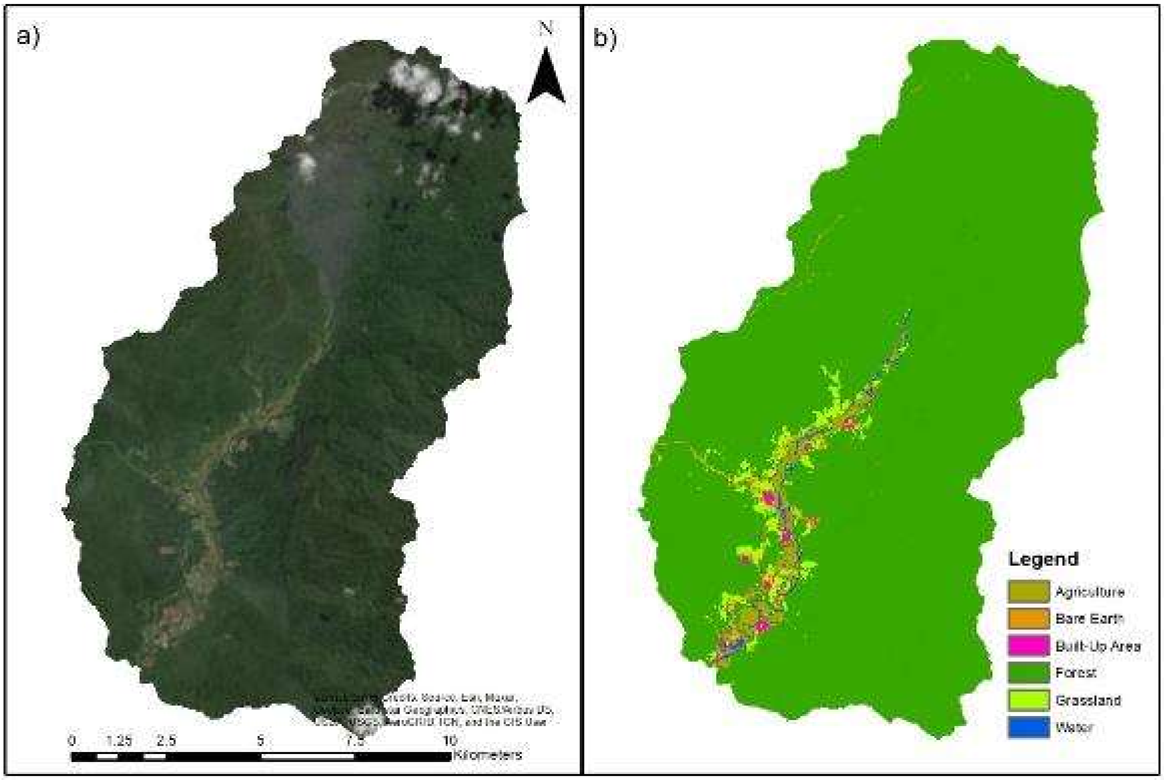

Figure 1.2: a) Map of the Upper Trusan Catchment, b) Land cover of the Upper Trusan Catchment.

1.2.3 Topography and soil type

The Digital Elevation Model (DEM) of the Upper Trusan Catchment and the soil map are shown in Figure 1.3a and Figure 1.3b respectively. The Trusan is a rather typical mountain valley river, with steep valley sides and a high gradient, predominately plain bed or transitional plain bed to pool riffle channel morphology. There is a narrow floodplain, typically 200 - 300 m wide. The hillsides range up to an elevation of 2056 meters, and these areas were historically kept as preserved forest where the local communities used for hunting, planting, and foraging. The floodplain has an average elevation of 750 meters. This floodplain is mainly used as agricultural land and is a hotspot where human activities have constantly increased over the years.

The soil type in the Upper Trusan Catchment can be classified into 5 classes. These classes are gley soil, recent alluvial soil, red-yellow podzolic soil, skeletal soil, and mixture of skeletal soil and red-yellow podzolic soil. The catchment largest soil type is formed of skeletal and red-yellow podzolic soil and the smallest is skeletal soil. The map indicates that the soil at the river floodplain areas are mainly formed of recent alluvial soil at the upstream and gley soil at the downstream. These datasets were used in the respective chapters to support the setup of hydrological and hydraulic model.

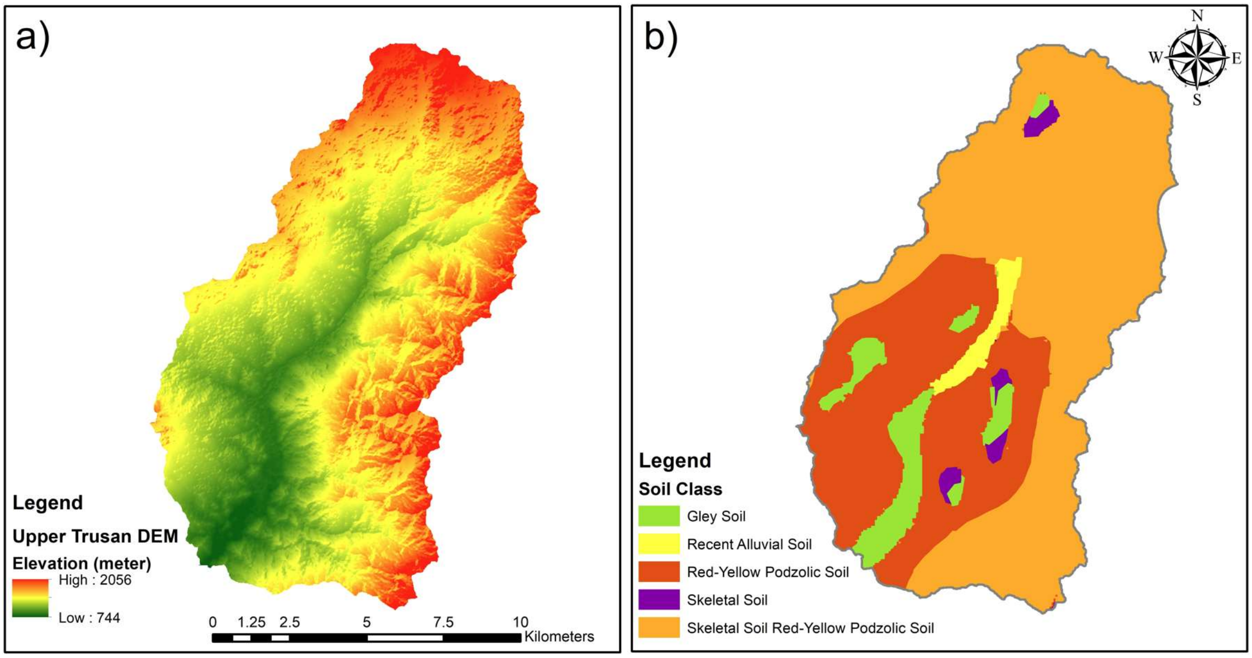

Figure 1.3: a) Digital Elevation Model, and b) Soil map of the Upper Trusan Catchment

1.2.4 Climate and hydrology

The Upper Trusan Catchment has a tropical climate with high rainfall throughout the year. The annual rainfall recorded at the nearest rainfall station (i.e. Long Semadoh station) has a mean of 2528 mm, ranging from 1891 mm to 3625 mm in drier and wetter years respectively (Figure 1.4). The rainfall intensity is affected by two monsoon seasons: the Northeast and Southwest monsoons. The Northeast monsoon usually happens between November and February, while the Southwest monsoon normally happens between April to June but is usually less intense. Both these monsoons bring heavier rainfall in respective months (Figure 1.5). The temperature in the Upper Trusan Catchment ranges from 16 °C to 25 °C during the day, but some nights drop to lower than 11 °C. These temperatures are lower than lowland areas in Sarawak, due to the altitude of the Upper Trusan.

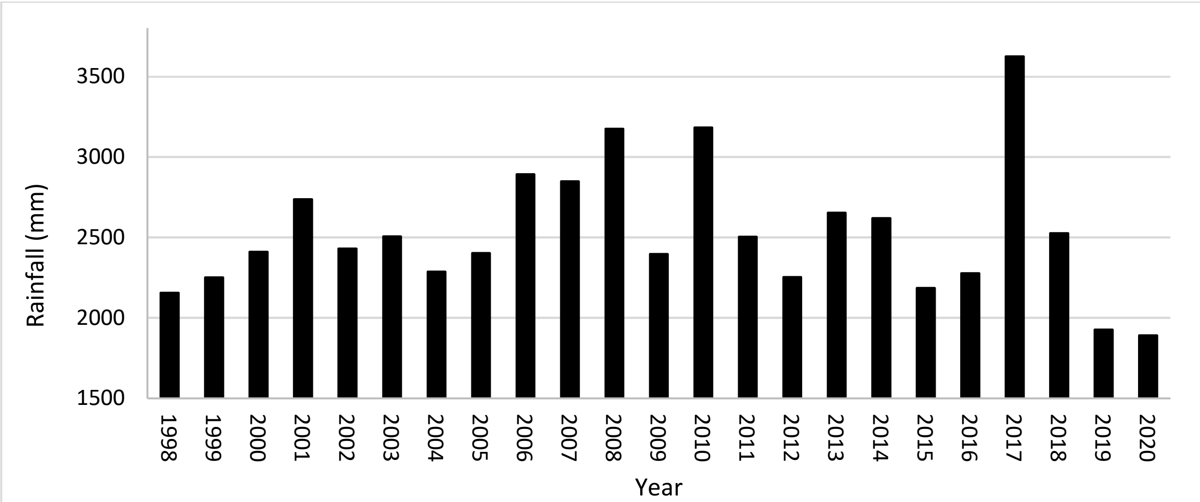

Figure 1.4: Total annual rainfall from 1998 to 2020 (data from DID Malaysia).

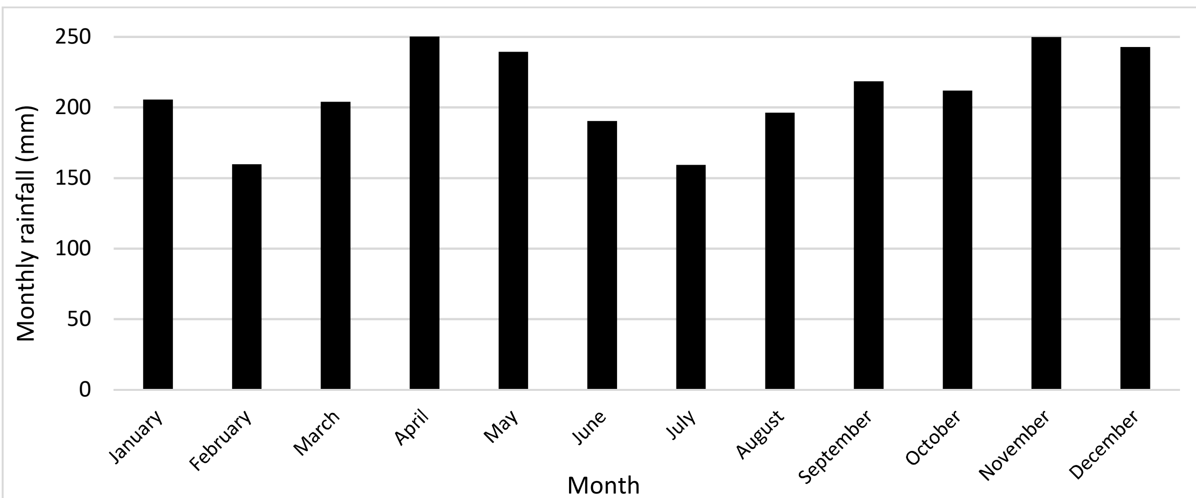

Figure 1.5: Average monthly rainfall computed from 1998 to 2020 (Data from DID Malaysia).

The only discharge gauging station available in the Trusan Catchment is located at Long Tengoa (Figure 1.1). Here, the mean annual flow is 108.7 m^3/s, and ranges from 16 m^3/s to 770 m^3/s. Figure 1.6 shows a typical annual hydrograph for Long Tengoa Station. Unfortunately, Long Tengoa station is located far downstream from the Upper Trusan Catchment and has very different land use and experiences water abstraction for agriculture and for potable supplies for the larger human population. Moreover, the record of long-term rainfall from Long Tengoa station is poor (patchy records), and the discharge rating curve is not reliable for flow higher than

179.2 m^3/s. These issues create uncertainties in understanding the hydrology of the Upper Trusan Catchment based on data for Long Tengoa (for which see Chapter 3).

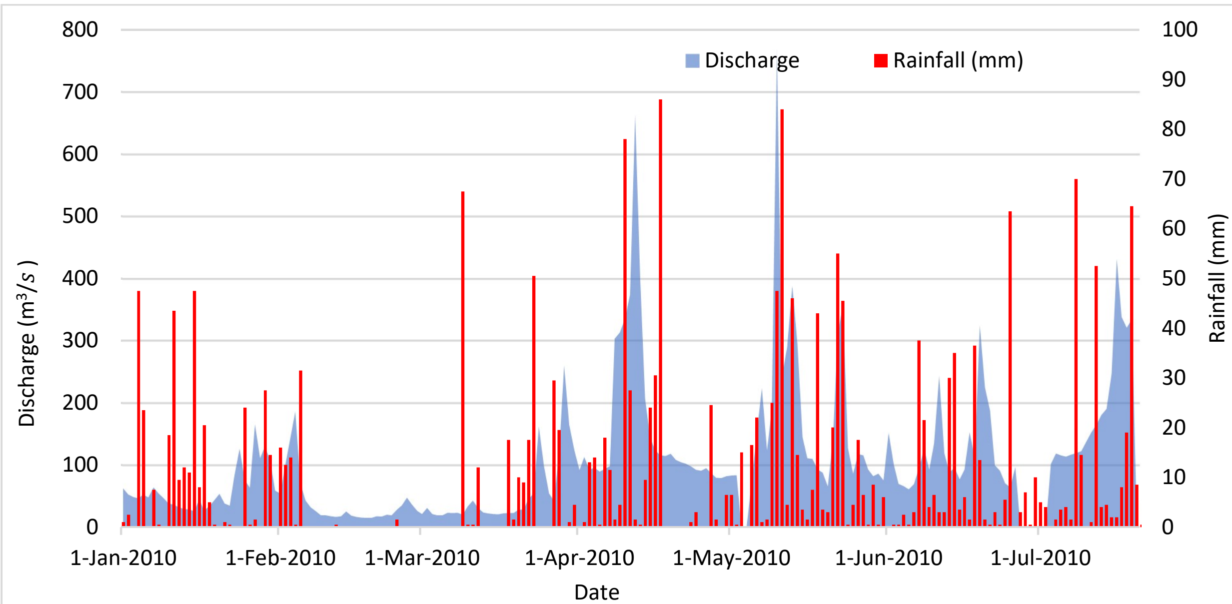

Figure 1.6: Rainfall-runoff recorded at Long Tengoa Station (Data from DID Malaysia).

1.2.5 The local community and flooding problems

Local communities in the Upper Trusan largely depend on farming, such as cultivating plants, rice paddy fields, and livestock, to sustain their livelihoods. The availability of nutrient-rich river floodplains has made rice paddy fields their main resource and these support the local economy. Many rice paddy plots are located adjacent to the river channel, and they make use of river water for irrigation and drainage. Irrigation and drainage use a number of man-made channels that cross the paddies and connect them to the river.

The WWF-UNM project was initiated because of increased flooding and erosion over recent years, reported by the local community. The overbank flows frequently damaged their crops and paddy fields, and accelerated bank erosion has caused land loss (Jude Toyat, 2019). Furthermore, because of unplanned road network expansion in the hilly areas close to river floodplains, hillslopes at various locations are subjected to severe landslides and wedge failure, which have contributed to increased fine sediment loads in the river. This fine sediment may explain the declines in fish catches reported by the local community.

Prior to WWF-UNM involvement, the response from the local community was to implement direct hard engineering that only addressed local symptoms of the high flows. Interventions included channelisation and the installation of gabion walls used to alter flows and reduce bank erosion respectively. Some such interventions are still taking place; e.g. Plate 1.1 shows the channelised channel near Long Semadoh. Not only have these failed to resolve the flooding and erosion, but in some cases they exacerbated problems in the downstream areas. Moreover, by affecting natural geomorphic processes and flow hydraulics, they may be contributing to the reported fish declines. Hence, it is generally accepted by the local community that past attempts at hard engineering have been unsuccessful, and accordingly they agreed to work with WWF and UNM to implement sustainable river management. This sustainable management involved not only treatment of the symptoms but efforts to understand and address the root causes of the high flows.

Plate 1.1: Channelised reach at Long Semadoh with large gravel shifted from the true right bank to the true left eroded bank.

1.2.6 Sustainable approaches in the Upper River Trusan

As mentioned above, in 2018 WWF and UNM initiated collaboration to study the causes and identify sustainable solutions to flooding and erosion in the Upper Trusan, and in so-doing help conserve the river and protect community livelihoods. Two pieces of work were conducted. The first was a hydrological and geomorphological assessment of the Upper Trusan. Notably, one of its conclusions was that the local communities were playing a role in the problem, most notably due to local forest clearance and clearance of riparian trees along extensive sections of the river; forest clearance was to provide land for crops and access for water buffalo, while riparian areas were cleared so that paddies could be extended right up the riverbank. The second piece of work was a review of best practices for managing riverbank instability and erosion, with a particular emphasis on work in tropical regions. Together the two studies led to general recommendations that were presented to the local community in 2019. WWF secured funding to deliver the next phase of the work, and it is this funding which supported the current thesis.

The general recommendations involved trialling local scale ‘green measures’ such as brush mattress, live fencing and coconut geotextile mattress (Plate 1.2) to help reduce erosion in the most problematic areas, while undertaking the modelling work needed to provide more spatially explicit recommendations for corridor and catchment scale measures. Local green measures were installed at several sites between 2019 and 2020, and evaluation of these forms part of this thesis (presented in Chapter 4). Concurrently river channel and catchment models were constructed to help evaluate the use of floodplain wetlands to help store floodwaters and reduce flood peaks downstream, and to better understand the role of land cover change as a driver of the flooding and identify critical areas that need to be protected or restored to reduce flooding and its impacts in the future.

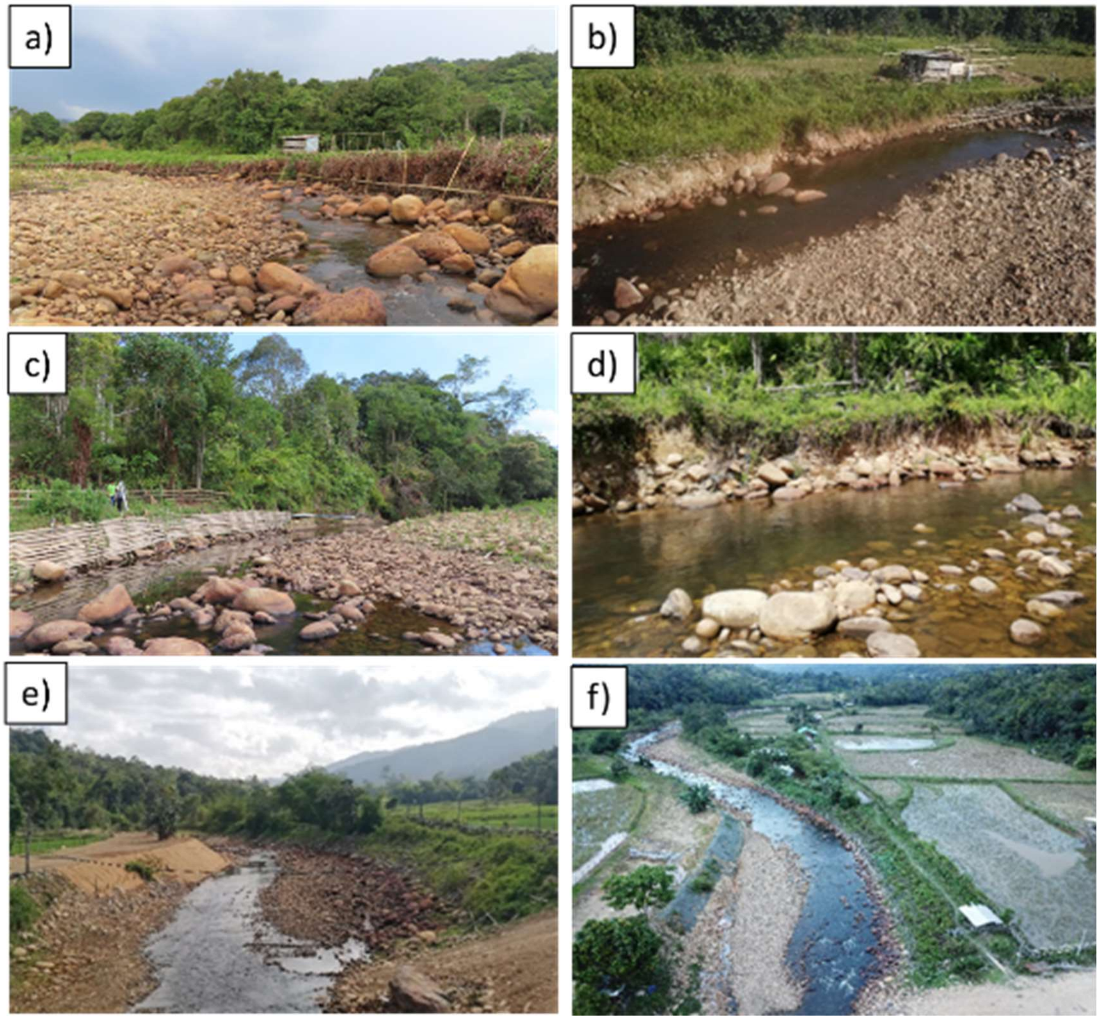

Plate 1.2: a) Brush wall installed at Site A in 2019 and b) is the exposed bank after brush mattress was washed out in 2020. c) Live fencing installed at Site B in 2019 and d) is the exposed bank after live fencing was washed out in 2020. e) coconut geotextile mattress (left) and brush mattress (right) installed at Site C in 2019 and f) is the photo taken in 2020 with green measures still remain intact at both side of the bank.

1.2.7 Aims and Objectives

Against the background set out above, the overall aim of the research presented in this is to **assess the feasibility of using sustainable river and catchment management to help solve flooding and erosion problems in the Trusan River.** The thesis considers management at three scales: (i) Green measures for local bank protection, (ii) floodplain retention for corridor scale flood risk reduction, and (iii) watershed management (e.g. preservation of natural land cover) for controlling hydrological change. Accordingly, the thesis has four specific objectives:

I. Assess the opportunities and constraints for local green measures to protect riverbanks from erosion (Chapter 4).

II. Identify the existing flood risk and evaluate the use of floodplain retention to reduce flood peaks and flood risk in the downstream areas (Chapter 5).

III. Assess the contribution that catchment management – notably forest conservation - could play in reducing erosion and flood risk (Chapter 6).

IV. To identify the challenges of adopting local, corridor and catchment scale sustainable river management measures, to inform adoption in other Malaysian locations (Chapter 7).

1.3 Methodological approach and thesis structure

Rather than a single methods chapter, details of the materials and methods specific to the work detailed in each chapter are presented in respective chapters. Figure 1.7 provides an overview of the thesis and the methods used to address each objective. Key aspects of the data collection scheme and an overview of the thesis structure are summarised below.

Chapter 2: Literature Review

A literature search was conducted to look at the state-of-art of local green measures in bank stabilisation and corridor scale management, to inform options available for the Trusan. It is recognised that local measures have limitations in reducing erosion and flooding, so broader scale approaches in sustainable river management were reviewed to assess their potential role in the Trusan.

Chapter 3: Hydrology of the Upper Trusan Catchment

As the Upper Trusan Catchment is not gauged, this required reconstruction of a hydrograph for the study area using a rainfall-runoff model. Chapter 3 presents the development and results of this modelling. HEC-HMS® was employed for rainfall-runoff simulation. The reconstructed runoff data were used to develop a long-term hydrograph for the river, from which flow duration curves and flow statistics were extracted to help inform later parts of the research. In particular, the hydrograph was used to quantify patterns in the frequency of bankfull and other indicative high flow events.

Chapter 4: Assess the opportunities and constraints for local scale green measures to reduce riverbank erosion

This chapter looks at rates and patterns of riverbank erosion in the Trusan and uses this to identify priority sites for local measures. A variety of different measures were then installed, and their success in reducing erosion was evaluated through a series of repeat surveys.

Chapter 5: Identify suitable areas for floodplain retention

HEC-RAS® software was used to build a flood model for a continuous 5km section of the Upper Trusan River (hereafter the 'study section'). The model was used to assess flood attenuation in the downstream areas and the potential of mitigating flood risk. A drone survey was conducted to obtain high-resolution DEMs needed for the flood model. Selected flood events from the reconstructed hydrograph (Chapter 4) were simulated to identify potential flood areas and subsequently provide recommendations for suitable areas for floodplain retention.

Chapter 6: Assess the contribution of catchment management to reducing erosion and flood risk

The focus here was conservation of natural land cover, and the impacts of loss of natural land cover on flood risk. Soil and Water Assessment Tool (SWAT®) was used to run a series of simulations to i) assess the effect of land cover change on the hydrological regime, ii) Identify susceptible areas where forest protection needs to be prioritised in order to limit further hydrological changes.

Chapter 7: Challenges of adopting local, corridor and catchment scale sustainable river management measures in tropical upland rivers.

This chapter synthesises all case study evidence gathered from each chapter. The relative merits of localised measures versus catchment management are discussed to highlight the significance of addressing the root causes of flooding and erosion rather than treating the symptoms. The chapter makes some recommendations based on results of the empirical parts of the thesis.

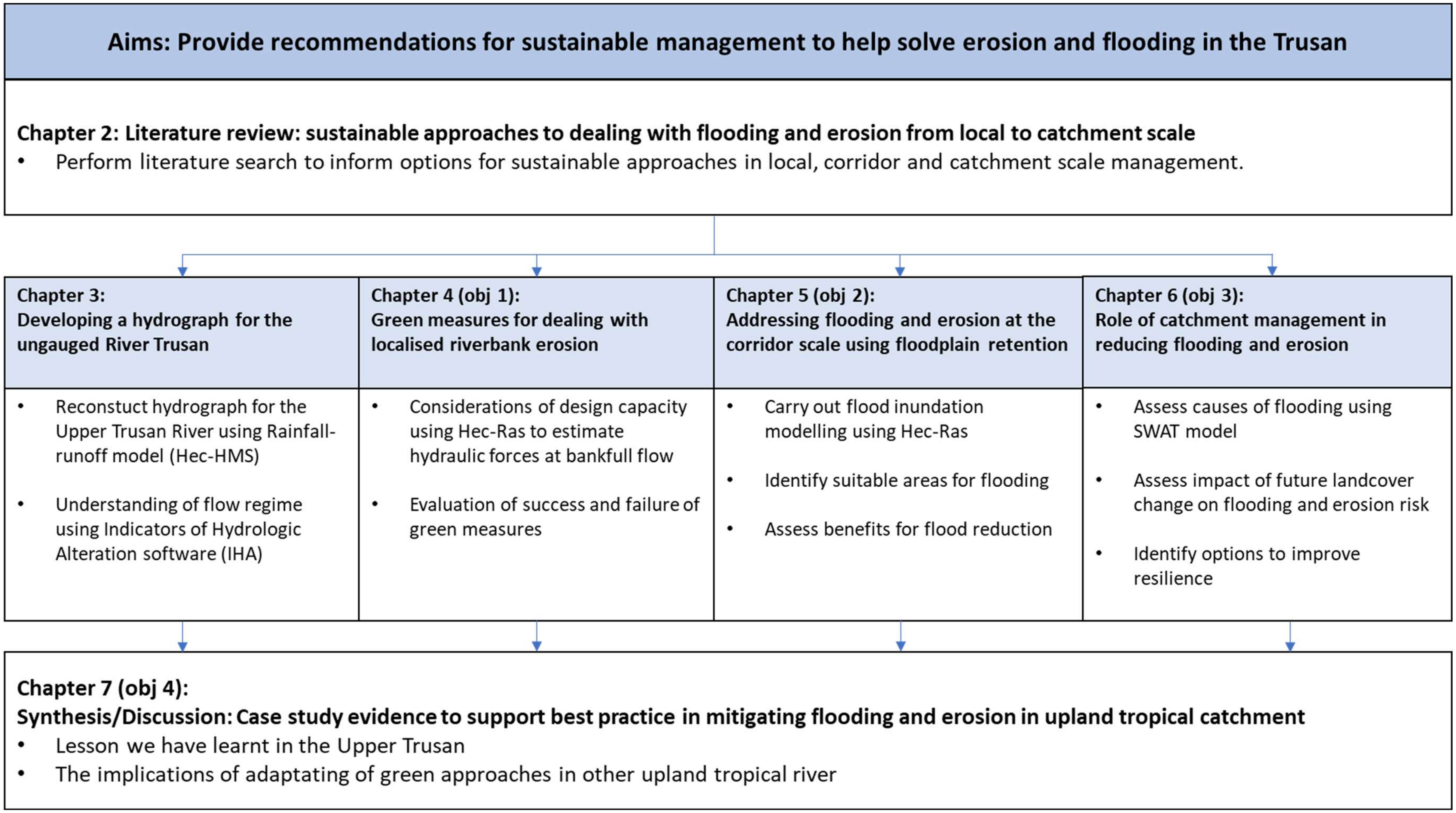

Figure 1.7: Overview of the thesis structure and the general tools and methods applied to address the objectives set out in each chapter.

CHAPTER 2: LITERATURE REVIEW

Local green bank protection measures near Long Telingan
Photo: Yih Yoong Lip, February 2020

2.1 Introduction

Climate change and changes in land cover and land use are causing increased flooding and exacerbating land erosion worldwide (WMO, 2021). Flooding and bank erosion cause land loss and degradation, as well as property damage and pose risks to lives and livelihoods. As a result, many rivers have been subjected to human interventions designed to contain floods and reduce erosion.

Historically, interventions have mainly involved 'hard engineering' measures such as river widening, straightening, over-deepening ('canalisation') and hard structures to embank (heighten) and protect riverbanks (Li & Eddleman, 2002). Hard engineering was favoured due to rapid urbanisation in the ninetieth and twentieth centuries, where immediate solutions were required to protect people and property.

Nowadays these traditional engineering interventions are recognised as failing to deal with the problem and because they compromise ecological health. Hence, softer approaches have slowly developed (Janssen et al., 2019; Zhang et al., 2019). These softer approaches come in a variety of forms and are referred to as green engineering, soft or bioengineering (Golden & Hoghooghi, 2018; Liao, 2019). Green approaches have become central to river rehabilitation and, more generally, river management. At the same time as the emergence of green approaches, the broader endeavours of sustainable catchment management as well as river restoration and rehabilitation have developed (de Vriend et al., 2015; Lashford et al., 2022; Pinto et al., 2019; Weng, 2005).

At the local scale, green approaches typically involve bank protection measures to create a natural channel and reduce erosion, often in smaller streams and rivers (Anstead et al., 2012; Nichols & Leiser, 1998; Provan & Murphy, 2021). They may include installing bank vegetation, or creating more natural, heterogeneous channels that bring additional biodiversity benefits (Allen & Leech, 1997; Lyn & Newton, 2015; Tardio et al., 2017). While local scale projects can effectively reduce the impact of floods and erosion in the short term, their effectiveness is often limited to the immediate area where they are installed (Newton & Lyn, 2015). Local scale approaches may therefore need to be combined with the corridor and catchment scale approaches to achieve significant reductions in flooding and erosion, particularly in treating the root causes (Beechie et al., 2010; Kondolf, 2006; Poff et al., 2016).

At the corridor scale, river restoration projects typically focus on larger rivers, including riparian zone and floodplains. Common approaches include restoring natural processes and habitats along the river by creating floodplain reconnection features and restoring riparian vegetation (Castellarin et al., 2011; Serra-Llobet et al., 2022). In recent decades, the notion of allowing rivers to flood and erode has emerged as a more sustainable corridor scale management approach. Various names for these approaches have been used, such as the erodible corridor, fluvial territory, freedom space, and river corridor. They are based on maintaining the hydrogeomorphological processes of the rivers and aim to improve flood resilience while not compromising river integrity (Biron et al., 2014). While extensive riparian and floodplain areas provide a more continuous and connected system for reducing the impact of floods and erosion, creating freedom space can be challenging, especially in urban areas where space is occupied. The reconnection of the floodplain may mean that the landowner might need to sacrifice lands for natural floodplain inundation, or even retreat from the floodplain altogether; the term 'managed retreat' had been used to represent this idea.

At the catchment scale, the management initiatives are typically applied to the entire watershed or catchment area that feeds the river. The goal is to reduce flooding and erosion by promoting sustainable land use practices, such as agroforestry and soil conservation, and by restoring wetlands and other natural buffers that can filter water and store floodwaters (Lashford et al., 2022; Lavers et al., 2022). Catchment-scale projects are often the most effective in reducing the impact of floods and erosion, as they address the root causes of these problems at their source (Umar et al., 2018). However, catchment-scale projects can also be the most challenging and complex. They require the cooperation of multiple stakeholders and agencies and may involve changes in land use and other long-term practices (Black et al., 2021; Wingfield et al., 2021).

This chapter aims to synthesise available information on sustainable and green approaches to river rehabilitation at local, corridor and catchment scales, particularly applications dealing with flooding and erosion (see Figure 2.1). The review was framed to address a set of nested questions: (i) What types of green approaches have been used? (ii) Where have they been used (geographically and by river type)? and (iii) What lessons can be learned from published work, in terms of successes and challenges to implementing green approaches to dealing with flooding and erosion?

2.2. Terms and definitions

This chapter uses ‘green measures’ or ‘local green bank protection measures’ to define local interventions designed to protect banks from erosion. Some literature refers this to as bioengineering, biotechnical, nature-based solutions or natural methods. Note that green measures are sometimes applied as part of a suite of measures that may include conventional engineering materials (e.g. geotextiles, rocks or concrete blocks). The chapter uses the term ‘corridor scale’ to define sustainable approaches to floodplain and riparian zone management. Catchment scale approaches, as defined for the purpose of this chapter, are actions focussed on protecting the integrity of hydrological processes through land use management.

Rehabilitation is distinguished from restoration. The former applies to any type of work designed to improve river physical or ecological condition, while the latter is used to define interventions where the goal is to restore the river to its original state. Restoration is now recognised as impractical in most cases and in fact many ‘restoration’ projects are better defined as rehabilitation.

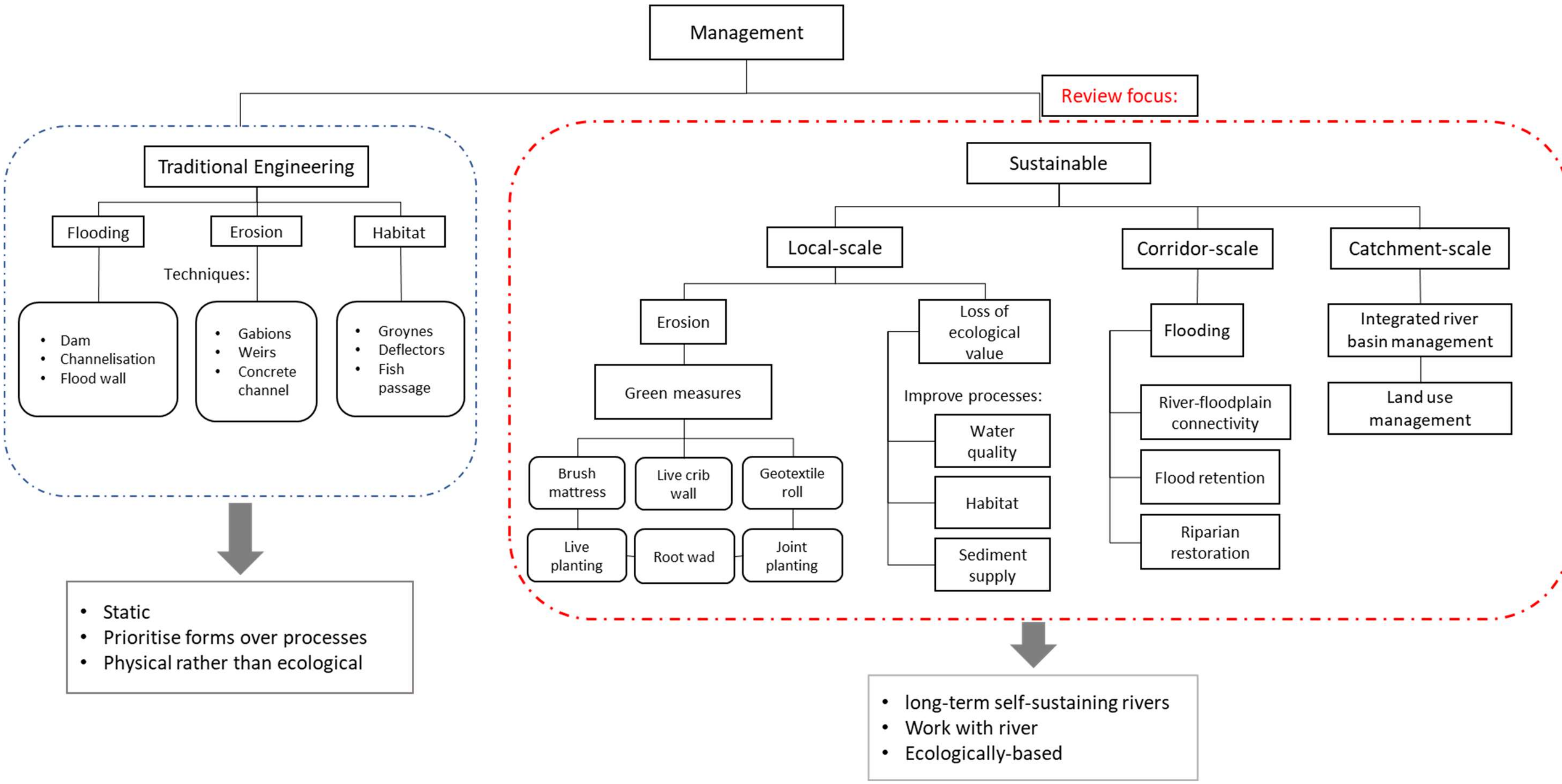

Figure 2.1: Schematic view of river management and role of sustainable approaches in river rehabilitation.

2.3 Methods and literature used

A literature search was conducted to understand the nature and extent of published work detailing local-scale measures. The search was performed in Scopus and Web of Science using a combination of keywords: (River OR Stream OR Wetland OR Floodplain) AND (Restoration OR Rehabilitation) AND ("Green approaches" OR "Green engineering" OR "eco-engineering" OR Bioengineering OR Biotechnical OR "Soft engineering" OR "Natural methods"). The search was executed on 1 April 2020. The subject area was narrowed down by excluding returns that were irrelevant to river science. For instance, genetics, molecular biology, medicine, business management, and accounting were excluded.

With these criteria, patterns in Scopus and Web of Science publication indicated that local green river measures have emerged as a recognised area of research interest only in the last 30 years (Figure 2.2). The earliest publication returned in the search was published in 1988. In the 1990s, more papers dealt with green measures of bank protection; these increases reflected recognition of the failure of traditional engineering measures and new efforts to find alternatives. This 'newness' possibly explains how many or most papers in the 1990s were conference papers (sometimes gaining access to the content was difficult). Of the 15 papers published in the 1990s, 14 described using soil bioengineering as riverbank protection (Verdi, 1998), bank stabilisation elements (Moses & Gorman, 1998; Nichols & Leiser, 1998; Schagrin et al., 1998; Wood, 1998) or efforts to improve the water quality and ecological status of the river (Sotir, 2001). Between 2000 and 2020, 4 to 12 papers per year were published. This figure is low, possibly reflecting the fact that such work is seen as very practical and hence not necessarily suitable for scientific publication. While the number of papers using local green measured have increased, they remain low compared to other types of river rehabilitation, e.g. a search for river restoration dam removal and river-floodplain connectivity returned more than 20,000 papers up to 2020.

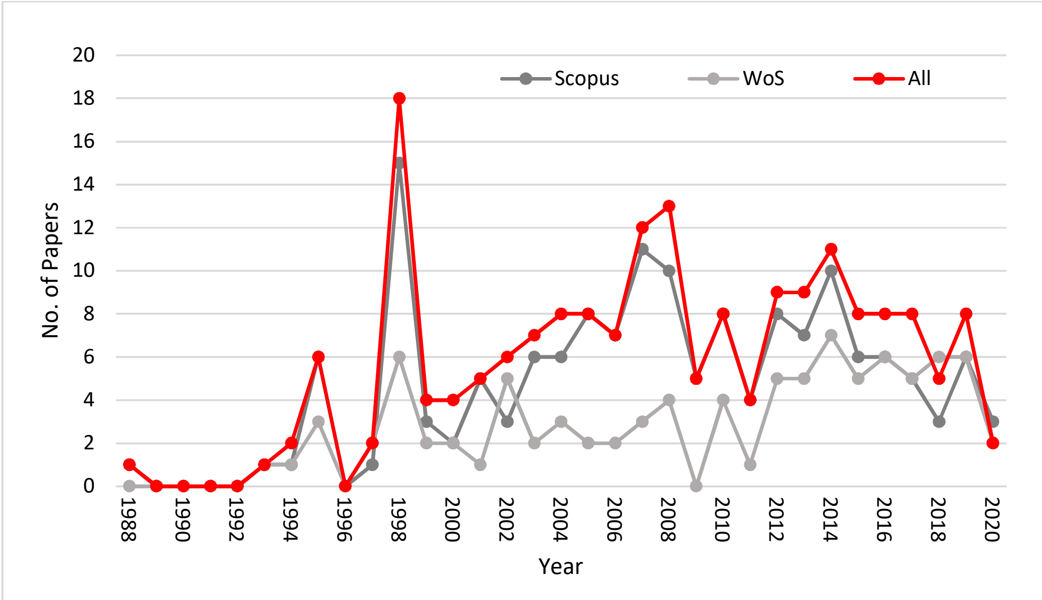

Figure 2.2: Documents focussed on local green riverbank protection by year from Scopus and Web of Science.

However, the results above include measures applied for roadside land erosion, hillslope erosion, and shoreline erosion (i.e. coastal protection). To exclude these, these papers were reviewed manually, non-accessible papers and those that were not related to green bank protection measures (i.e. green measures) were removed. All types of papers were reviewed (e.g. article, conference, review paper etc.) as the published literature related to the topics are limited. Additional material published in Asia and Southeast Asia was searched for in a less structured way (not using Scopus or WoS); this yielded a number of additional unpublished reports (e.g. Asian River Restoration Network, Japan River Restoration Network etc.). After the general review and filtering, 73 papers and reports were retained for review (see Table 2.4 & Table 2.5 in Section 2.4.4; Table A.1: Scopus Papers; Table A.2: Web of Science Papers; and Table A.3: Additional unpublished reports and papers in Appendix A). These tables summarise the geographical settings, goals, and the types of green measures applied in respective studies. The originated locations of these papers were plotted in Figure 2.3 to illustrate the geographic distributions of applied local scale green measures.

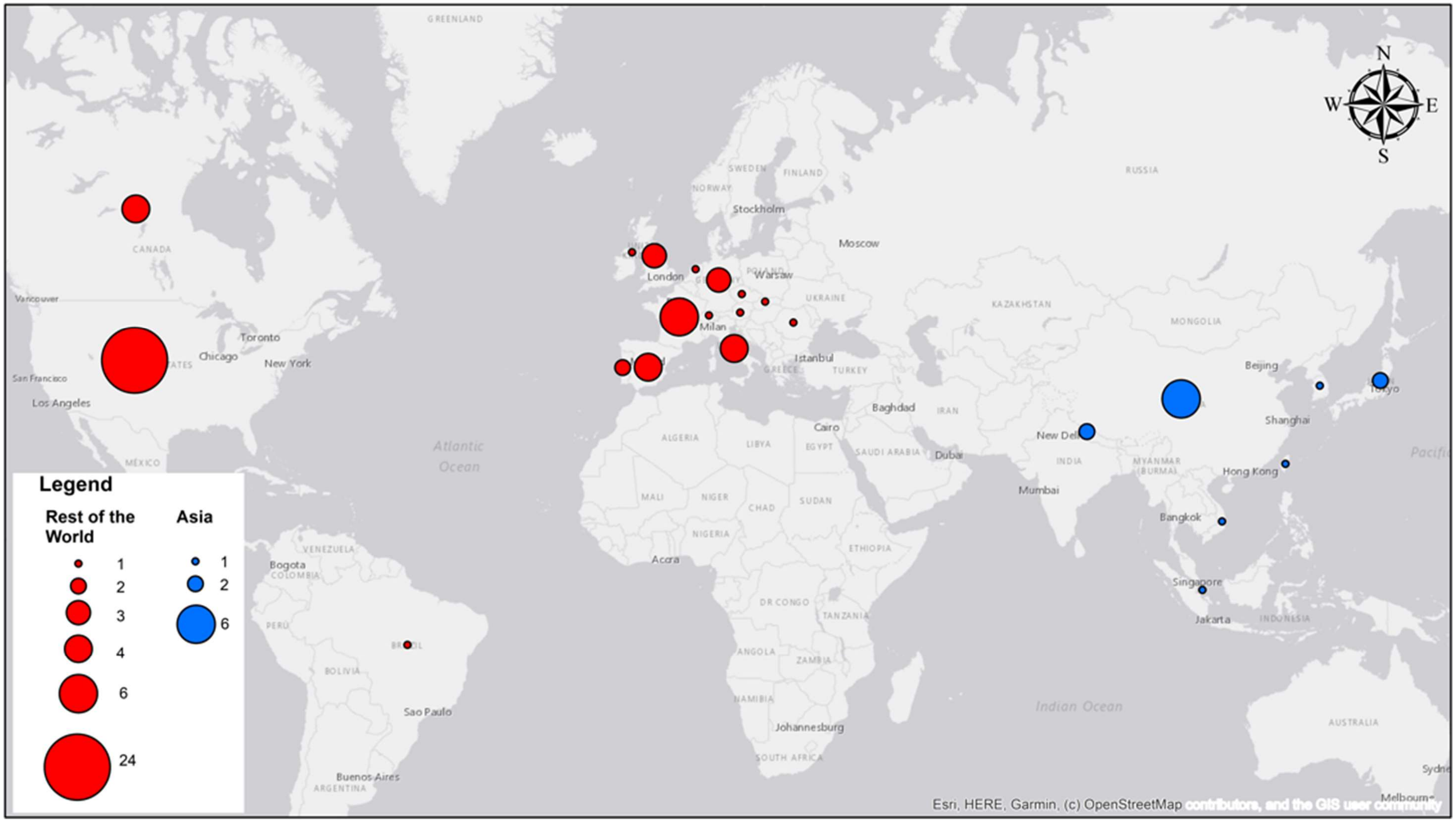

Figure 2.3: Geographic locations of river rehabilitation implemented with green measures. Size of the circles indicate number of papers published.

2.4 Review Findings

2.4.1 Local scale measures

2.4.1.1 Geographic distribution

The percentage of documented cases from specific countries is depicted in Figure 2.4. Green measure applications come predominantly from North America (51%), Europe (21%), and the United Kingdom (5%). There is one percent each from Central and South America, and none from Africa. Asian work comes predominantly from China, South Korea, and Japan (19%), with very few in tropical Southeast Asia (2%).

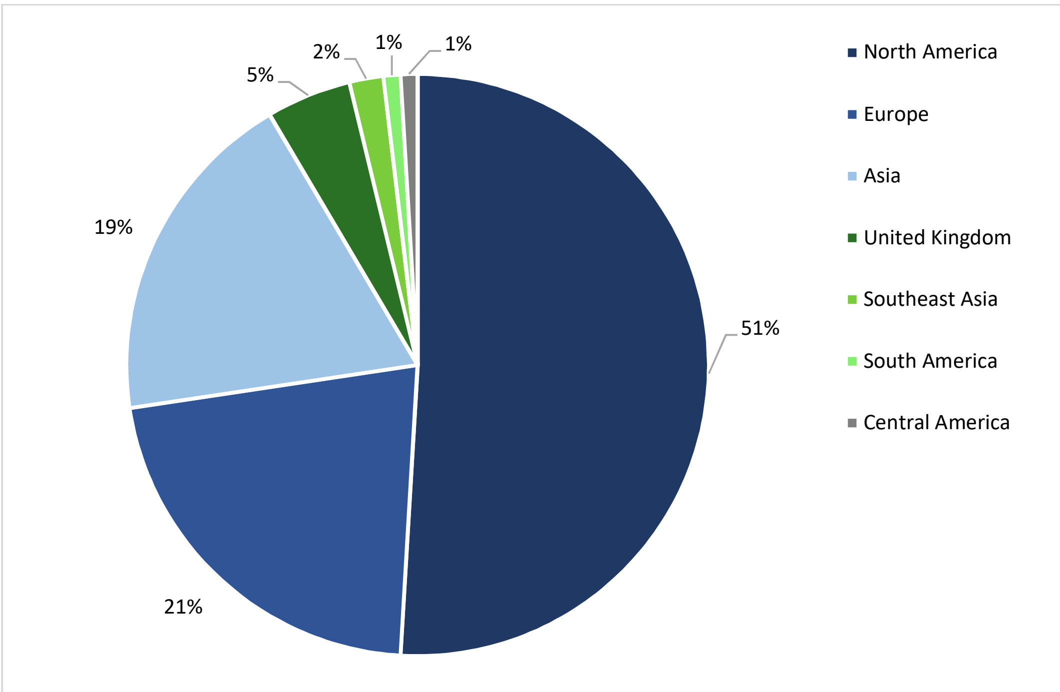

Figure 2.4: Percentage of green measures documented according to the continent (by cases from 73 papers).

Figure 2.5 shows the distribution of green measures within different environmental settings. Applications mostly come from non-urban lowland and lowland urban/sub-urban areas. Very few come from coastal or delta areas. For each environmental setting, fewer studies have been conducted in Asian than the rest of the world. The figure shows that very few applications of local green measures have been conducted in upland or mountain rivers in Asia.

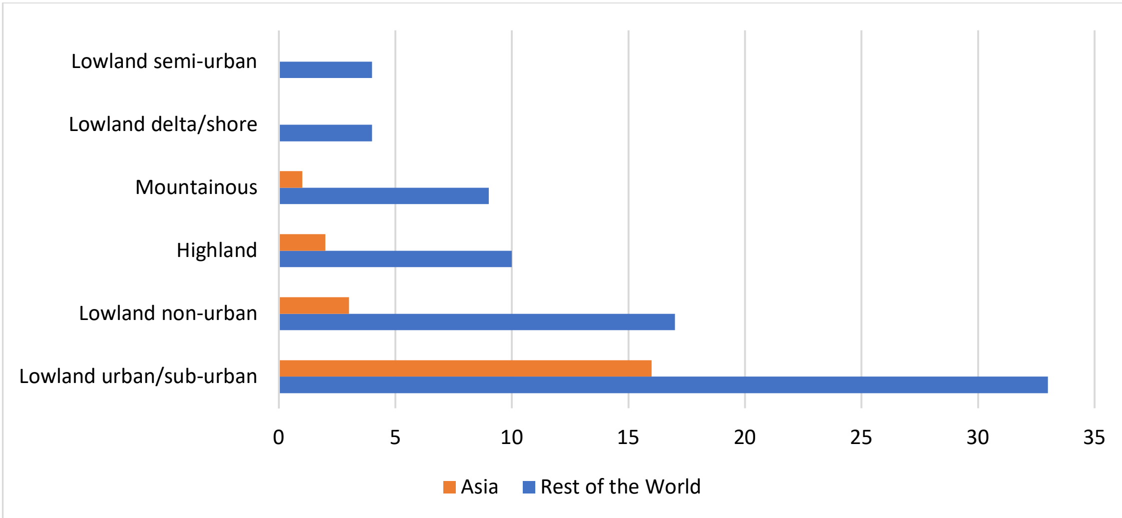

Figure 2.5: Green measures cases (Rest of the World and Asia) categorised according to environmental setting (total of 99 cases).

In Asia, most applications come from lowland urban/sub-urban locations in countries such as China, South Korea and Japan. This is likely due to the fact that China, South Korea and Japan have overgone major urban development in the last 30 years, many urban rivers including floodplains and wetlands were subjected to large-scale engineering modifications. Here,reen measures have more recently begun to replace these engineering approaches, as part of efforts to rehabilitate rivers. This resulted in higher number of cases in urban areas – in Singapore, for example, where green measures, green schemes, and water management strategies were implemented in urban rivers to preserve river conditions as part of wide adoption of nature-based solutions and principles of urban greening.

Green measures in non-urban areas can be seen in countries such as Nepal (Dhital et al., 2013) and Vietnam (mostly published in grey-literature), where forest has been cleared for agricultural expansion. Green measures in these areas have typically been implemented deal with localised erosion.

2.4.1.2 Effects of local scale green measures on form and process

This section presents the rehabilitation goals of using green measures in river rehabilitation. It deals with effects on both forms and processes. Form is the physical attribute (e.g. channel geometry) and is shaped by the dynamics of water runoff and associated patterns of erosion, sediment transport and deposition. Thus, any human interventions involving flow alteration and flood peak reduction potentially alter forms, as shown in Figure 2.6. Processes referred to here are sediment transport, physicochemical processes (e.g. chemical reactions taking place) and the biological processes (e.g. species dispersal), all of which are important for river biota and ecosystems. The frequency of detailing papers focussed on forms vs processes is shown in Figure 2.6.

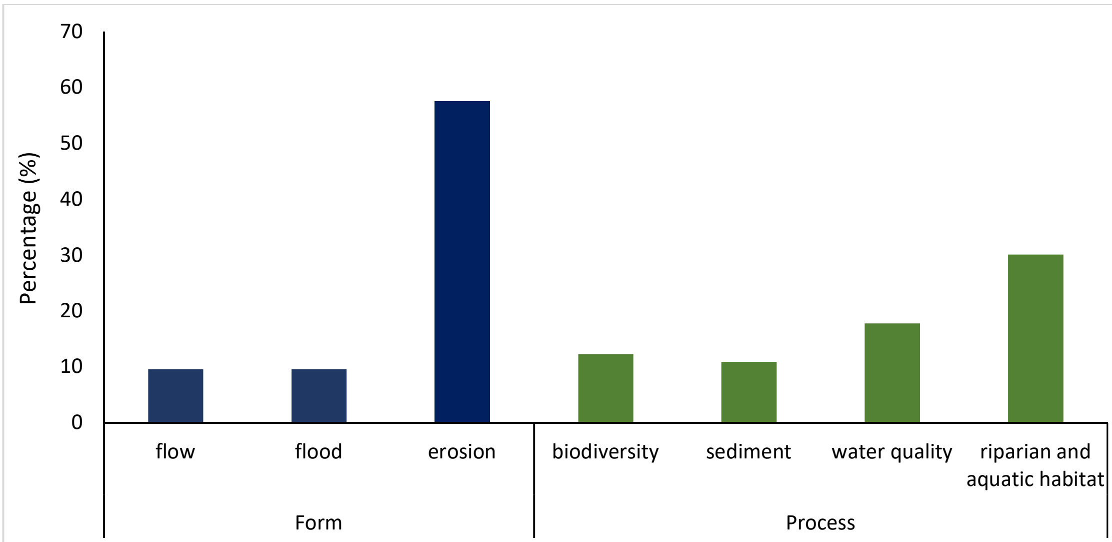

Figure 2.6: Percentages of papers returned in the literature search that dealt with using local green measures to improve form and process (percentage out of 73 returned papers)

Figure 2.6 shows that more than half (57.5%) of the papers describing the use of local green measures related to solving erosion issues, while only 9.6% of the studies used green measures to alter flow conditions; 9.6% focussed on form-based approaches to deal with flooding issues. It is widely recognised that erosion is a widespread problem especially in agricultural and urban areas where riparian vegetations have been cleared, and hence much of the published green measures work focussed on their use to tackle erosion issues.

There has been extensive literature on the effects of vegetation and enhancement in soil mechanisms. Studies have shown vegetated slopes have lower pore water pressure (Collison & Anderson, 1996) and higher shear strength than unplanted soil (Li & Eddleman, 2002). The plant species used can also influence mechanical and hydrological effects, with species capable of penetrating the entire subsoil layer tending to be preferred (Wu et al., 2015). Root diameter is important for root resistance, and species such as beech and maple have been shown to provide strong reinforcement (Vergani et al., 2012). Similarly, crib walls with dense cutting growth perform well on vegetated banks, and the soil cohesion significantly increases (Krymer & Robert, 2014).

Besides soil stability, river hydrogeomorphological traits such as stream discharge, bed material aggradation, sediment load, and channel slope contribute to riverbank erosion. Willow brush mattresses that can both support structural diversity and increase bank stability, making green measures that include such mattresses resistant even to high hydrological pressure (Schmitt et al., 2018). Ourloglou et al. (2020) performed hydraulics modelling to simulate the hydraulic condition of multiple scenarios (with and without green measures) and found that flow velocity and Froude number were lower for green measures than when channelisation was used to address high flow issue (Ourloglou et al., 2020). Of course, none of these alternatives address the issue of flow magnitude itself; this requires management at a different scale, as dealt with in detail later (section 2.4.2 & 2.4.3).

As shown in Figure 2.6, local green measures are often applied to improve river processes, with these used to improve riparian and aquatic habitat (31.1%), water quality (17.8%), sediment transport (11%) and biodiversity (12.3%). A recent example of process-based river management and rehabilitation is given by Blackburn et al. (2023). This work was designed to improve habitats for an endangered species but did this not by creating habitat directly, but instead focussing on reinstatement of the natural processes that create this habitat. To this end, they reconnected a formerly disconnected tributaries; this reconnection allowed the tributary to supply sediment and water to its main stem river which has previously experienced sediment starvation (Blackburn et al., 2023). Blackburn et al. (2023) described how this reconnection has led to renewed sediment delivery and resulted in the formation of new morphological features in the main stem that provide suitable condition for the target organism.

Green measures have been shown to improve biological quality and macroinvertebrate communities by improving water quality. For example, installation of coir fibre logs, erosion control fabrics and live willow to reduce erosion and sediment loads improved biological index values (Giupponi et al., 2017). Another study showed that the sites with green measures had higher biomass and new organic habitats (e.g. woods and roots), while a high abundance of pollution-tolerant taxa, and low richness and diversity were observed at unrestored sites

(Sudduth & Meyer, 2006). However, some have suggested that the effects of green measures on macroinvertebrate communities and biological quality are minimal (Schmitt et al., 2018). Green measures alone can only increase macroinvertebrate indices at local scale, while the impact on overall chemical constituents and bacteriological elements is insignificant (Schmitt et al., 2018; Selvakumar et al., 2010; Shih et al., 2010). Extensive and marked river degradation in urban areas may mean that the contribution of green measures to improving water quality is almost negligible. Hence, rehabilitation should extend to reducing stormwater runoff volumes and associated pollutants (Barrett, 1999; Curado et al., 2014; Fang et al., 2016).

For biodiversity, several studies examined the coleopteran and plant diversity (Cater et al., 2007; Cavaillé et al., 2013; Hook et al., 2009). All showed that the diversities of the riparian zone installed with green measures and hard engineering (as toe protection) were higher than when either green measure or hard engineering were applied alone. A large proportion of willows from the live fascine grew rapidly, forming dense vegetation at the riparian zone., while the riprap at the bank toe was important in preventing scour at the bottom (Chen et al., 2010).

2.4.1.3 Types of green measures applied

Lots of different types of green measures have been used to help with bank protection, improve riparian conditions or instream integrity. Figure 2.7 shows the types of green measures detailed in published work included in the review. Live stakes, live cuttings and live fascine were the most common techniques applied (32%) for bank protection. Other measures that were also preferable were live planting/ joint planting, seedlings and revegetation (33%), as these materials can be acquired locally and handled easily. The other less common (4 % to 8 %) green measures applied were coir roll (synthetic or organic), brush layer, live crib wall, brush mattress, and tree revetment. The use of logs, live palisade and soil lift was the rarest among all other measures.

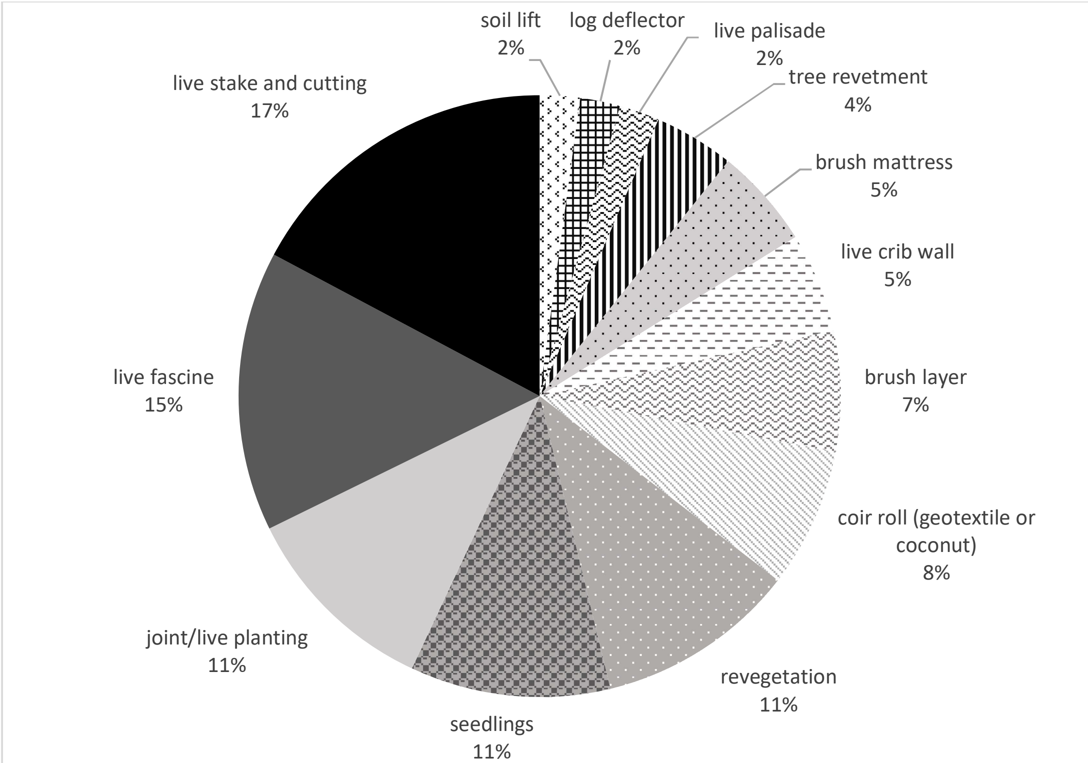

Figure 2.7: Percentage of local green bank protection measure types applied in river rehabilitation (based on cases)

Live stakes and live cuttings have been commonly applied on a graded bank, to encourage vegetation growth. Due to the availability of willows (Salix) in Europe (Pinto et al., 2016) and America (Shields Jr. et al., 2008), the use this plant is used in many riverbank stabilisation projects. The characteristics of willow plants, such as flexible branches, firm main stems, sparse branches, and deep fibrous roots, are very effective in withstanding high flow, reducing flow velocity and increasing soil stability. Additionally, the sparse branches of willow cuttings were used to trap sediment and reduce sediment yield at eroded gullies (Rey & Burylo, 2014).

Live fascines have been commonly installed on steeper bank slopes, where the brushwood or other plants were tied in a bundle and formed a fence structure to protect the bank. Live fascines have sometimes been installed vertically as in-stream bank protection measures to create roughness and provide immediate surface and subsurface drainage (Voicu et al., 2020). They can also be installed on sloping banks, forming rows of horizontal steps along the bank slope. However, fascines are most commonly applied along with other green measures such as erosion control blankets and seedlings (Buchanan et al., 2012; Jones, 2008).

The other green measures were generally those that involved basic planting techniques (i.e. ***joint planting***), using native or locally available plants, such as tree shrubs and willow whips, to revegetate eroded banks (Carone et al., 2006; Horton et al., 2015). The seedlings have been used along with soft materials (e.g. geo-grid and erosion control matting) that provide a suitable medium and protection for germination. For the precautionary steps, the transferring of seeds needs to be adequate, especially for the fresh seed-containing hay, raked material, vacuum harvesting and seed-containing soil (Kiehl et al., 2010). In addition, good quality of seed and soil are required to ensure the success of live planting/ joint planting, seedlings and revegetation (Newton & Lyn, 2015). Once the plants have reached their full size, bank stability is maximised.

The green measures that are less common are ***coir rolls, brush layers, live crib walls, brush mattresses, tree revetment, live palisades and log deflectors***. These measures tend to be used where immediate effects are required. Some of these measures, such as live crib walls and log deflectors need to have technical specifications that relate or address the river characteristics (e.g. stream power distribution, sediment and channel planform) to ensure long-term stability. Crib walls with dense vegetative growth greatly enhance soil cohesion and infiltration in the upper part of the riverbank. Studies indicate that crib walls are more effective in locations with low channel gradients, well-developed floodplains, moderate channel sinuosity, and low bank height ratios than those of confined and channelised rivers (Krymer & Robert, 2014).

Brush layers, brush mattresses and live palisades are commonly used on regraded bank slope to reduce near-bank flow velocity and trap sediment. Brush layers adopt soil layers or soil lift techniques to provide optimum bank slope stability. This involves wrapping soil within a coir mat and placing them in rows of steps forming a gradual slope at the riverbank (Cavaillé et al., 2013; Rey & Burylo, 2014). Native plants or cuttings are normally inserted into the soil, and the full-grown state of this has high resistance to velocity and shear stress (Lyn & Newton, 2015). Brush mattresses are most effective when used with rock toe protection, as such protection is needed to reduce undercutting and scour from the bank toe (Frothingham, 2008). The initial resistance to velocity and shear stress of brush mattress is significantly lower than the full-grown state (i.e. vegetated) (Lyn & Newton, 2015).

More broadly, the use of a wood element is increasing in river rehabilitation projects, generally, to improve the hydromorphological and ecological status of rivers. The application of large wood (i.e. ***root revetment and log deflector***) was predominantly applied in central Europe, and most projects successfully showed positive effects on fish species and hydromorphological status (Dixon et al., 2016; Kail et al., 2007).

Other green measures were found but are implemented as in-stream features. For example, wood structures are also used as check dams and wooden sills (Rey & Burylo, 2014) to mimic natural riffles, create pools, and reduce flow. Some incorporated check dam with hydroseedlings (Galicia et al., 2019), bamboo structures (Tardio et al., 2017), and living vegetation (Rey & Burylo, 2014) to mimic the natural in-stream features. Another innovative and natural way applied in the USA and UK has been by reintroducing beaver into the rivers to allow them to build pools and riffles and has shown effectiveness in enhancing plant growth and reduced sediment transport (Barrett, 1999). However, there are risks in using large wood in river rehabilitation where wood elements can catch flow easily, and any failures (e.g. entrainment of wood debris) or collapse of wood structures will cause a blockage within the river channel. Hence, the wood placement has to consider channel size, wood mobility and decay rate to avoid failures.

Green measures are often coupled with hard elements or hard engineering solutions to improve their strength and durability withstanding high flow. The most common bank toe protection is rock toe and riprap (Figure 2.8), which uses large rocks and cobbles to form an armoured layer at the bank toe. This requires careful weighing and sorting the boulders, which are then tied together in rolls to maximise the bulk mass (Shields Jr. et al., 1995). Several projects have shown that applying rock toe and riprap at the toe zone of green measures is most effective in establishing a stable bank, especially in dealing with turbulent eddies, high velocity base flow and flow contraction (Buchanan et al., 2012; Krymer & Robert, 2014; Raymond & Smestad, 2008). Vegetation with bank toe protection structures has a good plant survival rate, and the bank may remain stable after planting for years (Shields Jr. et al., 1995).

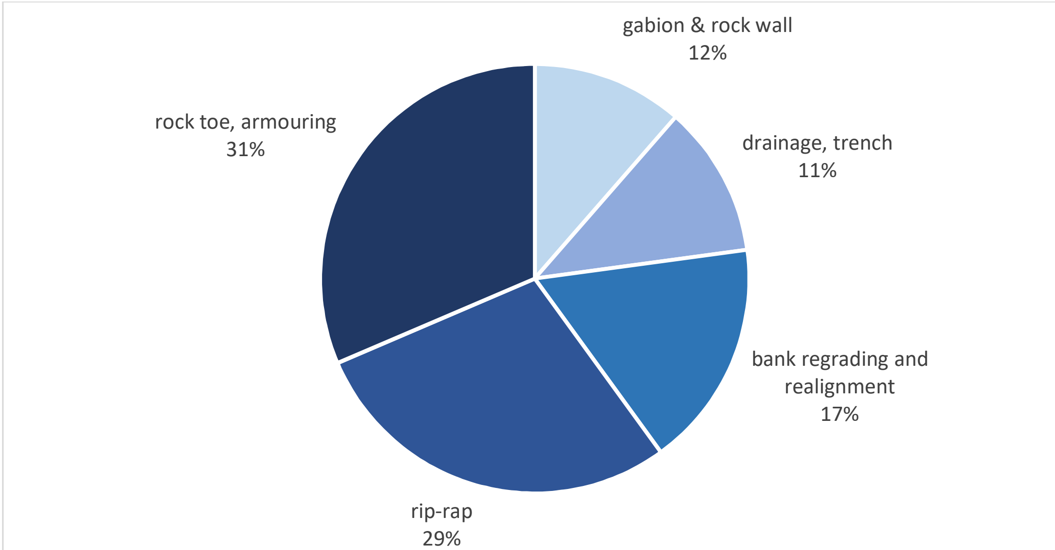

Figure 2.8: Percentage of hard engineering measures applied along with local green bank protection measures (based on cases).

Besides reinforcement at the toe zone, several projects realigned channel geometry and regraded unstable banks before applying green measures (Nichols & Leiser, 1998; Raymond & Smestad, 2008; Voicu et al., 2020). These modifications were to create a stable reach, lengthen the flow path (Hazell et al., 2007), reconnect the floodplain and restore flood terraces (Rogers & Doeing, 2009). The suggested minimum bank slope needs to be 1:1 (horizontal: vertical), but most authors strongly recommended bank with a more gradual slope (Allen & Leech, 1997; Elliott et al., 2016; Raymond & Smestad, 2008). Some projects demonstrated natural techniques such as using bamboo as a retaining wall (Tardio et al., 2017) and building live palisade or brush layers to form slopes with steps (Petrone & Preti, 2010). However, these interventions need a good understanding of flow hydraulics to inform the design capacity of green measures. Most of the work that combines green measures with bank realignment was successful in stabilising banks (Anstead et al., 2012; Giupponi et al., 2017; Hazell et al., 2007) and improvement in aquatic and riparian habitats tended to occur where these were goals (Elliott et al., 2016).

2.4.1.4 Critique of the local measures applied in the Trusan

The local green measures used in the Trusan were brush mattresses, brush walls, live bamboo fencing and geotextile matting. Brush walls and brush mattresses in temperate regions were demonstrated by Jones et al. (2008) and Rey et al. (2017), effectively reduced flow speed and trapped sediment due to their rough brush surface. Nevertheless, toe scouring emerged as a common issue, damages were observed after flood with a 25-year return period, as indicated by Jones (2008).

Live bamboo fencing was demonstrated by Tardio et al. (2017), to reduce bank erosion. Bamboo has proven to be a viable material for constructing a retaining wall to retain soil. It can effectively withstand flow, thereby preventing soil erosion. Live walls made of other material fascines, featuring partially buried bundles with the ability to root and grow, were shown by Lyn et al. (2015), provide durable, long-term protection against surface erosion.

Geotextile matting or coir rolls are often applied in conjunction with live planting and stakes to serve as immediate soil control measures during early stages. While scant literature details their use, studies by Lyn et al. (2015) and Selvakumar et al. (2010) indicate that coir rolls may face scouring issues when installed at the toe zone.

Table 2.1 summarises some of the studies that are most relevant to the current work. These studies highlighted the key issues of green measures at their study sites and have given analysis on their performance.

Table 2.1: Approach and findings summarised from key selected studies

Green measure	**Source**	**Approach and findings**
Live cuttings, live plantings	Wang et al. (2016)	Provided estimation of bank stability and flood reduction after revegetating the bank with live plantings (e.g. trees) through factor of safety calculation and modelling. Studies indicated that root development could significantly increase the bank stability. Model results suggested revegetation could reduce flood peaks and minimise sediment movement and channel dynamics.
Synthetic Geotextile Matting	Selvakumar et al. (2010)	Study focused on the improvement of stream macroinvertebrate and water quality, but provided very little context on the success of riverbank stabilisation. Sampling results indicated that green measures successfully improve the biological quality for macroinvertebrate indices. Combination of live stakes with erosion

		control mat and rock toe helped to stabilise the bank and successfully prevented bank sloughing and incision.
Brush layer, Brush mattress	Jones, C (2008)	Documented the installation details and provided post-flood condition based on field evidences. Monitoring after flood event (25-year flood) showed that small amount of brush was displaced and settling was identified at the toe of rip-rap.
	Rey et al. (2014)	Provided long-term assessment to quantify the number of sediments that brush layers can trapped and their survivability. Study suggested that Brush layer and brush mat could trapped 0.18 m^3/yr and 0.21 m^3/yr respectively, with survival rates up to 75%.
	Schmitt et al. (2018)	Study assessed the potentials of green measures to improve ecological diversity. Very little context was given on the state of the riverbank after installation. Field investigation shown that brush mattresses appear to enhance bank stability and provided protection against flood.
Live fascine	Voicu et al. (2020)	No post-installation monitoring. Provided basic design principle and proposal to incorporate live fascine in river rehabilitation project to promote aquatic habitats and wildlife corridors.
	Janssen et al. (2019)	Focus on enhanced riparian habitat quality and multi-taxonomic diversity with the use of green bank protection measures. Study highlighted that willow fascine could not mitigate larger scale environmental degradations. Study did not provide condition of green measures.
	Tardio et al. (2017)	Analysed the design capacity of bamboo structures from an engineering perspective by addressing slope instability and its loading towards the structures. It was suggested that bamboo can be used as natural materials for check dam and retaining wall.
Live cribwall	Krymer et al. (2013)	Given good post-monitoring results and provided hydrological condition and stream power at the Southern Ontario watershed. Results found that cribwalls with dense cutting growth perform well on streambanks that offer a greater amount of soil cohesion, nutrients, and infiltration in the mid and upper sections of the bank. In streams with moderate channel slopes and stream power distribution that is above the watershed mean, streams with well-developed floodplains, sinuous channel planforms, and low bank height ratios perform better than those that are confined, straightened, and have greater bank height ratios.

2.4.1.5 Local measures – lessons and conclusions drawn from published work

The literature provides much general support for the use of green bank protection measures, and argues that, if successful, these could greatly increase soil stability and provide ecological benefits. Literature is, however, primarily concentrated around the pre-implementation phase. Studies have predominantly focused on providing proposals, frameworks, technical guidance, cost estimates, and some performance evaluations in controlled or simulated environments (e.g. via modelling). Literature that looked at the post-implementation phase in real rivers (i.e. rather than computer of lab simulations) were rather qualitative and the study periods were short.

In general, it is clear that the performance of green measures varies in different hydrological and geographical settings. Localised bed scouring and bank toe erosion are the common issues of green bank protection measures, especially during the early implementation stage. The existing soil stability, bank condition, methods of installation, and choice of green materials could play a major role in determining the efficiency of green measures in bank stabilisation. While many studies stress the need to replace hard engineering structure with green measures or soft-engineering, only very few studies have given good long-term monitoring evidence of its success and failures. Even fewer provide good empirical data on their effectiveness in reducing bank erosion and most lack the hydrological information to link hydrological conditions and the performance of the measures, in terms of their its capacity to withstand these conditions and the flow forces associated with them. Thus, despite large amount of documented literature, it remains hard to know why measures succeed or fail, what the most appropriate methods, approaches and measures are for different local circumstances.

2.4.1.6 Key Research Gaps

A significant body of research and the contributions of existing literature are undoubtedly invaluable in laying the groundwork for green bank protection projects. However, a noticeable research gap emerges in the form of limited attention to post-implementation changes and long-term sustainability especially in certain regions and river types. Several critical aspects of this gap are elaborated as below:

i) **Limited amount of study in Southeast Asia** – It is known that green bank protection measures have low permissible velocity and shear stress in withstanding flow forces compared to conventional hard engineering structure. The Southeast Asia region experiences extremely regular high intensity rainfall (Chuan, 2005) and consequently hydrological extremes. Hence, the performance of the green bank protection measures (in term of durability and workability) in this region might differ from what was found in vast majority of literature that were conducted in America and Europe countries. Studies are therefore needed in the region to evaluate their utility.

ii) **Lack of continuity analysis in its durability and its long-term efficiency in reducing bank retreat** – Several guidance documents on the use of green bank protection measures are available. This guidance is usually based on project experience through field trials but lacks post-implementation monitoring. The documented reports and grey-literature are practical rather than quantitative/scientific in nature. Hence, field data are needed to help better understand factors contributing to their success or failures in stabilising eroding banks or reducing bank retreat This point was made Selvakumar et al. (2010) more than a decade ago, but data remain scarce.

iii) **Lack of hydrological or geomorphological context** – Most studies detail their geographic location but rarely provide detailed information on the hydrology or hydraulics (flood magnitude and frequency and associate flow forces). This is an important gap as these factors are key in determining its success and failures. River settings such as bed material and soil type, as well as the rates of bank retreat hardly be found in the literature. Thus, there is a need for studies of green measures which provide this type of information to help a full understanding of the river setting and the role this plays in success or failure.

2.4.2 Corridor Scale: Riparian management and managed flooding

2.4.2.1 The riparian zone

A riparian zone, sometimes called a riparian buffer, is a vegetated region (e.g. trees and bushes) next to a river that filters and controls water and sediment flow. It is generally known that buffer strips could diffuse pollution mitigation, natural flood management etc., and vegetations on this strip could help to stabilise the riverbanks. Riparian management and regulated floods require these buffers to minimise flooding, protect water quality, and sustain aquatic ecosystems.

However, agricultural practices at riparian zone often led to land clearing, and in turn, resulting in water quality degradation through bank erosion, sediment runoff and contamination by urine, faeces from livestock. Riparian clearing has a significant impact on other processes taking place in rivers and streams (Allan, 2004). Rivers are typically warmer during the summer and get fewer energy inputs as leaf litter where agriculture or other anthropogenic activity extends to the river border and natural riparian forest is cleared (Quinn, 2000). Moreover, riparian vegetation serves as a significant source of food for the entire food chain in streams, from dissolved and particulate organic matter to terrestrial invertebrates (Ramey & Richardson, 2017), giving diverse habitats for terrestrial (beetles, amphibians, birds, etc). The entire trophic structure of river corridors may change if this habitat and nutrient sources are altered. In addition to providing a natural barrier against erosion, restoring woody vegetation along eroded riverbanks can help to restore these processes (Allan, 2004). The absence of such benefits should be emphasised when using conventional engineering methods in river management.

As a result of wide range of ecosystems that riparian zone can provide, management is now essential to maintain the beneficial effects on hydrogeomorphic processes. In heavily grazed fields, riparian buffer strips are created by fencing off property next to rivers to keep cattle out and keep their waste from polluting the waterway (Aguiar Jr. et al., 2015). These fences can also help to reduce bank erosion and poaching by preventing livestock from gathering at riverside (Anstead et al., 2012; O’Callaghan et al., 2019). Moreover, buffers are often used in conjunction with managed flooding practices by providing buffer between the streams and surrounding development to attenuate flood and reducing downstream flooding (Cole et al., 2020). The vegetations and trees at the riparian buffer strips can help to slow down flood water and thus, protecting adjacent land from erosion and sedimentation. Zhang et al. (2017) suggested that good riparian management practices help to reduce sedimentation by up to 74.07 %, while also reducing severity of bank erosion (Zhang et al., 2017).

2.4.2.2 New paradigms

The "room for the river" or "space for the river" approach is a concept that emerged in river rehabilitation to manage flooding and erosion. This approach is based on the idea that rivers are dynamic systems that naturally change over time. Attempting to control or contain them can lead to negative consequences, such as increased flooding, erosion, and habitat degradation. The approach involves creating more space for the river to expand and flow during periods of high flows, such as by removing or relocating buildings and infrastructure from flood-prone areas and allowing floodplains to flood naturally (Koepke, 2020; Selvakumar et al., 2010). This can help reduce the risk of flooding and erosion in downstream areas by slowing the water flow and reducing the amount of sediment and debris carried downstream (Dixon et al., 2016). In addition to reducing the risk of flooding and erosion, it can provide various other benefits, such as creating new habitats for wildlife, improving water quality, and enhancing recreational opportunities (Selvakumar et al., 2010).

It is recognised that room for erosion is required for the river to maintain a dynamic equilibrium state. The term ‘erodible river corridor’ had been used to conceptualise this idea. Allowing low risk areas to erode naturally helps dissipate river energy and so reduce erosion risk downstream. A common practice is to provide green bank protection measures for the areas that need to be retained and allow areas without any properties to erode naturally (Buffin-Bélanger et al., 2015; Hazell et al., 2007). Erosion is important to preserve the river sinuosity and allow stream power dissipation at meanders. The erodible river corridor concept provides long-term stability for rivers and helps to balance sediment aggradation and erosion.

Several studies have discussed the adaptation of settlements to flood risk. To reduce economic losses and damages caused by floods, land use zoning can be integrated with flood risk management (Der Sarkissian et al., 2022; Junger et al., 2022; Tariq et al., 2021). Additionally, reforestation or revegetation of riparian zones can help to reduce the magnitude of flood peaks downstream. The presence of trees and vegetation, along with their size and density, can influence floodplain retention capacity (Habersack et al., 2015; Rak et al., 2016; Schober et al., 2020). Proper land use and riparian management could also relieve mass groundwater movement, thus, reducing alteration of surface water movement and flood frequency (Elliott et al., 2016). For rivers near agricultural land, mulching, strip-cropping, forest tree planting, and controlled livestock mobility significantly reduce stress on near-bank soil movement (Horton et al., 2015; Meals, 2001; Zuquette et al., 2007).

2.4.2.3 Corridor scale natural flood management, findings, and strategies

Floodplain management is an effective approach to reducing the risk of flooding. By preserving, restoring, or creating natural floodplains and implementing strategies like land-use regulations and floodplain mapping, lives and property can be protected, flood damage can be reduced, and resilience increased. Studies have shown that using floodplain areas for flood retention (i.e. reconnecting rivers to their floodplains) significantly reduces flood peaks and prolongs flood waves (Jonoski et al., 2019; Suman & Akther, 2014). In lowland areas, protected or managed floodplains increase the storage capacity (Apel et al., 2009; Czech et al., 2016). The protected floodplains delay the activation of storage volumes which optimise retention capacity, helping increase peak flow attenuation effects. Without proper management, floodplains could be activated during the early stages of a flood event; this minimises the capacity, and the storage volume has little influence on the flood peak (Castellarin et al., 2011). Better management can help with such issues.

A study by the National Institute of Building Sciences found that every dollar spent on floodplain management can save up to six dollars in future flood damage costs (Gall & Friedland, 2020; NIBS, 2019). In response to the Cedar River flooding in 2008, a flood mitigation plan that included the acquisition of flood-prone properties, the creation of new green spaces, and the restoration of natural floodplains was developed. Since then, Cedar Rapids has not experienced a major flood event, and the city has been able to reduce the risk of flooding for its residents (Tate et al., 2016).

Another example is the city of Boulder, Colorado, which has implemented a comprehensive floodplain management plan that includes land use regulations, mapping, and acquiring flood-prone properties (Hemmati et al., 2021). In 2013, Boulder experienced a major flood event that caused extensive damage to the city. However, because of the city's floodplain management strategies, the damage was less severe than it could have been, and the city recovered more quickly (ASDSO, 2014).

2.4.2.4 Challenges of natural flood management

Corridor scale approaches can be challenging, especially in urban areas. They often require coordination between multiple stakeholders and the willingness to make difficult land use and development decisions. In urban areas with existing property near the rivers, it would require appropriate catchment and stormwater management. Otherwise, manmade structures such as flood walls, levees and flood retention would have been used as the immediate flood defence structures (De Santoli et al., 2008).

One significant challenge is selecting the appropriate modelling approach that accurately represents the complex hydrological processes and accounts for uncertainties when trying to simulate flood magnitude or areas most at risk (Tayefi et al., 2007). There are several types of flood models, such as hydraulic, hydrological and combined models, each with its strengths and limitations (Wang et al., 2019). The quality and completeness of data, such as topography information, rainfall, and hydrological understanding, are crucial for creating reliable flood models and assessing the effectiveness of flood mitigation measures. However, obtaining high-quality data can be challenging due to various factors such as limited resources, accessibility issues, and technical difficulties (Arnold et al., 2012). Modelling floods in ungauged basins, where no or limited hydrological data is available, is even more challenging for researchers. Researchers must rely on indirect methods, such as regionalisation techniques or remote sensing, to estimate the necessary input data (Emam et al., 2017).

Additionally, data from different sources may have inconsistencies, making integrating them into a coherent model difficult. Another challenge is the uncertainty associated with future climate scenarios and the potential impact on flood risk, which requires a robust methodology to account for such uncertainties (Rafiei Emam et al., 2018). Overall, addressing the challenges related to data quality and uncertainty is critical to effectively implementing corridor scale approaches to reduce flooding.

Another challenge is calibrating the model to represent the observed flood events accurately. Calibration involves adjusting the model parameters to minimise the difference between observed and predicted flood data. However, the accuracy of the calibration depends on the quality and quantity of data available, and the level of uncertainty associated with the data (Shivhare et al., 2018). Researchers must also validate the model by testing its performance on different flood events than those used for calibration. Finally, communicating the model results to stakeholders, policymakers, and the public is also a significant challenge. Flood models can be complex and difficult to interpret and presenting the results in a clear and accessible manner is critical for decision-making (Lim et al., 2022). Researchers must use visualisations and other communication tools to help stakeholders understand the implications of the model results and the uncertainty associated with the predictions.

2.4.2.5 Prerequisites and tools for river corridor scale approach

Application of hydrogeomorphology concepts often involves combining Geographical Information System (GIS) or Remote Sensing analysis (e.g. aerial photographs and Digital Elevation Models) with field observations (Biron et al., 2014). GIS data allow for the determination of key river attributes, such as bankfull discharge and floodplain width, along with understanding the temporal evolution of the main channel (Biron et al., 2014) and modelling channel erosion sensitivity (Piégay et al., 2005). Combining data in this way helps address connectivity across the four river dimensions. Moreover, field data can now be used to model historical erosion (e.g. meandering patterns) and predict future erosion patterns to define the ‘erodible’ or ‘fluvial’ corridor boundary. This method determines where the river will meander and dissipate energy and where bank protection is needed. The information helps to inform decisions in the planning stage by balancing the need for fluvial corridor stabilisation with expansion zones. Past examples showed good outcomes in areas with different valley geometry and human activities (Biron et al., 2014; Larsen et al., 2007; Piégay et al., 1997).

Moreover, the hydrogeomorphic approach can help interpret floodplain landforms to determine contemporary flood hazards and determine floodplain extents (Baker, 1994). The approach uses specific decision rules to categorise floodplain landforms as erosional, depositional, stable, ice-affected or wetland riparian surfaces, which are then used to classify flooding (high to low flood severity (Biron et al., 2014)). The most severe flood zoning class reflects close connectivity between the channel and the floodplain and should be preserved in a freedom space management approach. The flooding spaces are often illustrated along with the recurrence of flood surfaces delineated from hydraulic modelling (HEC-RAS®; Patel et al., 2017; ShahiriParsa et al., 2016). Overall, the flood spaces from the hydrogeomorphic mapping cover larger surfaces than those from the typical hydraulic modelling.

Several studies have shown that using floodplain areas for flood retention (i.e. reconnecting rivers to their floodplains) significantly reduces flood peaks and prolongs flood waves (Jonoski et al., 2019; Suman & Akther, 2014). Many have used hydrodynamic modelling methods to simulate floodplain inundation and evaluate changes in flood risk in downstream areas. The hydrodynamic model simulates water's behaviour and how it interacts with the surrounding environment. The model uses mathematical equations to represent the physics of water flow and take into account factors such as topography, channel geometry, and flow rates (Clilverd et al., 2016). Popular models for river systems include HEC-RAS®, MIKE 11®, and LISFLOOD-FP® (Liu et al., 2020; Shustikova et al., 2020). These models simulate different scenarios, such as the impact of reconnecting rivers to their floodplains or the effectiveness of different flood management strategies. By comparing the results of these simulations, researchers can assess the benefits of flood retention and inform flood risk management.

2.4.2.6 Lessons from published work on corridor scale approaches

Several key findings are of application of corridor scale measures summarised in Table 2.2. In terms of implication to the Trusan, a number of conclusions can be drawn:

i. Evidence from published work suggests that improving river-floodplain connectivity and using the floodplain as flood storage area could potentially reduce flood peaks and attenuate flood waves in the Trusan.
ii. The flood peak reduction ratio largely depends on the floodplain areas and geometry. Hence, in the case of the Trusan it cannot automatically be assumed that floodplain storage will resolve flooding issues – specific assessments need to be undertaken to establish the storage potential of the river's floodplain.
iii. Inundation mapping is commonplace in flood studies, but normally is done within the context of assessing risk rather than as part of studies to evaluate storage potential.

This is certainly the case in Tropical SE Asia, where very few studies have combined mapping and modelling to assess storage and its benefits at large (river-valley) scales.

iv. There are very studies focused on rivers in rural mountainous regions like the Trusan, where the valley space is confined and development on floodplains led to significant changes in the valley geometry. The characteristic of steep slope geometry and its unique floodplain terrain, combined with its flashy hydrological regime could result in distinct flood patterns and constraints for floodplain storage.

v. Specific practices such as the use of lateral control gates and water access channels to route floodwaters could lead to different flood reductions, so such options need to be considered in the Trusan.

Table 2.2: Summary of findings from the literature review on corridor scale flood management.

Source	**Study Area**	**Objectives of Study**	**Findings**
Farrag et al. (2022)	Rhine River, Germany	Investigate the role of hydrodynamic interactions and floodplain storage on flood risk.	Floodplain storage is significant in lowering flood levels and discharges, and halves the flood risk.
Ongdas et al. (2020)	Yesil River, Kazakhstan	Investigate performance of HEC-RAS® 2D model to simulate flood scenarios and its capability to produce flood risk map.	Computational mesh sizes for the geometry data did not affect the model performance. With appropriate calibration it is found that model could predict the extent of flood inundation for 10- to 100-year flood events. Most settlements experienced flooding under 100-year flood condition.
Jonoski et la. (2019)	Huai River, China	Investigate the potential risk of flood storage area that pose on nearby agricultural and residential areas.	More detailed representation of terrain and land cover in the model shows different outputs compare to lumped model calculation. Study shows that optimal operational strategies that involve controlling gates opening that link river with storage areas could affect the flooding pattern and help to assess damages.
Schober et al. (2020)	Austrian River	Conduct integrative analysis of land use changes and consequences on flood risk.	Changes of floodplain land use, topography, riverbank profile could change the flooding characteristics significantly. Loss of floodplain areas bring detrimental effects towards flood peak

			reduction and flood wave translation which in turn affect flood risk downstream.
Clilverd et al. (2016)	Glaven River, United Kingdom	Identify the hydrological conditions and the effects of pre- and post-river restoration.	Removal of embankments resulted in widespread floodplain inundation and frequent localised flooding at river edge. Improved river-floodplain connectivity helps to reduce 24% of the peak discharge for large flood event.

2.4.2.7 Key Research Gaps

Based on the review presented above, it is evident that there are a number of knowledge gaps related to the corridor scale measures to reduce flooding. These are:

i. **Lack of high-resolution geometric data in assessing the existing flood risk and the potential benefits of floodplain retention** – Most studies used lower resolution geometric data obtained from satellites. Lack of detailed information limits the ability to understand flood dynamics, identify flood prone areas, and quantifying the effectiveness of flood mitigation measures. Higher resolution 3-D data such as available from drones could bring great improvements.

ii. **Lack of good empirical data on the effects of floodplain storage and retention on flood reduction and propagation** – The actual flood levels and the timing of flood wave propagation can hardly be found in the studies. Actual conditions can be reflected more accurately in hydrodynamic models if such data are included as part of flood modelling studies.

iii. **Lack of studies in high energy tropical rivers** – Highland tropical rivers are characterised by unique geographical and hydrological settings. While the concept of 'Freedom Space for Rivers' has been promoted, its feasibility in regions prone to extreme weather conditions remains largely unexplored, especially in conditions where space for freedom may be constrained by the fact that floodplain land is of great value to local communities. This lack of scientific investigation into the applicability of the concept in such high-energy tropical river environments hinders our understanding of its potential benefits and challenges in the Trusan.

2.4.3 Catchment scale: approaches to reduce flooding and riverbank erosion

2.4.3.1 The notion of catchment scale approaches and applications

Catchment scale approaches refer to a holistic way of managing flood risk by considering the entire catchment area, including tributaries, rather than just individual sections of the river (Ferguson & Fenner, 2020). The main idea behind catchment scale approaches is to work with nature, rather than against it, by implementing measures that aim to slow down and store water upstream, and reducing the amount of water that reaches downstream areas (Iacob et al., 2017; Rouillard & Spray, 2017). Some common integrated catchment scale approaches include sustainable drainage systems in urban areas and, in rural areas, good land use management. Land use management involves retaining natural vegetation cover, or implementing practices such as agroforestry and soil conservation to reduce erosion and increase the natural storage capacity of catchments.

The concept of catchment management has been around for many years, but it has only gained widespread recognition as an effective flood management approach in recent decades (Rouillard & Spray, 2017). In the past, flood management mainly focussed on building hard engineering structures such as dams and levees, channelising rivers, and constructing drainage systems to divert water away from urban areas (Miguez et al., 2015). However, this approach often exacerbated flooding downstream by increasing water flow and reducing the natural capacity of rivers to store water (Lulloff, 2013). The catchment scale approaches commonly address the root causes of increased flooding by looking at the land use and soil as means of reducing runoff.

Many countries have adopted catchment scale approaches to managing floods, with some of the most notable examples being in America, Australia, and European countries. In the UK, catchment management has been a key component of flood risk management since the late 1990s (Buuren et al., 2018). The Environment Agency, which is the government body responsible for managing flood risk in England, has implemented various measures, including natural flood management techniques such as tree planting and soil management (Orr et al., 2008). Future climate projections indicate increases in peak flow, and afforestation provides the greatest benefits mitigating such changes, especially when crops in lowland areas are replaced with forest (Iacob et al., 2017). In Australia, catchment management is seen as a key tool for managing water resources and reducing the impact of flooding. The Australian government has invested heavily in catchment management programs, which focus on improving land use practices, reducing erosion, and increasing the natural storage capacity of rivers (Dufty et al., 2020). In the US, catchment management is mainly focussed on reducing the impact of flooding on urban areas. This involves implementing measures like green infrastructure, which uses natural features such as wetlands and rain gardens to absorb and store water (Russo et al., 2008).

2.4.3.2 Prerequisites and tools for catchment scale approaches to flood management

Tools for the process have been developed and are now widely adopted. For example, Integrated River Basin Management (IRBM) is a commonly used framework designed to support and coordinate the conservation of water, land, and related resources (Evers, 2016). It aims to maximise water and catchment resources' economic and social benefits while preserving freshwater ecosystems. Thus, it is a critical tool to support many aspects of sustainability.

Effective catchment scale approaches require accurate data on catchment characteristics, such as topography, land use, and hydrology. This data can be used to develop effective flood management strategies. This understanding can regulate the spatial distribution of human activities (e.g. land use), commonly called spatial planning. Several tools and models, such as Soil and Water Assessment Tool (SWAT®), Precipitation Runoff Modelling System (PRMS®), and Hydrologic Modeling System (Hec-HMS®), are now available to help with such planning (Markstrom et al., 2015; Scharffenberg et al., 2010). Among these tools, SWAT® is the most widely used model to simulate surface runoff and groundwater movement and predict the environmental impact of land management (Wang et al., 2019), as well as to help with spatial planning within the context of climate change (Brouziyne et al., 2022; Yang et al., 2022). SWAT® has been widely used in temperate regions but less in the tropics (Strauch & Volk, 2013; Tan et al., 2019) However, it has great utility for helping understand hydrological functioning in tropical catchments experiencing deforestation and, in turn, informing decisions on spatial planning and catchment management.

Moreover, effective catchment-scale approaches also require engagement with multiple stakeholders and cross-sectoral collaboration. Effective engagement between stakeholders, including local authorities, landowners, and water companies, is necessary to ensure that measures are implemented promptly and coordinated.

2.4.3.3 Catchment scale approaches, findings and management strategies

Forest protection is one of the most critical land use management strategies to reduce runoff generation. Forest is important in catchment functioning, regulating floods and controlling soil erosion (Cooper et al., 2021). Studies have shown that the destruction of primary forests has significant negative impacts on biodiversity (Edwards et al., 2011), carbon emissions (Begum et al., 2020; Martin et al., 2015), and soil and water quality (Coe et al., 2011). Large-scale logging has been linked to catastrophic floods and river degradation (Sokolova et al., 2019). Southeast Asian countries such as Malaysia are a hotspot of tropical deforestation, especially for industrial logging, but efforts to reform the logging industry have been rather ineffective (Bryan et al., 2013; Hansen et al., 2013). Protecting natural forests from logging is the only viable approach to safeguard primary ecosystems. Most reduced-impact logging strategies prioritised sustaining income for the logging industry rather than protecting streams and rivers (Putz et al., 2008). Legislation exists to protect riparian areas, but limited compliance and enforcement mean that river habitats are still vulnerable. Preventing the destruction of primary forests is essential for successful catchment-scale management and is a preventative measure for maintaining river health and reducing flooding.

Soil and water conservation practices are also essential. Generally, global warming effects differ worldwide, and several models exist to predict likely effects in different ecoregions. Future forecasts agree on an increase in mean annual rainfall and the frequency and magnitude of extreme events (Tan et al., 2021). This will potentially exacerbate soil and channel erosion; hence, good land and soil management practice becomes more imperative under climate change. The World Organisation for Conservation Approaches and Technologies (WOCAT) aims to develop efforts to reduce land degradation through Sustainable Land Management (Hanspeter & Godert, 2008). Various measures were recommended by WOCAT classified under structural, agronomic, and managerial categories.

2.4.3.4 Challenges of catchment scale approaches to flood management

Catchment management has many challenges but linking across many of these is the issue of scale (Wingfield et al., 2021). By virtue of their spatial extent, larger catchments tend to have complex and diverse ownerships, increasing numbers and diversity of stakeholder groups, and more types of water demand; they also frequently have more diverse land use and land cover types (Lashford et al., 2022). These scale-related factors can make implementing an integrated catchment management plan challenging. Additionally, large and heavily modified (urban or industrial) catchments may have limited capacity to control activity or restore them to their original state. Along with associated uncertainties such as future climate change and changes in land use, it is more challenging to develop effective flood management strategies. Hence, small to medium size catchments provided perhaps a better opportunity, as typically their ownership is less complex, and opportunities for consensus and shared responsibility are greater than in large, urbanised catchments (Kumar et al., 2019; Lim et al., 2022).

2.4.3.5 Key findings and implications for the Trusan

Several key findings on the catchment land use and its associated impact on runoff are summarised in Table 2.3**.** Key implications for the Trusan are as follows:

i. It is generally acknowledged that changes in land use (e.g. intensification of urban and agricultural land use) brings an effect to runoff generation. Hence, it is evident that conservation of natural forest cover, where possible, should be an overarching priority for the Trusan, to reduce flood risk in the future.
ii. The effects are complex such that the runoff processes could vary spatially due to distinct soil structure, soil type, and spatially varying slope degree across the basin. Thus, modelling tools are extremely useful to help understand locations-specific benefits. SWAT® model which is a distributed model that takes into account of these hydrological drivers as hydrological response unit is one of the most useful tools being applied to help predict the hydrological output accurately.
iii. While models are useful, there remains a number of issues with their application. The fact that the model is equipped with multiple hydrological parameters sets (SWAT: more than 700 parameters combination), makes model equifinality a common source of uncertainty for accurate runoff prediction. Equifinality also limits the understanding of links between parameters and catchment characteristics (Wu et al., 2022). Thus, models need to be applied with caution.

Table 2.3: Summary of findings from the literature review on catchment scale land use management.

Source	Study Area	Objectives of Study	Findings
Tan et al. (2021)	Kelantan River Basin, Malaysia	Assess the hydrological extremes and responses to climate change	Under future climate scenario, the annual precipitation, streamflow, max and min temperatures are projected to increase by 6.9%, 9.9%, 0.8◦C and 0.9◦C, respectively.
Tan et al. (2019)	Southeast Asia (SEA)	Review the current applications, challenges and future directions of SWAT studies in SEA	SWAT® performed well in SEA, but many lack of parameterisation details. Key challenges are data scarcity and reliability of the data. Future studies should focus on SWAT parameterisation modification based on SEA climate, geographical and land use conditions.
Shrestha et al. (2018)	Songkhram River Basin, Thailand	Assess land use change impact on hydrology and water quality	Future land use change scenarios under economic and conservation scenarios are responsible for 5-6.5 % increase in streamflow.
Silva et al. (2018)	São Francisco River basin, Brazil	Assess the hydrological response to land cover changes	SWAT® performed well in tropical region: Conversion from pasture land to bare soil has the greatest impact and influence on runoff (increase of ≈70%) and sediment yield. Conversion from pasture land to natural vegetation decreased runoff by ≈30%.
Lin et al. (2015)	Jinjiang Catchment, China	Analyse the impact of land use change on catchment runoff using different time step	Reduced forest and increased cropland and urbanised area will increase the magnitude of flood peaks. Study shows that simulation in different time scales could have varying change in runoff.
Gashaw et al. (2018)	Andassa Catchment, Ethopia	Evaluate and model the hydrological impacts of land use changes	Land use change (decreased in vegetation cover) that occurred within the period from 1985 to 2015 shows that the annual flow, surface runoff, and water yield have increased by 2.2%, 9.3%, and 2.4% respectively.

2.4.3.6 Key Research Gaps

Based on the review presented above, it is identified that there are a number of knowledge gap related to the catchment scale measures to reduce flooding. These are:

i. **Limited examination of runoff sensitivity to land use changes** – At the sub-basin scale, runoff processes exhibit spatial variations driven by unique soil structures and topographical features. Limited literature within this context poses challenges in comprehending the interactions between land use, water and soil, as well as their combined contributions to runoff generation at the subbasin level.
ii. **Limited evidence showing how local changes in runoff are transferred to surface water runoff that propagates downstream** – Limited literature exists to effectively translates variations in water yield into the occurrence of flood events. This poses gap in the analysis of runoff generation, where the emphasis should not only be on the magnitude of increase in runoff generation but also on identifying the threshold at which it elevates the frequency of overbank flow.
iii. **Lack of good gauged data and advanced empirical data analysis** – Current research primarily relies on crude assessments of surface runoff impacts, as land use changes are often simulated by modifying parameters within methods like the Flood Estimation Handbook (FEH) produced by UK Centre for Ecology and Hydrology. The ungauged basin problem remains the main challenge in many studies, restricting good prediction of rainfall-runoff relationship.
iv. **Limited data availability in tropical region for SWAT® model** – Application of SWAT® model faces a notable constraint due to the scarcity of databases related to soil, land use, and water resources derived from tropical regions. Its primary focus has historically been on temperate climates. Consequently, there is a pronounced gap in data coverage and examples of model application for tropical regions, especially in the context of using the model to help guide land cover conservation of land use management.

2.4.4 Incorporation of local, corridor and catchment scale measures

Published literature indicates that it is impossible to solve all river issues (e.g. flooding and erosion) with green measures, especially in urban environments. Many authors have stressed that sustainable flood management at the corridor and catchment scale needs to be included in rehabilitation initiatives to achieve sustainable long-term rehabilitation goals. Table 2.4 and Table 2.5 summarises the suggested flood management strategies and desired rehabilitation goals. Some projects that incorporate local and corridor scale measures were shown to be successful where geotextile and seedlings (Hazell et al., 2007), live wood barriers (Zuquette et al., 2007) and live willow stakes (Selvakumar et al., 2010) were implemented at the downstream eroding bank, while floodplains in upstream areas were allowed to be inundated. Moreover, combination of the local scale green measures and other corridor scale approaches, such as removing in-stream features, allowing erodible corridors and reconnecting floodplain and longitudinal connectivity, work well together in reducing downstream flood and erosion (Barrett, 1999; Hazell et al., 2007; Voicu et al., 2020).

Table 2.4: Green measures applied with sustainable management (Scopus)

Country	Geographic location	References	Green measures	Composite	Goals	Flood management
Romania	Mountainous	Voicu et al. (2020)	Live planting, live fascine, coir roll	Regrade bank	Water quality and erosion	Longitudinal connectivity
China	Lowland urban	Fang et al. (2016)	Sediment dredging, hydrophytes restoration and artificial floating islands	-	Water quality (eutrophication), purification	Dredging, multiple pond wetland
United Kingdom	Mountainous (Headwater)	Dixon et al. (2016)	Log-jam	-	Reduce flood, alter flow	Floodplain, land use, flood risk management
USA	Lowland urban	Etra et al. (2015)	Vegetative geogrid, coil woven, grass seeded, root wad	Rock toe, rip rap	Erosion	Sustainable river management
Northern Ireland	Lowland non-urban	Horton et al. (2015)	Join planting, willow planting, living wall	Rock armouring at toe	Water quality, habitat (pearl mussel), erosion	Direct transfer of mussels, livestock fencing, protected areas
USA	Highland (rural)	Buchanan et al. (2012)	Brush mattress, willow fascine, hydroseeding, live stakes	Rock toe, geotextile	Flood, habitat, water quality, stabilise	Management, post-study
USA	Lowland Urban	Selvakumar et al. (2010)	Coir fibre logs, erosion control fabrics, live willow stakes, seedlings	Rock armouring, rock veins, step pools	Water quality, macroinvertebrate, habitat	Reconnect floodplain, strict water quality standard
USA	Lowland non-urban	Hazell et al. (2007)	Geotextile as underlayer, seedlings	Riprap, realignment, remove bridge	Reduce sediment loss, stabilise bank, habitat	Create more floodplain (form)
USA	Lowland Urban	Sudduth et al. (2006)	Geotextile fabric, live cuttings, joint planting, tree revetment	Riprap	Bank stabilisation, habitat, macroinvertebrate	Proposed better catchment management
USA	Highland	Meals D. W (2001)	Willow cuttings, live stakes, fascines, tree revetments, brush rolls, revegetation, shrubs	-	Water quality (reduce phosphorus, bacteria, reduce sediment,	Land use, livestock management
Europe	N/A	Kiehl et al. (2010)	Seedlings, transfer seed with hay	-	Evaluate methods for plant species introduction	Good agricultural management

Italy	Highland	Carone et al. (2006)	Hydro-seeding, turf transplant, eco-cells, live staking, shrubs	-	Removing sediment and bank stabilisation	Floodplain connectivity, sediment filter system, shrubs planting in flooded area
USA & Germany	Lowland non-urban (1), lowland urban (1), highland (1)	Barrett K.R. (1999)	Staked, coconut fibre logs, fibre mat, erosion control blanket, beaver check dam	stone apron	Bank stabilisation, water quality, reduced flow velocity, habitat	Floodplain, work with nature, wetland plant dissipates shoreline energy, improve water quality

Table 2.5: Green measures applied with sustainable management (Web of Science)

Country	Geographic location	References	Green measures	Composite	Goals	Flood management
USA	Lowland urban	Koepke, J. (2017)	Revegetation, turf reinforcement matting, roll erosion control products	Stream barb, grade control structures	Bank stabilisation, achieve dynamic equilibrium, ecological value	Dynamic Equilibrium, redirective control practices, floodplain connectivity, freedom of space
USA	Lowland non-urban	Elliott et al. (2016)	Revegetation, woody vegetation, trees and shrubs	Removing invasive species, embankment, rock layer, turf reinforcement mat, seedlings, regrade bank	Bank stabilisation, habitat, restore culturally significant plant	Best practice landuse, operational controls
UK	Lowland semi-urban	Anstead et al. (2012)	Willow spilling	Back-filling, bankline adjustment	Bank stabilisation, biological performance of willow, geomorphological effects	Riparian management
Italy	Lowland urban	de Santoli et al. (2008)	Vegetated rock wall, coir fibre roll, hydro-seedlings	Rock wall, boulders	bank stabilisation, flood	Flood wall, flood retention
Brazil	Lowland urban (near shore)	Zuquette et al. (2007)	Trees, revegetation, seedlings, geotextile, wood barrier	Gabion, regrade bank, drainage, windbreak, riprap, check dam	bank stabilisation, ecological value, water quality	Agricultural management, strip cropping mulching, water policy, territorial planning

2.5 Key points

Exploring the opportunity of applying multi-scale measures in different geographical settings

Generally, the amount of funding available for river rehabilitation projects in Europe and America tends to be higher than in Southeast Asia, due to a variety of factors such as the level of economic development, government priorities, and environmental regulations. For example, in Europe, several large-scale river restoration programs are funded by the European Union, such as the Danube River Basin Management Plan and operate under the Water Framework Directive. Similarly, several federal and state-level programs in America fund river restoration projects, such as the US Army Corps of Engineers' Environmental Restoration Program and the National Fish and Wildlife Foundation's Restoration and Stewardship Program. These programs have allocated billions of dollars to restore and protect rivers nationwide (USACE, 2004).

In contrast, in Southeast Asia the funding available for river rehabilitation projects may be more limited, although there are still efforts to restore degraded rivers in the region. For example, the Mekong River Commission has initiated several river restoration projects in the Mekong River Basin, with funding from international organisations such as the World Bank and the Asian Development Bank (Campbell, 2016). However, beyond these major flagship projects, examples of basin wide initiatives are limited in Global Soth countries.

It is important to note that tropical rivers have distinct hydrology due to the climate, land cover and catchment characteristics. Tropical streams are more likely to receive higher insolation and intense rainfall, and experience more frequent flood events (Boulton et al., 2008). Hence, applying sustainable approaches in these regions is important but may face different challenges. Moreover, it is notable that most studies are focussed on urban or lowland rivers. This is mainly due to more high population densities and the value of infrastructure here, which means the ‘costs’ of flood damage are perceived to be greater. Meanwhile, remote, non-urban upland rivers may be experiencing problems, but examples of local green measures, corridor and catchment scale initiatives are relatively scarce here.

In Southeast Asia countries, there is a recognition of the need integrated river basin management (IRBM) plans to address water-related issues. However, the method and execution framework for integrated basin management, and especially for stakeholder engagement, remains unclear in many countries, especially in Malaysia. Moreover, catchments require distinctive frameworks designed specifically for each sub-basin area, further complicating the decision-making process and the implementation of IRBM. In Malaysia, the increasing demand for urban expansion, agricultural land expansion, deforestation and logging all call for efforts to adopt IRBM.

IRBM needs integrated approaches involving multiple stakeholders and disciplines, so that all parties mutually agree on decisions. Lim et al. (2022) recommended establishing a conceptual framework for a successful stakeholder engagement within each river basin as a key requirement for successful IRBM. Engagement is needed to both to understand priorities and challenges faced by stakeholders and involve them in decisions about river and catchment management.

As part of this, the fundamental work for effective management is to understand catchment hydrological functioning, particularly concerning the effects of land use on runoff. Several tools are available to help with this. SWAT is the most widely used tool in temperate regions (Strauch & Volk, 2013; Tan et al., 2019) but less has been done with this model in the tropics. However, it is very useful for understanding the implications of land cover change of river flows and, in turn, the role that conservation of natural land cover can play in flood mitigation. It can therefore help guide decisions about land use planning and catchment management.

Malaysia: Moving Towards Sustainable Approaches?

Malaysia is a tropical country with an average rainfall of 2500mm. Flood and high-flow events are inevitable in urban and upland rivers. Urban rivers in Malaysia have a higher flood risk due to rapid development and poor urban stormwater planning. In the past, flood mitigation measures followed in the footsteps of European and Western countries, where wider and deeper concrete river channels were proposed to mitigate flood risk. Heavily engineered rivers occur in most urban areas in Malaysia. This has resulted in physical degradation, reduced aesthetic values, and damaged river ecosystems (Mohamed et al., 2015).

The awareness of environmental issues remains very low in Malaysia compared to European and Western countries. Some restoration efforts have been instigated by the Department of Irrigation and Drainage (DID), a Malaysian Government department. However, most of the rehabilitation projects only address water quality issues and land cover change, and the works were focussed on cleaning and purifying rivers (Omar & Sohaili, 2015; Weng et al., 2003) rather than focussing on natural fluvial processes or physical habitat integrity.

River rehabilitation projects using green approaches are very new in Malaysia. Many past projects were conducted without being documented. Thus, it is difficult to identify the number of works conducted. Most of the literature discussed the mechanisms and cause of bank erosion (Roslan et al., 2013; Yusoff & Abidin, 2013), but published literature regarding riverbank stabilisation in Malaysian rivers is very limited. Mohammed et al. (2009) detailed three case studies of using biotechnical block systems in Malaysia, with these designed to revegetate the bank and reduce scouring. Green revetment materials were installed at the riverbank to promote vegetation growth. Although this is not the same as bioengineering, it illustrates some effort in using green materials in river rehabilitation projects. The case studies revealed that all the implemented measures had successfully promoted vegetation growth and functioning over 8 years after installation, without being washed away (Mohammed et al., 2009). Other common biotechnical measures implemented in Malaysia are sand-filled mattresses, geotextile bags, composites geo-containment systems and hydro seedlings.

The key point however is that while certain practices have been adopted in some locations, there are no examples of where local, corridor and catchment scale measures have been evaluated in the same location to see how they may help reduce flood risk.

Monitoring of river rehabilitation remains limited, not least because project funds are often only sufficient for the planning and implementation stages, and long-term monitoring is excluded. However, many authors have used modelling approaches, including some in Malaysia. These simulations allow the authors to predict the drag coefficient (Muhammad et al., 2015, 2018), velocity distribution (Muhammad, Yusof et al., 2016), and flow characteristics and sediment transport in the restored river (Darus et al., 2004). In another Malaysian study, experiments and tests were conducted to evaluate the suitability and success of green measures in an urban channel (drainage system) to reduce erosion (Muhammad, Alias et al., 2016). A turf reinforcement mat and erosion control blanket were constructed in test channels to evaluate these biomaterials. Both were found to be hydraulically suitable for erosion control and as alternative stabilisation materials to traditional methods.

While Malaysia is slowly moving towards adoption of green approaches, progress is slow and much remains to be done. Examples to show the role of these approaches are needed to help demonstrate their value and, in turn, help ensure wider adoption.

2.6 Key gaps addressed in this thesis

The foregoing literature review identified a number of knowledge gaps related specifically to sustainable green approaches for local scale, corridor scale, and catchment scale approached. A number of these gaps are addressed in this current thesis, as detailed below:

i) **Post-project assessment of local measures. Chapter 4** trials and evaluates a number of different local scale measures for bank protection, specifically their suitability for remote, high-energy rivers such as the Trusan.

ii) **Empirical and quantitative documentation. Very often, measures are implemented but without any efforts at collating data to understand reasons for success or failure. Chapter 4** addresses this gap by providing robust, data-driven evidence from field data and modelling outputs that helps to identify the effectiveness of these approaches.

iii) **Accurate, high-resolution assessment of flood risk and utility of floodplain retention. Chapter 5** employs high-quality geometric data and comprehensive geospatial and hydrological analyses to provide precise evaluation of existing flood risk and the potential for flood reduction through floodplain retention areas. This addresses the need for accurate and evidence-based flood risk assessment, a critical aspect of flood management.

iv) **Identification of hydrologically sensitive areas and land use effects. Chapter 6** contributes to a deeper understanding of the complex relationship between variations in land use conditions and runoff generation. Importantly, it acknowledges the complex interplay of land management changes and their varying impacts across different scales, highlighting the limitations of small-scale changes in making catchment-scale differences. Specifically, it identifies hydrologically sensitive areas where reforestation can be strategically implemented to help reduce flood risk.

v) **Filling the tropical research gap.** This thesis provides in-depth examination of sustainable approaches at various scales to address flooding and erosion issues in tropical regions, providing a substantial contribution to a field where research in these areas has been lacking. By investigating the unique challenges and environmental conditions specific to tropical regions, the thesis offers detailed hydrological analysis and discussed the applicability of sustainable practices for river management. It delves into the intricate dynamics of tropical river systems, addressing issues such as localised land use changes, floodplain retention, and the identification of hydrologically sensitive areas. This gap related to the final research objective, and is the subject of discussion in the final synthesis chapter of the thesis.

CHAPTER 3: HYDROLOGY OF THE UPPER TRUSAN CATCHMENT

Aerial view of village and rice paddy fields at Puneng Trusan
Photo: Yih Yoong Lip, February 2023

3.1 Introduction

The overall aim of the restoration work in the Trusan was to mitigate flood risk and implement riverbank protection measures to limit erosion. Both of these require a fundamental understanding of hydrological regime of the river (e.g. magnitudes and timings of high flow), to support the design of mitigation plans and measures. A major issue, however, is that there is no flow gauging station in the upper part of the catchment, where the flood minimisation and bank protection measures are needed; while there is a gauge further down the catchment, this has a very different valley form and land use characteristics to the upper part of the catchment and so a simple area-based conversion would not be appropriate for developing a hydrograph for the Upper Trusan.

The goal of the work described in this chapter was to produce a hydrograph for the Upper River Trusan (Figure 3.1). This hydrograph was then used for two of specific purposes:

i) To understand the general hydrological regime of the Trusan River, in terms of flow magnitude and timing and recurrence intervals.

ii) To assess the occurrence of overbank flows and, hence, flooding. For this, a hydraulic model was first used to estimate bankfull flows in the Upper Trusan. The hydrograph was then interrogated to look at the frequency, duration and magnitude of events (floods) that exceeded bankfull. This analysis is used later in the thesis to inform the flood risk modelling.

iii) To assess the frequency and duration that flows are at or close to bankfull. This information was then combined with hydraulic models that were used to simulate flow hydraulics at bankfull discharge. In turn, this understanding of flow hydraulics (notably shear stress) was then used to help to understand the forces experienced by green measures.

These elements are described in Figure 3.1 and Figure 3.2.

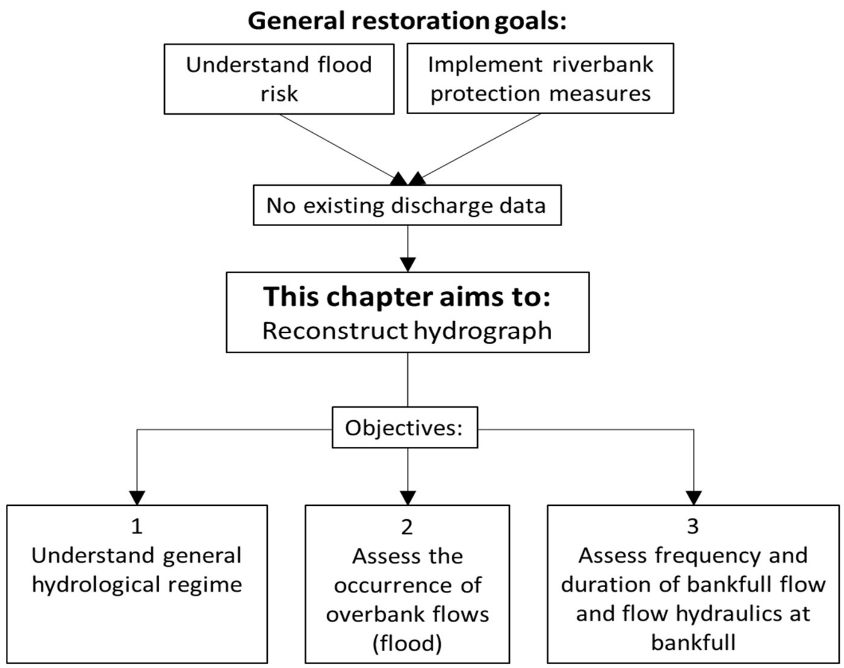

Figure 3.1: Overview of chapter's aim and objectives.

This chapter describes how a model was built to develop a hydrograph for the Upper Trusan. It uses the rainfall-runoff relationship for a neighbouring catchment (Kemabong catchment) that has a similar forested land cover to the Upper Trusan, which was applied to rainfall data for the Upper Trusan to predict discharge here. The chapter begins by describing how this hydrograph was constructed; it then details how it was used to address objectives i – iii. The chapter contents and associated methods are summarised conceptually in Figure 3.2.

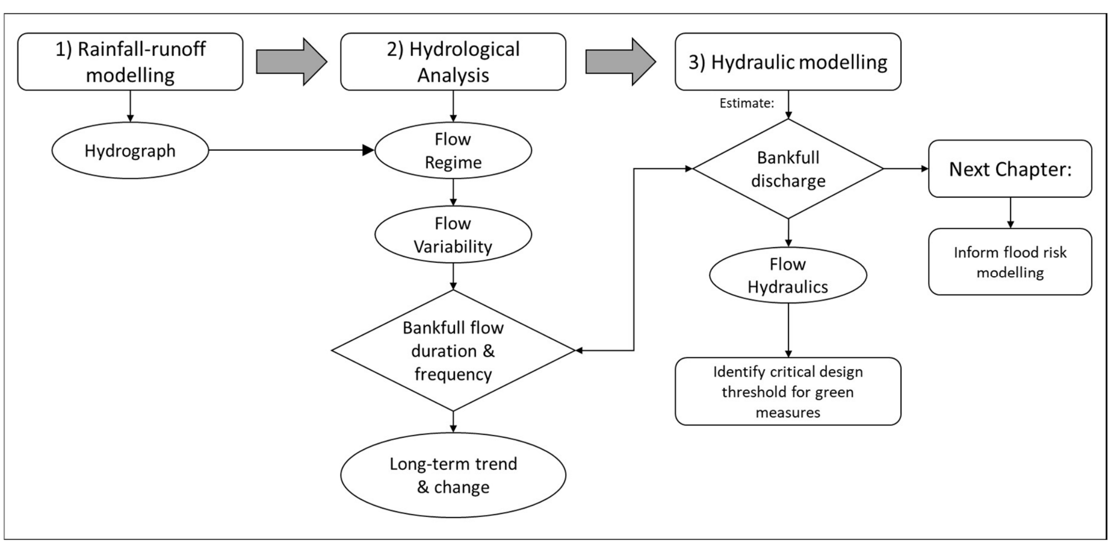

Figure 3.2: Systematic workflow of synthesis of methods employed in this chapter.

3.2 Study Area and Dataset

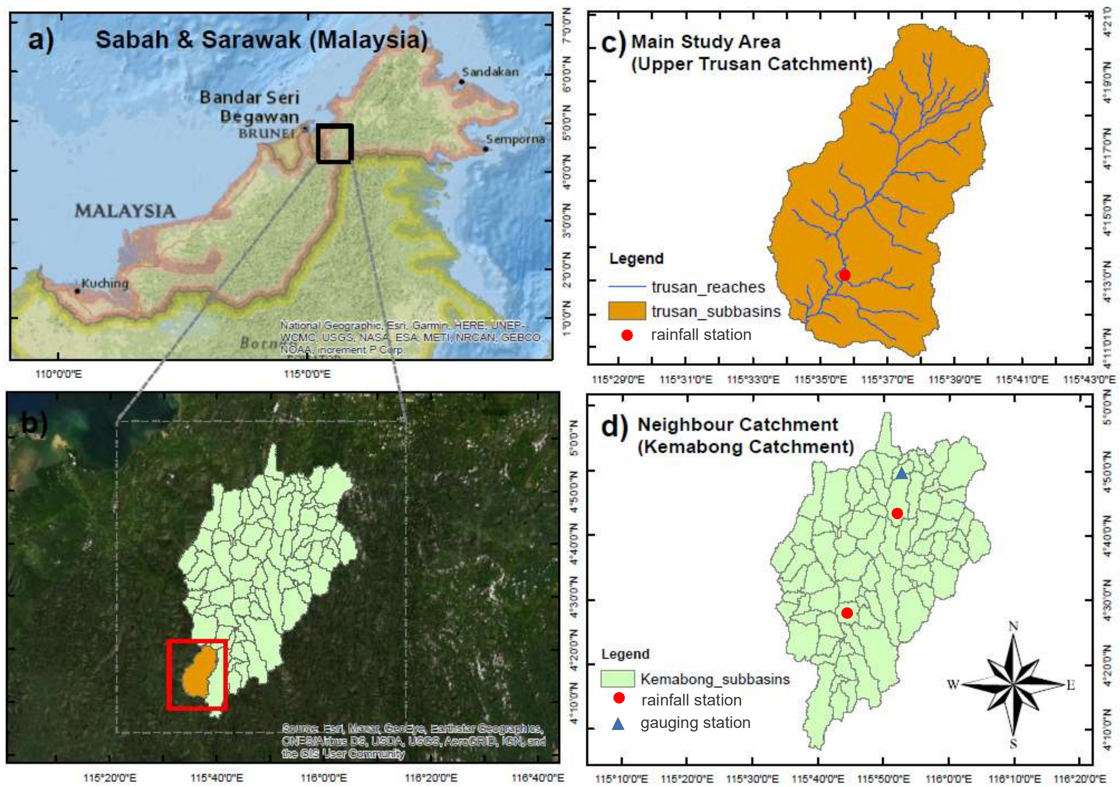

Figure 3.3: Map of Study Area, a) Map of Sabah and Sarawak (Malaysia), b) Upper Trusan and Kemabong Catchment, c) Upper Trusan Catchment, and d) Kemabong Catchment.

Figure 3.3a gives the map of Sabah and Sarawak, showing the general location of two catchments, while Figure 3.3b-d show the Upper Trusan and Kemabong in more detail. The hydrograph was reconstructed for the Upper Trusan catchment (Figure 3.3c) by developing a rainfall-runoff model based on its neighbouring catchment; this can be defined as a 'regional approach'. This approach involved the transfer of hydrological parameters from one catchment to another (e.g. from gauged to ungauged catchment) to estimate runoff in the ungauged catchment. In this case, the Kemabong catchment (Figure 3.3d) was selected due to its similarity in catchment characteristics (e.g. topography and land cover) and the availability of matched rainfall and flow data.

The Upper Trusan has a catchment area of 140 km^2 with a thick canopy layer of forest; land cover has remained largely unchanged for the past decade, according to the historical satellite images (Marteau et al., 2018: unpublished report). There is a rainfall station located at Long

Semadoh (red dot in Figure 3.3c). The rainfall data (Table 3.1) from the period of 1999 to 2020 were acquired from Department of Irrigation and Drainage (DID) Sarawak. This rainfall was then used to simulate flows for the Upper Trusan catchment (i.e. in the rainfall-runoff model), based on the rainfall-runoff model developed for the Kemabong. The Upper Trusan has an average monthly rainfall of 220mm, and the climate is characterised by distinct wet and dry seasons. The wet season is predominantly influenced by the tropical monsoon that commonly occurs in between November to February. The remaining months have a lower precipitation rate compared to the wet season, but the overall precipitation is still high. The only noticeable dry months are July to September, with monthly precipitation less than 100mm.

Table 3.1: Hydrological data obtained from DID Sabah and Sarawak.

Region	Station	Year
Kemabong	Rainfall	1990 - 2020
	Discharge	1990 - 2020
Bakuku	Rainfall	2010 - 2020
Long Semadohh	Rainfall	1998 - 2020

The Kemabong catchment overall has an area of approximately 3233 km^2 and the land cover is similar to the Upper Trusan. This catchment has multiple sub-basins that drain to the main River Padas. The outflow of the catchment has an average annual discharge of 94.82 m^3/s (2010 to 2019 data). Two rainfall stations and one discharge station (see legend in Figure 3.3d) are available in this catchment. The rainfall stations are located at two different sub-basins, one located at the upper basin (Bakuku) and the other located at the lower basin (Kemabong); the gauging station is located at the downstream part of the Kemabong catchment, but land cover across the whole area upstream from here is similar to the Trusan (forested). The rainfall and flow data recorded in these stations were obtained from DID Sabah (Table 3.1). The rainfall and discharge data were used in the rainfall-runoff model.

3.3 Methods

3.3.1 Rainfall-runoff modelling

3.3.1.1 Rainfall-Runoff model description

Rainfall-runoff modelling is commonly used to estimate runoff for ungauged catchments by extrapolating the hydrological parameters that govern the rainfall-runoff relationship from a nearby gauged catchment (Blöschl, 2005; Pumo et al., 2016; Sauquet & Catalogne, 2011). For the case of Upper Trusan, the modelling structure is shown in the schematic diagram (Figure 3.4). The hydrograph for the Upper Trusan catchment was simulated using rainfall and a set of catchment traits (e.g. infiltration) that dictate the conveyance of rainfall through the catchment system, and which then determine the runoff entering the channel. The model was first built for the Kemabong catchment, and the hydrological parameter values from the calibrated and validated model were then used as the basis for the Upper Trusan model, with the observed rainfall for the Upper Trusan used to predict the river flow.

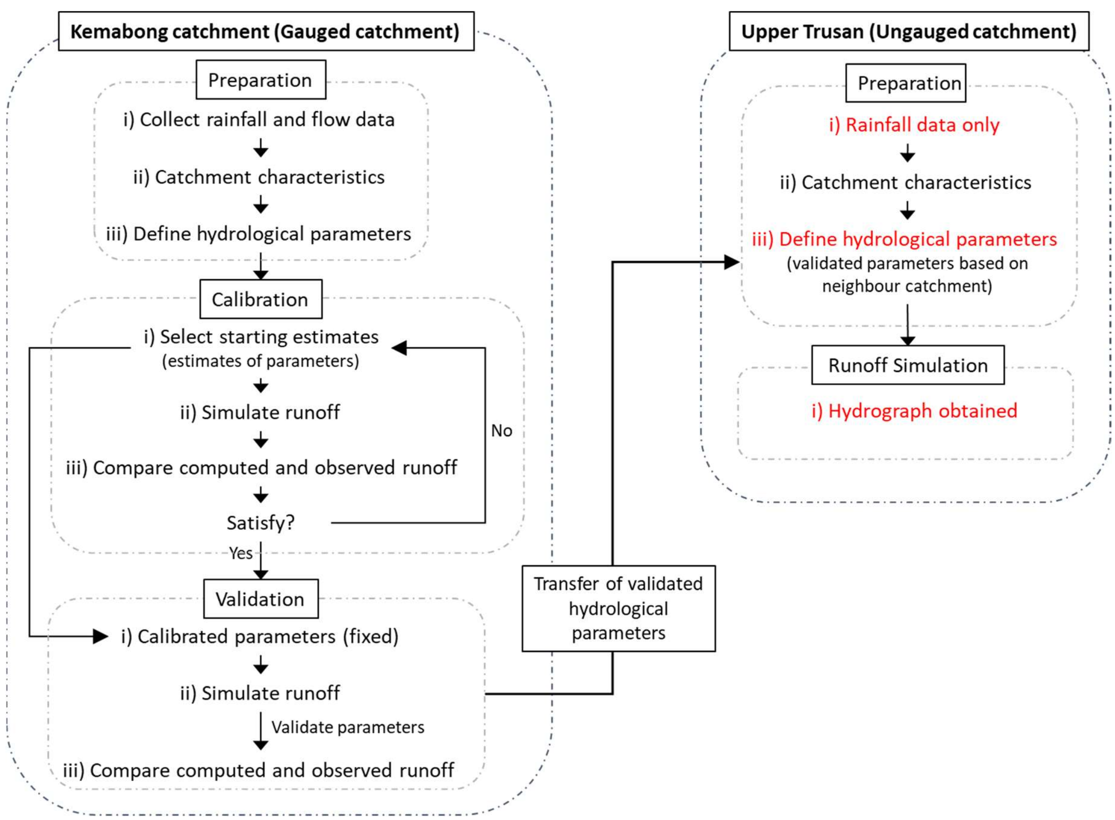

Figure 3.4: Schematic diagram of development of rainfall-runoff model and reconstruction of the hydrograph for the ungauged Upper Trusan.

3.3.1.2 Method of transforming rainfall to runoff

The HEC-HMS® hydrological modelling software (U.S. Army Corps of Engineers, 2012) was used to simulate rainfall-runoff processes for the Kemabong and Trusan catchments, and compute runoff (river discharge) using rainfall. For this, rainfall was transformed to discharge using information on infiltration and the interaction of subsurface processes that are conceptually represented by several catchment elements (e.g. canopy, loss and baseflow). Several transformation methods are available in HEC-HMS® to simulate the distribution of runoff volume over time. The most well-known of these is the Unit Hydrograph (UH) method (U.S. Army Corps of Engineers, 2012). This has the advantage that it requires only a relatively small number of parameters to simulate discharge. The UH method was adopted for the present work, applied using the Snyder Unit Hydrograph. Parametric UH developed by Snyder (1938) is a simple method that can be applied to ungauged catchments (Snyder, 1938). It allows unit hydrograph parameters (e.g. constant loss, catchment lag, peaking coefficient & baseflow) to be estimated from catchment characteristics based on the relationships that were developed by Snyder; these represent the hydrological parameters of a catchment that allow estimation of discharge from rainfall.

3.3.1.3 Determination of catchment characteristic used for UH modelling

The Snyder UH model first requires the input of basin descriptors such as catchment area, channel length and channel weighted slope. A 12.5-meter resolution Digital Elevation Model (DEM) covering Upper Trusan and Kemabong catchment was obtained from ALOS PALSAR® Imagery (Dataset: ASF DAAC, 2021). The basin descriptors were determined by measuring the Digital Elevation Model (DEM) using ArcGIS tools in ArcMap®. Subsequently, the DEM was imported to HEC-HMS® for the catchment delineation functions (e.g. catchment boundary and reaches). Here the built-in GIS tool in HEC-HMS® was utilised to help identify sub-basin characteristics that comprise flow path length, flow path slope, basin slope and basin relief. To achieve this, the DEM sinks were filled to ensure the continuity of the terrain. The software then estimated the flow direction and flow accumulation to characterise the movement of water across the landscape. The sub-catchments, or areas that contribute to specific river or stream segments, were then delineated. The boundaries of these sub-catchments were drawn and stored as shapefiles, enabling the creation of Kemabong subbasins. The Kemabong basin was initially divided into 80 sub-basins. However, due to the limited availability of rainfall and flow gauging stations, a simplification was necessary, resulting in the division of the basin into two primary subbasins: the upper and the lower basin, based on the river network. Each of these subbasins contains one rainfall station - the Bakuku station in the upper basin and Kemabong station in the lower basin. The flow gauging station at the most downstream end of the Kemabong basin was selected at the final outlet point. The two subbasins were connected through the main river, which was identified as the longest flow path.

After the parameters related to catchment characteristics are identified, some other UH parameters for initial model input are needed (e.g. standard lag and peaking coefficient). In many cases these parameters are unknown, and so have been estimated initially based on the best judgement. Otherwise, the estimation can be done by taking locally developed relationships based on historical storm events and catchment physical features. In this case, some of these unknown parameters were determined using previous work (discussed in section 3.3.1.4), and the remaining parameters were estimated based on best judgement.

3.3.1.4 Calibration and validation procedure for Kemabong catchment

The calibration of the model is an essential step to enhance the level of efficacy of UH parameters. Subsequently, validation of the model is to evaluate the performance of the calibrated model over the period of historical records, which have not been used in the calibration. In this case, the records of Kemabong rainfall and flow data in 2012 were used to calibrate the model, and the records from 2013 to 2015 were used to validate the model.

The model for Kemabong catchment was calibrated over approximately monthly timeframes (i.e. for each month separately over the year 2012). There was a total number of 9 calibration models (Table 3.2) rather than 12, since some events fall at the end of the month, so the period of calibration was extended into the next month to include the whole event. The objective of this is to match the observed-simulated runoff volumes and timing of peaks of the hydrographs by calibrating the UH parameters.

Table 3.2: The period of calibration.

Calibration	Period	Nash-Sutcliffe Coefficient
1	6 January 2012 – 9 February 2012	0.711
2	10 February 2012 – 17 March 2012	0.423
3	18 March 2012 – 20 April 2012	0.838*
4	21 April 2012 – 25 May 2012	0.856*
5	26 May 2012 – 3 July 2012	0.453
6	4 July 2012 – 14 August 2012	0.861
7	31 August 2012 – 13 October 2012	0.763
8	14 October 2012 – 17 November 2012	0.370
9	18 November 2012 – 31 December 2012	0.291

Note: * is plotted in Figure 3.5. The remaining is shown in Appendix B.

The calibration step can be divided into two sequential phases: i) initial estimation of UH parameters (starting values) and ii) calibration module to search for optimal UH parameters. Before the calibration module is run, starting values for all the UH parameters (e.g. catchment lag, channel lag, peaking coefficient and baseflow) are needed. Some of these parameters were estimated from a series of equations that were developed DID Malaysia (Manual of Design Flood Hydrograph Estimation for Rural Catchments in Malaysia – HP11). These equations were derived by forming relationships based on historical storm events and catchment physical features across Sabah and Sarawak, specifically for rural catchments, so are appropriate for the current study (Department of Irrigation and Drainage Malaysia, 2018). DID Malaysia used data from 748 storm events from 43 catchments throughout Sabah and Sarawak to derive the equations for the parameters (Department of Irrigation and Drainage Malaysia, 2015). The equations **(Equations 1 – 4)** that are used as the initial input parameters in the Kemabong hydrological model, where L_g is the catchment lag time in hour and Q_B is the baseflow, are as follows:

The best fit catchment lag equation for Sabah (1) and Sarawak (2):

$$L_g = 5.145A^{-0.1174}L^{0.2417}S^{-0.7157} \quad (1)$$

$$L_g = 2.701A^{-0.2954}L^{0.6795}S^{-0.3737} \quad (2)$$

Design baseflow for Sabah (1) and Sarawak (2):

$$Q_B = 0.0783A^{0.8653} \quad (3)$$

$$Q_B = 0.0111A^{1.1682} \quad (4)$$

A is the catchment area, L (km) is the total length of channel from the centroid to the outlet flow of catchment, and S is the weighted slope. The catchment lag time is the lag from the centroid to the outlet flow of catchment, which is derived as best fit catchment lag equations (Equation 1 & 2). The baseflow equations (Equation 3 & 4) were estimated from all the gauged streams in Sabah and Sarawak and are scaled according to the catchment size.

After all initial parameter values were determined, they were used as input parameters for the simulation. The simulation was computed at a daily time-step over each month. Then, the calibration module in HEC-HMS® was used to optimise all the initial input parameters, with observed flow values functioning as the benchmark for the optimisation process. The process uses a univariate gradient search procedure to identify the optimal parameters estimates (Feldman, 2000). The partial derivatives of the objective function were minimised with respect to the unknown parameters. However, the optimisation does not calculate the global optimum solution of the objective function. The objective function of the calibration module was set to Peak-Weighted Root Mean Square Error (RMSE), that minimised the average distance between observed and simulated, with larger weight given to flows greater than the mean (Feldman, 2000). The models were calibrated until the Nash-Sutcliffe efficiency (NSE) achieved a good value (Nash & Sutcliffe, 1970). The models with poor NSE values (lower than 0.6) were discarded. The performance evaluation criteria are shown in Table 3.3.

Table 3.3: Classification for Nash-Sutcliffe efficiency coefficient.

Classification	Coefficient of efficiency (Calibration)	Coefficient of efficiency (Validation)
Excellent	E ≥ 0.93	E ≥ 0.93
Good	0.8 ≤ E < 0.93	0.8 ≤ E < 0.93
Satisfactory	0.7 ≤ E < 0.8	0.6 ≤ E < 0.8
Adequate	0.6 ≤ E < 0.7	0.3 ≤ E < 0.6
Poor	E < 0.6	E < 0.3

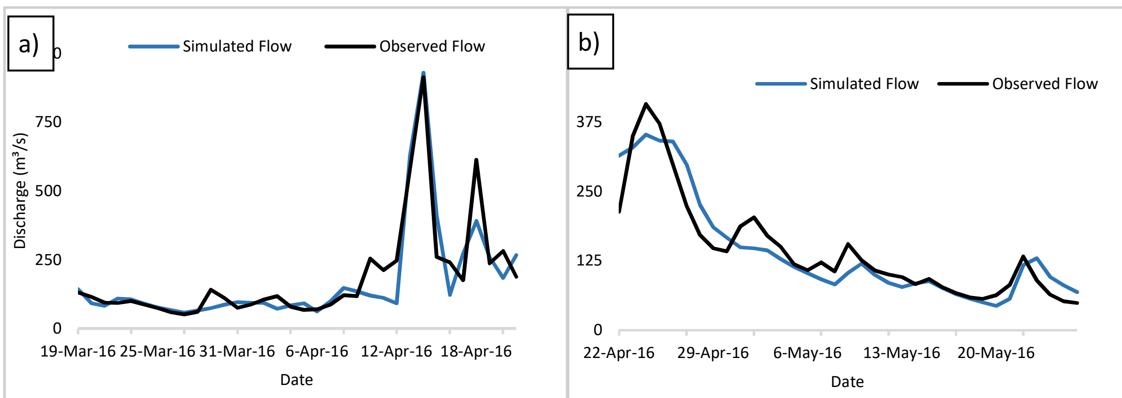

Figure 3.5: Model calibration using HEC-HMS®, matching simulated and observed flow in a) March and April 2012, and b) April and May 2012.

Figure 3.5a and Figure 3.5b are the examples of model calibration output (for the periods of March to April and April to May 2012). All calibrated parameters were extracted from the models with Nash-Sutcliffe efficiency value greater than 0.6 (Table 3.3). The mean values of each optimised parameter were taken as the final calibrated parameter values.

For the validation process, the final calibrated parameters were fixed and the simulated flow is required to match the observed flow to an acceptable degree based on of Nash-Sutcliffe efficiency values (by convention, E > 0.6). The validation models were simulated for a series of events (n=5) that occurred over 2013 to 2015, with the period of validation summarised in Table 3.4 The selected period consisted of dry and wet seasons. Figure 3.6a and Figure 3.6b are examples of model validation outputs (March 2014 and December 2015); the remaining outputs are shown in Appendix C. The model performance was then evaluated again according to the criteria shown in Table 3.3.

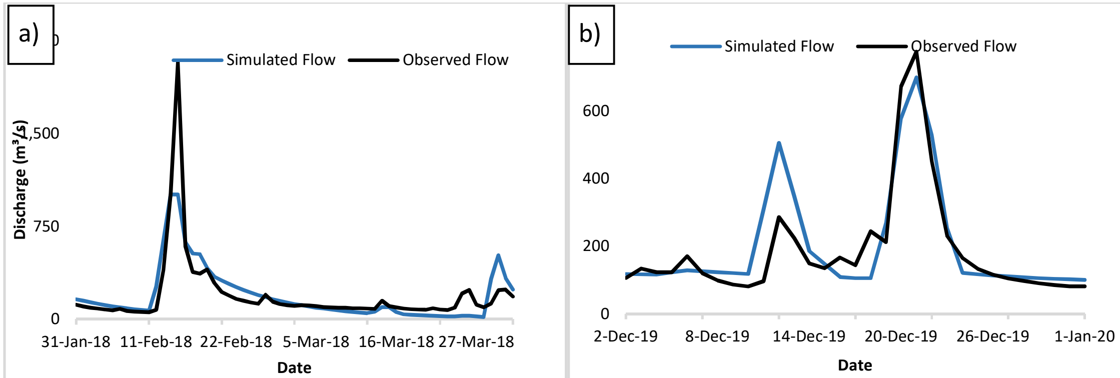

Figure 3.6: Model validation using HEC-HMS®, validating simulated and observed flow in a) March 2014 and b) December 2015.

Table 3.4: The period of validation

Validation	Period	Nash-Sutcliffe Coefficient
1	May 2013 – July 2013	0.328
2	August 2013 – September 2013	0.653
3	February 2014 – March 2014	0.677*
4	October 2014 – December 2014	0.424
5	December 2015	0.736*

Note: * is plotted in Figure 3.6. The remaining is shown in Appendix B.

3.3.1.5 Runoff simulation for the Upper Trusan catchment

The calibrated and validated parameter values were then transferred to the ungauged Upper Trusan to generate a hydrograph for this part of the basin. Fixed parameter values were used for the simulations, which covered the period 1999 to 2020. Note that the routing method for channel lag in the Trusan differs from the method applied in the calibration model due to the lack of available information; the kinematic wave routing method was applied since the channel geometry could be determined from available topographic maps.

This approach creates a hydrograph for a given location using a model that represents runoff processes for the catchment upstream from here. Given that the rainfall data applied to the Trusan are for the weather station at Long Semadoh, the modelled area was that upstream from here and, accordingly, the simulated hydrograph is for the river at Long Semadohh (Figure 3.7). Analysis of the flow regime should be taken as being for Long Semadoh, located at the downstream end of the study section; the other study sites are upstream from here (Figure 3.7b).

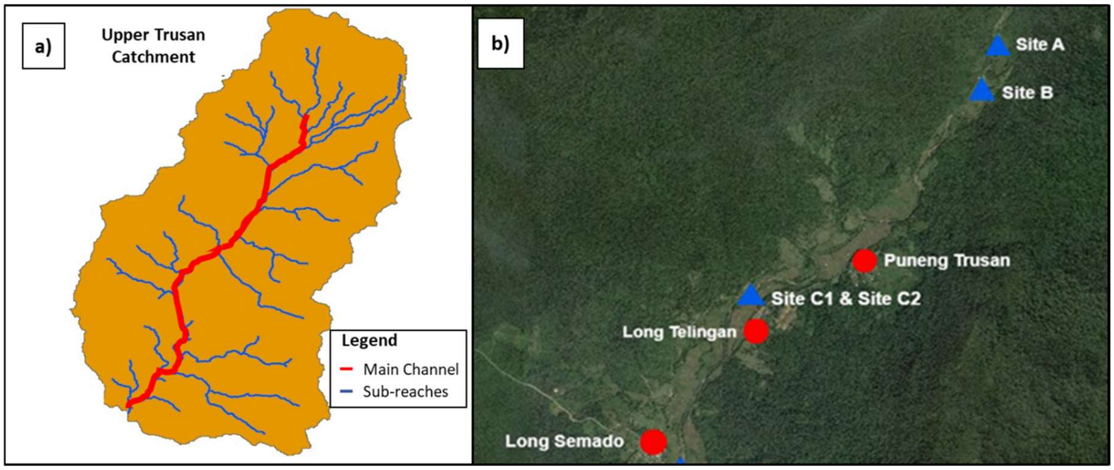

Figure 3.7: a) Map of study area and b) location of study sites and villages. The hydrograph was simulated for the channel at Long Semadoh (bottom end). Green measures were installed at Site A, B, C1 and C2.

3.3.2 Hydrological analysis

The simulated hydrograph (22-years period from 1999 to 2020) for the Upper Trusan was used to help understand key traits of the river's hydrological regime. The general workflow for hydrological analysis is summarised in Figure 3.8. The analysis was conducted to address goal number one (Section 3.1) which focussed on understanding aspects of flow magnitude and timing.

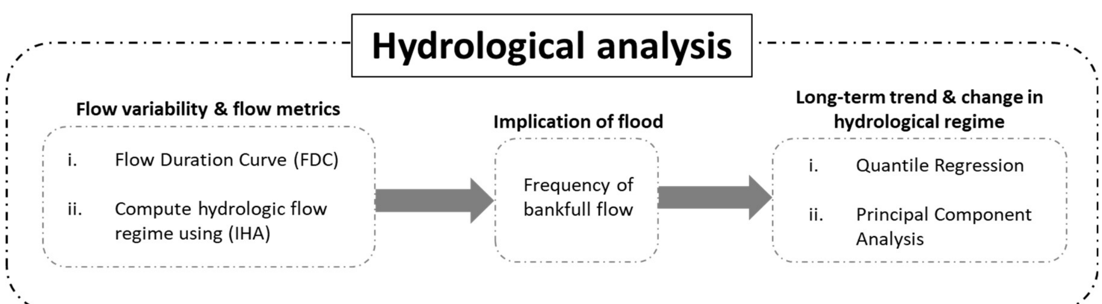

Figure 3.8: Schematic workflow of the hydrological analysis.

The analysis starts by (i) producing a Flow Duration Curve (FDC), (ii) monthly mean flow and (iii) computing hydrologic flow regime statistics using the Indicators of Hydrological Alteration (IHA®) software program (The Nature Conservancy, 2009). Then, the hydrograph was analysed to assess (iv) frequency and duration of bankfull flow exceedance (for Site A & B only) and (v) assess long-term trends and change in the river's hydrological regime.

3.3.2.1 Hydrological regime of River Trusan

The FDC was used to identify Q_{95}, Q_{90}, Q_{50}, Q_{10} and Q_5 with IHA® software used to extract complementary statistics on flow magnitude, timing and event duration (e.g. duration and timing of Q_{90} events). FDCs were produced for the whole period, and for each year separately. For these, the exceedance probability (P) was calculated using **equation 5**:

$$P = 100\left(\frac{M}{(n+1)}\right) \quad (5)$$

Where P is the probability that a given flow will be equalled or exceeded a percent of time, M is the position of ranking on the list, and n is the total number of daily discharges for the period of record. Then, the hydrograph was used to run through the IHA software which a large set of flow descriptors were generated. A subset of these (Table 3.5) were then used to help characterise key aspects (i.e seasonality, magnitude, timing, frequency and duration) of the Upper Trusan's flow regime.

Table 3.5: Flow regime characterisation.

Key Aspects	Hydrologic Parameters
1. Seasonality	• Mean monthly flow
2. Magnitude of critical flow	• Extreme low peak • Moderate flow peak • Moderate flow rise rate • Moderate flow fall rate • High flow peak • High flow rise rate • High flow fall rate • Extreme high flow peak • Extreme high flow rise rate • Extreme high flow fall rate

3. Timing of annual minimum and maximum flow	• Week of minimum • Week of maximum
4. Duration and frequency of critical flow	• Extreme low duration • Extreme low freq. • Moderate flow duration • Moderate flow frequency • High Flow duration • High Flow frequency • Extreme high flow duration • Extreme high flow frequency

The IHA® software allows the user to either use the default settings or user-defined settings to define high and low flow, high flow pulses and flood definition (The Nature Conservancy, 2009). In our case, the default configuration was used to separate moderate and low flow, where flows that exceeded 75% of daily flows were classified as moderate flow; flows that were below 50% of daily flows were classified as low flows. Note that the moderate flow begins if the increment between two flow levels is more than 25% (i.e. moderate flow start rate threshold). Subsequently, events with peak flow exceeding 5 times the median flow were defined as high flow, and events with peak flow greater than 7 times the median flow were defined as extreme high flow. In IHA®, the duration of high flow event was calculated from the rising limb of the peak flow events to the recessed baseflow, similarly for the frequency (number of occurrences).

Lastly, the frequency and duration of flow exceeding bankfull were calculated for Site A and Site B to show how frequent the flow overtops the bankfull edge. Because Site A and B proved to have the clearest bankfull edge (more detail in Section 3.3.3), the analysis of bankfull frequency and duration are undertaken for these two sites only. These two sites were several kilometres upstream from Long Semadoh, so the hydrograph for Long Semadoh was corrected to reflect the respective decreases in catchment area at these two sites (Site A & B). The frequency here represents the number of events that exceeded the threshold of bankfull flow, whereas the duration shows the number of consecutive days that flow exceeded bankfull flow.

3.3.2.2 Long-term trend and change in hydrological regime

The final analyses applied to the simulated hydrological data were quantile regression and Principal Components Analysis (PCA). The purpose of the quantile regression was to look for evidence in long terms changes in the magnitude of higher flow events. It has been used before for assessing long term hydroclimatological trends in Sabah and Sarawak (Sa'adi et al., 2017). The quantile regression was applied using R statistical computing software. In R, package 'quantreg', that was developed by Koenker (2005) was employed for the regression analysis (Koenker, 2005). The 0.90 quantile and 0.99 quantile that represent the high flow were plotted.

PCA was applied to help understand inter-annual differences in flow regime, assess evidence of any linear trends in the long-term regime and (if present) identify the flow metrics driving this trend. PCA is used to reduce the dimensionality of a multivariate dataset, and to illuminate its interpretation by identifying a smaller number of variables. It is a data transformation technique that is applied to summarise larger dataset to a lower number of dimensions for further analysis (Roessner et al., 2011). PCA was applied using PAST® (version 4.06) statistical free software. Each year's discharge series (1999-2020) was represented using metrics Q_{95}, Q_{90}, Q_{50}, Q_{10} and Q_5 and PCA was applied to the resulting data set for the 20-year period.

3.3.3 Hydraulic model: Estimation of bankfull flow and flood frequency

In order to better understand the flood condition in the Upper Trusan River, the peak discharges generated from the rainfall-runoff model are translated to flood occurrence and duration. This methodological approach requires the long-term hydrograph generated from the rainfall-runoff model and estimation of bankfull threshold limit to help determine the annual flood frequency and the duration. To achieve this, hydraulic modelling was applied to help estimate the bankfull flow for selected site. The selected sites are based on the locations where the green measures were implemented. The frequency of flood events were calculated based on the number of times that the flood peaks exceeded the estimated bankfull threshold (red dotted line) as shown in Figure 3.9**.**

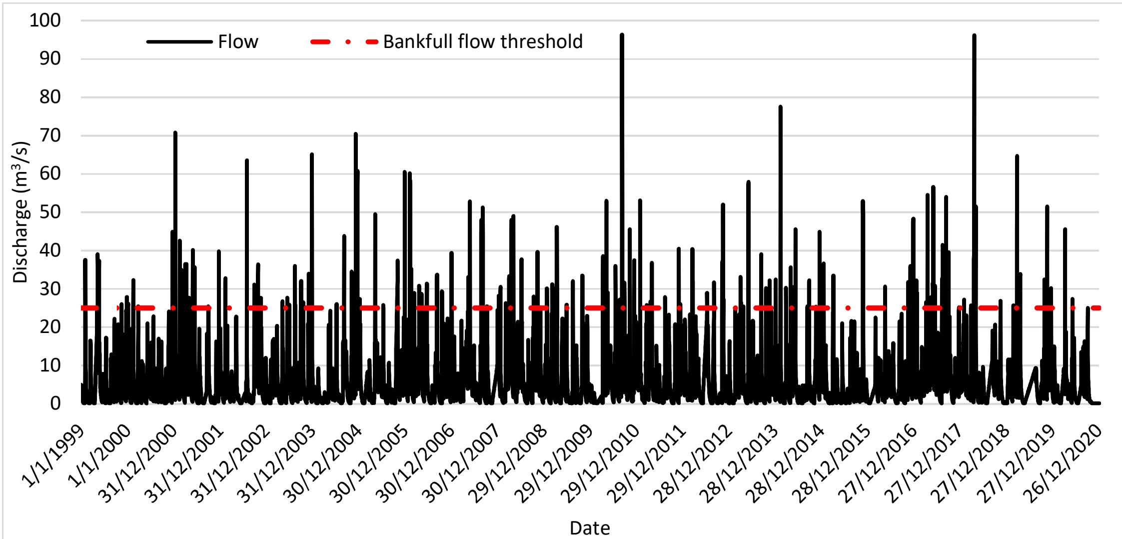

Figure 3.9: Simulated long-term runoff at Long Semadoh.

As the selected sites were spread across the basins, the runoff at each sites varies. To account for this, a simple catchment area ratio was applied to the simulated runoff at Long Semadoh to estimate the discharge at the sites that are located upstream. The transformed hydrographs were then analysed to look at the flood frequency and duration at respective sites.

This approach then provides the hydrological settings in the Upper Trusan River, which in turn help us to understand the conditions that the green measures have to withstand as well as the frequency and magnitude of the high flow events that cause flooding. In Chapter 4, flow forces at bankfull flow were estimated to further provide the hydraulic context and which of this information allows us to determine the criteria that are required for the green measures to perform adequately.

3.3.3.1 Two-dimensional hydraulic modelling description

Two-dimensional hydraulic modelling was undertaken to estimate bankfull flow and flow hydraulics at all four sites. This used the Hydrologic Engineering Center's River Analysis System (HEC-RAS®), free software developed by the U.S Army Corps Engineers (2018). The modelling focussed on estimating the bankfull flow and help to understand the frequency of overbank flows.

The bankfull flow refers to the discharge that reaches the transition between the channel and the floodplain before overflowing the bank edge. As mentioned earlier (Section 3.1 – Introduction), identifying the discharge that reaches the bankfull height is important for us to identify how often the river overtops its banks and so inundates floodplain. This flow is also a critical discharge for the riverbank protection measures, as the hydraulic forces exerted on the banks are likely at their maximum.

The model first estimated the bankfull flow for each site by simulating a gradual increasing flow until the water surface elevation reaches the height of bank edge. Then, the discharge at this water level were determined by extracting from the model output.

3.3.3.2 Determination of bankfull edge

In order to simulate flow at bankfull, the indicators of bankfull edge or bankfull height were identified (Bent & Waite, 2013). The indicators were identified by locating the bank slope, vegetation and point bars that form at meanders using the high-resolution two-dimensional maps produced from the drone surveys conducted in year 2019. The bank edge line was drawn (Figure 3.10a & Figure 3.10b: examples for Site A and Site B) based on the identified indicators in plan view along with respective sites using the drone maps. The hydraulic model was then used iteratively to fill the channel to the point that this line is reached. For visualisation in this chapter, the three-dimensional DEMs used to build the hydraulic model were used to extract transects to show the water level at representative points of interest.

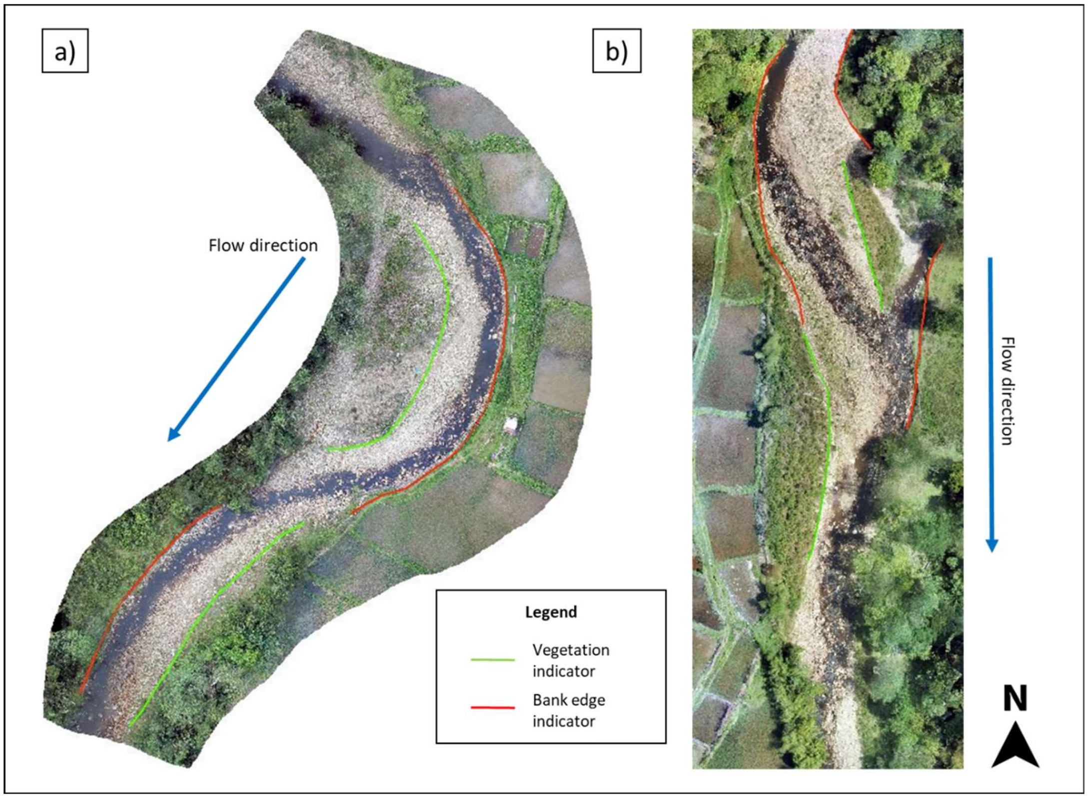

Figure 3.10: Two-dimensional maps of a) Site A and b) Site B, with bankfull edge indicators.

3.3.3.3 Hydraulic model setup

The two-dimensional (2D) hydraulic modelling first requires the input of terrain model and the definition of model projection. The Digital Elevation Models (DEMs) that were produced for each site from the drone based aerial surveys (i.e. conducted in year 2019) were used as the terrain models. The DEMs were imported in RAS-Mapper (plug-in in HEC-RAS®) to create terrain layers. Once the bankfull edge was identified, flow within this area (polygon area defined by upstream and downstream limits of each site and bankfull edge) was simulated using the 2D flow computation algorithms. This involved simulating flow hydraulics across the river channel for each site in grid cells ($< 1\mathrm{m}^2$) that contained computation points on regular interval. The manning's roughness coefficient (n) of 0.04 was assigned to each cell within the areas.

Subsequently, upstream and downstream boundary condition lines were created at both ends of the 2D flow areas to provide boundary condition values for unsteady flow simulation. For the upstream boundary condition (i.e. inflow at the upstream), a hydrograph with gradually increasing flow was applied, whereas normal depth (water surface slope) was applied for downstream boundary condition. For this the water surface slope for each site was measured using the built-in ArcGIS tool in HEC-RAS®.

The bankfull flow was determined at the point when the simulated water level reaches the top edge of the riverbank. Table 3.6 summarises the bankfull flow and water level estimated for each site using the hydraulic modelling procedures mentioned above.

Table 3.6: Summary of bankfull flow for study each site.

Site ID	Water surface slope (Normal depth)	Bankfull flow	Estimated Water Level (meter)	Return Period
Site A	0.008	≈ 20 m^3/s	≈ 1.2	15 year
Site B	0.020	≈ 30 m^3/s	≈ 0.77	20 year
Site C	0.017	≈ 80 m^3/s	≈ 1.44	100 year
Long Semadoh	-	≈ 75 m^3/s	-	100 year

Note: Estimated water level at bankfull is plotted in Figure C.15 to Figure C.17 under Appendix B.

3.4 Results and Discussion

3.4.1 Hydrological regime of the Upper Trusan

3.4.1.1 Flow statistics

Figure 3.11 is the Flow Duration Curve (FDC) for the 22-years period (1999 to 2020), while Figure 3.12 shows curves for each year separately. The long-term median flow for River Trusan at Long Semadoh is estimated to be 3.5 m^3/s . The 90th and 95th percentile (Q_{90} and Q_{95}) represent the low flows and the 5th and 10th percentile (e.g. Q_5 and Q_{10}) represent high flows. The Q_{90} and Q_{95} are 0.3 m^3/s and 0.18 m^3/s respectively whereas the Q_5 and Q_{10} are 21.4 m^3/s and 13.2 m^3/s. Out of the 22 years flow, the maximum and minimum recorded flows were 96.4 m^3/s and 0.1 m^3/s respectively. The flow value corresponding to a 5-year return period event for Upper Trusan is approximately 8.4 m^3/s (20% of chance that this flow will be exceeded in any given year), with a 10-year return period event being approximately equal to 13.2 m^3/s (10% of chance that this flow will be exceeded in any given year).

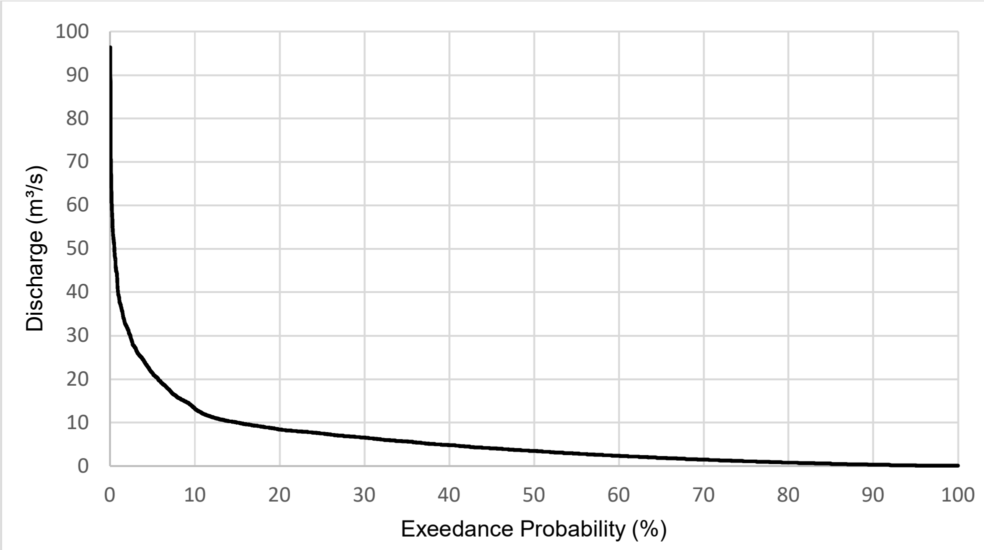

Figure 3.11: Flow duration curve (22 years) for Long Semadoh.

The annual flow duration curves (Figure 3.12) indicate considerable variation in annual flow regimes; e.g. Q_{50} varies from around 2 m^3/s to 7 m^3/s between years, which equates to a threefold difference in the annual median flow. The FDCs show a steep slope at the high flow region (i.e. 5th percentile), which indicates that the River Trusan is characterised by a flashy nature to high flows. This is a very common scenario for upland rivers with small catchment area.

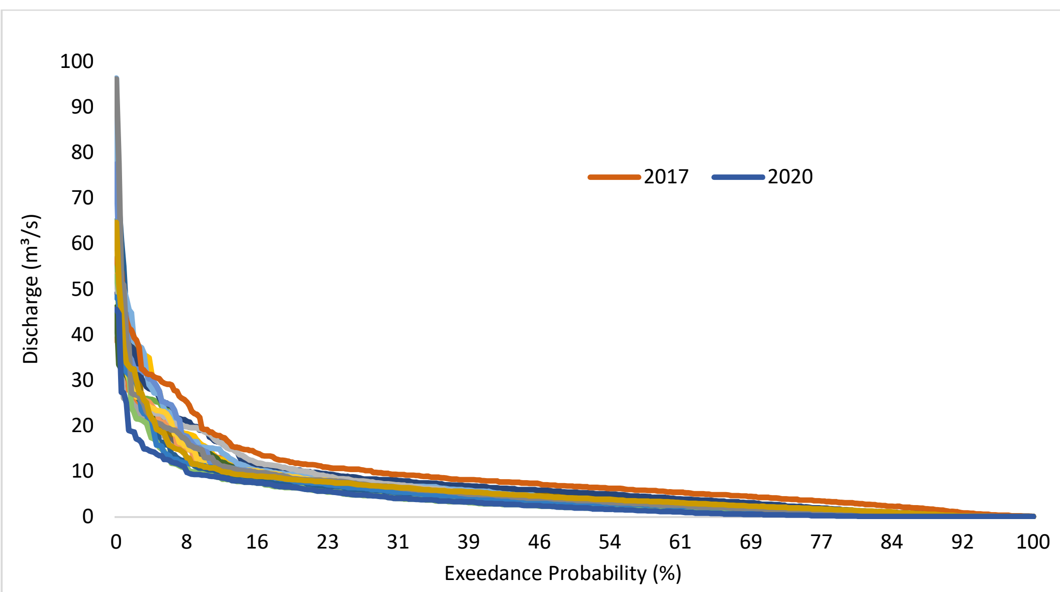

Figure 3.12: Yearly Flow Duration Curve for each of the years from 1999 – 2020 for Long Semadoh. The years with highest (2017) and lowest (2020) median flows are highlighted.

3.4.1.2 Seasonality

The mean monthly flow was plotted (Figure 3.13) to assess seasonality (e.g. wet and dry season) of the Trusan River. It can be seen that the Trusan River has two wet seasons which fall in the periods from November to January, and the period from April to June. These two periods have a higher mean flow (6 m^3/s to 8 m^3/s) compared to the rest of the months. This corresponds to monthly rainfall; e.g. average monthly rainfall from November to January is associated with the monsoon season in Sarawak. However, the probability of heavy rainfall for the months outside of November to January are still very high, and correspondingly. This is where the magnitude of monthly flow in April, May and June is considerably higher than the median (6 m^3/s to 7 m^3/s).

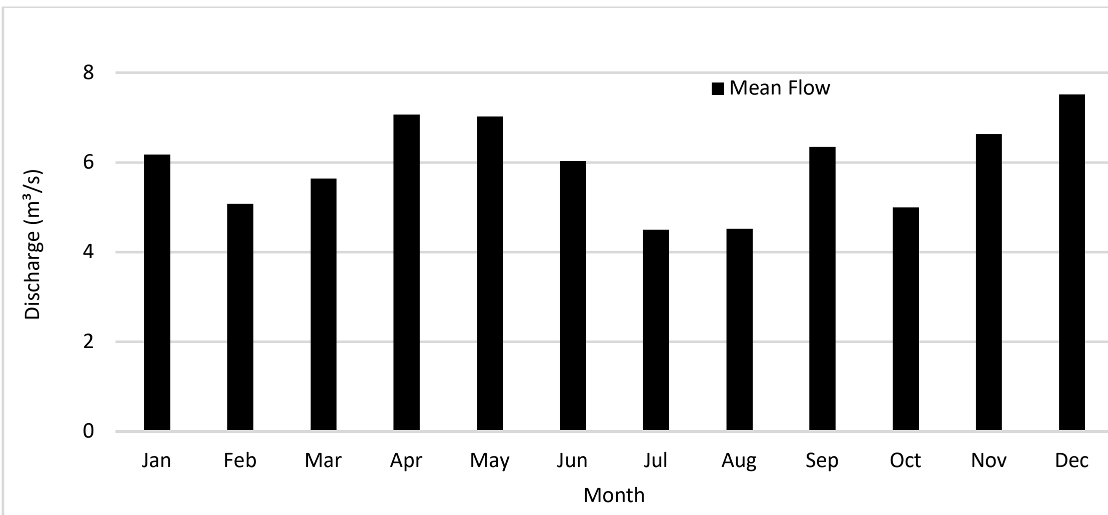

Figure 3.13: Mean monthly flow for period of 22 years (1999 – 2020).

3.4.1.3 Magnitude, timing, frequency and duration of flows

IHA® computes many statistics, but only a subset of these is used here to help describe the flow regime of the Trusan; these were chosen to represent high flows (as a main focus) but also low flows. Flow metrics are categorised into groups which represent the magnitude, timing, duration, frequency of certain types of flow event.

The results from the IHA® software analysis (Table 3.7) indicate that the high flow peak has a mean magnitude of 21.45 m^3/s, and extreme high flow peak has a mean magnitude of 32.45 m^3/s. The mean magnitude of moderate flow was 11.78 m^3/s, which is half of the high flow peak magnitude. The rise rate for the extreme high flow events is higher than the high flow events. This relates back to the steep slope of FDC at the high flow region which is common for small catchments like the Upper Trusan.

Table 3.7: Magnitude of critical discharge.

Flow components	Mean value	Coefficient of dispersion
Extreme low peak (Q)	0.1	0.625
Moderate flow peak (Q)	11.78	0.1561
Moderate flow rise rate (Q/day)	5.4	0.309
Moderate flow fall rate (Q/day)	-1.563	-0.3125
High flow peak (Q)	21.45	0.09557
High flow rise rate (Q/day)	8.95	0.287
High flow fall rate (Q/day)	-3.725	-0.2573
Extreme high flow peak (Q)	32.45	0.1834
Extreme high flow rise rate (Q/day)	14.18	0.3638
Extreme high flow fall rate (Q/day)	-6.447	-0.3241

The timing of annual minimum and maximum discharges is shown in Table 3.8. The results indicate that week 9 (February) is the week of having minimum discharge and week 22 (May) is the week of having maximum discharge. The timing of these annual minimum and maximum discharges reflects the dry and wet months of February and May.

The duration of high flows and extreme high flows is the same (both mean duration of 5 days; Table 3.9). The frequencies of high and extreme high flows in any given year are 3 and 6 respectively.

Table 3.8: Timing of annual minimum and maximum discharge.

Hydrological parameter	Timing	Coefficient of dispersion
Week of minimum	Week 9 (February)	0.4112
Week of maximum	Week 22 (May)	0.3518

Table 3.9: Frequency and duration of critical discharge.

Flow components	Mean (days)	Coefficient of dispersion
Extreme low duration	9	0.708
Extreme low freq. (mean/year)	5	0.45
Moderate flow duration	4	0
Moderate flow frequency (mean/year)	7	0.714
High flow duration	5	0.3
High flow freq. (mean/year)	3	0.667
Extreme high flow duration	5	0.575
Extreme high flow freq. (mean/year)	6	0.833

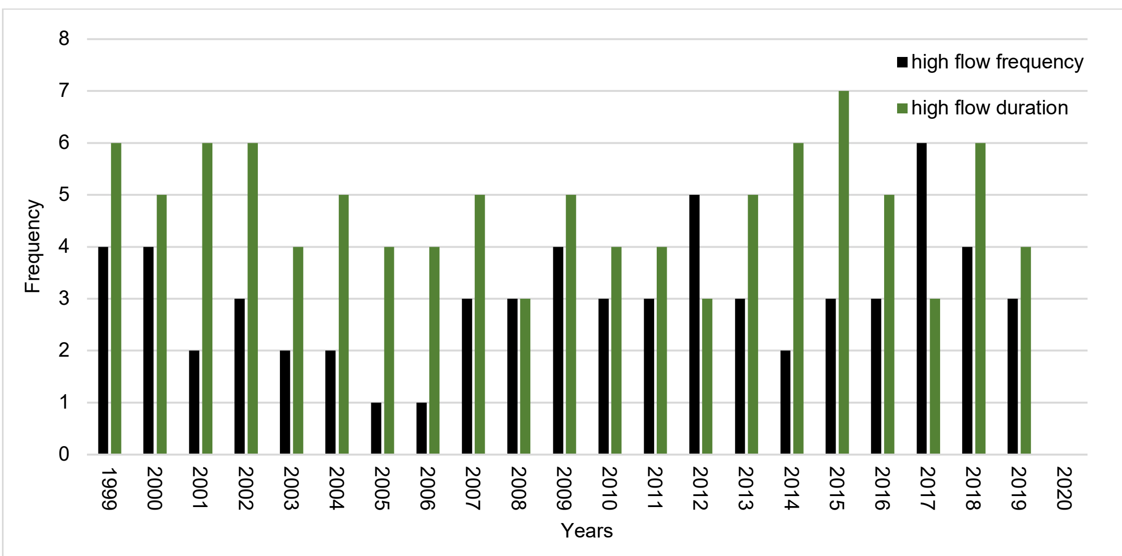

Figure 3.14: Frequency and duration for high flow events. Frequency values are the total number of events each year that flows exceeded the high flow threshold (5 times median); duration is the number of days that these events lasted for.

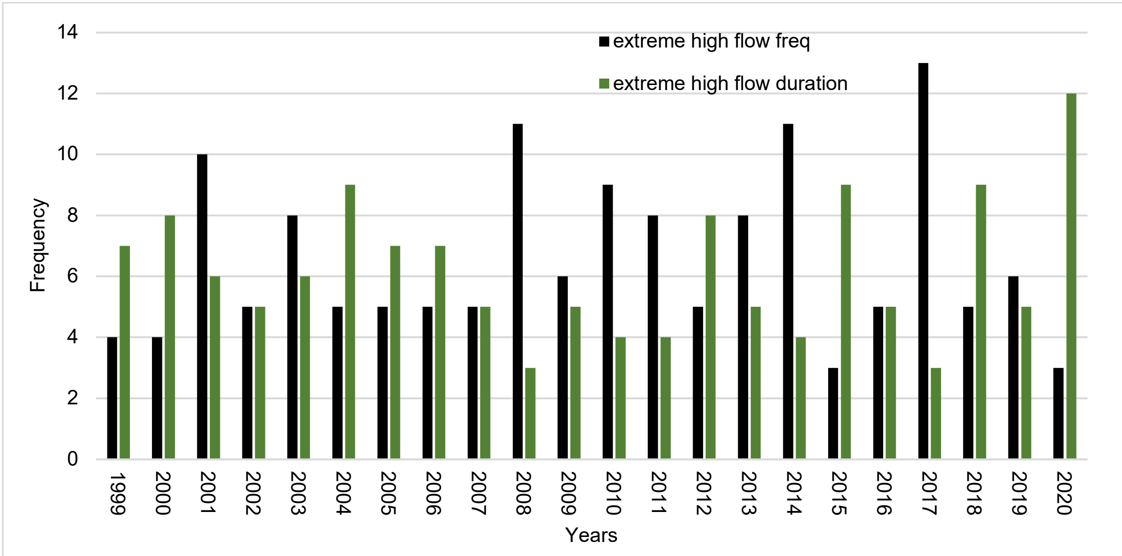

Figure 3.15: Frequency and duration for extreme high flow events. Frequency values are the total number of events each year that flows exceeded the extreme high flow threshold (7 times median); duration is the number of days that these events lasted for.

Figure 3.14 and Figure 3.15 show the time series of the flow frequency and duration of high (5 times median) and extreme high (7 times median) flow events in each year. Frequency of high flow varies from 1 to 6 occurrences, whereas the frequency for extreme flow varies from 2 to 13 occurrences. The average duration for both types of events is 5 days, but this varies between 3 and 7 days for high flow and 3 to 12 days for extreme high flows.

3.4.1.4 Bankfull flow frequency and duration

All the above analyses are based on the hydrograph constructed for Long Semadoh and relate to flow magnitudes etc. at this site. The current section describes patterns separately for Site A and B and focuses specifically on bankfull flow.

Figure 3.16 and Figure 3.17 show the frequency/duration patterns for events at or exceeding bankfull over the 22-year period**.** Site A bankfull was estimated at 20 m^3/s and Site B 30 m^3/s. At Site A, there were around 50 events at bankfull over the 22 years, with these mostly lasting two consecutive days (67% of all events); only one event (2% of all events) lasted 3 days (and event in 2010). Thus, bankfull flows typically last 2 days, with flows receding by the third day.

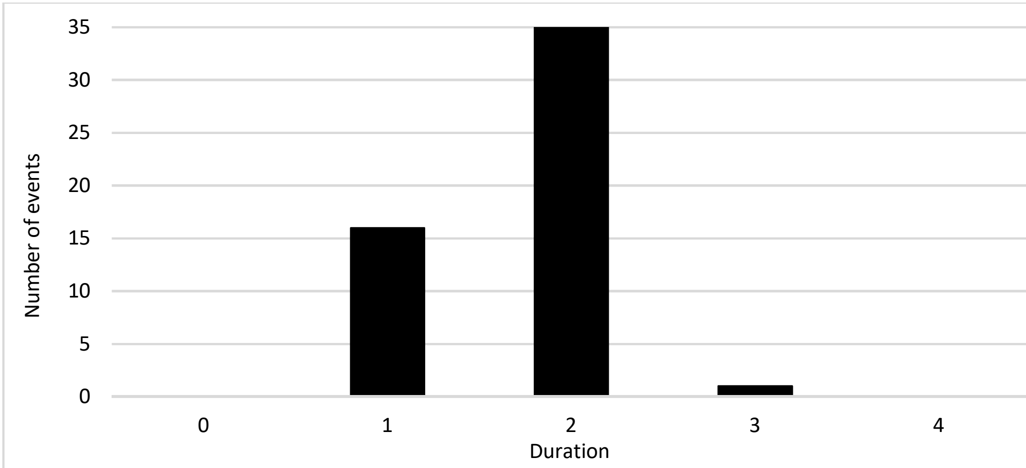

Figure 3.16: Frequency/duration statistics for bankfull flow (20 m^3/s) at Site A.

The frequency of events exceeding bankfull at Site B (Figure 3.17) was much less than at Site A due to the higher bankfull flow and channel size here. Most of the events that exceeded bankfull at Site B lasted for one day (61.5% of all events); 38.5% of the total events lasted for 2 days and no event lasted for 3 days.

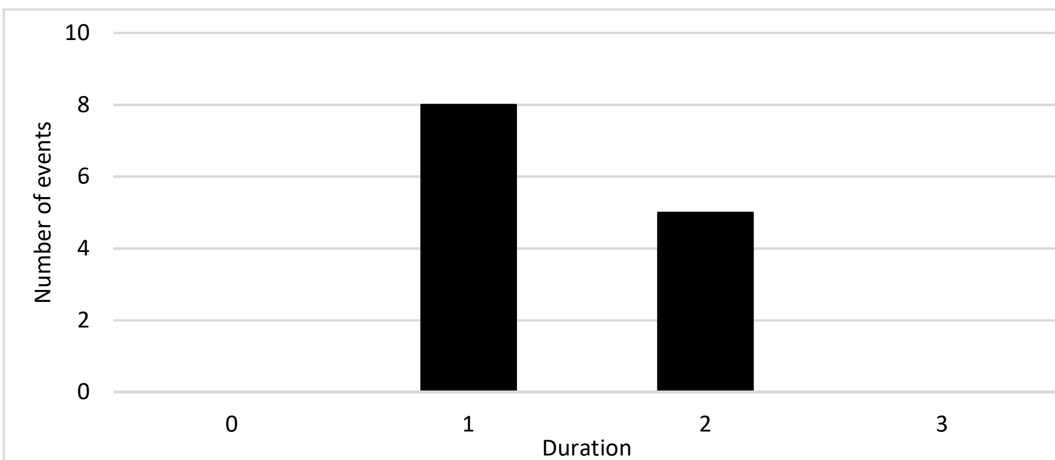

Figure 3.17: Frequency/duration statistics for bankfull flow (30 m^3/s) at Site B.

3.4.1.5 Long-term trends in the hydrological regime of Upper Trusan

Figure 3.18 shows quantile regression modelled for 0.90 quantile (purple line) and 0.99 (red line) quantile of the daily discharges for Long Semadoh. Both of these lines can be considered to represent the upper limits to the distribution of discharges; i.e. 99 percent of all flows are less than quantile 0.99 and 90% are less than quantile 0.9. Quantile 0.99 did not show any significant change over time (p-value > 0.05; Table 3.10). The 0.90 quantile proved to decrease significantly (p-value < 0.05), but the low slope value (-0.00032) indicates that the change over the 22-years period is very small. Thus, the analysis does not provide any evidence of an increase in the upper limits of discharge (i.e. as defined by these two quantiles), and in fact the only change evident is a very limited decrease in the magnitude of Q_{10} over time.

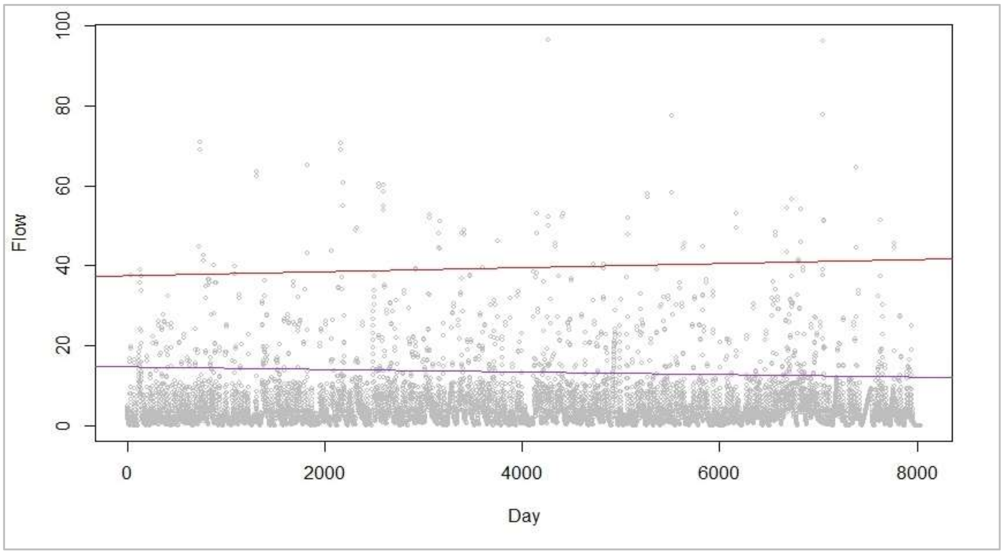

Figure 3.18: Regression line plotted for quantile 0.99 and 0.90 that represent the high flows (m[3]/s) at Long Semadoh.

Table 3.10: Quantile regression output.

Quantile (tau)	Slope	Std Error	T-value	p-value
0.99	0.00052	0.00070	0.74048	0.45903
0.90	-0.00032	0.00016	-2.02497	0.04290

Figure 3.19 shows the principal component analysis (PCA) output in which each year was characterised by its by Q_5, Q_{10}, Q_{50}, Q_{90} and Q_{95} values. The high flow descriptors vary most between years (the longest arrows on Figure 3.19). The 5th percentile (Q_5) and the 10th percentile (Q_{10}) point in opposite directions, indicating that years with high values of one typically have low values of the other. Low flow does not vary much between years (short arrows). Thus, most between year variability in discharge in the Upper Trusan is driven by differences in the magnitude of high flow events.

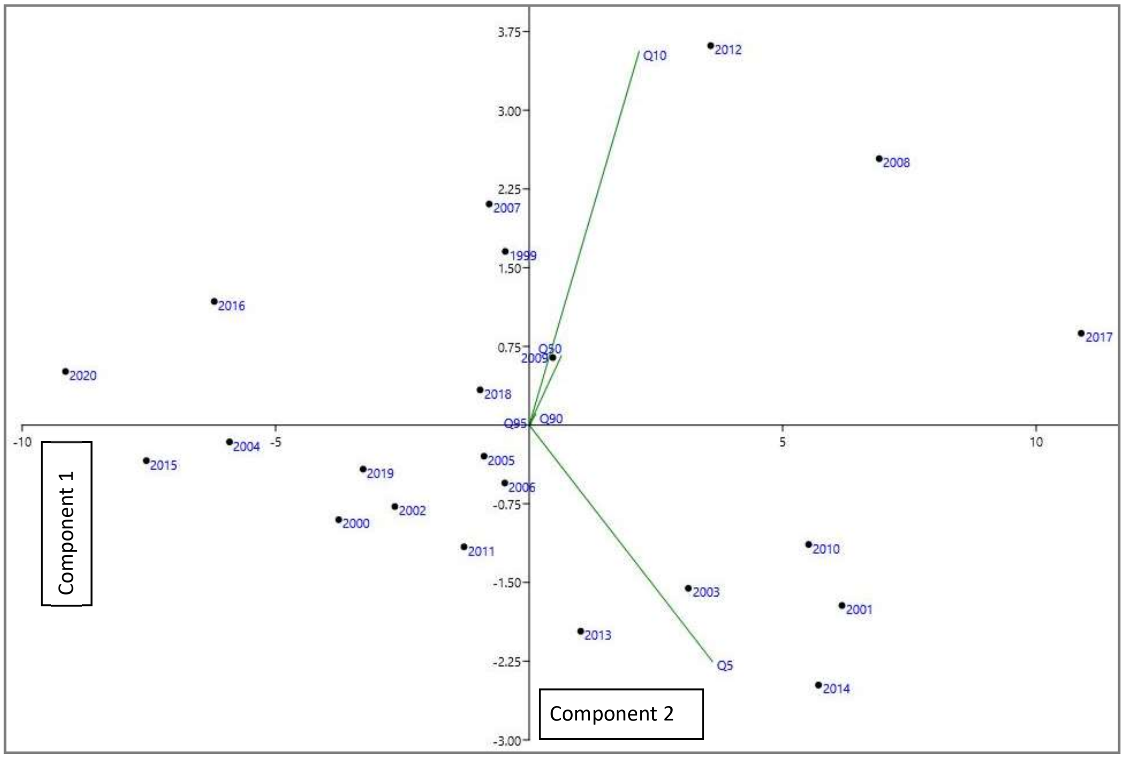

Figure 3.19: Principal component analysis (PCA) diagram of yearly flow exceedance probability.

Since both Q_5 and Q_{10} exhibited marked inter-annual variation, the discharge values for these percentiles were plotted for each year to look for evidence of any trends in high flows. According to the plots (Figure 3.20), the 5th and 10th percentile flow did not exhibit any significant increasing or decreasing trend (p-value > 0.05). This corroborates the findings of the quantile regression – there is no clear evidence of long-term changes in the high flow part of the Trusan hydrological regime.

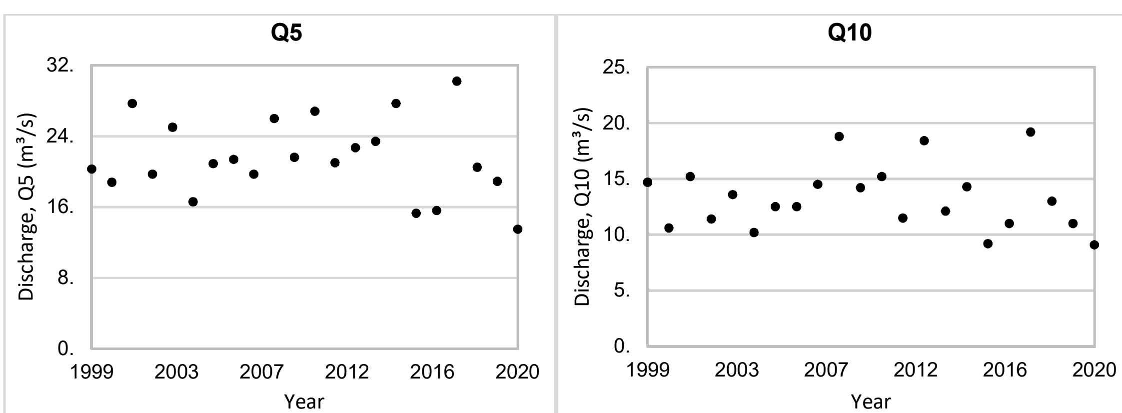

Figure 3.20: Yearly discharge at Q_5 (left) and Q_{10} (right).

3.5 Key points

i. The purpose of this chapter was to develop a hydrograph for the Upper Trusan that could be used to understand the river's flow regime, particularly the magnitude, frequency and timing of the high flow events that potentially cause erosion and flooding.

ii. The modelling work using data from a nearby basin indicated that at Long Semadoh, at the downstream end of the study section, the Upper Trusan has a median flow of 3.5 m^3/s, a Q_{10} of 13 m^3/s and Q_5 of 21 m^3/s.

iii. Bankfull flows estimated at the study sites ranged from 20 m^3/s (upper site) to 75 m^3/s (lower site), with the 22 years' time series indicating that these flows are exceeded for a total of between 1 and 9 days each year; bankfull events lasted no more than 3 days. This sets an upper limit to the period that bank protection measures need to withstand maximum flow forces.

iv. The hydraulic models provide estimates of velocity and shear stress at bankfull that can be used to assess flows forces experiences by bank protection measures.

v. Once coupled with a hydraulic model of the whole study section, the hydrograph constructed for the Upper Trusan can be used to help identify areas that are flooded at particular discharges and help assess reductions in flood peaks that could be created by managed flooding of certain areas. These two elements are the subject of Chapter 5.

vi. The time series analyses provided no clear evidence of any changes in the magnitude of higher flows in the river, or increased occurrence high flows. These analyses were based on a constructed hydrograph that used observed rainfall data and assumed no land cover change. Marteau et al (2018) analysed long-term rainfall data in the Upper Trusan and found no evidence of long-term directional changes. While we know from Landsat data that there has been no extensive land cover change in recent decades, it remains possible that small scale clearance may have caused changes to very localised flooding that are not detectable from the analyses presented here. This is addressed later in the thesis using the SWAT® model (Chapter 6).

CHAPTER 4: POTENTIAL AND CONSTRAINTS OF LOCAL SCALE GREEN MEASURES TO ADDRESS LOCAL RIVERBANK EROSION PROBLEMS IN A REMOTE UPLAND RIVER

Green bank protection measures installed near Long Telingan
Photo: Yih Yoong Lip, February 2021

4.1 Introduction

Climate, land cover, and land use changes have resulted in the increased frequency and magnitude of high river flows in many parts of the world (Kumar et al., 2022). Growing interest in sustainable river management has meant that traditional engineering approaches to reducing the flooding and erosion risks associated with high flows are increasingly being replaced with so-called ‘green’, ‘soft’ or ‘sustainable’ engineering approaches (Biron et al., 2014). These approaches extend from local measures designed to address issues in locations where problems are most acute (Ourloglou et al., 2020; Tardio et al., 2017) to corridor scale measures (Jonoski et al., 2019; see also Chapter 5), and up to catchment scale management typically focussed on the conservation of natural land cover (Golden & Hoghooghi, 2018; Lashford et al., 2022; Wilkinson et al., 2014).

At the local scale, traditional engineering measures to reduce erosion include re-engineering river channels such as widening, over-deepening, sometimes replacing the whole channel with concrete or metal piling (Li & Eddleman, 2002), and using gabions for bank protection (Henderson & Douglas Shields, 1994). However, these measures are nowadays regarded as dissatisfactory from an ecological perspective (Wohl et al., 2015). Moreover, while concreting an eroding bank may reduce erosion in situ, it neither reduces flow magnitude nor dissipates any river energy and often results in a situation where the problem is exported to downstream sections (Brookes, 1985). Various hard in-stream engineering structures, typically called hydraulic ramps, are capable of dissipating river energy (Korpak et al., 2021), but these also create ecological problems (e.g. barriers to fish migration; (Plesiński et al., 2021).

To avoid such issues, green bank protection measures have now been applied in many areas to protect banks from erosion. These typically involve using natural materials which provide protection from flow forces and help dissipate energy (Barkdoll et al., 2004; Rey & Burylo, 2014); they include live fencing, brush walls, and brush mattresses (Douglas et al., 2008; Hook et al., 2009; Schmitt et al., 2018). These measures are often used as part of river restoration or rehabilitation initiatives. However, many examples of their use are in urban or suburban areas, or in middle and lower parts of catchments where the loss of riparian vegetation has caused erosion, while they are also used in tidal sections (Halajova et al., 2019; Krymer &

Robert, 2014; Petrone & Preti, 2010). In these settings, green measures have proved successful in reducing erosion, including in tropical regions. For example, Singapore and Nicaragua have significantly reduced erosion in meanders by adopting such measures (Liao, 2019; Lim & Lu, 2016; PUB, 2018), with additional benefits related to how plants used for stabilisation not only enhance slope stability but trap fine sediments (Petrone & Preti, 2010); such measures also enhance riparian habitat quality which has biodiversity benefits, and can improve in-stream water quality (Janssen et al., 2019; Li et al., 2006).

High rates of forest clearance in upland tropical rivers threaten river integrity because of flooding, bank erosion and increased fine sediment loads (Luke et al., 2017; Umar et al., 2018). However, in many upland areas, local communities are heavily reliant on river floodplain agriculture for livelihoods (e.g. Bario, Sarawak). Consequently, the often-dramatic erosion of riverbanks results in an economically significant loss of productive land (Tripathy & Mondal, 2019) in remote rural areas. The use of green bank protection measures to reduce erosion in such areas is attractive from ecological and social perspectives, key challenges are that measures must resist hydraulic forces associated with the frequent high flows that characterise upland tropical rivers, and that remoteness may mean that measures need to be installed without the benefit of heavy machinery (Petrone & Preti, 2010). Given these possible constraints, assessments of opportunities and constraints on green bank projection measures in upland tropical rivers are needed to help assess their utility as part of the sustainable river and catchment management.

Local communities in the Upper Trusan Catchment, a remote area on the border between Malaysia and Indonesia, have reported increased riverbank erosion. A walkover survey conducted in 2018 found that approximately 30 % of the riverbank length (extending from Puneng Trusan to Long Semadoh; see Figure 4.2) suffered from high to severe erosion (Marteau et al., 2018). However, no assessment of the rates of retreat has so far been undertaken, so no evidence is available to support the claim of an increased rate of bank erosion.

This chapter uses remote sensing data to assess the magnitude of historical bank retreats in the upper Trusan and uses this information to inform decisions about where green bank protection measures should be prioritised and installed. Various green bank protection measures were then trialled and their success in reducing erosion was evaluated using follow-up surveys. These were implemented as an immediate remediation measure to tackle localised riverbank erosion in problem areas and were conceived as part of a suite of measures that looked at the development of solutions at the river corridor (Chapter 5) and catchment (Chapter 6) scale. The overall aim of the work described in this chapter was to assess which measures work best in the Trusan and understand the factors contributing to any observed differences in success.

4.2 Study area and context

The study area was described in detail in the introductory Chapter 1. The river in the study area (Figure 4.1) is generally small, with a channel width of 10 to 30 meters and a gradient (slope of 1.3 %). The study is delimited at its downstream end by the village of Long Semadoh; the study section extending from here to the uppermost end has a total length of 10 km. The 'Upper Trusan' – i.e. upstream of Long Semadoh - has a catchment area of 140 km^2. Within this area, local communities rely on river floodplains for rice paddy farming, fishing, and livestock farming to sustain their livelihoods. However, due to frequent flooding and erosion, the increasing rate of land loss and flood damage are increasingly threatening the livelihood of the local community.

The catchment is subjected to high rainfall throughout the year due to its tropical climate. The total annual rainfall recorded at the nearest rainfall station (i.e. Long Semadoh station) has a mean of 2528 mm, and the rainfall intensity is generally high. However, there is no flow gauging station available in the upper part of the catchment, which hinders the understanding of the hydrological regime of the river. Hence, a rainfall-runoff model was developed (see Chapter 3) to reconstruct the hydrograph for the Upper Trusan. Key insights from the hydrograph, such as flow magnitudes, timing, and high flow duration, served as a fundamental support for developing mitigation plans and measures for flooding and erosion.

Historically, the local community (supported by logging concessionaires who have heavy machinery) has installed gabions to tackle erosion in certain areas and some sections have been canalised. However, these interventions were not successful and, accordingly, WWF and Nottingham became involved to look at and tackle the problem in a different way.

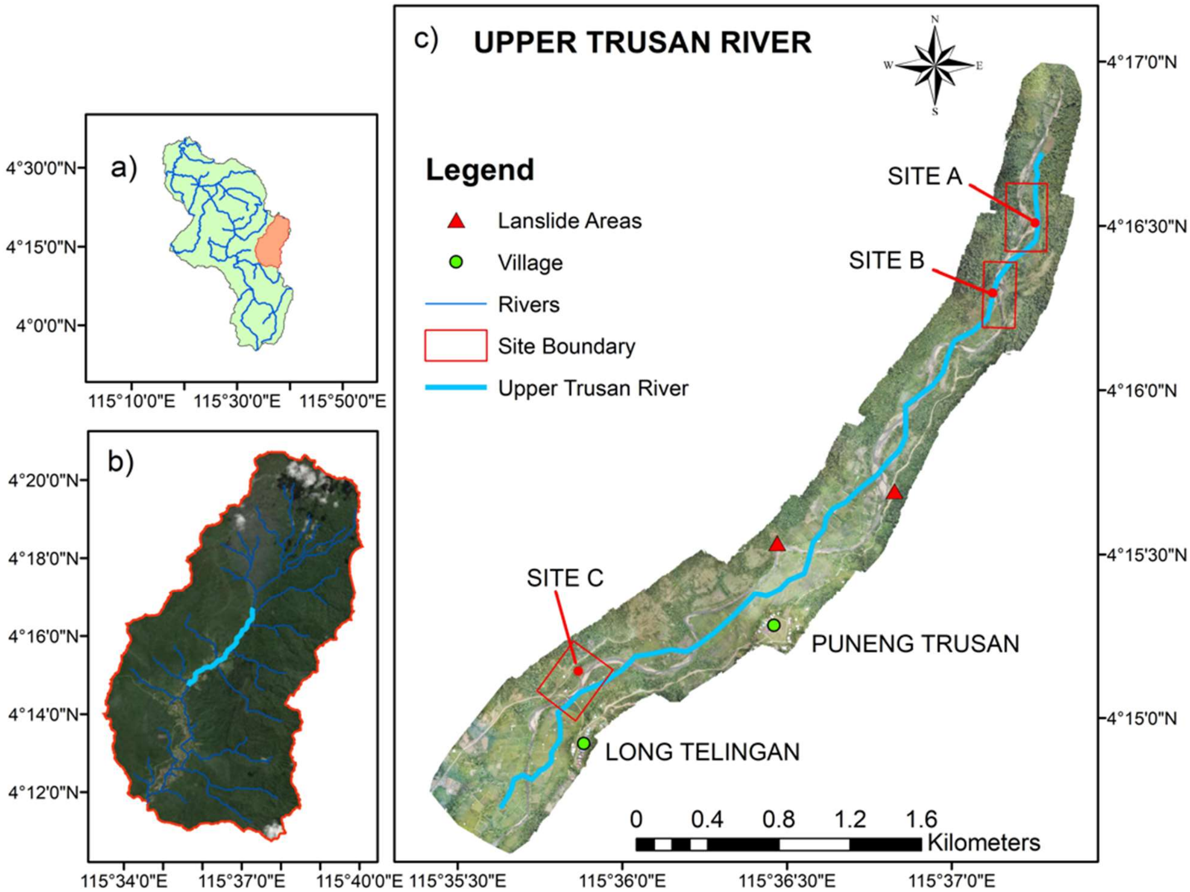

Figure 4.1: a) Main Trusan Catchment b) Upper Trusan Catchment (sub-catchment of the main catchment) c) Study Sites at The Upper Trusan River.

In 2018, preliminary studies on the causes of flooding and erosion were carried out (Marteau et al., 2018) and several general recommendations were made. One recommendation was to trial local scale 'green measures' such as brush mattress, live fencing, and coconut geotextile mattress to help reduce erosion in the most problematic areas. The selection of sites for these measures was based on the assessment of erosion (described below) but importantly also based partly on discussions with the local community. The community discussions helped us identify eroding locations that they felt should be prioritised because of factors such as individual community members whose sole source of income was a paddy area that was being lost to erosion.

The first installation of green measures commenced in June 2019 at Site A, followed by Site C, and Site B. With the cooperation and manpower of the local community, the installation of the green measures was completed within a four-month period. A geomorphic survey (based mainly on 3-D models developed from UAV imagery) was undertaken upon completion of installation at each site, serving as a reference point for subsequent monitoring. Full details are given below.

4.3 Methods

4.3.1 Identifying planform changes and historical bank retreat using satellite imagery

Satellite images were used to assess the planform changes and historical bank retreat (1988-2021) to help understand the magnitude and nature of observed bank erosion in the Upper Trusan. The satellite images were acquired from Google Earth Engine® (GEE), as shown in Table 4.1. The satellite images dated 2016 and 2021 were taken from Sentinel-2; the images dated 1988 and 2014 were taken from Landsat-5 and Landsat-8 respectively. The satellite image dated 1988 was the oldest in the Landsat-5 dataset. The Sentinel-2 satellite image has a resolution of 10 m x 10 m, while the Landsat-5 and Landsat-8 satellite images have a resolution of 30 m x 30 m.

Table 4.1: Summary of data used to assess planform change and bank retreats.

No	Data	Year	Resolution	Source
1	Sentinel-2 MSI Level 2A Surface Reflectance	2016, 2021	10 m x 10 m	Copernicus Sentinel-2
2	Landsat 5 TM Collection 2 Surface Reflectance	1988	30 m x 30 m	GEE LANDSAT-5
3	Landsat 8 OLI/TIRS Collection 2 Surface Reflectance	2014	30 m x 30 m	GEE LANDSAT-8

Firstly, we illustrated general changes in channel planform across the 33-year period (from 1988 to 2021), with specific satellite images representing 1988, 2014 and 2021 used in the analysis. Any changes in sinuosity and noticeable migration were determined with reference to the channel line. For this, we will particularly look at the changes in the upper, middle, and lower section (Figure 4.2).

Secondly, two sets of satellite images were used to assess bank retreat for the whole study section continuously. One used Landsat satellite images captured in 1988 and 2014, and the other used more recent satellite images captured by Sentinel-2 dated 2016 and 2021. However, the resolution for the old images from Landsat Satellite is only 30 metres, which implies that any changes under 30 m between 1988 and 2014 could not be detected. For more recent images from Sentinel-2 Satellite, the resolution is at 10 meters, so only changes of more than 10 meters over the 5 years period are detected.

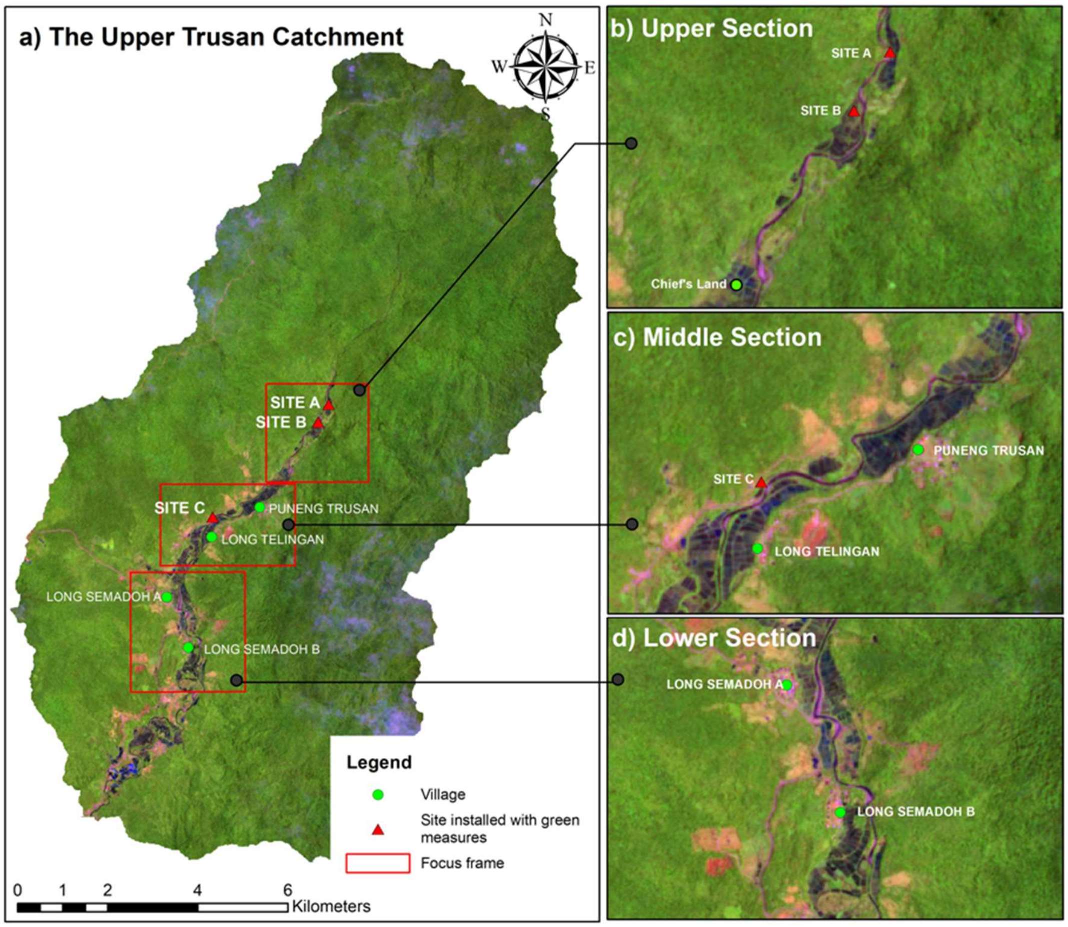

Figure 4.2: Map of the Upper Trusan Catchment on the left. The focus frames of the upper, middle and lower sections are portrayed on the right.

For Landsat satellite images, a band combination of 6, 5, and 2 was used for the red, green, and blue channels, respectively, to distinguish water and land. However, Landsat satellite imagery with coarse resolution at 30 meters created a challenge in identifying the bank line. As a result, the channel line was delineated based on the blue pixels representing the river channel instead of the bank line. The temporal changes between channel lines were identified as bank retreat.

For Sentinel-2 satellite images, a band combination of 12, 8, and 3 was used for the red, green, and blue channels. At 10-meter resolution, the river channel and land were visible, and the bank line was delineated following the edge of the river channel. The channel and bank lines were delineated using the ArcMap® tool, and bank retreat was measured using a measurement tool under the condition of the same spatial projection.

4.3.2 Installation of Green Measures

The implementation of green measures consisted of three phases: conceptualisation, coordination, and installation. In the conceptualisation stage, various types of green bank protection measures were selected for different sites to provide an opportunity to assess their relative effectiveness in the Upper Trusan River.

The choice of measures to trial was based on published literature, mainly based around evidence of techniques that have been widely used in America and some European countries and which on this basis were considered potentially successful in the Trusan (i.e. some measures used in lowland rivers were clearly not appropriate in the Trusan). These remediation measures are often called ‘bioengineering’ or ‘biotechnical’. They commonly serve as nature-based solutions to river management initiatives. Due to the limited availability of machinery and access roads in the Upper Trusan, we recognised that the design of green measures needed to be simple and use local materials. The selected green measures for the Trusan River were brush walls, bamboo fencing, geotextile mat and rolls, and brush mattress (Table 4.2).

The coordination stage involved logistic arrangement, materials collection, and organisation of manpower. Most materials for green measures, such as bamboo, wood logs etc., were collected locally. The local community suggested specific plants and materials since they were knowledgeable about the availability and traits of species in the area (e.g. fast-growing species, deep-rooted species etc.). All were chosen as being native species. Synthetic coconut fibre geotextile rolls and matting (see below) and materials for anchoring, such as steel rebar, were acquired from suppliers. The local community was the primary manpower for the installation of green measures, along with the University of Nottingham and WWF staff involved in the project. Because no heavy machinery was available to grade riverbanks, we fitted the design to match the circumstance at each of the chosen sites. Thus, where banks were vertical, we fitted a brush wall (at Site A), but where they were already graded because of previous (failed) engineering, we installed a brush mattress (Site C).

The installation of green measures took part at one site at a time according to the scheduled plan, as shown in Table 4.2. The schedule revolved around the availability of the local community and the timing of the wet season – i.e we worked during dry periods and when local community members were not busy with other activity related to rice production. This is a critical point and is discussed later. The brush wall was first installed at Site A in June 2019, followed by brush mattress at Site C. Then, bamboo fencing was installed at Site B in July 2019.

Just as we were about the commence these works, one member of the local community (to protect his property) engaged a logging concessionaire to come and canalise part of one of the sites (Site C). The excavated material was used to create a high flood embankment on the true right bank. However, this was not planted or covered to stabilise it in any way, so was likely to be quickly undermined and eroded. We, therefore, used some of the project funds to purchase geotextile matting and rolls to help stabilise this slope. These were installed at Site C (true right bank) in September 2019.

Table 4.2: Date of installation of various types of green measures at different study sites

Village	Site Name	Paddy Field Owner	Type of Installation	Date of Installation
Puneng Trusan	Site A	John Ating	Brush wall	12-13 June 2019
	Site B	Labo Ating	Bamboo fencing	22-23 July 2019
Long Telingan	Site C (Right)	Balang Dawat	Geotextile mat & rolls	23-25 September 2019
	Site C (left)	Baru Dawat	Brush mattress	14-15 June 2019

The brush mattress and brush wall are shown in Plate 4.1. Both are similar measures built on eroded banks to serve as immediate protective layers and to dissipate river flow energy. The brush mattress was laid flat at the true left bank of Site C, where the bank slope was most gradual, while the brush wall was built vertically at the true left bank of Site A, where the bank slope was vertical. The primary materials for the wall and mattress were live cuttings, with wooden logs and bamboo used to provide supporting frameworks to fix the measures in place.

For the wall, the frame structure was first built with bamboo, and each joint was tied together in the form of diagonal lashing. Once positioned the frame was firmly driven into the riverbed at the bank toe, and strings were tied to the frame to support the vertical wall (see Plate 4.1: right). Some soils were partially used to fill the gaps between the bank and brush wall to ensure good soil contact. Branch cuttings were laid perpendicularly to the river flow on top of the bamboo frame. Leaves and twigs were used to fill the gaps between the cuttings until the bank was barely visible. For the brush mattress, live materials were placed across the slope to cover it completely, with the frame then dropped over this and secured with wooden posts (see Plate 4.1: left). The brush mattress and wall allowed an assessment of the appropriateness of measures on sloping and vertical banks respectively in the Upper Trusan.


Plate 4.1: Brush mattress installed at the true left bank of Site C (left) and brush wall installed at Site A (right).

To compare with the brush wall, bamboo fencing was installed at the true right banks of Site B as shown in Plate 4.2 (left). The eroded bank was almost vertical at this site (as with the site where the brush wall was installed), with a bank height of 1 to 2 meters. The fencing was made of bamboo poles arranged in rows to form a fence-like structure. Bamboo poles were driven into the bank to anchor bamboo rows to the bank forming a fence across the bank. The original design was for live bamboo to be used but this did not happen in practice – older, non-living bamboo that the community could more easily access was used.

Coconut geotextile matting was installed last at the true right bank of Site C, as shown in Plate 4.2 (right). This site was partially intervened with embankment and regrading at the bank slope. The channel width is wider here compared to Site A and Site B, with a bank height of approximately 3 meters. Coconut geotextile matting was laid on the embankment to reduce soil loss and rolls were placed along its base as toe protection. The initial plan was to revegetate the protected bank with seedlings and live cuts. However, due to the constraints of time and manpower, the bank was not revegetated.

Plate 4.2: Bamboo fencing at Site B (left), Coconut geotextile mat installed at true right bank of Site C (right).

4.3.3 Evaluation of the success of green bank protection measures

To evaluate the success of green bank protection measures, regular repeat surveys were planned in the form of walkovers and aerial surveys following installation. Surveys were conducted from installation (June 2019) up until March 2020. However, due to the Covid-19 outbreak, the movement control order (MCO) implemented in Malaysia prevented further repeat surveys. During a lengthy period of travel restrictions, the local communities kept us updated about any damage or washout of measures. Some photos were taken by them, capturing evidence of high flow and post-flood conditions, but the planned repeat surveys were not possible until the very end of 2021, with the first opportunity to visit the site being in December 2021. Between installation and the December 2021 survey, two large floods occurred, providing an opportunity to assess the resistance of the measures to these (timing indicated in Figure 4.3).

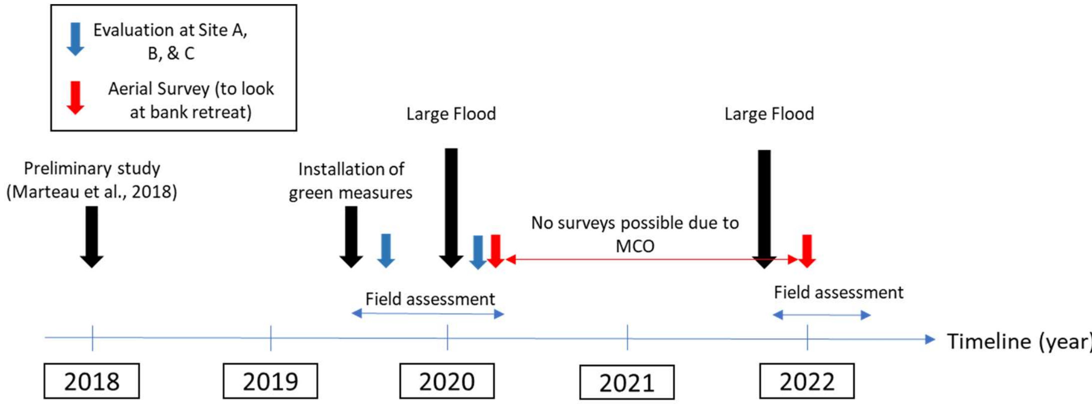

Figure 4.3: Timeline of the study period with key events

In the field surveys, evidence such as erosion and bed scouring were recorded in the form of photographs, and the potential causes of failure or success were documented. At the same time, aerial surveys were conducted to produce reach-scale orthomosaics and Digital Elevation Models (DEMs) for each site. Successive orthomosaics were compared to illustrate and quantify the overall geomorphological change within the channel in response to the high flows and, in particular, to assess the rates of bank retreat at each site that resulted from these flows.

The field data collected were coupled with hydraulic models (see below) to help understand the reasons for successes and failures. Hydraulic models were developed to estimate hydraulic forces exerted on the measures (see section 4.3.6).

4.3.4 Aerial survey setup and data collection

Orthomosaics were used to monitor bank retreats for each site after the installation of green measures. An orthomosaic is sometimes called an orthophoto, orthoimage or orthophotograph. It is an aerial map geometrically rectified and stitched from a series of individual images on which the scale is uniform. A georeferenced orthomosaic can be used to measure actual distances precisely, hence changes in the position of a riverbank. Throughout the study period, DJI® Mavic Pro was used to perform UAV flights and to capture aerial images. The drone has a 3-axis gimbal camera with a CMOS® sensor and 12.35 Mega Pixel maximum resolution. The images were captured in jpeg stills during the drone flight, setting the highest resolution (i.e. 12.35 MP). The ISO was set to auto mode to allow optimum exposure and motion blur in the images. The ISO varied from 100 – 1600 depending on light conditions.

In order to avoid errors related to water surface reflection and glare in submerged areas, the flights were undertaken in overcast conditions. Nevertheless, water glare cannot be entirely avoided in every image due to variations in cloud cover resulting in a slight difference in exposure and colour. To minimise this, images used for a mosaic were captured in a single short round for each site to ensure similar conditions in images (as per Marteau et al., 2018). In the first UAV survey carried out at Site A, and C, the drone was piloted and controlled manually at a constant height and optimum speed for the entire flight. The drone was flown in a zig-zag pattern along the riverbanks to capture images with overlapping areas. This flight path optimises image overlapping for producing 3D point clouds and Digital Elevation Models (DEMs). Due to the subsequent availability of new software (Pix4D Capture®), the flight paths in the following aerial survey were pre-programmed. The application allowed us to program the flight path according to the designated path and set the altitude, camera angle and speed to optimum values.

4.3.5 Georeferencing Orthomosaics and Digital Elevation Model (DEM)

The orthomosaics and DEMs generated for each site were georeferenced using fixed Ground Control Points (GCPs). GCPs are reference points on the earth surface that have known geographic locations, which are often used for precision UAV mapping to deduce positional uncertainty in Structure-from-motion (Sfm) photogrammetry. In the Upper Trusan, we used laminated A4 size paper with large crossed markers at the centre as GCPs. They were placed evenly on the ground and spaced strategically across the whole perimeter of each monitoring site. The position of GCPs was surveyed with a Topcon® HiPer Ga/Gb using Real Time Kinetic (RTK) setup, in which Ga and Gb were denoted as base and rover, respectively. The horizontal accuracy of the measured coordinates had a minimum accuracy of 10mm, while the vertical dimension had a minimum accuracy of 15mm.

GCPs were imported to the mapping software (Pix4d®) to position the orthomosaic accurately and DEM in real-world space. Some of these GCPs were assigned as Check Points (CPs) to assess the positional errors of the orthomosaic maps and DEMs. Pix4d® created a mosaic by looking for matching points in images. This mosaicking process can introduce some errors, as not all points may match perfectly. Thus, this error can be reduced by adding the GCPs to represent the real-world coordinates of some points. The accuracy of the reconstruction is controlled by the configuration, number, and location of GCPs, but the gain in accuracy is little by adding more GCPs. According to an analysis done by the manufacturers of Pix4d, the optimum number for GCPs is approximately 5 to 10 for an area of 34 acres. All our mosaics cover less than 10 acres, and we have an average of 10-15 GCPs in each one.

The survey network formed the basis for all assessments of change in planform, cross-sectional shape, and long profile of the sites, as determined from the DEMs. Initial estimates produced by Pix4d® suggest that errors for X, Y, and Z are 5 - 10 cm. This magnitude is acceptable for our work which focuses on assessing bank erosion and general channel change (e.g. gradation, scour); e.g. rates of annual bank retreat in the order of metres were estimated by Marteau et al. (2018), while median bed sediments are in the range of 32-128 mm.

4.3.6 Hydraulic model construction

Two-dimensional hydraulic modelling was undertaken to estimate bankfull flow and flow hydraulics the sites. This used the Hydrologic Engineering Center's River Analysis System (HEC-RAS®), free software developed by the U.S Army Corps Engineers (2018). The modelling focussed on bankfull flow and helped to understand the interaction between flow hydraulics (e.g. velocity and shear stress) and bank erosion at this high flow, as well as the frequency of overbank flows. New hydraulic models were built for Sites A, B and C using the DEMs produced as mentioned above. DEMs are shown in Figure B.6 (Appendix B).

The bankfull flow refers to the discharge that reaches the transition between the channel and the floodplain before overflowing the bank edge. It is essential to determine the bankfull discharge to identify how often the river overtops its banks, and so inundates the floodplain. This flow is also a critical discharge for the riverbank protection measures as the hydraulic forces exerted on the banks are likely at their maximum. Hence, the flow hydraulics at bankfull were computed using the hydrodynamic model to help identify and estimate the flow forces during maximum channel flows. This model also allowed computation of velocity and shear stress at bankfull flow. The estimation of bankfull flow for each site was mentioned in Chapter 3; two-dimensional maps and cross-sectional profile were used to visualise hydraulic flow conditions at bankfull and identify areas where velocity and shear stress are maximised.

4.4 Results

4.4.1 Planform changes and historical bank retreat

The Trusan is a dynamic river, with dynamism evident by channel changes that happened over the course of the period for which the satellite images were obtained. Planform changes in the upper section of the Upper Trusan River is shown in Figure 4.4, followed by the middle and lower sections in Figure 4.5 and Figure 4.6 respectively. Generally, changes within the channel are evident in channel planform at different places and times, resulting changes in sinuosity and migration of channel across the floodplain.

For the upper section, changes were most notable in the lower part, where the meanders were straightened out. The meanders in 1988 shifted by approximately 90 meters, forming a straighter channel in 2021. However, the changes at the other locations were less significant, with a change of fewer than 30 meters.

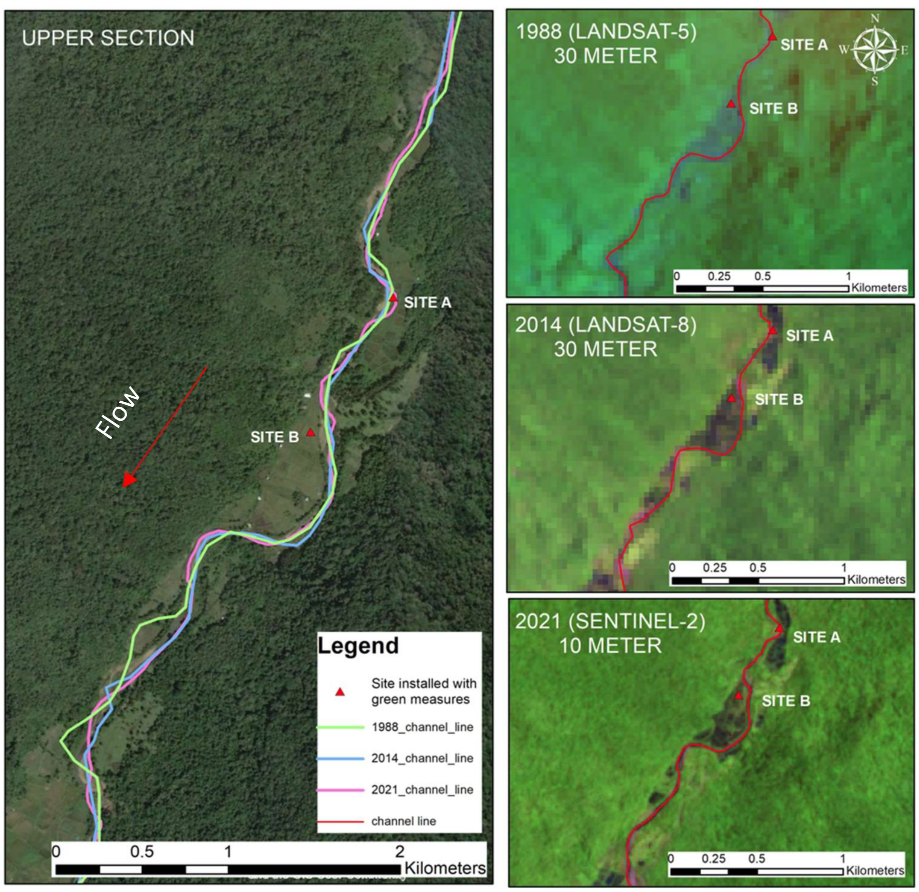

Figure 4.4: Channel evolution at the upper section of the river from 1988 to 2021. The channel line was delineated based on the channel in each respective satellite image (images on the right).

For the middle section, no major planform changes occurred and of most channel near Puneng Trusan remained stable. The changes were within 30 meters, most of which occurred at the outer bend of the meanders.

Several locations were changed for the lower section, with more than 30 meters of shifts between 1988 and 2021. At the section near Long Semadoh A, the channel line varies between 1988, 2014 and 2021. According to the communication with the local community, this section was frequently subjected to erosion. In 2014, it is noticeable that the channel (blue line) meandered to the true left bank. However, the shift from 2014 to 2021 was due to channelisation work in 2019, where the local community decided to protect the bank using hard engineering solutions. There was also a major change at the section near Long Semadoh B, where the meander was more obvious in 2021 but straightened immediately below.

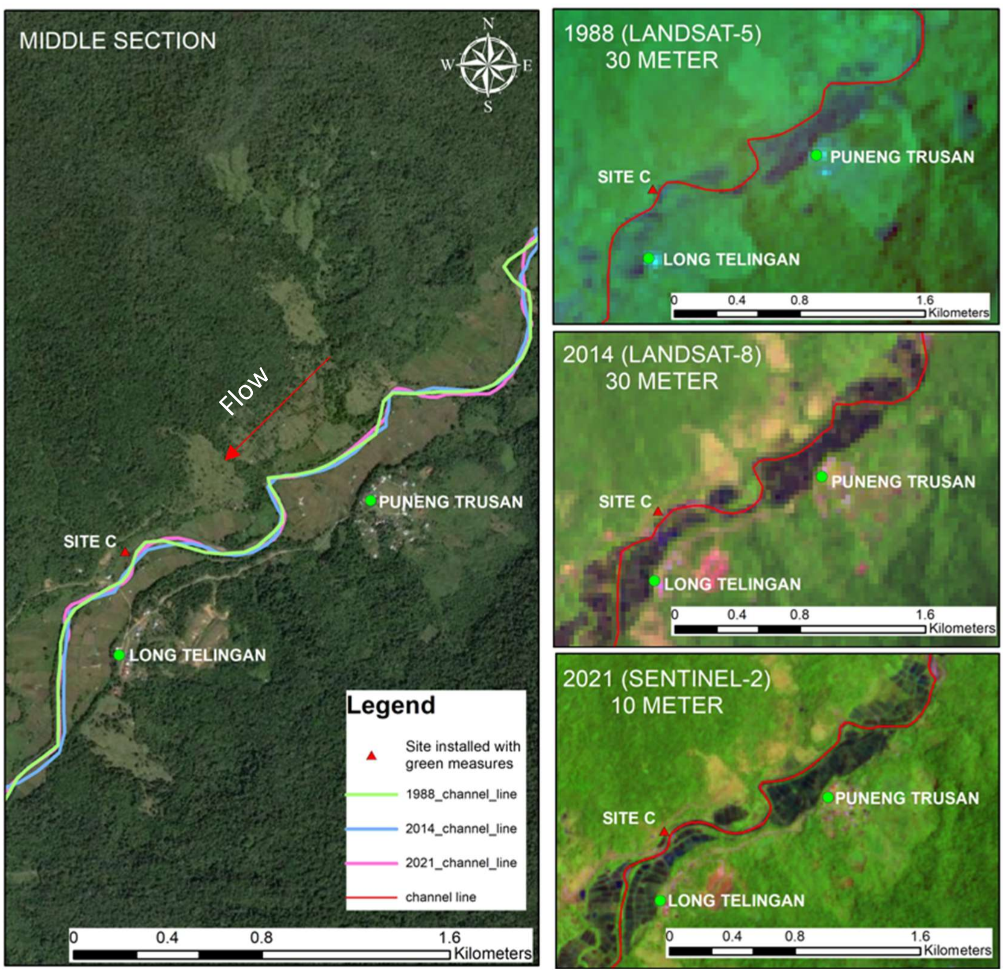

Figure 4.5: Channel evolution in the middle section of the river from 1988 to 2021. The channel line was delineated based on the channel in each respective satellite image (images on the right).

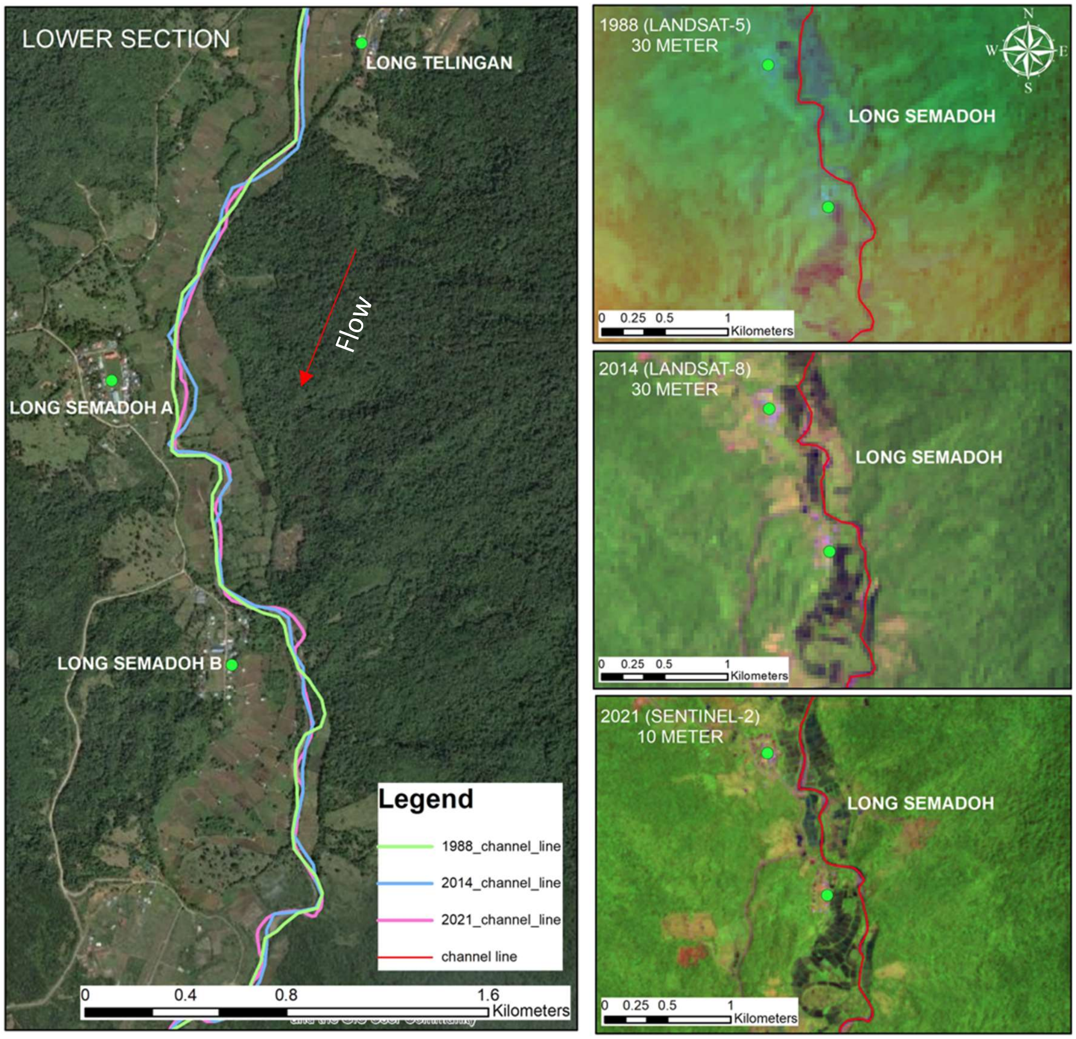

Figure 4.6: Channel evolution in the lower section of the river from 1988 to 2021. The channel line was delineated based on the channel in each respective satellite image (images on the right).

The areas of bank retreat observed between 1988 and 2014 is shown in Figure 4.7. The analysis suggests that an average of 2.3 meters of the riverbank was eroded yearly in affected areas, with a maximum detectable bank retreat of 95 meters observed between 1988 and 2014. The highest rates of bank retreat (ranging from 82 to 95 meters) were observed at the section near Long Semadoh, and between Site B and Puneng Trusan. In contrast, the bank retreat at Site A and Site B were minimal, with changes less than 30 meters. Overall, patterns suggest the upper and lower part of the river section were subjected to more bank erosion.

The bank retreat observed between 2016 and 2021 is shown in Figure 4.8. In average, the bank retreat from 2016 to 2021 was considerably higher than that between 1988 to 2014. The analysis indicated that an average of 6 meters of the riverbank was eroded annually in affected areas, with a maximum detectable bank retreat of 44 meters between 2016 and 2021. A Bank retreat of 44 meters occurred at the river section below Long Semadoh. The results also suggested a higher amount of bank retreat at Sites A, B, C than over the 1988-2014 period, with bank retreat that ranges from 10 to 30 meters. Notably, the bank retreat at the section between Site B and Puneng Trusan was notably high. This suggests that this section was consistently vulnerable to bank erosion over the 33 years from 1988 to 2021.

Figure 4.9 and Figure 4.10 summarise information on the extent of bank retreat. Values show the percentage of riverbank length in the study section (along both banks) that experienced detectable retreat over the two periods. Between 1988 and 2014, 4.72% of the bank length experienced bank retreat of 30 to 45 meters and 3.71% experienced bank retreat of 45 to 60 meters. Other areas experienced more severe erosion, with 4.67% of the riverbanks experiencing a bank retreat of at least 60 meters. Between 2016 – 2021, 3.75 % of riverbanks experienced 10 to 20 meters bank retreat, and 4.83 % of riverbanks experienced 20 to 30 meters bank retreat. In 5-years period, less than 2 % of riverbanks were observed with retreat more than 30 meters.

Overall, the analysis of satellite images suggests that a minimum of 10-12% of bank length in the study area experienced erosion that was severe enough to be detectable in these low-resolution images. Comparison of the average retreat over the two periods support local communities' views of an increase in erosion, and hence concerns over loss of paddy land.

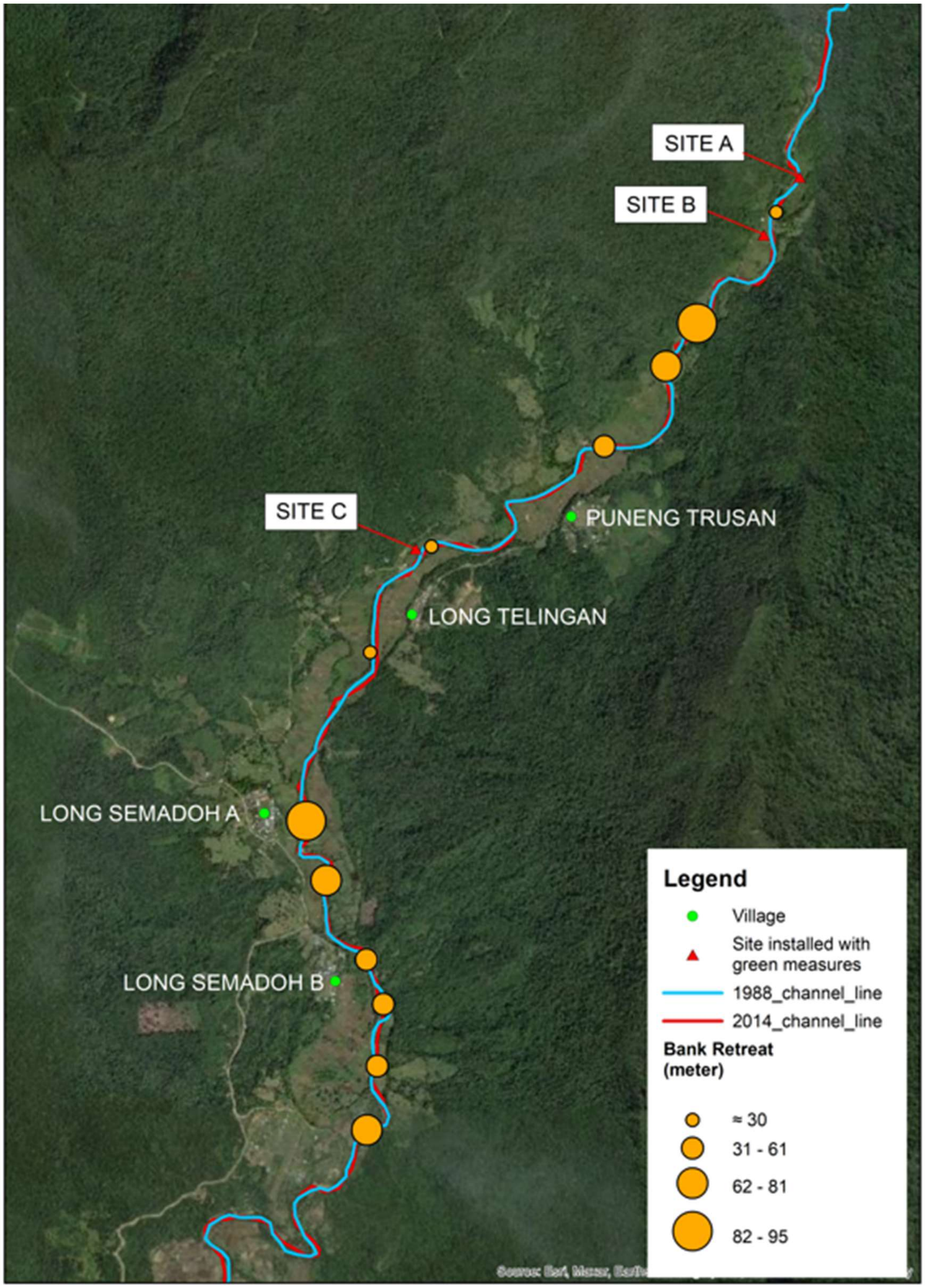

Figure 4.7: Bank retreat observed between 1988 and 2014 using satellite images captured by Landsat-5 and Landsat-8. The size of dots represents the magnitude of bank retreat. Locations with no dot indicate that bank retreat is lesser than 30 meters which is undetectable.

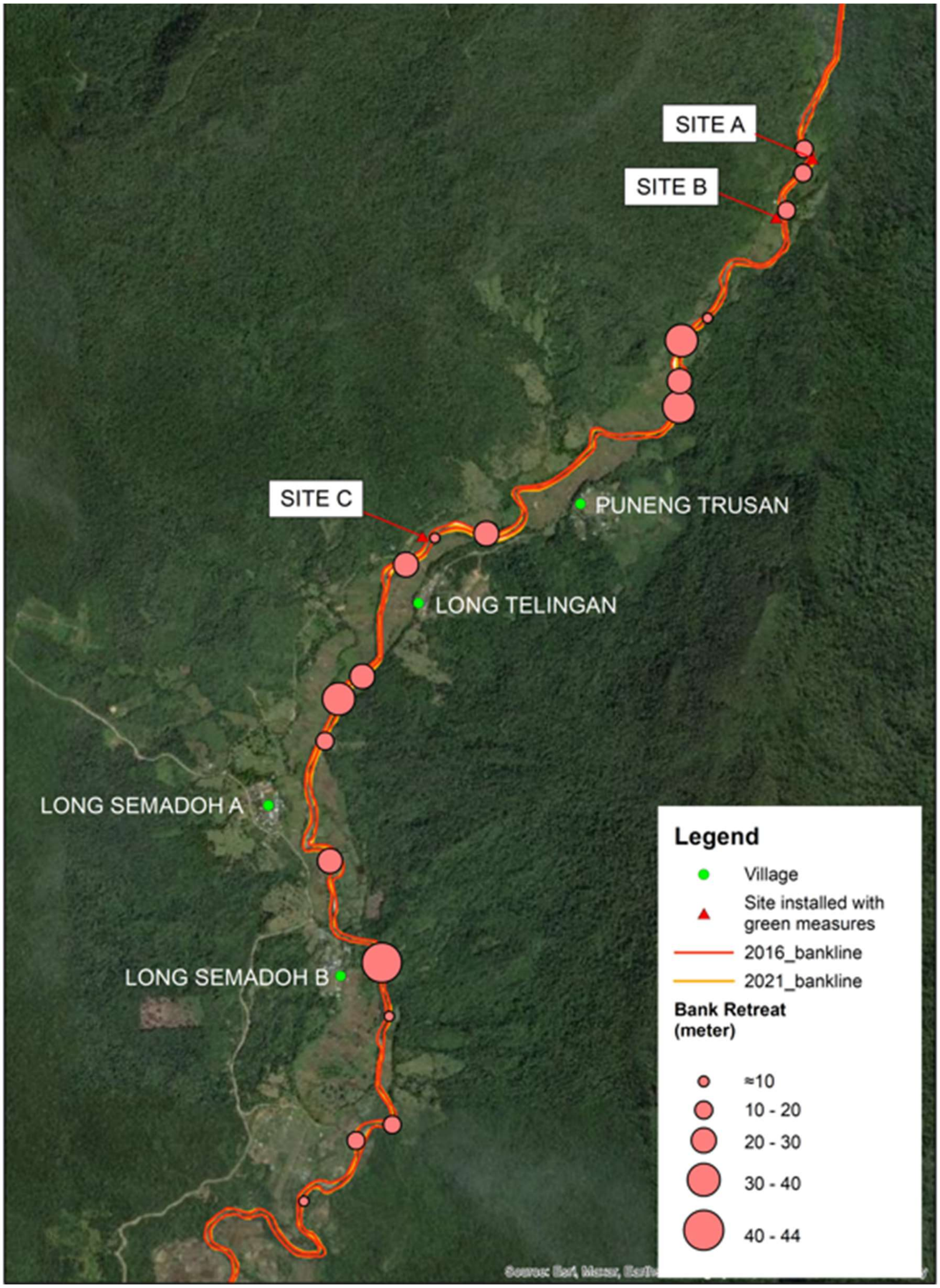

Figure 4.8: Bank retreat observed between 2016 and 2021 using satellite images captured by Sentinel-2. The size of dots represents the magnitude of bank retreat. Locations with no dot indicate that bank retreat is lesser than 10 meters which is undetectable.

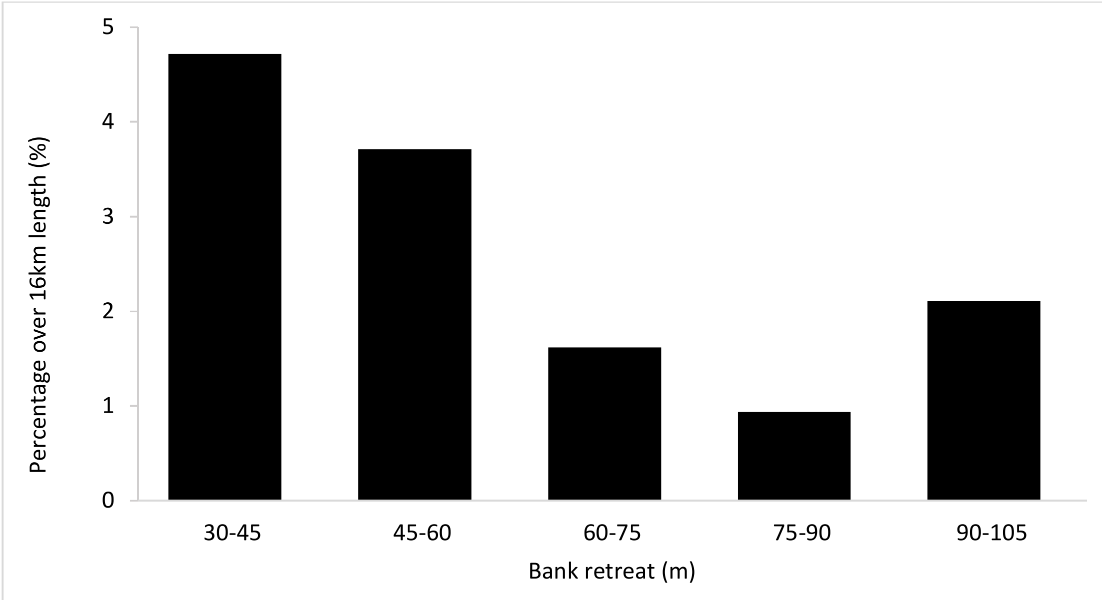

Figure 4.9: Cumulative percent plot for the bank retreat occurred between 1988 to 2014.

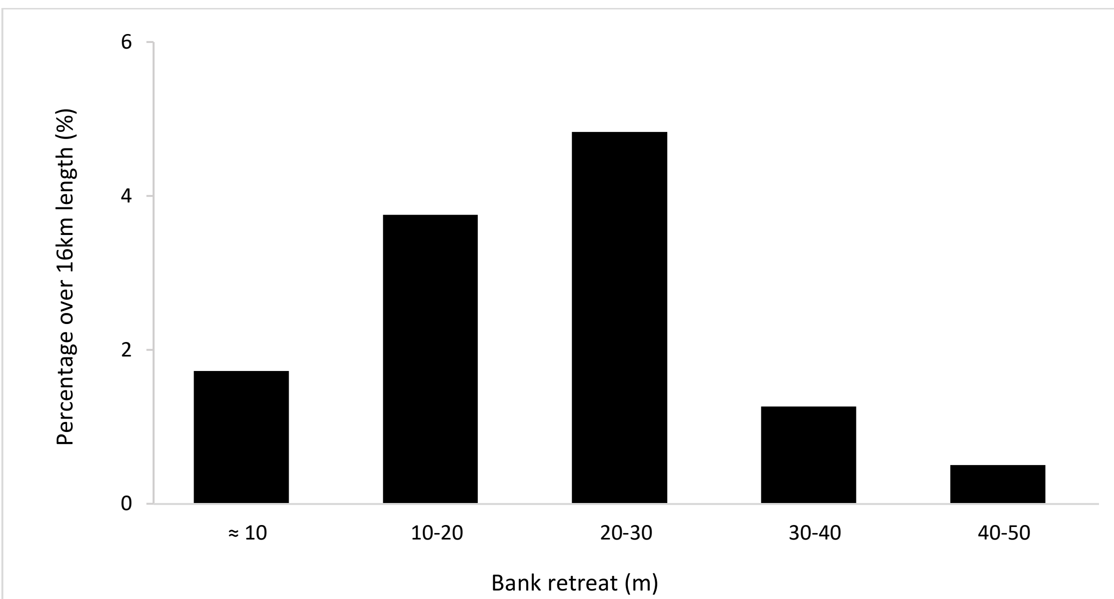

Figure 4.10: Cumulative percent plot for the bank retreat occurred between 2016 to 2021.

4.4.2 Evaluation of green bank protection measures

Overview

Figure *4.11* shows the hydrograph simulated for Long Semadoh from January 2019 to December 2020. It can be seen that flood peaks occurred frequently in the Upper Trusan River, with each of the study sites experiencing multiple bankfull flow events. With an estimated bankfull flow of 75 m^3/s, rivers here experienced approximate 9 times bankfull events annually. Hydraulic models were used to look at hydraulic conditions at respective bankfull flow for each site and a discussion of these is integrated into the text below. Summary tables (Table 4.3 & Table 4.4) are presented to synthesise key points. Table 4.3 compares what was originally proposed for each site to what was implemented, highlighting their overall success or failure. Table 4.4 then highlights some factors that may have contributed to the failure of some measures. The permissible velocity and shear stress obtained from previous literature are shown in the table.

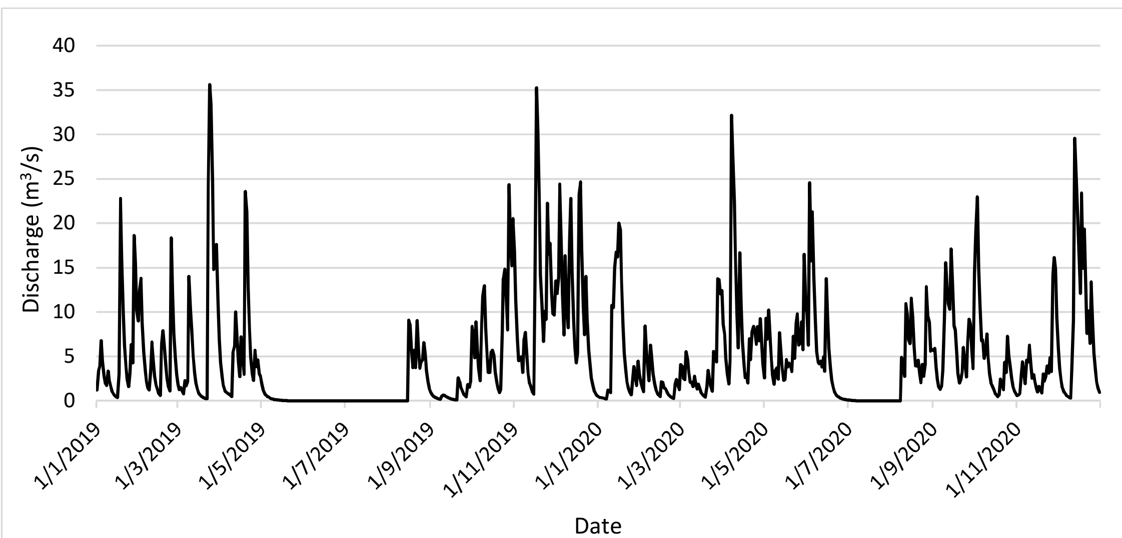

Figure 4.11[1]*: Hydrograph generated for Long Semadoh using SWAT® model (see Chapter 6 for detailed information). The hydrograph represents mean daily flow from January 2019 to December 2020. Zero flow was due to missing rainfall data and model did not simulate these periods.*

[1] The long-term hydrograph simulated by SWAT was compared with the HEC-HMS output in Chapter 3 that serves as prerequisite analysis to understand the hydrology of the Upper Trusan Catchment. The comparison indicates that both models have a good correlation of $R^2 > 0.6$, and their peak timings align closely, with only minor variations in magnitude. This indicates a good level of similarity between the two models in terms of their predicitions.

At the time of the survey, green measures (i.e. coconut geotextile mat and brush mattress) installed at Site C remained in good condition despite some minor damages. However, the brush wall at Site A and the live fencing at Site B were washed away after the high flow occurred in December 2019. Despite the washout the orthomosaic produced by the aerial survey indicates that no major erosion occurred at the sites, so even the 'failed' measures provided temporary protection to the bank during high. The failure of these measures provides valuable information that we can use to refine designs and installation, as well as help to stress the importance of maintenance in the months following installation. For example, fencing built with split bamboo were ineffective, so this needs reconsidering. On the other hand, brush mattresses implemented at Site C were successful, and we should consider using this approach at other sites. A general issue is that some measures departed from the original designs (mostly due to installation difficulties). In many cases, installed measures were only partly completed. In addition, there was limited maintenance; such maintenance is critical in the first months after installation. These issues are detailed further in the sections that follow.

Table 4.3: Summary of measures and their overall success

Site	Original proposal(s) and some specific details	What was done	What was done and/or failed to happen	Success or failure
A	1) Brushwall 2) Fence 5 m from banktop planted as protective riparian strip	1) Brushwall.	1) No fence or planting. 2) Vegetation. Failed to grow (Plate 4.4). 3) Gaps between bank and measures and gaps due to die-back of vegetation may have produced weak-spots.	Failed to hold but stopped bank erosion over a high flow period
B	3) Combination of geotextile roll and live fencing. 4) Live fencing using young, flexible cuttings woven between wooden posts. 5) End should be tucked well into the bank to avoid 'catching' the flow and causing more erosion. 6) Ideally using plants that can grow new shoots once installed.	1) Split bamboo in upper section (right bank)	1) Live fencing was not live, so it could not increase stability over time. 2) Gap between bank and measures. 3) Geotextile roll not installed to protect toe.	Largely failed, though most likely the bamboo fence limited the bank erosion over the high flow period
C	Note that after designs were originally proposed, the community did some engineering work, creating an earth mound on the true right bank. Rather than focusing on the area down from the bridge, we switched focus to the upstream section. We suggested protecting the earth mound locals asked for ideas to protect the opposite bank, so we suggested a brush mattress. The areas where we proposed the work had vegetated naturally, so locals suggested adding some fencing further downstream. Again, as with the mound, not original designs/sketches were made that included this fence; we worked ad hoc and suggested a live bamboo fence.	1) Brush mattresses	1) Provided bank toe protection	Succeeded
		2) Coconut geotextile matting, planted and/or seeded	1) Seedings and revegetate banks. 2) Provided Bank toe protection	Succeeded

Table 4.4: Green measures design and assessment

Site	Implemented Measures	Issues	Factors contributed to failure & recommendation (or discussion)	Measure	Permissible Shear (kg/m²)	Permissible Velocity (m/s)	Citation
A	Brush wall	Brush wall was damaged partially in December and washed away entirely in February as a result of high flow.	1) Rigidity of fixings (post and rope) and lack of maintenance. Conduct period maintenance to improve and maintain the condition of wall (e.g. fill gaps formed by dead vegetation. 2) Gap between bank and wall. Backfill with seeded soil and stones needed. 3) Limited/no regrowth of vegetation. Installation needs to be followed by a reasonably long period before high flows, to allow for growth, rooting etc. 4) Bank slope almost vertical, this might induce higher shear stress. Regrading bank to ideal slope and applies change from brush wall to mattress. 5) The presence of coarse gravels at the base of the bank restricts plants growth, increasing difficulty in penetrating posts firmly into the bed. Hence no toe protection. Use logs or geotextile roll, or changing to mattress may help. 6) Need to ensure longer term success by implementing complementary measures as originally proposed.	Brush mattress (initial)	1.95 – 20.0	1.22	A, C, D
				Brush mattress (grown)	19.0 – 40.0	3.66	A, B, C, D, E
B	Split Bamboo	Split bamboo wall instead of live fencing, and not backfilling to afford protection or facilitate regrowth. Washed away in December.	1) The fencing here suffered from similar problems to the wall at WP3, with the nature of the site and coarse bed material impeding installation. 2) Live fencing wasn't live, so we need to ensure living material in next phases - Consider regrading bank and /or having steps, with fascine or rolls forming vertical elements in each step.	Live fascine	6.1 – 15.14	1.83 – 2.44	B, C, D, F
C	Brush mattress	Brush mattress on the left bank largely successful but still some need to encourage further vegetation growth;	1) No major issues but maintenance is required to strengthen the mattress in places where vegetation growth is limited. Once grown should provide protection from flow forces here. 2) Bank toe protection is required.	Brush mattress (initial)	1.95 – 20.0	1.22	A, C, D
				Brush mattress (grown)	19.0 – 40.0	3.66	A, B, C, D, E
	Coconut geotextile matting	Geotextile matting was damaged partially; little vegetation growth on the matting so not really being used as per design specification of such matting.	3) Failed to regrowth vegetation as no seeding were applied on geotextile matting. Provide seeding or shoots that can help to revegetate the bank. 4) Fertilise the bank and maintain the condition of geotextile matting.	Coconut fibre with net	11.0	0.91 – 1.22	C, G

A) Florineth (1982) B) Gerstgraser, C (1988) C) Gray, D. H and Sotir, R. B. (1996) D) Schiechtl, H. M. and Stern, R. (1996) E) Fischenich, C (2001) F) Schoklitsch, A (1937) G) TXDOT (1999)

Site A – Brush Wall

Site A is the uppermost site located at the upstream of the study section. At this site, severe erosion has occurred at the outer bank (e.g. true left bank). The eroded bank has a steep slope, and most of the erosion was due to cantilever failure where the flow undercut the bank. A gravel bar has diverted the flow into two routes, one to the main channel and another to a slightly smaller secondary channel at the inner side of the gravel bar. The flows from the two channels converge at the downstream end of the bar, where velocities and shear stresses are high.

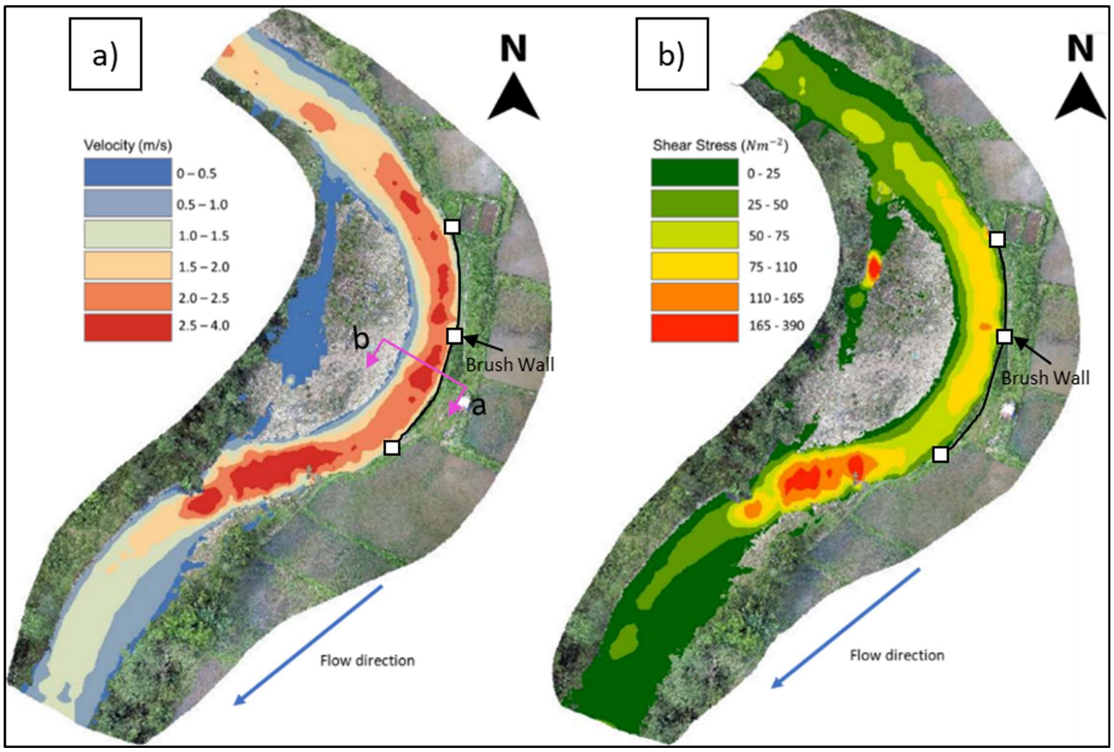

Figure 4.12: a) Velocity and b) shear stress estimated from 2D hydraulic model at bankfull discharge (20 m^3/s: 20-year return period) for Site A.

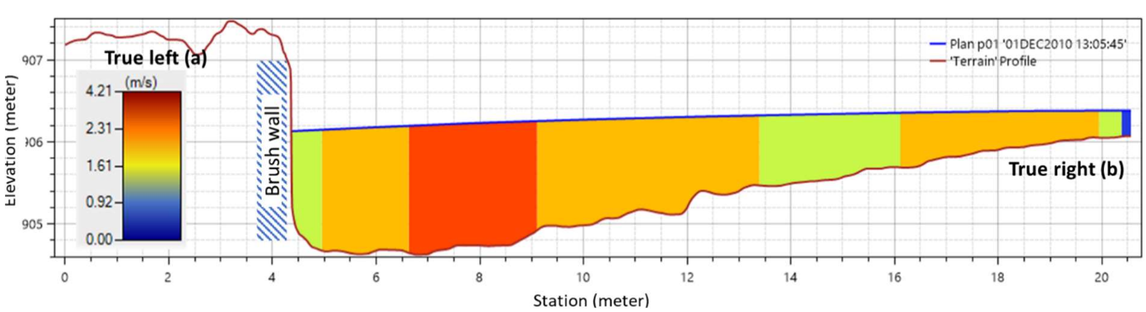

Figure 4.13: Cross-section velocity profile at Site A (transect a-b in Figure 4.2).

Based on the shear stress map generated (Figure 4.12) for this site at bankfull flow, very little water moves through the side channel and the shear stresses appear to be high in the main channel (≈ 110 Nm^{-2}). Due to the combination of the meander bend, and flow routing, greater shear stresses are exerted at the meander bend. This helps explain the phenomena of bank erosion here. However, the erosion at the meander bend is due to undercutting of the bank, indicating that the bank erosion and collapse at this site can occur even if the discharge is below the bankfull flow. An extensive area of high velocity and shear stress is evident at the downstream end of the gravel bar although erosion in this region is not as severe as the meander bend.

According to the hydraulic model, velocity could reach 4 m/s at the bankfull flow of 20 m^3/s at Site A. The cross-section velocity profile (Figure 4.13) shows that near-bank velocity was approximately 2 m/s. The brush wall remained in place from June 2019 until December 2019 when it was partly washed out, leaving some damaged structures on the bank. The November flood at the site reached 35 m^3/s. The plants installed in the brush wall did not root properly and so the wall was not a living one as was intended; most died over time and were not replaced so the wall may have had lower threshold than the theoretical design one.

Nevertheless, the UAV surveys indicated that over the period there was no detectable bank retreat at Site A (Plate 4.3), compared to an average annual rate of 2.3 to 6 meters recorded historically. Even though the wall itself was washed away, the bank did not recede, and so the wall provided protection against the extreme flow of December 2019. The rough surface of the brushes reduced flow velocity and deflected the flow to some degree. In addition, even a simple visual inspection of the images shows that the sediment size on the gravel bar has changed – coarser surface material in February 2020 than in June 2019. Clearly, the wet season flows were competent to alter the bed condition.

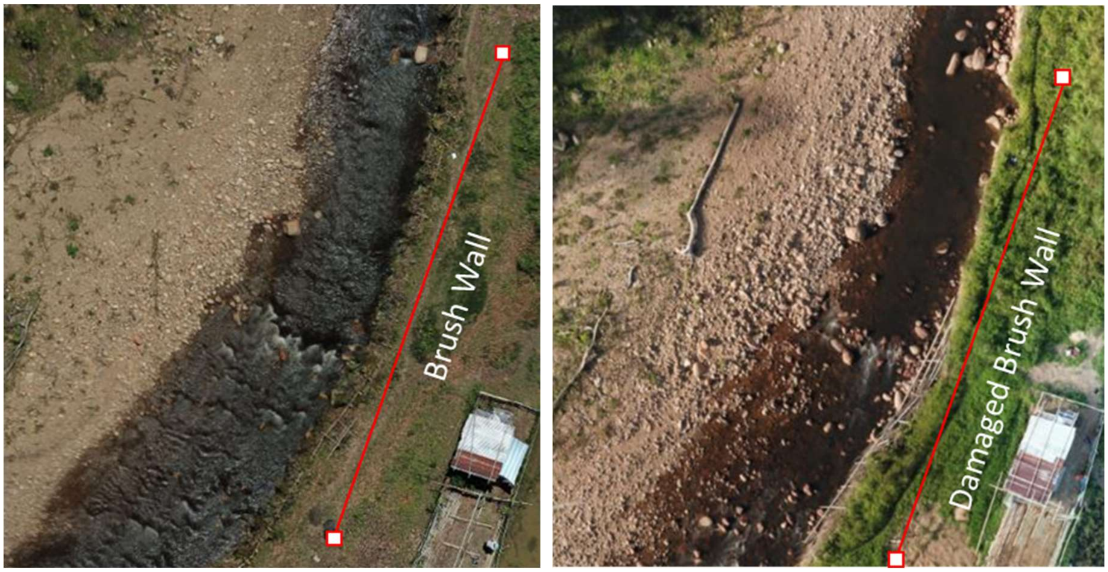

Plate 4.3: Cropped section of Site A, captured in June 2019 (left) and February 2020 (right).

The main objective of brush wall installed at Site A was to revegetate the bank and increase soil stability. Brush walls are designed with a rough surface (eg. willows, plants and branches) to dissipate energy from the flow and trap fine sediments. As seen from Plate 4.4 (top) and Plate 4.4 (bottom) captured in September and November 2019, the vegetation growth on the bank was very limited, with the wall becoming progressively less dense due to the decay of life material. Some spots were sprouting, and the planted bamboo showed signs of growth, but the vegetation growth rate on the bank slope was low. Most plants or brushes were dried up, and the posts (frame) were partially damaged. Some of the posts were detached from the bank by the flow (Plate 4.5); in this condition, it no longer provided energy dissipation functions.

Plate 4.4: Brush wall at Site A (top) captured on 29th September 2019, (bottom) captured on 29th November 2019.

The low flow period from September to November would have been an excellent opportunity to improve and maintain the condition of this remediation measure. However, work was targeted at installing new measures at other sites (including some unplanned ones) rather than maintenance.

Plate 4.5: Bank after brush wall was washed away in December 2019 at Site A.

There are several types of failure for riverbanks (Table 4.5). Most of the erosion in the Trusan consists of slab failure, undermining of banks (e.g. geomorphic processes) and erosion due directly to human activities, including cattle trampling (Marteau et al., 2018). In Plate 4.5 and Plate 4.6, there was clear evidence showing that slab and cantilever failure occurred at Site A. Most of the bank at Site A have a steep bank angle and are undercutting (Plate 4.5). According to field observation, the banks have a weak bottom layer, which easily fails due to low cohesion. Vegetation was dense on top of the bank, but the roots were shallow and only provided cohesion to the upper layer. In addition, the vertical surface of the eroded bank was exposed without any vegetation. Steep bank angles will also induce higher shear stress acting on the bank.

Table 4.5 summarises the mode of failure that are relevant to all the sites and lists options for protection. In the case of Site A, this supports the idea that regrading the banks would improve chances of success, though due to the remote location (no vehicle tracks to this site) such work would have to be done manually. The table also stresses the need for toe protection.

Table 4.5: Options for structural protection (Fischenich, 2000).

Mode of failure	Description	Options for structural protection
Slab failure	Slab failure planes pass below the rooting layer and shallow stabilisation measures or positive pore pressures may be critical	Reduce tension cracks by lowering the bank angle. Install stress crack protection to avoid further deterioration. A retaining wall can be built if space is restricted to defend against deep toe scour and positive pore water pressures.
Cantilever failure	Cantilevers are caused by erosion of weak layer in the bank.	Armouring layer can be used to avoid weak layer undermining, filter installation to prevent piping, and re-vegetation to boost soil tensile strength.
Soil fall	Soil fall occurs on steep, undercut banks of low cohesion. It contributes to bank retreat due to flow, wave or piping erosion.	Reduce soil fall by regrading the bank to a lower angle and protecting the surface with vegetation or riprap. Stabilised steep bank with a vertical wall allows for deep toe scour if the room is limited.
Dry granular flow	Dry granular flow is a surface failure that occurs on undercut banks with no effective cohesion.	Use geogrid, geotextile, or vegetation in conjunction with toe protection and active management to minimise trampling or mechanical damage to the bank.

Plate 4.6: Eroded bank after brush wall was washed away in December 2019 at Site A.

Coarse gravel at the bottom of the banks contributed to cantilever failure. Gravel (non-cohesive material) has no effective cohesion and is poor in resisting shear stress. When the force is high enough to lift the gravel at high flow, they are transported away, and undercutting will occur (Plate 4.6). Moreover, the presence of only gravel at the bottom layer might be a factor that restricts the growth of vegetation. Soil is required for vegetation growth, so applying a brush wall on a steep bank filled with coarse gravel provides short-term protection to the bank but fails to serve as long-term protection if plants cannot grow or regenerate.

Site B – Bamboo Fencing

Site B is located at few hundred meters downstream from Site A. The river channel at this site is wider than Site A, with large alternating gravel bars exposed at lower water stages. Both banks have historically suffered from moderate to severe erosion at this site, and the bank (true left) downstream collapsed due to cantilever failure.

Based on the flow hydraulics maps generated for Site B (Figure 4.14), the velocity of the flow (Figure 4.14a) at the upstream area was higher (2.5 – 3.5 m/s) than the downstream area (2.0 – 2.5 m/s). The shear stress (Figure 4.14b) across most of the channel was moderate (75 - 100 $\mathrm{Nm^{-2}}$) at bankfull discharge; the exception was the middle region which exhibited highest shear stress (> 135 $\mathrm{Nm^{-2}}$). The shear stresses at the outer bank were notably higher than the other areas. This is partly due to the channel geometry (i.e. curvature of banks) that induced higher shear stress; this is the area where severe bank erosion has occurred.

The simulated near-bank velocity (Figure 4.15) range from 2.6 m/s to 3.5 m/s at Site B has exceeded the suggested permissible velocity (2.44 m/s) for this type of live fencing. The fencing provided protection up until the December 2019 flood, at which point it was washed out. After washout, erosion occurred rapidly. Plate 4.7 shows that the bank with fencing in place to give an idea of the protected bankline and two months after the washout.

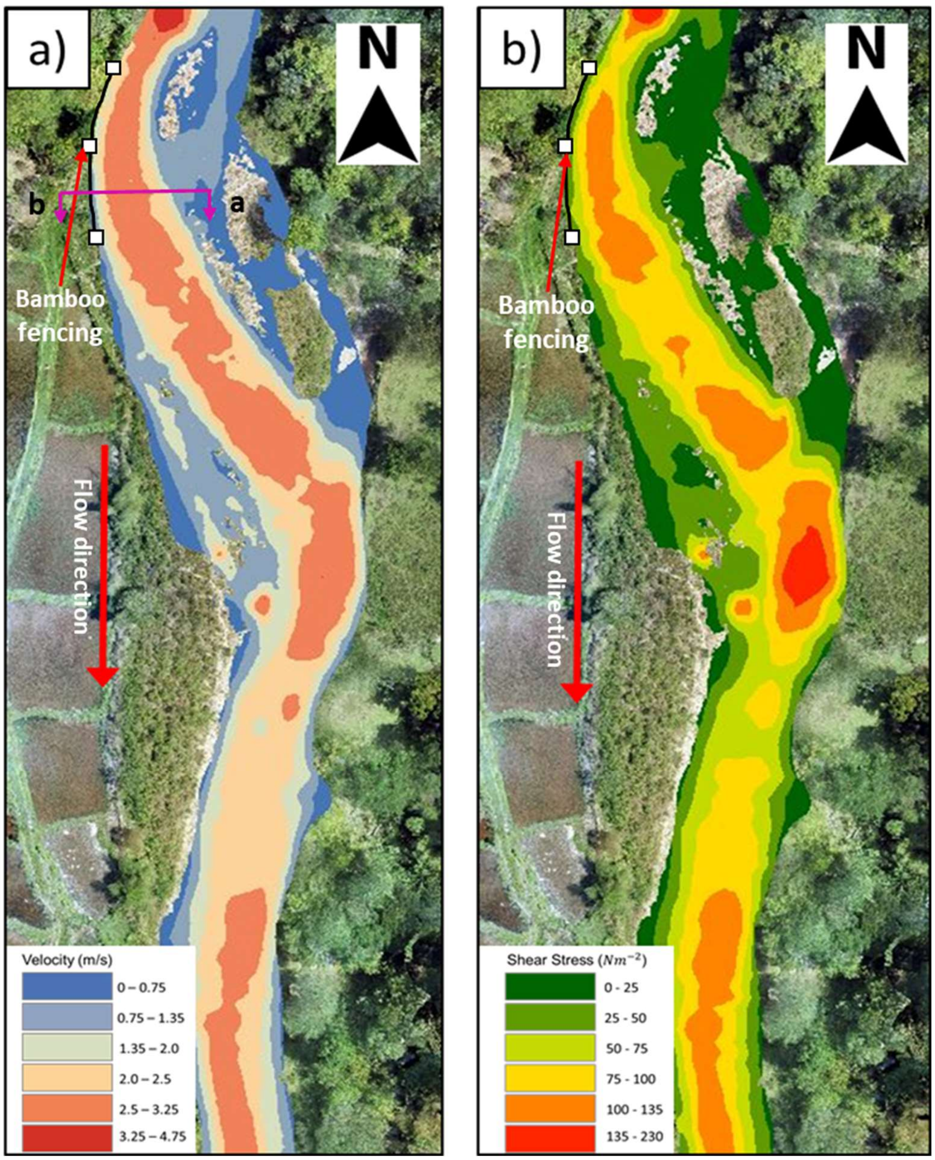

Figure 4.14: a) Velocity and b) shear stress estimated from 2D hydraulic model at bankfull discharge (30 m^3/s: 40-year return period) for Site B.

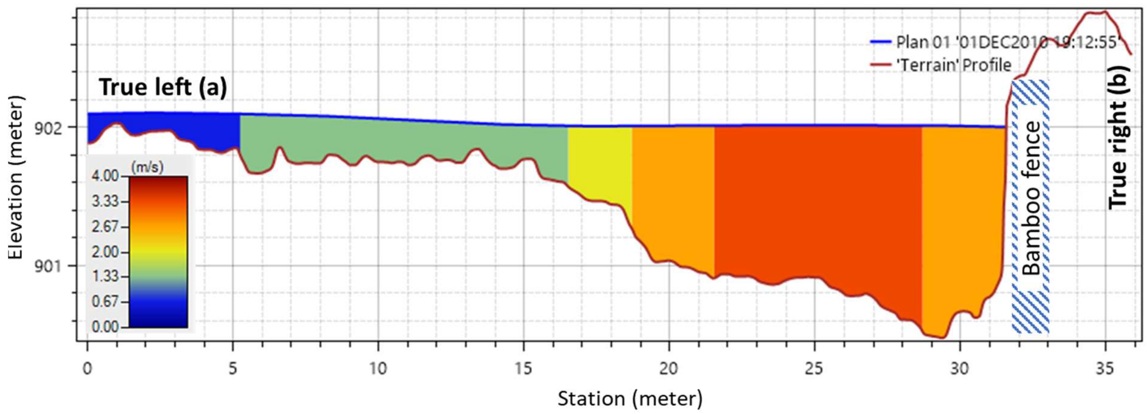

Figure 4.15: Cross-section velocity profile at Site B (transect a-b in Figure 4.14).

Plate 4.7: Cropped section of Site B, captured in September 2019 (left) and February 2020 (right).

The bamboo wall at this site was not built to the design specification, and the fact that it was non-living (no roots to help stability and increase roughness) likely contributed to its failure to withstand the high flows during the December 2019 during high flow. Plate 4.8 is the original proposal and design of live fencing for Site B, showing live bank protection with young and flexible cuttings woven between wooden posts. The gap behind the live fencing was supposed to be backfilled with seeded soils and stone to promote vegetation growth. It is noted that the fencing should be tightly woven and ideally use plants that can grow new shoots once installed. Moreover, the design included the provision of 5 to 10 meters of riparian to allow plants and trees to be planted.

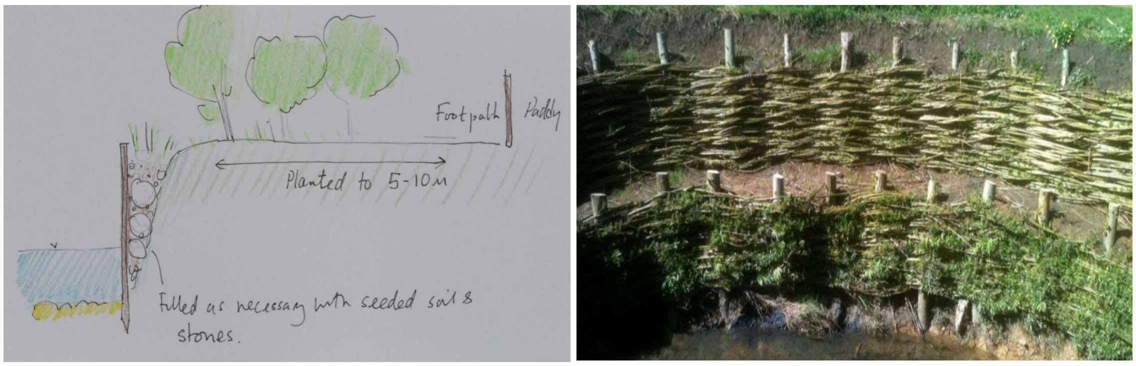

Plate 4.8: Original proposal of live fencing.

Plate 4.9: Live fencing at Site B. Left: completed installation of the bamboo wall with an extent of 40 meters. Right: close view of bamboo wall showing split bamboo (28th September 2019, source from Belinda Lip).

The completed structure built at Site B was a simple bamboo wall instead of live fencing (Plate 4.9: left). Split bamboo was used instead of using live materials for the fences (Plate 4.9: right). No backfilling or seeding or backfill was done. Understandably, it proved hard to install bamboo frame securely into the bed without machinery due to the hard armouring layer at the toe. Given that the posts did not penetrate the bed, the posts were loosened by the uplift forces during high flows. Without toe protection, the gap at the base is likely to have acted as a weak point. In addition, the bank slope is almost vertical (Plate 4.10 & Plate 4.11), which contributes to soil instability and a higher possibility of failure. Regrading or providing a step in the bank should be considered.

Several lessons were learnt from this case, and the highlighted issues were as follows: i) Fencing was made from split old bamboo sections, ii) large gaps between the fence and bank as the fence was not flexible to enclose uneven bank surface, iii) no live bamboo observed, and no planting was done, iv) lack of toe protection, v) gravel bed condition increases the difficulty for installation, and vi) large gaps appeared at the ends; these might catch the flow and increase erosion.

Plate 4.10: Eroded bank after the brush wall was washed away in December 2019 at Site B.

Plate 4.11: Eroded bank (soil fall) at the lower section of Site B.

Site C – Brush mattress and Coconut geotextile mat

The hydraulic model output for Site C is presented in Figure 4.16**.** The channel size here was wider than the others, straighter and less complex. This is partly due to historical river channelisation, which had altered the natural geometry of the river, though over time it had recovered more of its natural form.

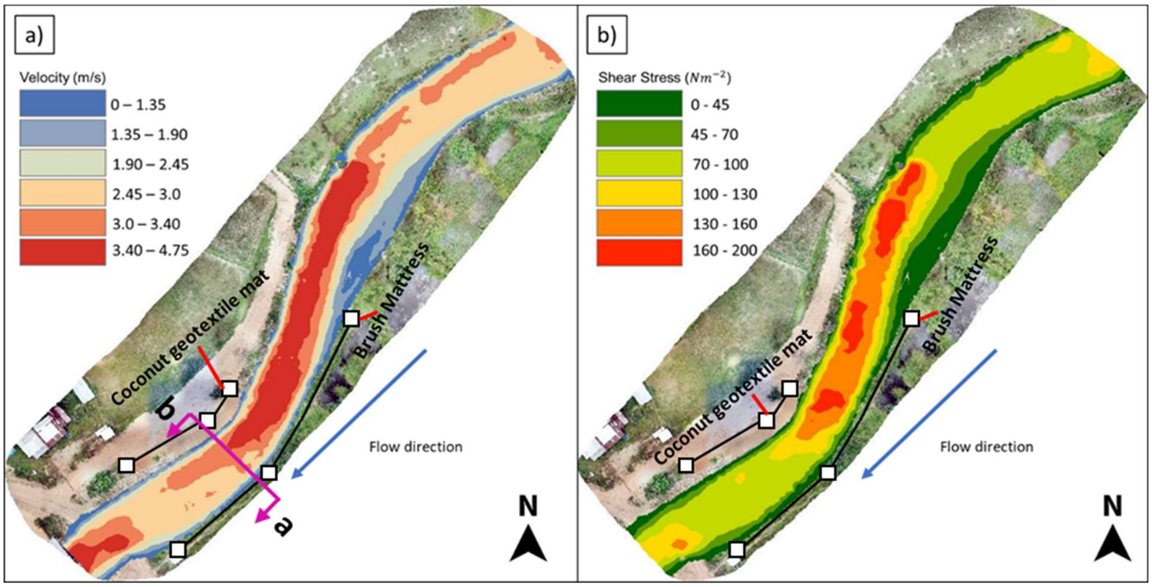

Figure 4.16: a) Velocity and b) shear stress estimated from 2D hydraulic model at bankfull discharge (80 m^3/s: 100-year return period) for Site C.

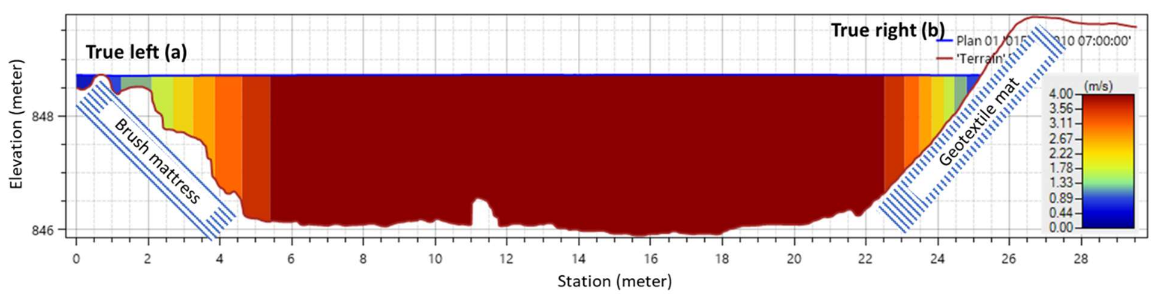

Figure 4.17: Cross-section velocity profile at Site B (transect a-b in Figure 4.16).

An area of high velocity occurred slightly to the right of the channel center line and induced shear stress exceeding 160 Nm^{-2} over an extensive area. As the water approaches the slight bend towards the downstream end of the site, velocity, and shear stress decrease. However, under the bridge at the end of the site, the flow forces increased again. This correlated with the historical undermining of the bridge here.

The brush mattress installed at the site did not fail. It exhibited a reasonably good growth rate of vegetation after its installation, as shown in Plate *4.12*. The vegetation on the bank observed in February 2020 was denser than the images captured in September 2019. The orthomosaics of Site C show no major erosion at this site, with both banks remaining in good condition over the high flow period.

At the flow of 80 m^3/s, the model (Figure 4.17) suggested that the brush mattress has to withstand a velocity of 2 m/s to 3 m/s, while the coconut geotextile mat has to withstand a velocity of 3.0 m/s to 4.75 m/s. For the brush mattress, this velocity falls below the permissible velocity of 3.66 m^3/s suggested by the past literature. Thus, reasons the success of this measure are quite clear – the wider channel and sloping bank help ensure hydraulics are within bounds of capacity for brush mattress. For the coconut geotextile mattress, the velocity at bankfull flow has exceeded the permissible velocity suggested by the literature. This is likely to explain some damage at the bottom of the geotextile mattress (Plate *4.12*: highlighted in red).

The coconut geotextile matting prevented a landslide or any major erosion on the true right bank, but it was partially damaged after high flow. As evident in Plate *4.12* (right: highlighted in yellow), a large new accumulation of gravel was deposited at the right bank, forming a new bar feature. This is an indication of the dynamism of the river here.

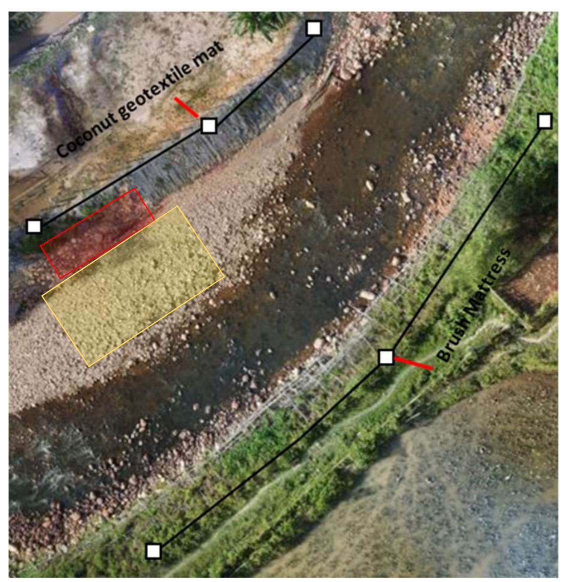

Plate 4.12*: Cropped section of Site C captured in June 2019 (left) and February 2020 (right).*

4.4.3 Post-washout bank retreat

The results of bank retreat monitoring from February 2020 to November 2021 (post-washout of green measures) for each site is shown in Figure 4.18. The monitoring indicates that when the green measures remain in place, they can reduce erosion. Based on the comparison of each successive orthomosaics collected, no major erosion occurred between June 2019 and February 2020 at Site B (as discussed above) - only minor erosion occurred at the true right bank of Site B after the green measures were washed away. However, the erosion rate at Site B (Figure 4.18) from February 2020 to November 2021 was most noticeable, whereby the bank was left unprotected for this entire period. Site C experienced highest erosion within this period, while Site A experienced minimal erosion. The eroded areas for each study site over the period from February 2020 to November 2021 is summarised in Table 4.6. See the paragraphs below for detailed bank conditions.

At Site A, excessive aggradation of sediments occurred adjacent to the gravel bar, so rather than erosion, the original bank line was buried.

At Site B, the recent flood in September 2021 has caused major damage to the paddy field across the area, indicated in green hashed lines (Figure 4.18).

At Site C, most of the erosion occurred at the meander bends. There was significant soil loss at the true left bank right before the steel bridge. That was caused by high hydraulic forces induced by the bridge footing and pillar. The bridge was partially damaged after the high flow events. It was disconnected from the land as the bank had eroded.

Table 4.6: Summary of eroded areas for each study site over the period from February 2020 to November 2021

Site	Eroded Area/m^2 (True right)	Eroded Area/m^2 (True left)	Total eroded area/m^2
A	-	216.58	216.58
B	565.5	581.3	1146.8
C (before bridge)	535.51	278.62	814.13
C (after bridge)	1138.73	92.79	1231.52

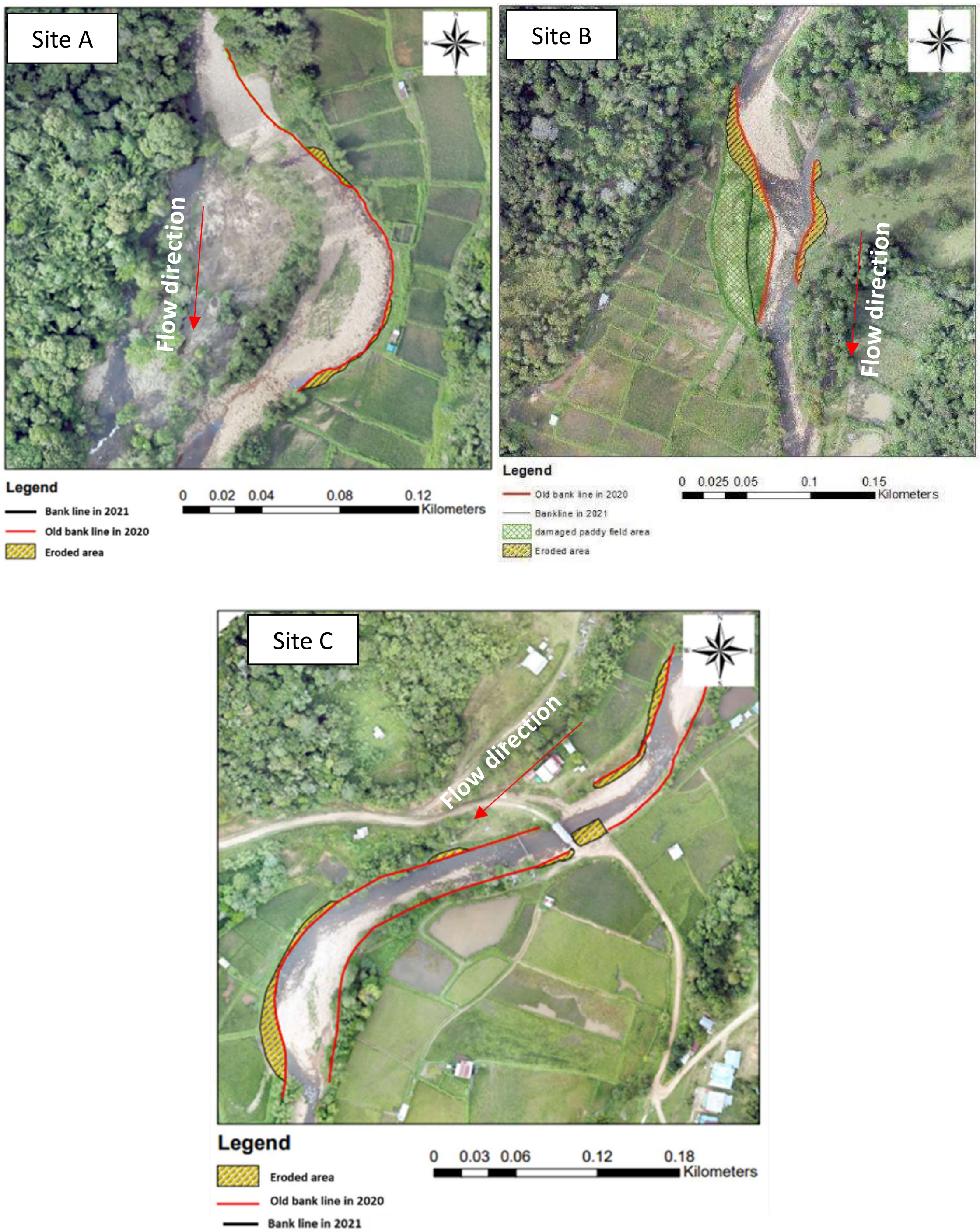

Figure 4.18: Bank Erosion at Site A, B and C. The erosion is shown as a difference between the old bank line in Feb 2020 (red) and the bankline in Nov 2021 (black).

4.5. Discussion

4.5.1 Summary points and key considerations

This chapter focussed on understanding the magnitude of historical bank retreat in the upper Trusan and the potential for green measures to arrest this. The work also focussed on understanding the factors contributing to differences in success. The key points are summarised as below:

I. Changes in planform over the last three decades, with the upper part of the study section experiencing the most significant changes. Despite the low resolution of the satellite images, bank erosion was evident in at least 10 - 12% of the 12 km length of bank (both sides) in the study section, with total retreat in the order of tens of m in many areas.

II. The brush mattress and coconut geotextile matting worked reasonably well. The brush mattress exhibited a good growth rate of vegetation, while the geotextile mat prevented landslide and major erosion over a two-year period.

III. The brush wall was ranked the third best option. It remained in place for several months and no bank retreat occurred during this period. However, it was washed out by one of the large floods that occurred within the study period.

IV. The bamboo fencing showed signs of damage quickly after high flows. The fencing provided temporary protection but once it was washed erosion occurred rapidly.

V. The monitoring indicates that green measures can reduce erosion when they remain in place. No major erosion occurred at Site A, B and C when the measures remained intact. The regraded banks provide better stability for the green measures to grow and bank toe protection is critical to prevent undercutting.

VI. Lack of maintenance and incomplete installation for the green measures are the main factors contributing to failure in the Upper Trusan. Poor maintenance, such as failing to maintain the rigidity of poles and supporting structures, could worsen the structural integrity before the vegetation reaches full-grown condition. The gaps between the measure and bank prevented vegetation from growing, eventually leading to ‘flow catching’.

At most sites, the installation of green measures was impeded at the bank base due to a hard armouring layer (large cobbles). A critical issue going forward is designing measures that can be installed in such circumstances but also have a protective toe. Any gaps between the bank and brush wall should be filled with seeded soil and stones once the installation is completed. A seeded organic medium is required for vegetation to grow. As green measures commonly require repair and maintenance, maintenance works such as backfilling soil, seedling, and replanting degraded woody material are expected periodically to ensure the measures are in good condition. A key consideration for Site A is to remove some of the flood water using the old diversion canal to flood the abandoned rice paddy adjacent. This would reduce flood peaks at this site as well as site B.

4.5.2 Literature context

Green measures have been widely applied predominantly in the Europe countries and the USA as an alternative to the hard structures for riverbank erosion control. Past literature has discussed extensively the benefits of green measures, design guidance, key considerations for application, and their cost-benefit relations. However, most literature lacks long-term monitoring to assess their performance to reduce bank retreat and their failure threshold. This study focussed on determining the potential and constraints of green measures in reducing erosion and assessing the feasibility of applying local scale green bank protection measures in the setting of a high-energy tropics river. Close monitoring using repeated aerial survey helped to identify their performance in erosion control and identified the conditions for successful performance and use.

Table 4.7 summarises the findings from the current study compared with the literature findings. The permissible velocity and shear stress in this study were determined using the hydraulic model. To do this, we regularly monitored the green bank protection measures, and we kept track of when the river reached its bankfull flow, relying on reports from local communities. Findings from this study suggests that brush wall, brush mattress and coconut geotextile matting have similar permissible velocity and shear stress compared to the literature. However, bamboo fencing in this study is particularly poor in withstanding high flow. The fence was washed away after the flood event occurred in December 2019. At this site shear stress is relatively high ($> 60 \mathrm{N/m^2}$) at the outer bank, contributing to its early failure.

Table 4.7: Comparison between literature and current findings

Literature					**Current**			
Source	Green measures	Related findings	Permissible		Green measures	Current findings	Permissible	
			Velocity	Shear stress			Velocity	Shear stress
A, B, C, D, E	***Brush mattress*** willow posts, cuttings, branches, and fascine.	Brush wall was displaced and showed sign of settling at the toe after flood event (Jones, 2008).	1.22 - 3.66 (grown)	19 – 40 (grown)	***Brush wall*** Bamboo post, tree branches, and cuttings.	Brush wall remained in placed but was partially damaged after first high flow events. Due to lack of maintenance, brush wall was eventually washed away.	1.2 – 1.8	25 - 45
A, B, C, D, E	***Brush mattress*** willow posts, cuttings, branches, and fascine.	Study suggested that brush layer and brush mat could trapped 0.18 m^3/yr and 0.21 m^3/yr respectively, with survival rates up to 75% (Rey et al., 2014).	1.22 - 3.66 (grown)	19 – 40 (grown)	***Brush mattress*** Bamboo post, tree branches, and cuttings.	Brush mattress did not fail after few high flow events. Some patches shown good vegetation growth. Toe of the measure was damaged and bamboo posts were displaced.	1.5 – 2.5	30 - 65
C, G	***Geotextile matting*** Synthetic erosion control mat.	Combination of live stakes with erosion control mat successfully prevented bank sloughing and incision (Selvakumar et al. ,2010).	0.91 - 1.22	11	***Geotextile Matting*** Coconut fibre geotextile mat	Geotextile matting was partially damaged after high flow but did not wash away after few high flow events. Particularly the toe zone was not well protected	1.5 – 3.0	30 - 60
B, C, D, F	***Live fascine*** Live bamboo structure, branches, and stems.	Bamboo structures shown to be a good element for natural check dam and retaining wall (Tardio et al. ,2017).	1.83 - 2.44	6.1 - 15.1	***Bamboo fencing*** Bamboo poles arranged in rows forming fenced-like structure	Damaged and washed away after small flood events. Bamboo fencing did not last at bankfull flow. The recorded shear stress at bankfull flow exceed 50 N/m^{-2}.	< 2.0	-

A) Florineth (1982) B) Gerstgraser, C (1988) C) Gray, D. H and Sotir, R. B. (1996) D) Schiechtl, H. M. and Stern, R. (1996) E) Fischenich, C (2001) F) Schoklitsch, A (1937) G) TXDOT (1999)

Some of the literature has shown successful examples of application of these measures, while some highlighted weaknesses and common failures. In most cases the literature emphasises successful outcomes and very few published works discussed the challenges or provide evidence and causes of failures. Lyn and Newton (2015) published two reports, one related to the concept and the other is the case study. The first report highlighted the importance of a preliminary study to support the design of green measures. The second report consists of evidence from field assessment. From the case study, it is recognised that failures are very common for green measures. This was because these measures are fragile at the early stage, and high flow can easily damage the measures before reaching a full-grown state. The commonly reported issues are bed scour, incision, toe failure, and washout.

The literature reveals that brush mattresses and brush layers are commonly used for riverbank stabilisation on regraded bank slopes. Several studies demonstrated the use of brush layers by putting live cuts of living plants into soil lifts or layers to provide better soil stability. This is done by wrapping soil layers with a coir mat and stacking them in steps along the riverbank (Cavaillé et al., 2013; Rey & Burylo, 2014). A prevalent issue for green measures, including brush mattress is bed scour, resulting from undercutting. Hence, brush mattress was coupled with a rock toe and riprap to form an armoured layer at the bank toe to prevent bed scour (Frothingham, 2008; Lyn & Newton, 2015; Newton & Lyn, 2015). At the early stage, erosion control matting was used to protect the brush mattress due to lower permissible velocity and shear stress (Lyn & Newton, 2015). In a full-grown state, brush mattress has better capability to withstand high flow.

Healthy and dense vegetation on bank slopes plays an important role in improving soil mechanisms and preventing erosion (Collison & Anderson, 1996). Healthy vegetation with deep roots that can penetrate the subsoil are best for mechanical effects. This makes live fascine and live stake the most widely used measures for riverbank stabilisation. The other common green measures that can be seen were generally those that involved basic planting techniques. Measures that involved direct planting enhanced the growth of vegetation and effectively stabilised the riverbank with a gradual slope (Rey & Burylo, 2014). Vergani et al. (2012) tested several species' ability to stabilise slopes at different reaches to promote root cohesion, tensile resistance, and soil reinforcement. It was shown that root diameter significantly corresponded to stress and force, confirming the strong dependence of root resistance on root size (Vergani et al., 2012). A Southern Ontario case study showed that crib walls with dense cutting growth work well on vegetated banks and promote soil cohesiveness (Krymer & Robert, 2014). Besides that, Collison and Anderson (1996) predicted slope pore pressures with and without vegetation using a two-dimensional finite analysis model. Results indicated that vegetated slopes have reduced pore water pressure, increased soil shear strength, and help to stabilise them. Li et al. (2006) stated that the shear strength of vegetated soil appears higher than that of disturbed soil as moisture content decreases. Wu et al. (2015) also found that vegetated soil has less water than unplanted soil (Wu et al., 2015).

Due to critical hydraulic conditions, several projects changed the shape of the channel and regraded unstable banks prior to installation of green measures (Nichols & Leiser, 1998; Raymond & Smestad, 2008; Voicu et al., 2020). The changes to the bank shapes and channel geometry were made to create a stable reach, lengthen the flow path (Hazell et al., 2007) reconnect the floodplain, and restore the flood terraces (Rogers & Doeing, 2009). The minimum bank slope is generally regarded as being 1:1 (horizontal to vertical), but most of the past interventions have strongly recommended banks with a more gradual slope (Allen & Leech, 1997; Elliott et al., 2016; Raymond & Smestad, 2008). Some projects used natural methods instead of traditional ones, like making a retaining wall out of bamboo (Tardio et al., 2017) building a live palisade or brush layers to make a slope with steps (Petrone & Preti, 2010). Some of the work done in the past that combined green measures with bank realignment successfully stabilised banks (Anstead et al., 2012; Giupponi et al., 2017; Hazell et al., 2007) and made aquatic and riparian habitats better (Elliott et al., 2016).

4.5.3 Implications for implementation of green measures at highland tropical rivers

Based on the literature cited above, some key reasons for success and partial failure were not unsurprising in the case of the Trusan, especially bearing in mind that it is a high energy upland river. What is notable, and a key contribution of the present work, is that most of the literature emphasised the successful outcomes and seldom highlighted or explained factors that could contribute to failure.

Notably, only certain green measures are appropriate in tropical highland river such as the Trusan and we learnt two critical lessons from this project that apply irrespective of the type of green measures involved. Firstly, the measures need to be installed fully and periodic maintenance checks are needed. For example, the bamboo fence was not backfilled with soil and split bamboo was used instead of live bamboo. Secondly, maintenance is essential to ensure the good condition of green measures especially in the first weeks and months following the installation. The brush wall protected the banks for several months but after die-back, it showed signs of wear and function less effectively because of gaps. However, no action was taken to maintain the wall by adding new live materials and allow it to reach the point that it was self-sustaining.

In the Upper Trusan, installation is heavily reliant on the local communities. However, rice farming and other agricultural work keep them very busy, and it is a challenge to find time to work on the installation and, in particular, set aside time for checks and regular maintenance in the first few critical months after installation. Moreover, some of the installation work was left incomplete – e.g. ends not safely secured, no backfilling - due to insufficient manpower and time. Frequent rainfall in the area only allows a very short window for installation before the next high flows comes along. This means there is limited time for the plants to grow, bed-in and colonise the riverbank. The hydrological study using SWAT® (Chapter 6) also indicated that the bankfull flow occurs typically around 9 times each year in the Upper Trusan, which means more frequent maintenance is required compared to the lowland rivers.

Other than that, it is recognised that the soil type at the floodplain areas is largely made of alluvial and gley soils. These soils normally are formed at the floodplain paddies areas and is known that their erodibility is relatively high compared to other soil types. Based on Kironoto (2000) and Asdak (2014), Alluvial soil has an erodibility value of 0.47 and Gley soil has an erodibility value of 0.51 – 0.56 (Liu, 1999), whereas the erodibility value of red-yellow podzolic soil is 0.166 which is much lower than the soil at the river floodplain. This shows that the riverbank at the river floodplain has higher erodibility due to their soil type. Hence, green measures need to be at fully grown conditions to help reduce the erodibility and improve the bank stability of such susceptible areas.

Additionally, some of the engineering work that occurred in the Trusan were completely out of the control and planning of this project. The work detailed in this thesis was done under the auspices of an existing community project but not all landowners subscribed to the testing of green measures and some therefore embarked on implementing their own (traditional) 'solutions'. The landowner at part of Site C brought in contractors to re-engineer the bank (a road reaches this site, so access is possible, unlike Sites A and B), resulting in two key things: grading of the left bank and the construction of a large embankment. We took the opportunity provided by the graded bank to see if the brush mattress works better on the graded bank than the vertical bank at Site A. The embankment constructed at Site C was not aligned to our project philosophy, but we agreed that to avoid problems with soil erosion on the embankment and fine sediment input to the river, we covered the embankment with geotextile matting. The landowner was meant to plant seedlings on the matting but failed to do so. These issues illustrate some of the challenges in areas where measures are left to local communities and NGO-sponsored projects (i.e. as in the Trusan) rather than being implemented by relevant government agencies such as (in Malaysia) DID.

4.6 Conclusion

This study involved numerous elements that incorporated analysis of historical morphological change, hydrological context, and performance evaluation of green bank protection measures that help to understand the limitations and their key success to implement these measures in tropical highland region. This study uses modelling approach to back-calculate the permissible velocity and shear stress that the green measures can withstand, and use this to understand how the strength of green measures could vary. Within the context of South East Asia, no one has done a similar comprehensive analysis before, with documented studies being rather qualitative and often lacked in-depth analysis. Moreover, past literature in the other region has given very little context on their hydrological and/or geographical settings, which hindered understanding reasons for their success and failures. Hence, this study is deemed to be novel and contributed to addressing one of the research gaps identified in Chapter 2.

The field evidence presented in this chapter provided some key insights into the potential and constraints of applying green measures in highland tropical rivers. The green measures applied in the Upper Trusan were found to be partially successful in reducing bank erosion but had limitations. The green measures that worked well were living materials, and because of regular high flow forces, grading banks before installation appears critical. Another key is that design and management should focus on ensuring measures are robust in the first few months of life, so they can stabilise properly. Green measures must be maintained well to ensure they remain in place for a long time.

There are several constraints identified in the study. It is recognised that inadequate materials selection and failure to follow proper installation procedures can contribute to failure. Split bamboo and dried twigs failed to rejuvenate vegetation, and many were damaged after high flows. Besides that, frequent high flows in the Upper Trusan leave a very short window for the installation of green measures, which means that vegetation has limited time to reach full-grown conditions. At the pre-mature stage, bank stabilisation is poor and green measures could not reach their full capability to withstand high flow. Additionally, heavy machinery was unavailable which creates difficulties for driving poles or logs into the ground to stabilise the green measures.

In future work, it is proposed that the eroded bank needs to be graded to something approximating a 45-degree slope before the installation of green measures. There is a need to use live materials, plants and seedlings to ensure that the measures installed are 'live' and can develop roots to stabilise the bank. Furthermore, toe protection is a recurring issue that green measures need to consider, as was evident in the Trusan. Providing toe protection could help solve issues such as undercutting that commonly occur in high-energy rivers and were prevalent in the Trusan.

In short, specific design features are of course important, but failings in the Trusan also related to incomplete installation or not following the design, as well as the lack of maintenance. The reasons for this stem from the limited time communities have to work on such projects. There was a rush to install measures at all the target sites before the wet season, and this contributed to some of the problems. All the installation at a site should be completed before moving to the next and time should be given for checks and maintenance of existing features, rather than installing new ones.

CHAPTER 5: ADDRESSING FLOODING AND EROSION USING FLOODPLAIN RETENTION

Landslide area and gabions at the Upper Trusan River
Photo: Yih Yoong Lip, February 2023

5.1 Introduction

River floodplains are low-lying lands adjacent to river channels that are naturally prone to flooding. They are composed primarily of nutrient-rich sediment from rivers. When river discharge exceeds bankfull stage, overbank flow will inundate these areas, slowly progressing towards the outer margin of the floodplain. The cyclical pattern of inundation and drying plays a significant role in supporting the dynamicity of river systems, contributing to high soil fertility and water availability (Shrestha et al., 2014). Floodplains are among the most beneficial and valuable places for people and communities have long occupied floodplain areas; however, this occupation contributes to increasing flood risk, especially due the current era of climate change (Mazzoleni et al., 2021; Wing et al., 2022).

Flooding accounts for approximately 40 percent of all global natural disasters (Baharom et al., 2013). Southeast Asia (SEA) is a region that is particularly vulnerable to frequent and severe flood impact due to its high and intense rainfall (WMO, 2021). Global climate change and catchment land use changes exacerbate flooding and associated land degradation and erosion in SEA. Several countries, such as Malaysia, Thailand, Vietnam and Cambodia, are currently affected by frequent flooding (Shrestha, 2013). According to the Department of Irrigation and Drainage (DID) Malaysia, 9 percent of the total area in Malaysia is vulnerable to flood disasters, affecting approximately 4.82 million people in the country (DID, 2009). Some details of flood trends were presented in the literature review (Chapter 2).

Urban rivers are commonly altered or controlled by hydraulic structures designed to protect human settlements from flooding. Flood protection measures such as flood walls, dykes and levees are often used to cut off the lateral connectivity between the floodplains and active channels by restricting overbank flow (de Vriend et al., 2015; Maxwell et al., 2021). However, some of these structures fail to prevent flooding and disruption in lateral floodplain connectivity and river morphology have made some floodplains no longer capable of retaining flood water, leading to higher flood peaks with shorter duration (Karim et al., 2020; Opperman et al., 2013).

Due to such issues, it is widely accepted that management of flood risk by focussing only on local measures related to heightening or otherwise engineering riverbanks are inadequate. Corridor scale management with the notion of allowing rivers to flood and erode has emerged as a more sustainable alternative approach. Past examples have adopted various names for this approach, such as the erodible river corridor and fluvial territory, and are reflected well by the term ‘giving back land to the river’ which is often used to encapsulate the underlying philosophy. Approaching flood management in this way, which is based on understanding the hydrogeomorphology of the rivers, is seen as improving flood resilience and so more beneficial for society (Biron et al., 2014; Buffin-Bélanger et al., 2015).

Several studies have shown that using floodplain areas for flood retention (i.e. reconnecting rivers to their floodplains) significantly reduces flood peaks and prolongs flood waves (Jonoski et al., 2019; Suman & Akther, 2014). Many have used hydrodynamic modelling methods to simulate floodplain inundation and evaluate changes in flood risk in downstream areas. However, most examples come from temperate regions, particularly in lowland, urban or semi-urban areas (Clilverd et al., 2016; Schober et al., 2020). In lowland areas, it has been shown that managed floodplains could potentially increase flood storage capacity (Apel et al., 2009; Czech et al., 2016). The managed floodplains delay the activation of storage volumes which optimises retention capacity and increase peak flow attenuation effects. Conversely, unmanaged floodplains are activated during the early stages of a flood event, which minimises their capacity and storage volume and so they may have little influence on the flood peak (Castellarin et al., 2011).

There is already substantial literature investigating these approaches to sustainable river management, but relatively little work has directly addressed the difficulties of applying them in upland tropical environments. Studies are needed in these environments for several reasons. First, annual rainfall levels and rainfall intensities are high, leading to frequent and rapid flooding. Second, upland river valley characteristics are very different to lowland ones and may influence storage potential (Consoer & Milman, 2018). Finally, high poverty levels in many rural tropical areas mean that communities are much less resilient economically to flooding than in other areas.

In other climate regions, a few examples from smaller rivers (ranging from 0.4 km to 6 km in length) have shown that restoring lateral connectivity by removing embankments could reduce total flood peaks in downstream areas by 12-25% (Acreman et al., 2003; Clilverd et al., 2016; Hammersmark et al., 2008). Subsequently, proper land use in floodplain areas could also potentially increase the retention capacity by increasing the surface roughness, which helps to slow down overbank flow runoff (Rak et al., 2016; Schober et al., 2020). Similar studies are needed in small and medium-sized tropical catchments to see if similar effects of restoring connectivity could be achieved when rainfall values and intensities are high.

This study focussed on the potential benefits of using floodplains for flood retention in a meso-scale upland tropical river that experiences frequent flooding and high rates of bank erosion. Floodplain retention capacity and its effectiveness in reducing flood peaks in downstream areas were assessed by testing scenarios with different channel-floodplain geometries. These scenarios represent options for flood management at the corridor scale and involve manipulating water level at which channel water flows onto the floodplain. Two-dimensional (2D) hydrodynamic modelling using HEC-RAS® was used to simulate flood scenarios in these areas. A flood inundation map was generated to understand the flood risk under existing conditions and inform flood mitigation plans for the future, specifically to identify strategic areas for flood retention. Floodplain inundation for a range of high flow events whose magnitudes and recurrence intervals were modelled, based on the work presented in Chapter 3.

5.2 Study area

The Trusan River and catchment were described in Chapter 1. The study area in the upper part of the Trusan is located close to the Sabah border, is mostly mountainous, and has an altitude of 800 - 900 meters above sea level. The whole of the study area is 140 km^2 and the river length is 10 km. Average monthly rainfall is 220 mm, and the climate is characterised by wet and dry seasons. The wet season is influenced by the tropical monsoon that commonly occurs between November and February, with higher precipitation rates. The remaining months have lower precipitation than the wet season, but the overall precipitation is still high. The only noticeable dry months are July to September, with monthly precipitation of less than 100 mm.

Most of the river reaches in the 10 km section have a median sediment size in coarse gravel fraction, and the bed and exposed bars mostly have an armouring layer of gravel-cobble sediments. The river has a gradient of 0.013 m/m. Along the 10 km study section, total floodplain area is approximately 4.7 km^2 with a width ranging from 400 to 500 metres.

These floodplains are the primary agricultural resource (e.g. rice paddy fields) for the local community. Various small channels are used to route irrigation water from the river to the paddies at certain stages of rice production. An estimated of 25 percent of floodplain areas are paddy fields, while 5 percent are used for livestock grazing. The remaining floodplain areas are grasslands, built-up areas, or bare earth, accounting for 62 percent of total floodplain areas. Outwith the floodplain, land cover is mostly a thick canopy layer of forest; this forest covers approximately 95% of the total area of the Upper Trusan. According to the historical satellite images, the land cover has remained unchanged for the past decade (see Chapter 6) despite minor deforestation and disturbance.

The flood modelling focussed on the upper 6.5 kms of the study area (Figure 5.1), directed by the location of some of the most acute recent flooding problems. Some paddies here have been abandoned due to flooding. The remoteness of the area means that much of it is not accessible to vehicles, and accordingly most management is manual. During high rainfall the river carries a high fine sediment load, and when banks overspill and the floodplain is inundated, large volumes of fine sediment are deposited on top of the paddies. The increased frequency of such events means that manual (by shovel) removal of this sediment is simply impractical and, as a result, some paddies have been abandoned. This impacts livelihoods. The present work was undertaken to help understand if managed flooding – i.e. to targeted areas – could help reduce such problems and make the community more resilient to future climate and flooding regimes.

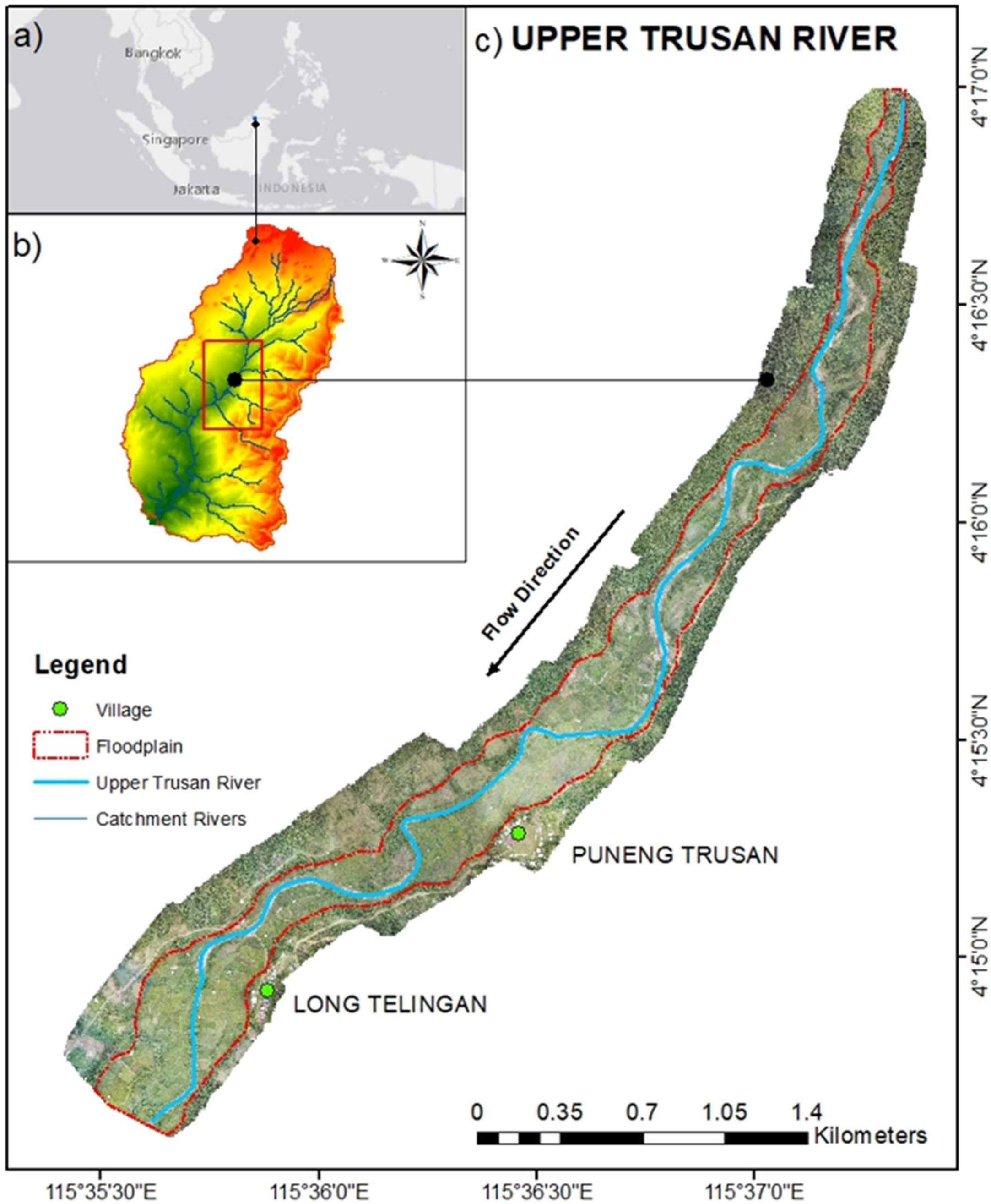

Figure 5.1: a) Geographic Location of b) The Upper Trusan Catchment c) main study area in the Upper Trusan River.

5.3 Methods

5.3.1 Data acquisition

At the heart of the work presented in this chapter is the need to understand how the morphology of the river channel and floodplain influences inundation and the effectiveness of managed flooding for reducing downstream floods. Literature reveals that river and floodplain slope, width, and roughness are commonly regarded as the most influential factors in determining effectiveness (Dutta et al., 2013; Mihu-Pintilie et al., 2019; Rak et al., 2016). As a result, flood modelling requires the incorporation of high-resolution geometry data.

In the Upper Trusan, digital photogrammetry based on the Structure-from-Motion (SfM) algorithm applied to close range photographs obtained from a drone was used to obtain the required geometry data. This technique is widely used in fluvial applications to produce Digital Elevation Models (DEMs) representing the geometry or topography or fiver channels (Marteau et al., 2017; Smith & Vericat, 2015). The aerial survey was conducted in November 2021 for the whole reach, including the extent of floodplains; total flight coverage was 2.9 km^2. A DJI Mavic Pro drone® was used to perform UAV flights and capture aerial imagery. The drone has a 3-axis gimbal camera attached with a CMOS® sensor and 12.35 Mega Pixel maximum resolution. The images are captured in jpeg stills during the drone flight to ensure that the data are at the highest resolution (i.e. 12.35 MP). The ISO is set to auto mode to allow optimum exposure for the images. The ISO varies from 100 to 1600 depending on light conditions.

In order to avoid errors related to water surface reflection and glare in submerged areas, the flights were undertaken in overcast conditions. Nevertheless, water glare cannot be entirely avoided in every image due to variation in cloud cover resulting in a slight difference in exposure and colour in each photo. The DJI® Pilot app developed by the DJI® technology company was used to pre-program the flight paths and settings. The images captured have a side overlapping of 70 percent and a frontal overlapping of 80 percent. The flight altitude remains constant at 150 metres above the ground throughout the survey, with the camera angle of 90 degrees pointing downwards. However, the survey covering a large extent of the area could not be done in one single mission due to limited battery life. Hence, the survey was divided into eight missions spread over three days.

Before carrying out the drone flight, 32 laminated A3-sized Ground Control Points (GCPs) were placed evenly on the ground and strategically across the entire perimeter of floodplains. GCPs are necessary for precision UAV mapping to deduce positional uncertainty (i.e. enhance accuracy) in Structure-from-Motion (SfM) photogrammetry. The position of GCPs was surveyed with Leica Viva® GS16 Rover and Base with Real Time Kinetic (RTK) setup. The horizontal accuracy of the measures coordinates is up to 8 mm, while the vertical accuracy is up to 15mm. Once the ground survey was done, the pre-programmed flight missions were performed.

5.3.2 Data processing

The aerial images were post-processed using Pix4D® mapper photogrammetry software. Before importing the images to the software, they were filtered manually based on the image quality. Images that were overexposed, blurred and have excessive glare were removed to avoid matching errors during the stitching process. Pix4D® mapper is a fully automated software where the calibration of camera parameters, image pairing and matching of tie points were optimised internally. The selected images were imported to the software for these processes (e.g. calibration and image matching) mentioned in order to generate sparse point clouds.

Next, the coordinates of the surveyed GCPs were used to georeference the sparse point cloud. This is a process where we adjusted the initial computed position of sparse cloud by positioning the images to the centre of respective GCPs. Spatially corrected sparse clouds allowed point cloud densification in the next step. Pix4D mapper provides an overall error for the GCPs used for the registration to provide identification for the quality of point clouds generated. However, these registration errors for GCPs only represent the error associated with translational, rotational and scaling errors. Hence, 4 out of 32 GCPs were assigned as Check Points (CPs) to assess the positional errors of the point clouds. The summary of the registration errors and model precision computed by Pix4D mapper is shown in Table 5.1.

Table 5.1: Registration errors and model precision for the Upper Trusan DEM.

Markers	Mean error (m)			Root mean square error (m)			Maximum projection Error (m)
	X	Y	Z	X	Y	Z	
GCPs	-0.0004	-0.0013	-0.0184	0.0579	0.0485	0.106	0.10
CPs	-0.0214	0.00159	0.0234	0.0959	0.0509	0.153	0.078

The final dense point clouds produced have an average density of 11 pixels per cubic meter with an average pixel resolution of 6.53 cm. Although Pix4D® mapper generated Digital Surface Model (DSM) and Digital Elevation Model (DEM) automatically, the DEM was still subjected to errors where the noise caused by vegetation and trees was not entirely removed. Moreover, the interpolation between voids was smoothened excessively in Pix4D®, resulting in loss of terrain details (e.g. bank slope).

To reduce the loss of topographic information, CloudCompare® (CloudCompare v2.12, 2022), an open-source point cloud processing toolkit was used to process the dense point cloud. The point cloud dataset was first filtered using a ground filtering plugin (CSF) to remove non-ground points (e.g. vegetation, trees and buildings). The remaining noise was removed manually using a segmentation tool. Voids between points were filled using the mesh triangulation method, and points were generated on the mesh plane. Finally, the processed point cloud was resampled to 0.05-meter DEM, which was used in the 2D hydraulic model.

5.3.3 Hydraulic Modelling

The HEC-RAS® hydraulic modelling software developed by the US Army Corps of Engineers (HEC-RAS® v6.2) was used. A 2D model was developed to simulate flows in the river channel and across the floodplain, to assess the current flood risk and the retention capacity of the floodplain. The DEM produced from aerial survey was used as geometry data input in the model and was projected under the spatial reference of BRSO East Malaysia (GDM2000).

The modelled area is about 2.9 km^2, while the length of the river is 6 km. The upper boundary of the model is located at the top end of the section; it was the input of selected peak discharges (shown in Figure 5.4 & Figure 5.5). The outflow at the lower end is represented by a lower boundary condition, specified by the friction slope that is consistent with the water-energy grade line and the bed slope.

2D hydraulic model requires computational cells to be defined over the terrain to simulate flows across the given terrain. The water surface elevation is calculated for each computational cell and the water movement is controlled by the computational cell faces (i.e. side of each cell) and underlying terrain. Hence, the size of each computational cell is critical in achieving high-accuracy computational results. Smaller cell sizes can delineate the terrain in detail but require a longer computation time. For this study, a grid size of 5 meters was used for the river channel, but because the floodplain was the main focus of the work, a smaller grid size of 4 meters was used for the floodplain topography. This smaller grid size allows the model to produce more accurate estimates of water surface level over the topographically complex area.

The HEC-RAS® model can perform 2D calculations for flow moving over the computational mesh using either the Diffusion Wave equations or the Saint Venant equations (i.e. Full Momentum method in HEC-RAS®). The simpler Diffusion Wave equations have shown to perform well in terms of water depth and velocity (Bates & De Roo, 2000). Hence the 2D diffusion wave equations solver were used since the numerical solutions are more feasible and shorten the computational time for simulations with multiple scenarios. The 2D diffusion wave equations are shown below:

$$c = \frac{V\Delta T}{\Delta X} \leq 2.0 \qquad \text{(With a max C = 5.0)} \qquad (1)$$

Or

$$\Delta T \leq \frac{2\Delta X}{V} \qquad \text{(With C = 2.0)} \qquad (2)$$

Where C is Courant Number, V is Flood wave velocity, ΔT is the computational time step and ΔX is the average cell size.

Table 5.2: Manning's Roughness values used in the flood model.

Land Use	Manning's roughness applied
River channel	0.04 (based on Limerinos equation, see below)
Paddy field areas	0.05 (based on Ree and Crow equation)

In order to create a more accurate model, a land use classification layer was applied to the model to provide spatially varying parameters for Manning's n values. Table 5.2 shows the n-values applied for the floodplain and river channel in the model. The Manning's roughness for the floodplain was selected based on Ree and Crow's (1977) roughness factors developed for open fields and cropland on floodplains based on field experiments. In the Upper Trusan, an n-value of 0.05 was most appropriate to define the paddy field areas in which the height of the crop was most likely to be twice the height of surrounding vegetation (Ree & Crow, 1977). In comparison, the roughness for the main channel was calculated based on the equation developed by Limerinos (1970) where the n value is related to the hydraulic radius and particle size based on samples from rivers with bed materials ranging from small to medium-sized boulders (Limerinos, 1970). The equation is shown below.

$$n = \frac{(0.0926)\, R^{\frac{1}{6}}}{1.16+2.0 loglog\,(\frac{R}{d_{84}})} \quad (3)$$

The model was validated using only the low flow data observed in July and September 2019. The discharge was gauged at several locations within reach using a Valeport® model 801 flow meter. The simulated water level was compared with the measured water level with an R-square of 0.9597 (Figure 5.2) and a mean absolute error of 0.13. Note, however that for safety reasons it was not possible to manually gauge during floods, so we recognise that strictly speaking the model is not validated for the (high) flow range that is the focus of the simulations. However, level of the large flood that occurred on 30th September 2021 was verified using the flood mark captured during the aerial survey conducted in November 2021. By comparing the flood level with the flood mark, results indicate that the simulated discharge (at 425 m^3/s) predicted the inundation areas accurately and flood level matches the flood mark (Appendix D: Figure D.4 & Figure D.5).

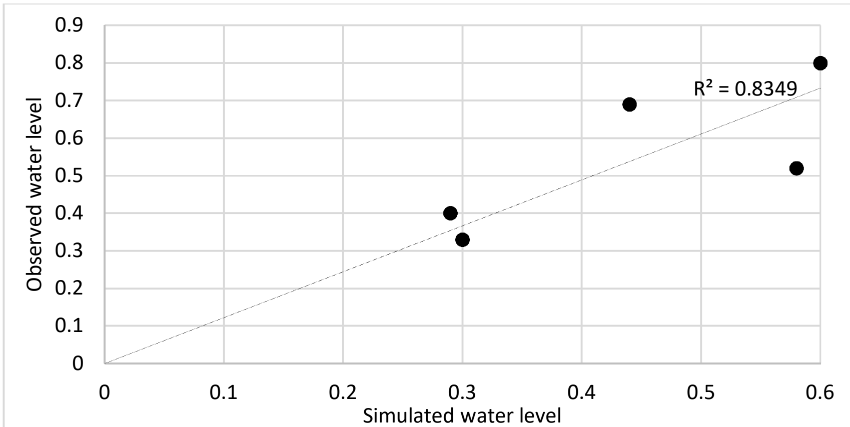

Figure 5.2: Simulated water level in HEC-RAS® vs water level measured in July and September.

5.3.4 Synthetic instantaneous flood hydrograph

In Chapter 3, we reconstructed a 22-years flow hydrograph for the Upper Trusan based on the rainfall-runoff model using a regional approach. This was useful for assessing high flow magnitudes, frequency and general patterns and trends in flow across annual and seasonal timescales. However, this hydrograph was generated at the daily time-step. This is too coarse for flood modelling, since the Trusan is flashy and floods often last only 1-2 days; a specific problem is that this timestep underestimates instantaneous flood peaks. For flood modelling, we therefore used the water level data from our recorder at Long Telingan (Figure 5.3; time period 2020 to 2021) to determine the magnitude and duration of some high flow events. This water level data is recorded at an interval of 15 minutes, giving the high temporal resolution that is needed to characterise flood events.

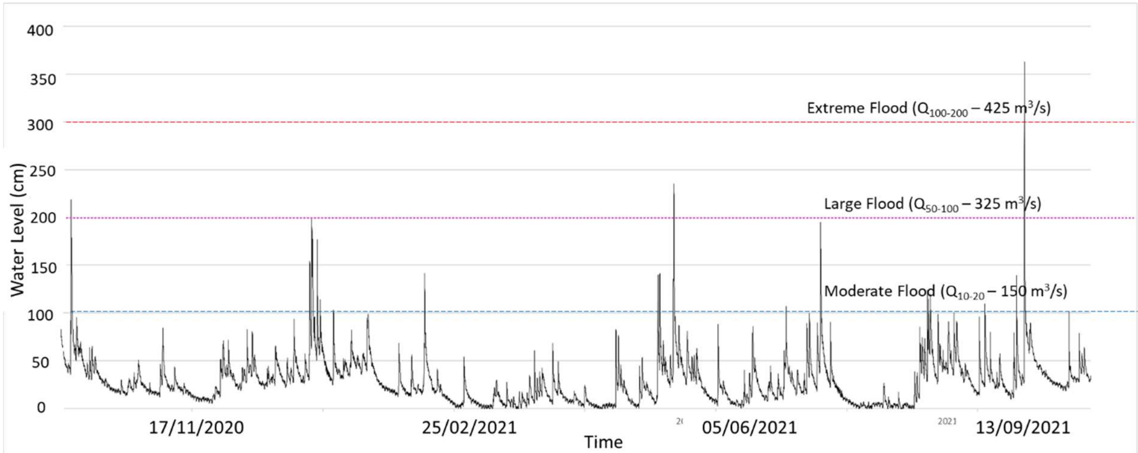

Figure 5.3: Water level recorded at Long Telingan from 2020 to 2021

The water level was transformed to discharge based on the stage-discharge relationship obtained from the HEC-RAS® model. The floods chosen for modelling floodplain inundation represent high flow events with different recurrence intervals such as $Q_{100-200}$, Q_{50-100}, Q_{10-20}, and Q_{1-5} (peak discharges with 100 – 200-year return period; 50 – 100-year return period; 10 – 20 year return period etc.)[2] For the simulation, 8 events were developed in total – a short duration (referred to a Type 1) and a long duration (Type 2) version of each of the four chosen magnitudes (Figure 5.4 & Figure 5.5 respectively).

With the roughness stated in Table 5.2, the maximum instantaneous peak flow was estimated to have a magnitude of 425 m^3/s ($Q_{100-200}$), and the water level recorded was approximately 4 meters from the bottom of the bed. The instantaneous peak flows estimated for Q_{1-5}, Q_{10-20}, and Q_{50-100} were 65 m^3/s, 150 m^3/s, and 325 m^3/s respectively.

[2] Given that the long-term hydrograph was reconstructed in mean daily flow time step, which the flow duration curve was produced based on this. In order to estimate the return period of simulated events, the instantaneous flow was converted to mean daily flow by averaging discharge recorded in 24 hours. However, the mean daily flow is largely based on the duration of instantaneous flow, where the same peak flow with different duration of flow might result in a different mean daily flow. Hence, the return period is not precise for the peak flow and is therefore given as a range to take into account of peak flow with different duration.

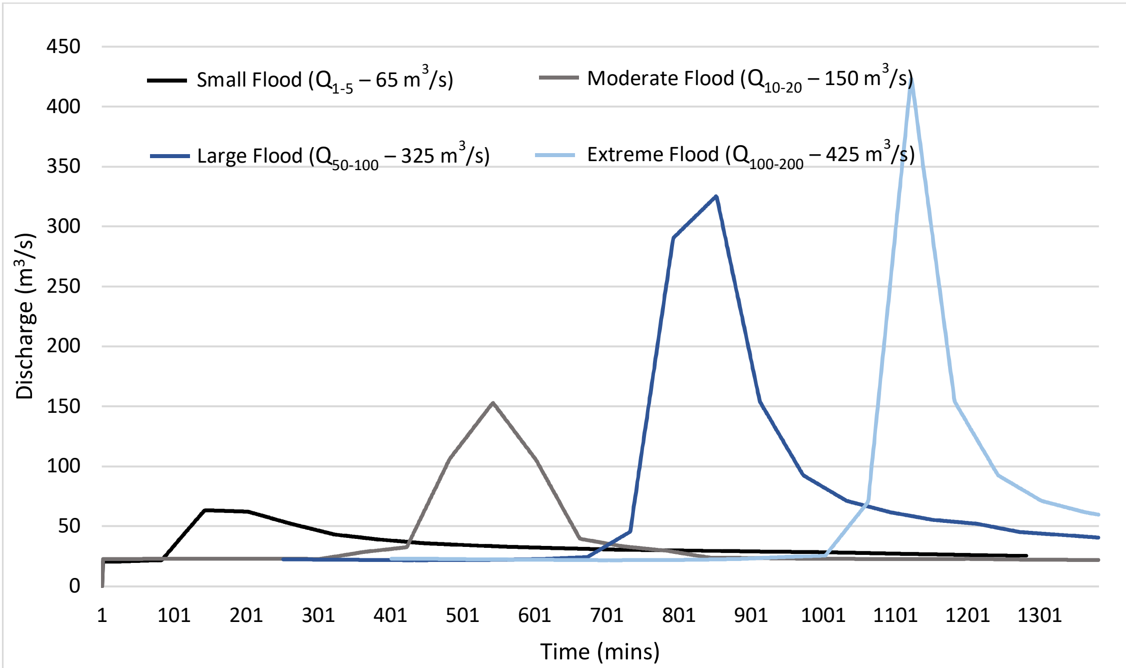

Figure 5.4: Shorter-type flood events (type-1) range from small to extreme flood.

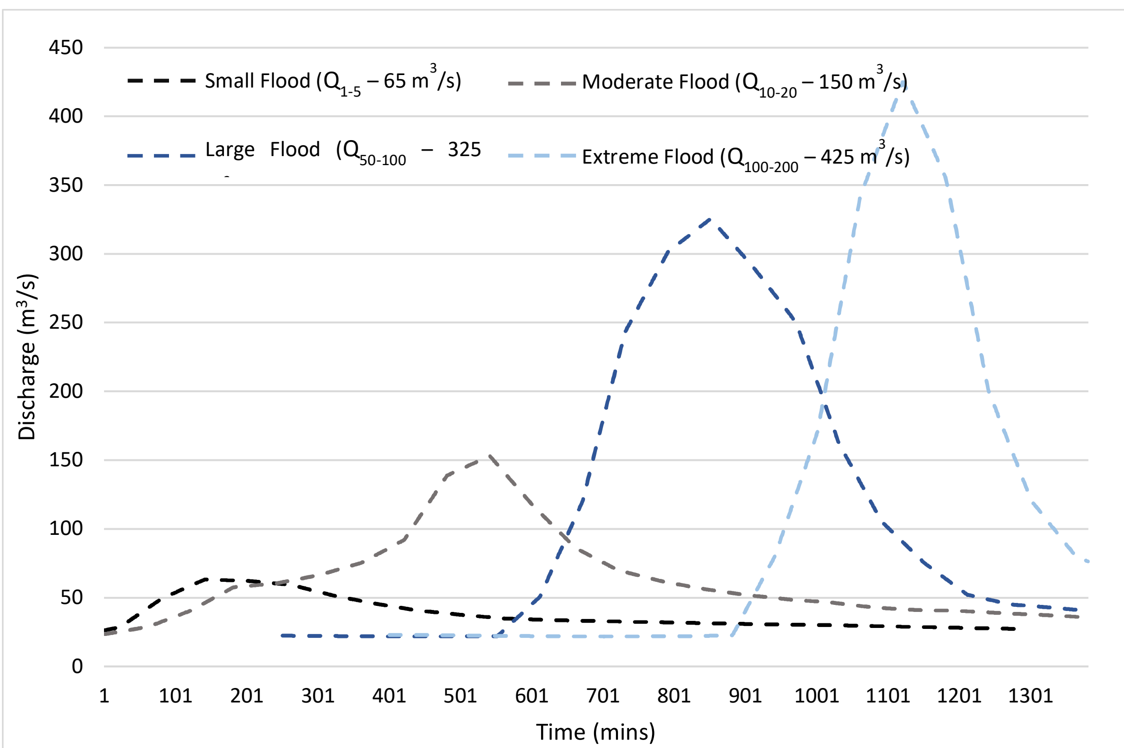

Figure 5.5: Longer duration flood events (type-2) from small to extreme flood.

5.3.5 Assessment of existing flood risk

HEC-RAS® was used to produce a flood inundation map to show areas prone to flooding. To understand the reasons why certain areas flood, local variability in topography was investigated. This was done by detrending the whole DEM, to better understand local variability in elevation. By detrending the DEM, the overall valley slope of the terrain is flattened without removing the local topographic variation. This is done by fitting a plane based on the water surface elevation points extracted across the valley slope. This plane surface was assumed to have the same slope as the sloped ground surfaces (i.e. original DEM). The raster calculator tool in QGIS® was used to perform a subtraction between the plane surface and DEM to produce the detrended DEM.

5.3.6 Channel and bank height modification

Altering the geometry of the river and its floodplain will alter inundation and retention and this was investigated as part of the study. The first analysis was to model flood inundation using current (unmodified) riverbank heights. Obviously higher riverbanks prevent overbank flows, while lowering the banks can help with managed flooding by allowing certain areas to flood at certain discharges/water stages. To assess options for managed inundation, we therefore lowered bank heights in selected locations in order to facilitate inundation of adjacent areas. We will refer to these as ‘gate-openings.’

There are two main parameters for the hydrological evaluation of flood risk reduction using floodplain retention: the reduction in flood peak (ΔQ) and the delay of flood wave (Δt), and we addressed each of these. With the latest version of HEC-RAS® 6.2, the terrain modification tool allows us to modify the DEM and create multiple scenarios with varying bank height.

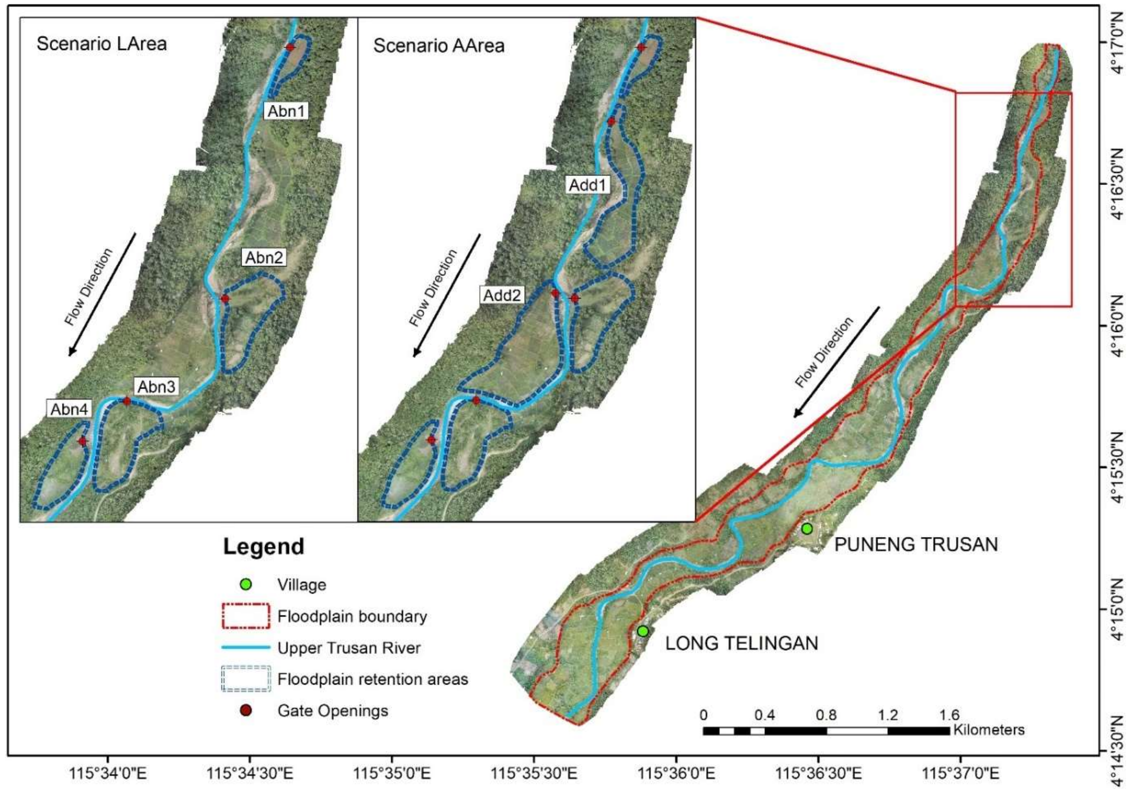

Figure 5.6: Locations of floodplain retention areas (blue boundary) in Scenario LArea and Scenario AArea

We focussed on using floodplains in the upper part study section as flood retention storage (so as to potentially reduce floodpeaks in downstream areas) and so altered the bankfull discharge here by creating gate openings in key locations. We developed two scenarios with different locations modified to allow flooding (Figure 5.6). For the first scenario (i.e. Scenario LArea: Limited Areas), we have chosen the abandoned paddy field areas only for flood retention. These limited areas are labelled Abn1-4; the other areas remain unchanged. It quickly became clear that only flooding such small, limited areas would have very little effect in terms of reducing downstream river channel discharges. We therefore developed a second scenario (i.e. Scenario AArea: All Areas) that included flooding two additional areas (Add 1 & 2 in Figure 5.6) that were active paddies. For the flood modelling, the true local topography of all the individual paddies was used, rather than a flat elevation across the whole floodplain area. The existing paddy plots, due to their network of small channels and dykes, created as system that functioned like a series of cascade reservoirs.

For each scenario, we tested the effects of three different bank heights that act as 'gate-openings' for conveying river flow to the floodplain (Figure 5.7). This is because a previous study has shown that the bankfull flow or so-called 'breach discharge' of the floodplains can influence peak flow attenuation (Castellarin et al., 2011). The required elevations of the gate openings were themselves developed using the DEMs and model, and each was chosen to have a specific breach discharge (the discharge that resulted in water rising above the gate opening level and flowing into the floodplain; Table 5.3).

Table 5.3: Scenario LArea and scenario AArea with low to high inflow point designed with specific breach discharge.

Scenarios	Inflow point	Breach Discharge (m^3/s)
LArea-low	Low	40
LArea -med	Medium	100
LArea -high	High	190
AArea-low	Low	40
AArea -med	Medium	100
AArea -high	High	190

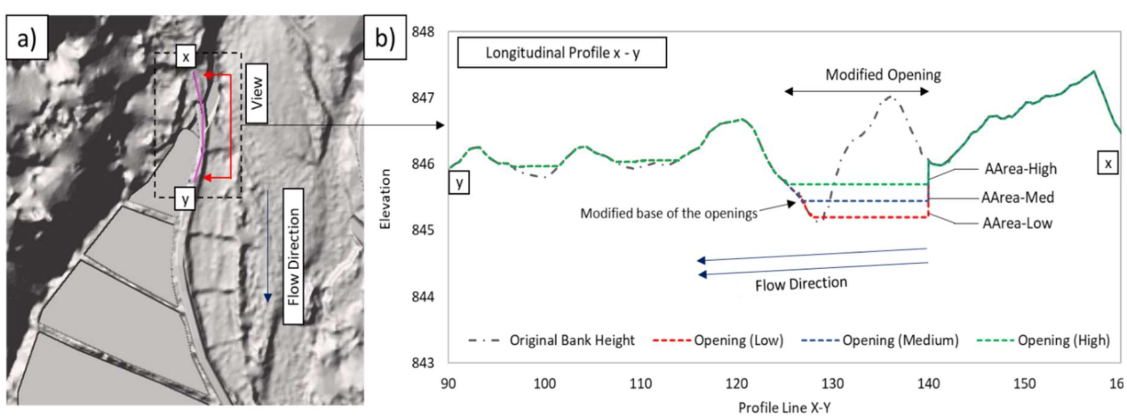

Figure 5.7: Long profile of bank height showing the opening at add2 (refer to Figure 5.6) that allows channel water to enter the floodplain with three different heights, where red is the low opening, blue is the medium opening and green is high opening. These heights were used to trigger water movement of channel to the floodplain

5.4 Results

5.4.1 Flood Inundation Map and detrended DEM

Based on the detrended DEM (Figure 5.8), it is notable that the upstream and the upper part of the downstream areas were located in a depression zone with lower elevation overall, while the middle and the lowermost part of the study area have a higher elevation compared to the other areas. The terrain elevation corresponds to the flood inundation map, where the middle section has a lower flood risk. Those areas with lower elevation (i.e. green pallets in Figure 5.8) have a higher risk.

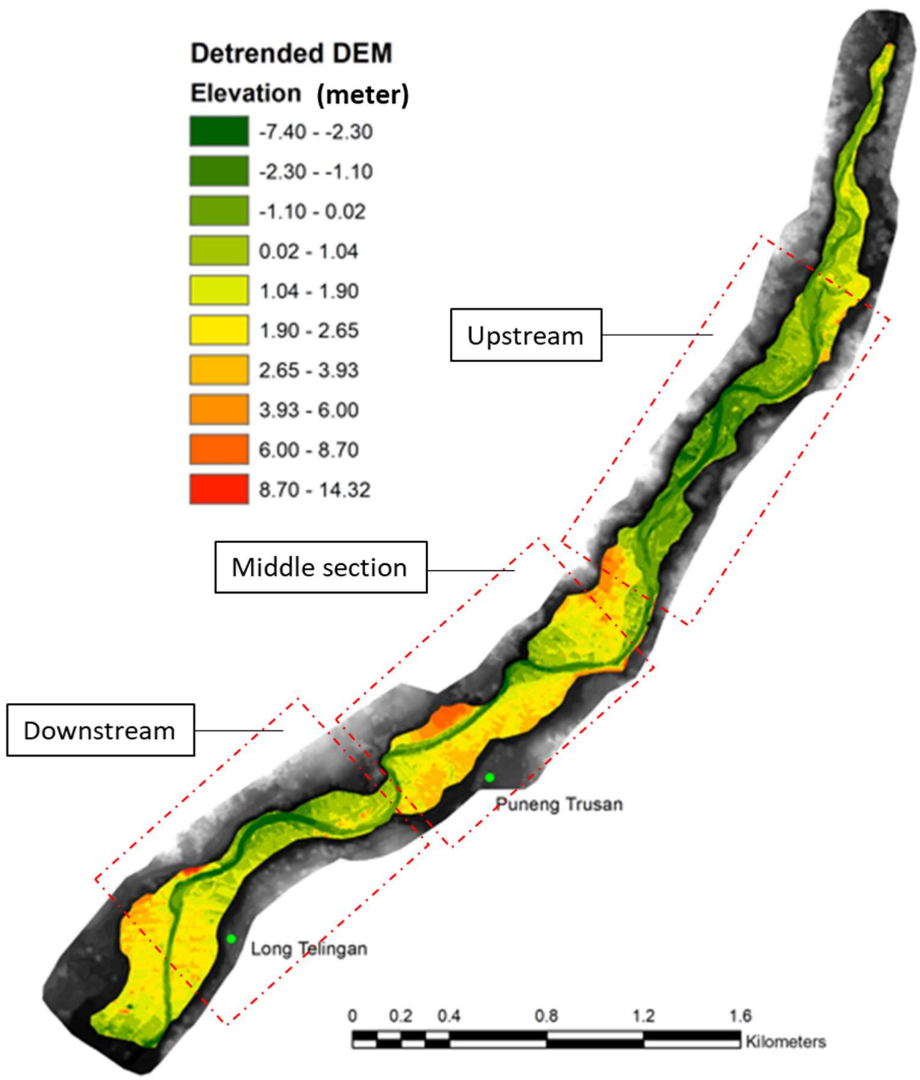

Figure 5.8: Detrended DEM of the study area

Figure 5.9 illustrates the flood inundation under the existing channel topographic condition and the area of floodplain inundated is summarised in Figure 5.10. Discharges that exceeded the 50 – year return period inundated most of the floodplains (0.39 km^2). For the discharge with 1 – 20-year return period, only some low-lying areas were inundated (0.02 – 0.125 km^2) with a lateral extent not more than 120 metres from the river channel. At return period of greater than 100 years, an estimate of 36.25% (0.53 km^2) of the total floodplain area was inundated. The upstream and downstream parts of the study section are more vulnerable to flooding, while the middle section still has some dry zones even at flows with return periods > 100 years.

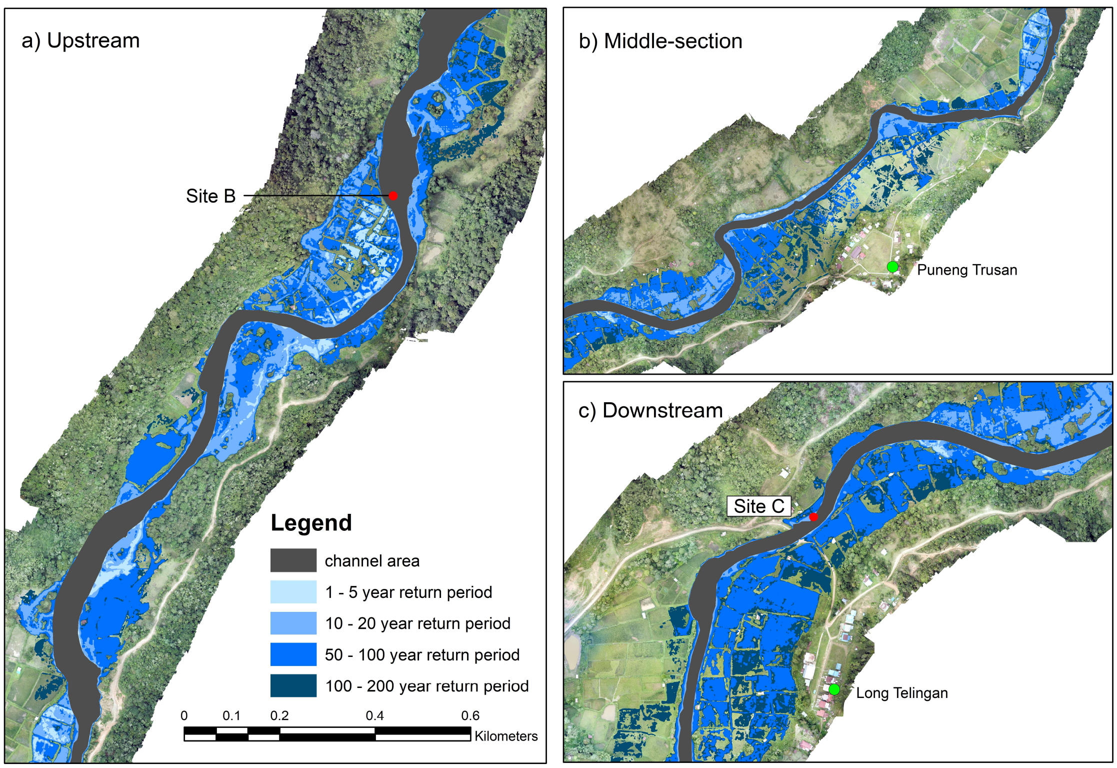

Figure 5.9: Map of flood inundation at the a) upstream, b) middle section and c) downstream simulated from HEC-RAS® for the 1-, 10-, 50- and 100-year return period discharges.

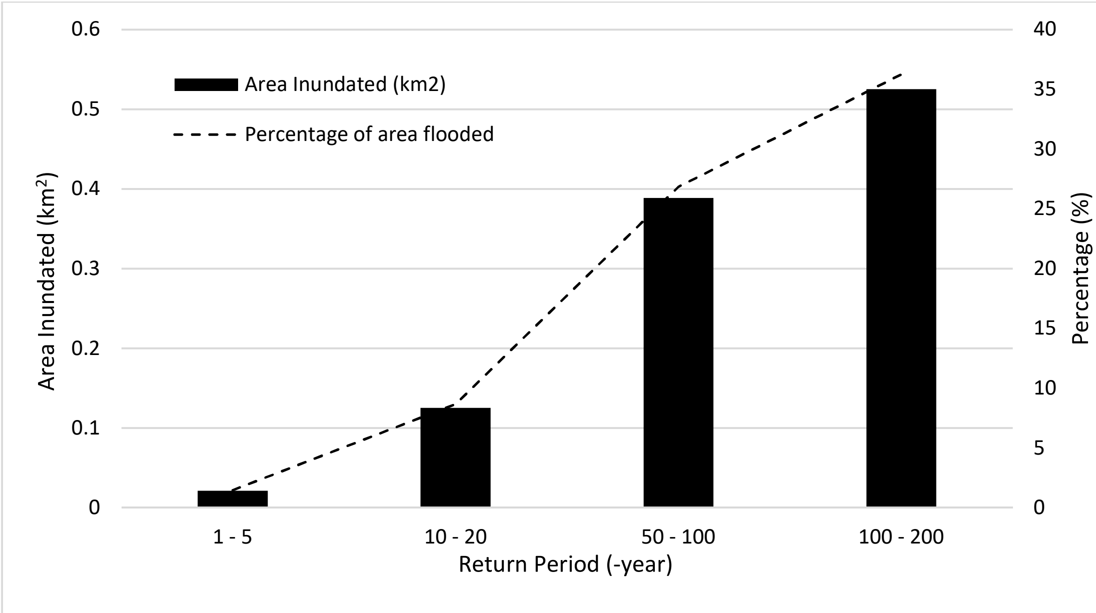

Figure 5.10: Total area and percentage of the floodplain inundated per each return period.

5.4.2 Flood peak reduction and potential retention capacity

The flood simulations show that the bank modification to alter water routing to the floodplain has a major influence on the flood hydrograph shape (e.g. peak reduction, wave translation). Some scenarios result in larger reductions in channel flow magnitude downstream and a greater effect on wave translation; some scenarios however had very limited effects. Figure 5.11 and Figure 5.12 show the effect of the floodplain inundation on shorter (type-1) and longer flood events (type-2) respectively. The scenarios that have the greatest effects on the magnitude of each type of event are highlighted in red; for comparison, the original hydrographs are shown in blue. Table 5.4 summarises the detailed outputs for each scenario (e.g. peak reduction, wave translation, total inundated area) and brings them together with the total inundated area downstream and change in water surface elevation. The scenarios that have little impact on flood event magnitude are shown in light grey.

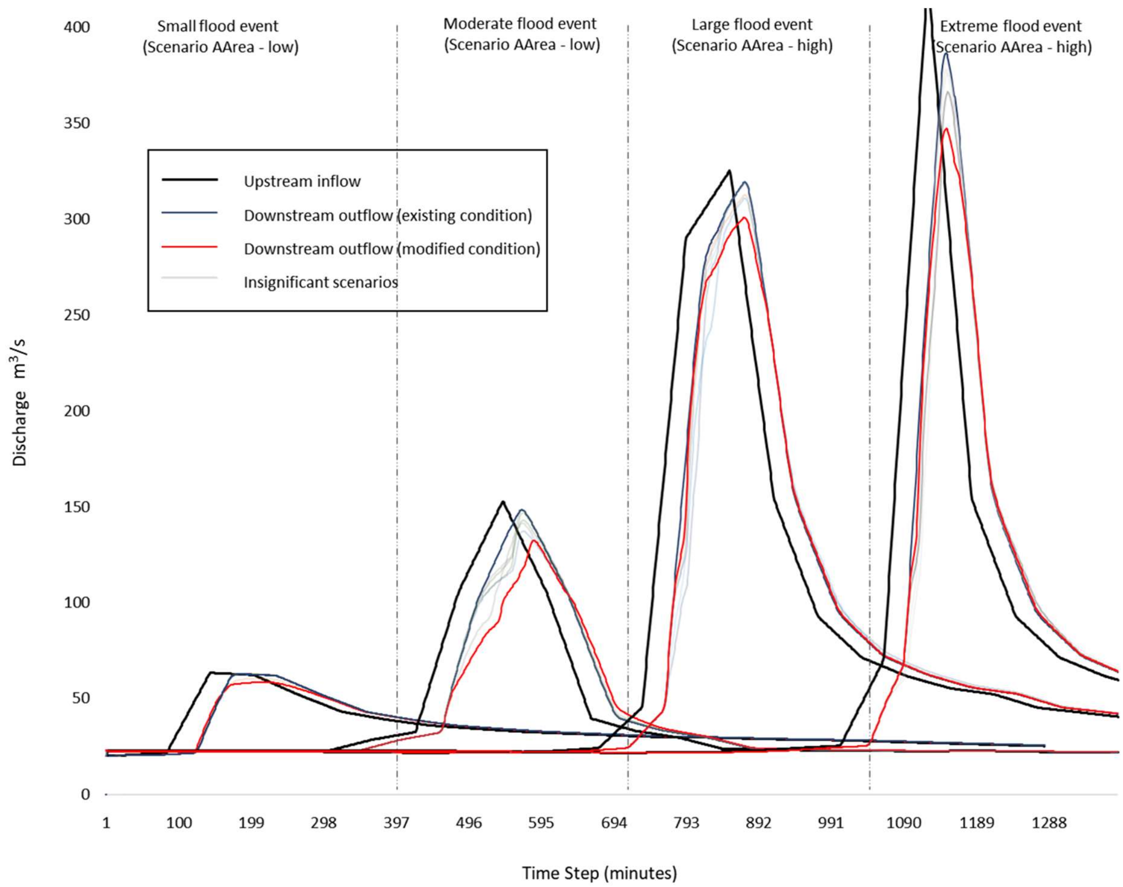

Figure 5.11: Comparison of flood attenuation results for the shorter-type flood events (type-1).

Generally, flood waves with shorter duration tended to be reduced more than longer events. For the extreme flood events, the reduction in the peak of shorter events is 75.90 m^3/s (scenario AArea-high = 18 %), while the reduction of the longer events is 16.39 m^3/s (scenario AArea-high = 4 %). Other than that, it was notable that the peak reduction for scenario AArea is generally higher than scenario LArea due to larger capacity for the retention of flood water. In scenario LArea-high, the peak reduction for the shorter extreme flood events is – 41.41 m^3/s while the peak reduction for the same flood event in scenario AArea-high is – 75.90 m^3/s. However, the floodplain has very little effect on longer flood events. In scenario LArea-high, the peak reduction for the longer extreme flood events is – 15.32 m^3/s (3.7 %), while the peak reduction for the same flood event in AArea-high was – 16.39 m^3/s (3.9 %).

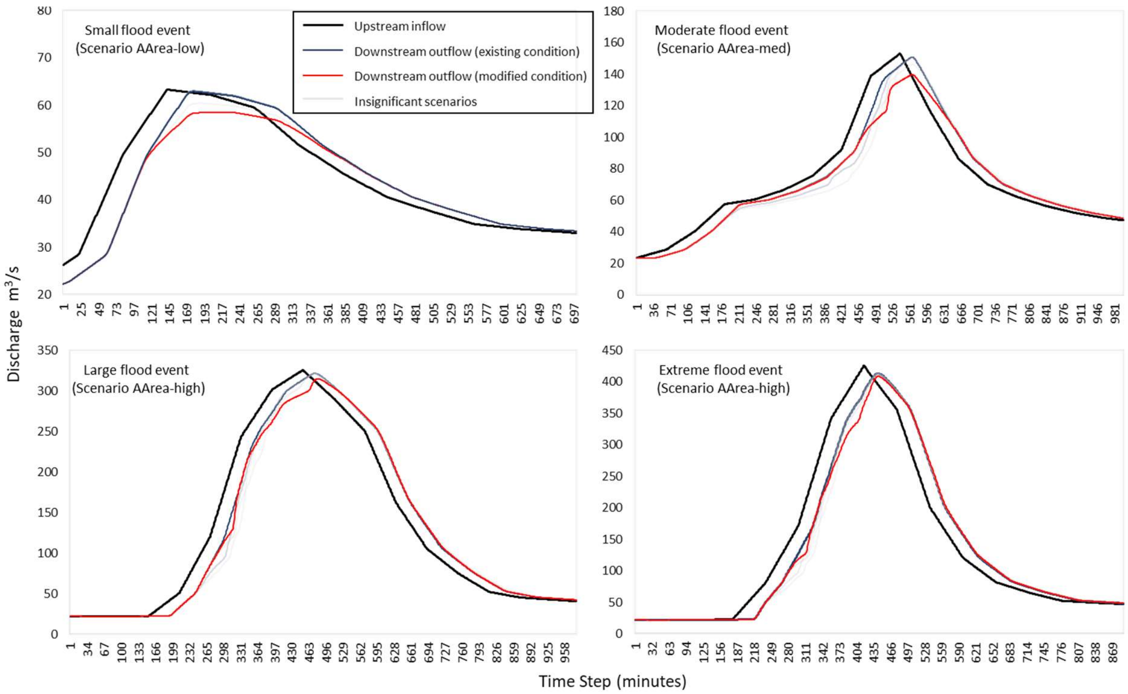

Figure 5.12: Comparison of flood attenuation results for the longer-type flood events (type-2).

The total floodplain areas inundated, and potential contributed volume are summarised in Table 5.4. Table 5.5 summarises the detailed outputs for each scenario (e.g. peak reduction, wave translation, total inundated area) and brings them together with the total inundated area downstream and change in water surface elevation.

Table 5.4: Floodplain retention area and the potential volume for scenario AArea and scenario LArea

Scenarios		Floodplain	Area (m^2)	Potential Volume (m^3)
AArea	LArea	Abn1	5790.7	6530
		Abn2	29214.6	10410
		Abn3	20182.05	23280
		Abn4	17609.9	34860
		Add1	32896.46	41050
		Add2	53833.26	62500

The simulation outputs also indicate that the height of the inflow point to the floodplain (and hence the breaching discharge) of the floodplains significantly influences the flood peak reduction. For shorter flood events, the most effective scenarios to reduce small and moderate flood are scenario AArea-low, while the most effective scenario to reduce large and extreme flood is scenario AArea-high. This implies that an inflow points with a low opening (breaching discharge of 40 m^3/s) is most suitable for small and moderate flood events; the inflow points with a high opening (breaching discharge of 190 m^3/s) is most suitable for large and extreme flood events.

In terms of the flood wave propagation downstream, the flood peaks downstream have a time lag (i.e. flood wave propagation) that ranges from 20 to 40 minutes. The small flood peak has the most prolonged time lag, while the large and extreme flood have the shortest time lag. The flood wave propagation for the small flood event in scenario AArea-low has the largest wave transformation (ΔT = 80 mins), followed by the moderate flood in scenario AArea-low (ΔT = 42 mins). The flood wave propagation for large and extreme events in all scenarios did not exhibit any significant change in wave propagation.

Among all scenarios for the longer flood events, the flood attenuation is most obvious for small and moderate flood events. In contrast, the peak reduction for large and extreme flood is not marked. The small flood scenario (AArea-low) is reduced by 8 percent of the inflow peak with a discharge reduction of 4.74 m^3/s (ΔQ). This contrasts with the moderate flood event in scenario AArea-med is reduced by 9 percent of the inflow peak with a discharge reduction of 13.41 m^3/s (ΔQ). The peak reduction for the large and extreme flood events is in the order of 3 percent and 4 percent.

Table 5.5: Summary output of the simulated scenarios for shorter-type and longer-type flood events.

Shorter Flood Events																				
	Small Flood (Shorter)					Moderate Flood (Shorter)					Large Flood (Shorter)					Extreme Flood (Shorter)				
Scenario	ΔQ	ΔT (mins)	Total inundated area	Downstream Inundated Area	Downstream WSE (m)	ΔQ	ΔT (mins)	Total inundated area	Downstream Inundated Area	Downstream WSE (m)	ΔQ	ΔT (mins)	Total inundated area	Downstream Inundated Area	Downstream WSE (m)	ΔQ	ΔT (mins)	Total inundated area	Downstream Inundated Area	Downstream WSE (m)
existing	-0.43	40	21306.86	5281.61	791.63	4.44	25	125402.34	53190.96	792.21	5.88	20.00	389043.24	222246.42	792.97	36.43	25.00	525352.95	326361.61	793.14
LArea-Low	3.11	60	56307.17	4317.19	791.61	11.37	27	154856.82	47406.99	792.17	6.13	20.00	405410.03	220611.74	792.97	44.22	27.00	523737.52	308794.92	793.12
LArea-Med	0.38	40	19077.89	5294.27	791.63	9.87	28	151045.54	48342.73	792.18	12.61	20.00	395895.45	211633.55	792.95	45.40	25.00	521359.82	306673.16	793.11
LArea-High	0.38	40	19062.62	5301.77	791.63	6.01	28	130719.96	51440.06	792.20	6.75	20.00	399715.53	220151.46	792.97	41.41	26.00	526302.17	314926.38	793.13
AArea-Low	5.00	80	81506.52	3590.10	791.60	20.36	42	209943.90	39613.93	792.12	6.25	20.00	439325.14	219495.17	792.97	46.90	28.00	536018.08	304017.14	793.11
AArea-Mec	0.67	40	30552.28	5145.24	791.63	15.53	28	174528.64	44317.21	792.15	14.44	20.00	423189.31	205141.63	792.94	56.48	28.00	516532.04	286392.63	793.08
AArea-High	0.55	40	15702.87	5191.21	791.63	4.45	27	110288.98	52854.82	792.21	24.48	20.00	396022.45	193731.37	792.9	75.90	25.00	471434.71	256175.7	793.01
Longer Flood Events																				
	Small Flood (Longer)					Moderate Flood (Longer)					Large Flood (Longer)					Extreme Flood (Longer)				
Scenario	ΔQ	ΔT	Total Inundated area	Downstream Inundated Area	Downstream WSE (m)	ΔQ	ΔT	Total inundated area	Downstream Inundated Area	Downstream WSE (m)	ΔQ	ΔT	Total inundated area	Downstream Inundated Area	Downstream WSE (m)	ΔQ	ΔT	Total inundated area	Downstream Inundated Area	Downstream WSE (m)
existing	0.27	35	22603.51	8470.76	791.62	2.29	23	129420.12	55078.76	792.22	3.92	23	404646.52	237178.72	792.97	12.17	24	563152.039	360300.11	793.24
LArea-Low	2.88	40	59549.32	7341.19	791.60	2.29	25	165020.12	55118.41	792.22	3.94	23	422736.33	237271.98	792.97	12.59	24	578518.89	359834.3	793.24
LArea-Med	0.22	35	19854.94	8494.90	791.62	6.74	26	158274.82	52889.79	792.20	4.05	23	420771.61	235458.59	792.97	12.81	24	577892.445	359238.77	793.23
LArea-High	0.22	35	19839.48	8494.89	791.62	2.83	25	136101.67	54738.84	792.22	4.63	23	416263.32	236007.77	792.97	15.32	24	572068.018	356584.33	793.23
AArea-Low	4.74	85	91592.66	6603.18	791.59	2.18	26	227827.37	55043.27	792.22	3.87	23	457375.30	237422.57	792.97	12.00	24	595458.03	360647.83	793.24
AArea-Mec	0.43	35	16305.73	8362.89	791.62	13.41	25	204103.81	49295.37	792.16	4.03	23	453962.10	235331.11	792.97	12.27	25	594279.562	360288.72	793.24
AArea-High	0.43	35	16278.23	8362.97	791.62	1.81	24	112966.74	55254.61	792.22	10.73	30	430728.67	223160.80	792.95	16.39	26	583097.831	354793.87	793.22

**Examples of flood scenarios are shown in Figure D.1 - Figure D.3 (Appendix D).*

Most significant (based on discharged reduced)

Second Most significant (based on discharge

Figure 5.13 and Figure 5.14 provide Principal Component Analysis (PCA) plots to help understand the overall effects of the modelled scenarios. The PCA was applied to the hydrological variables associated with each one (area inundated, reduction in discharge etc) and so allows a comparison of their effects and, accordingly their relative value (rank). For example, for the lower magnitude events (Figure 5.13: top left; AArea-low Right side of biplot) scenarios have the greatest effect on inundated area, reductions in discharge, reduced water surface level in downstream areas and change in wave translation, while current, LArea-med, AArea-med and AArea-high have similar and less clear effects; LArea-low is moderately effective, sitting between the two extreme groups. Given that the priority is to attenuate high and extreme flood events, according to the PCA results, the effectiveness of scenarios can be ranked AArea-med, AArea-high, AArea-low, LArea-high, LArea-med and LArea-low.

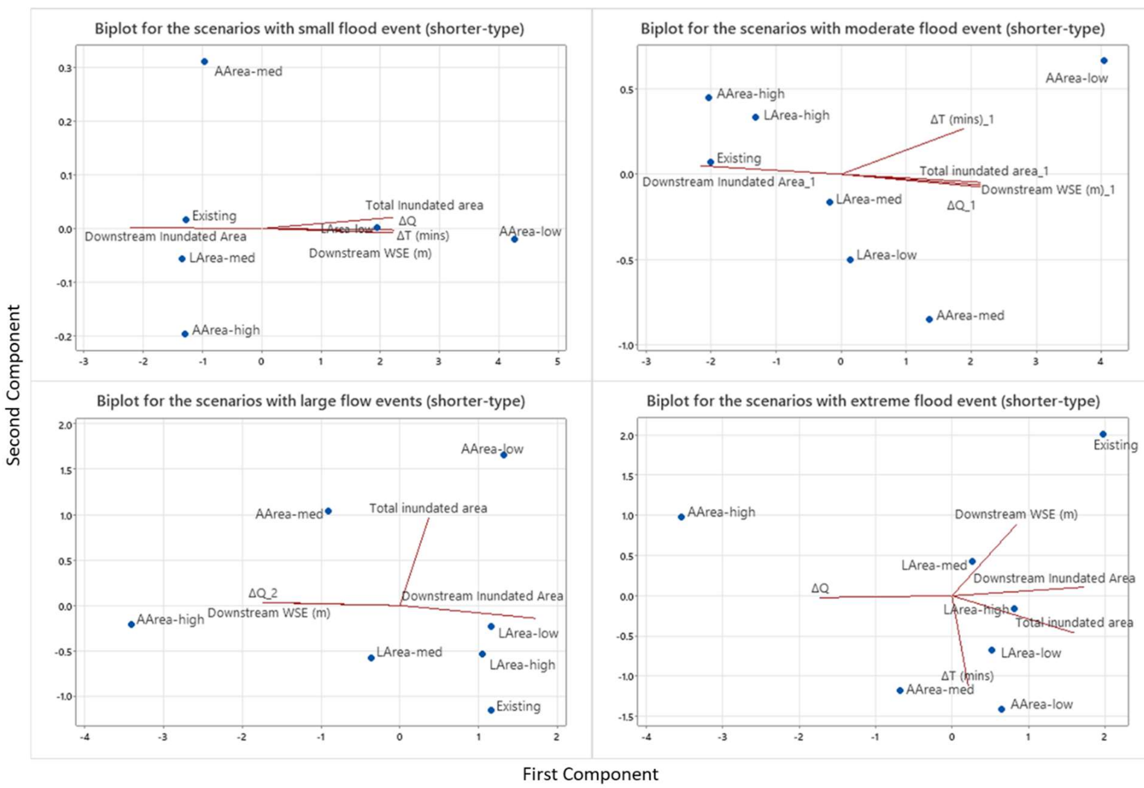

Figure 5.13: PCA plot for the scenarios simulated with shorter-type flood events, a) small flood event, b) moderate flood event, c) large flow event, d) extreme flood event.

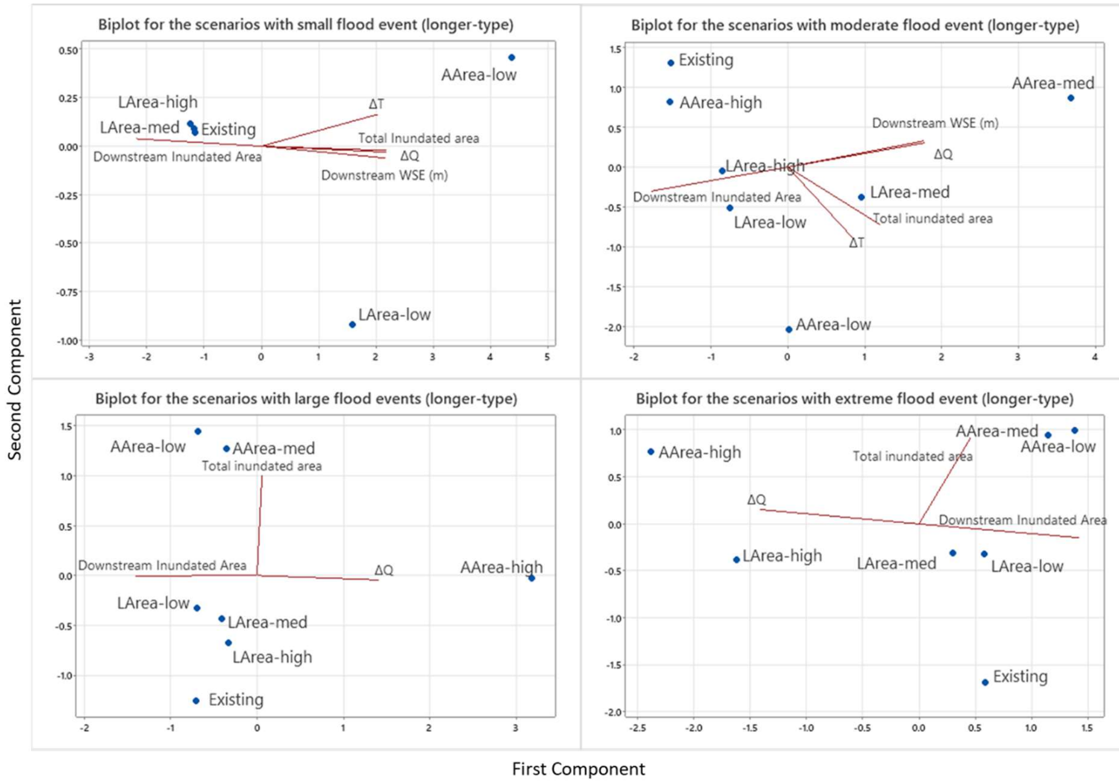

Figure 5.14: PCA plot for the scenarios simulated with longer-type flood events, a) small flood event, b) moderate flood event, c) large flow event, d) extreme flood event.

5.5 Discussion

5.5.1 Potential benefits of floodplains retention in the Upper Trusan

According to the simulations, floodplain retention in upstream parts of the study section could potentially reduce flood peaks. However, the reduction varied depending on the duration and the accumulated volume of the flood events. What is most notable from the work is that these upper floodplains can only reduce flood events with short duration, with the retention capacity insufficient for the longer flood events.

Figure 5.15 summarises the results of previous studies showing the area inundated against reduction in peak flow magnitude downstream. The cases were taken from various studies and there are total of 19 cases plotted. Based on the case studies (subset of Figure 5.15) at River Glaven (UK) and Bear Creek Meadow (USA) with similar catchment size to the Upper Trusan, allowing floodplain inundation could reduce flood peaks by 20 to 25 percent (Clilverd et al., 2016; Hammersmark et al., 2008). However, these works indicated that accommodating larger volumes required much larger areas (20 km^2 and above) than are available in the Upper Trusan. Accordingly, authors have suggested that flood retention strategies need to couple with strategic land use management to limit use of floodplain areas (Junger et al., 2022; Tariq et al., 2021) and the evidence presented here suggests that this is likely the best way forward in the Trusan.

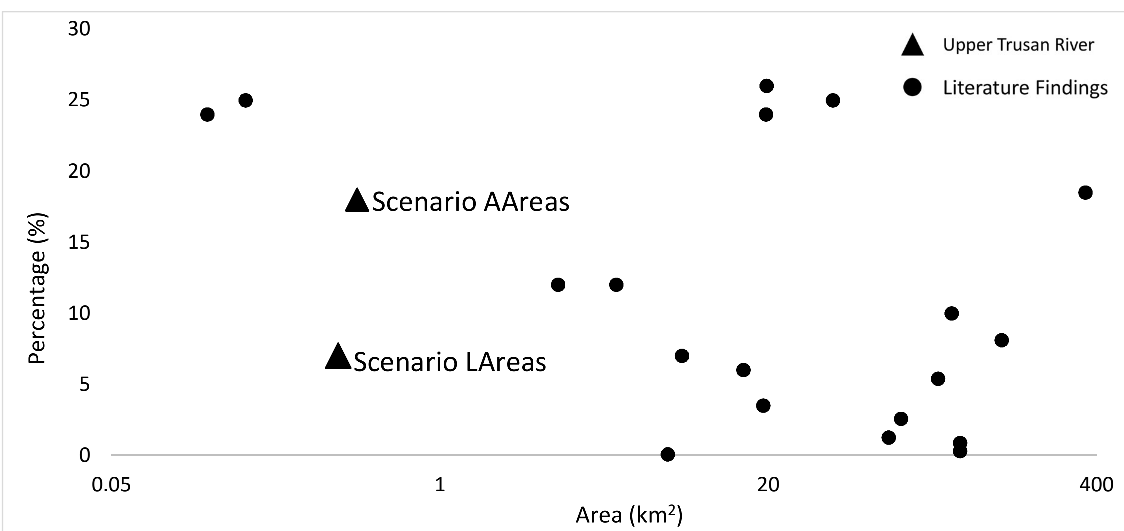

Figure 5.15: Comparison of floodplain retention areas and percentage reduction in flood peak achieved. There are total of 19 cases taken from various studies (cited in reference list)

The Upper Trusan River has much smaller floodplain areas than in most flood retention studies, with the adjacent floodplain areas inundated for the scenarios described being less than 1 km^2. Potential floodplain retention in the Trusan is constrained by the need for rice production, with most of the floodplains occupied by rice paddy fields that need to be protected from flooding. Furthermore, the land use of cropland and agricultural land (e.g. pineapples, buffalo grazing etc) in other parts of floodplain and lower hillslopes reduces the surface roughness of the floodplains which can lead to lower flood retention capacity. Our simulation shows that the reduction in flood peak was not enough to reduce flood risk downstream. With an extreme flood event (approximately 100-year return period), the upstream floodplains were inundated very quickly, and the flood wave propagated downstream in less than 30 minutes. This is partly due to the steep valley slope in the Upper Trusan River that creates high-energy environments with fast-flowing runoff.

Overall, the simulations suggest limited capacity for flood retention to have a major beneficial effect on flooding in downstream areas. This largely because the floodplain - which itself is limited in area – is used for essential rice production and so it is not considered practicable to 'sacrifice' enough of the area to allow for managed flooding.

5.5.2 Implications for river corridor management

According to the local community, high flood events that are occurring cause erosion and flooding. Hence, it is a priority to reduce flood peaks where possible. The simulation indicates that scenario AArea-med (breaching discharge of 100 m^3/s) that provides a total floodplain area of 0.16 km^2 is the optimum scenario to reduce medium to extreme flood peaks. Figure 5.16 shows where the channel banks can be lowered and the areas that are inundated to achieve this. For a longer duration flood, none of the modelled scenarios would significantly reduce effects; this means that more floodplain areas/rice paddies would need to be allowed to flood. However, it is very rare to have flood events that last longer than one day (based on the water level gauged at Long Telingan; floods normally recede within 24 hours) so the likelihood of occurrence of such events is relatively low.

The simulation conforms to the study carried out by Castellarin et al. (2011), whereby altering bank height could optimise storage for larger flood events. This is because activation of floodplain inundation is one of the main factors influencing the flood peak. The storage volume that is activated earlier might be fully used before the flood peak is reached. When the storage volume is full, any discharges beyond this volume will not be stored, and the floodplains will have little influence on the flood peak. Thus, managed floodplains by setting optimum bank height or building levee at the floodplain 'inlet' and 'outlet' should be considered in flood management in the Trusan to delay the activation of storage volumes (overbank flow) and increase the peak flow attenuation effects. Figure 5.17 shows the transformation of the flood hydrograph resulting from scenarios with different breaching discharges. For scenario AArea-low (green line), the flood water was allowed to inundate the designated floodplains at a lower discharge of 40 m^3/s. The peaking was similar to the existing condition because the full capacity of floodplain retention was reached. Conversely, scenario AArea-high has a higher breaching discharge (at 190 m^3/s) and has successfully reduced the flood peak despite some naturally overflow that occurred at 120 m^3/s.

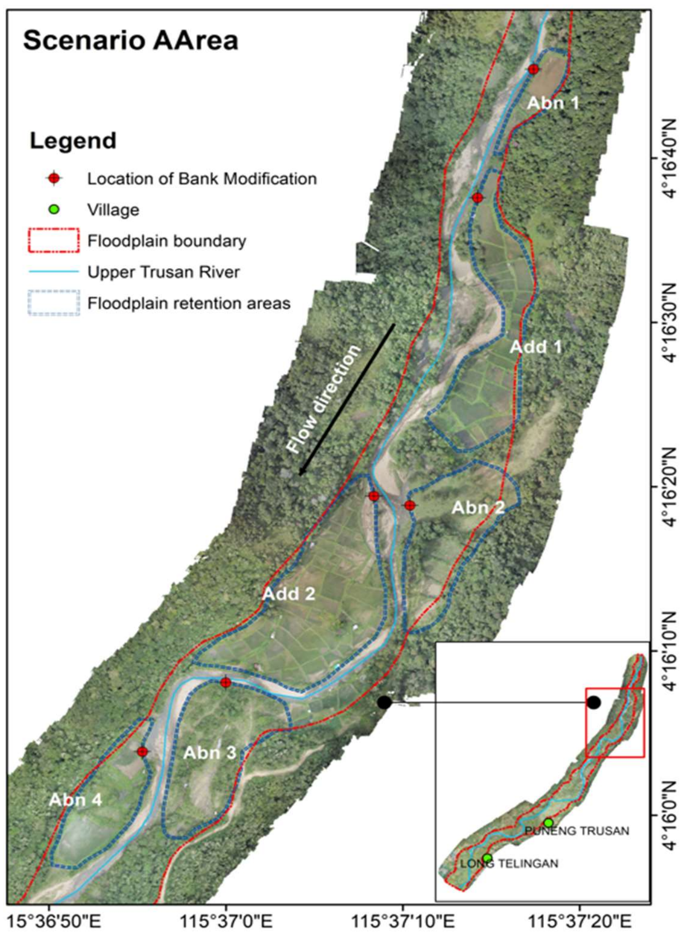

Figure 5.16: Location of channel banks (red dots) that can be lowered to allow inundation at respective floodplains.

In this study, we applied the 'cascade reservoir' concept, where the existing paddy field plots were used for water storage. Another option to increase the capacity of floodplain retention is to excavate and deepen these areas. However, this in unrealistic in the case of Upper Trusan River because of the access restrictions with limit the use of heavy machinery in paddy areas.

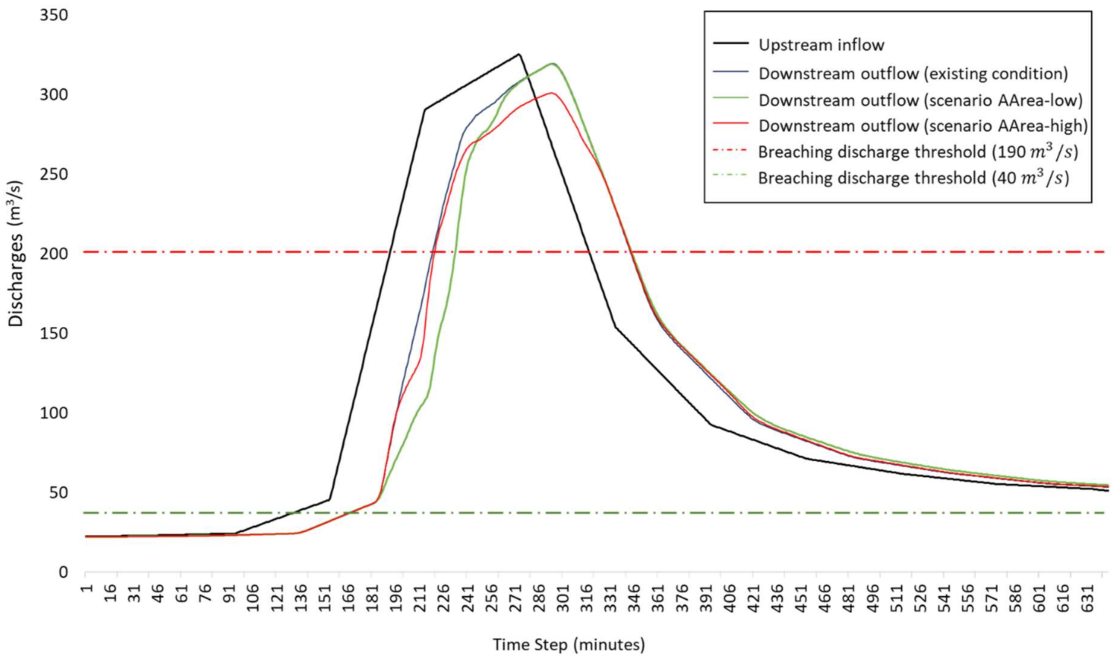

Figure 5.17: Flood hydrograph resulted from scenarios with various breaching discharge.

Rice paddy farming is the main agricultural activity that sustains the local community's livelihood in the Upper Trusan. Given the constraints discussed above, the recommended action for flood risk management is to have a strategic zoning approach to reallocate rice production to lower flood risk areas. The detrended DEM and the flood inundation map clearly show that some areas have higher terrain with lower flood risk (Figure 5.18). Based on the analysis, the total floodplain area in this river section is approximately 1.064 km^2, of which 0.3890 km^2 will be flooded in the event of 50 – 100 years return period (large flood). This means that approximate 36.6 % of the floodplain areas were subjected to frequent flooding. Instead of sacrificing all the upstream paddy field areas for floodplain retention areas, strategic agricultural zoning may be an alternative to reduce losses, and in the case of the Upper Trusan the areas with higher terrain elevation (Figure 5.18: shaded in red) which remain dry despite flood greater than 50-year return period are best to locate rice production.

These areas have lower flood risk, which provides space for agriculture and could potentially help to reduce crop loss due to flood damage.

In higher flood risk areas, frequent flooding is anticipated especially during the wet season. It is shown that Site A and B are prone to flooding, with only some small areas remaining dry during flood events. At these sites, crops should be harvested before wet season to reduce flood loss. Moreover, lower cost and quicker growth cycle crops are suggested to be planted at high flood risk areas to minimise economic loss. According to Tariq et al. (2021), it was found that rice harvest is more profitable when there is no flooding but suffers greatly when there is flooding because of the huge capital losses. On the other hand, maize planting suffers fewer losses in flood-prone areas and requires less capital than other crops (Tariq et al., 2021). In addition, crops with quicker growth cycle (e.g. maize and may be harvested even earlier, making it ideal for use as animal feed in the event of predicted flooding (Der Sarkissian et al., 2022; Osawa, 2022). Crops such as this should be considered in the Trusan for high-risk areas. The combination of zoning and managed inundation should increase resilience and appears a more feasible option for high-energy rivers like the Upper Trusan.

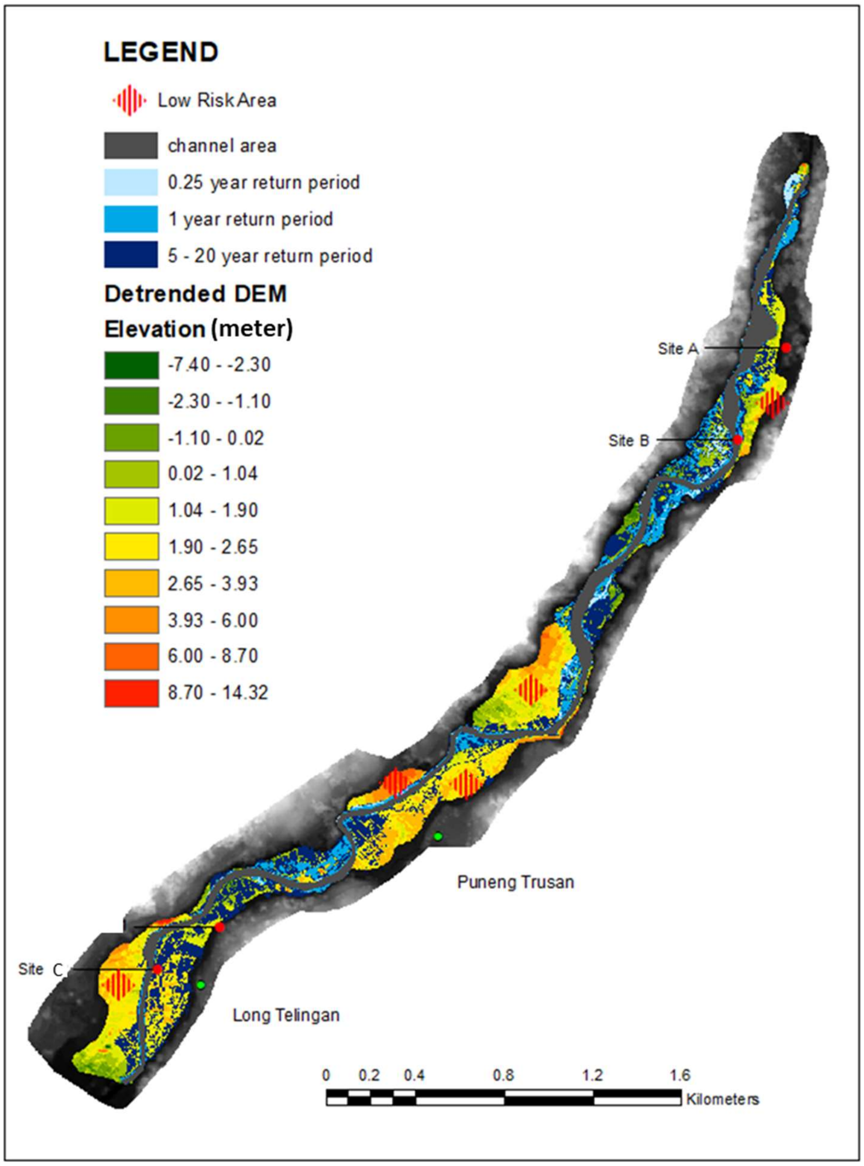

Figure 5.18: Flood inundation map, red shaded symbols represent areas with lower flood risk.

5.6 Conclusion

This chapter presented a flood inundation model for the Upper Trusan to inform on existing flood risk and flood mitigation plans for the future, specifically to identify strategic areas for flood retention. The results suggest that the floodplain retention capacity in the Upper Trusan is limited, and the flood wave propagates very quickly downstream in the steep valley of Upper Trusan. With the floodplain retention scenarios (i.e. LAreas and AAreas), they are only enough to accommodate flood events up to 150 m^3/s (moderate flood event). Any magnitude higher than this exceeded the retention capacity and caused major flood downstream despite retention upstream. Given that the available space for flooding is less than a kilometer square, it has very little effect on flood wave propagation. For small and moderate flood event, it is shown that the floodplain retention areas were not fully occupied with flood water. This means that there is enough capacity to reduce flood magnitude of small and moderate events and the 'gate-opening' could be lowered more to accommodate more flood and means higher reduction in flood peak. 'Gate-opening' height has a great effect on the retention capacity. Lowering the opening means that the flood water is allowed to fill the floodplain at the early stage of flood, thus, reducing the capacity for bigger flood.

The results provide useful information on the flood behaviour of the Upper Trusan and indication options for managed flooding and its capacity. In particular, the models suggested that there is limited capacity in the Upper Trusan to protect paddies from large and extreme flood event; the desire to reduce the magnitude and frequency of these events mean much of the valley floor (including paddy areas) would need to be flooded in order to affect a significant reduction in channel discharge downstream. Moreover, all flood scenarios indicate that using only the abandoned areas as floodplain retention areas are not enough to reduce any flood events. This means that the local communities need to sacrifice at least 0.12 km^2 of paddy areas (approximate 50 plots of average size paddy plots) for floodplain retention areas.

Given the likely impacts of climate change on flooding in Sarawak, reliance purely on managed flooding is unlikely to be a long-term solution. The recommended action for flood risk management is to have a strategic zoning map to reallocate the paddy field areas to lower flood risk areas and have a programme of managed retreat or abandonment' from higher risk areas.

Finally, the outcomes of the study indicate that the hydrodynamic modelling (2D) is very useful in the case of Upper Trusan to understand the existing flood risk and hydrodynamic interactions in steep valley. The model that incorporates with drone-based DEM shown to be feasible for the case of rural highland tropical river. The simulation performed remarkably well at low flow; however, it is noted that scarcity of flow data is an issue in the Upper Trusan. More of high flow data is needed for the future work.

CHAPTER 6: LAND COVER CONSERVATION AND MANAGEMENT TO IMPROVE FLOOD RESILIENCE IN A TROPICAL HIGHLAND RIVER

Small tributaries beside the paddy field areas near Puneng Trusan
Photo: Yih Yoong Lip, February 2023

6.1 Introduction

Deforestation is occurring at an accelerating rate (Edwards et al., 2019; Ritchie & Roser, 2021). In Sarawak, deforestation is partly due to legalised commercial logging carried out in the form of 'selective logging' (Bryan et al., 2013). In addition, forest has been cleared for agricultural plantations (notably oil palm), and some for urban expansion (Gaveau et al., 2016; Hon & Shibata, 2013). The loss and degradation of native forest in Sarawak has raised concerns because it represents a diverse ecosystem supporting globally significant flora and fauna (Alamgir et al., 2020). As well as biodiversity loss, loss of forest to urban development, infrastructures, and agricultural land use significantly impact water runoff, increasing flooding and pollution from nutrients, sediments, and contaminants.

Both academics and practitioners widely acknowledge the value of approaching sustainable river management from the watershed perspective. Conservation of natural land cover, including forest, can preserve the integrity of the basin and the river by maintaining water quality (Shrestha et al., 2018), reducing fine sediment inputs (Gyawali et al., 2022), and limiting hydrological alteration (Kashaigili, 2008). Such conservation is one of the cornerstones of catchment management which, at its heart, is founded on careful land use management (Dechmi & Skhiri, 2013).

Catchment management has many challenges but linking across many of these is the issue of scale (Wingfield et al., 2021). By virtue of their spatial extent, larger catchments tend to have complex and diverse ownerships, increasing numbers and diversity of stakeholder groups, and more types of water demand; they also frequently have more diverse land use and land cover types (Lashford et al., 2022). These scale-related factors can make implementing an integrated catchment management plan challenging in large catchments. Additionally, large and heavily modified (urban or industrial) catchments may have limited capacity to control activity or restore them to their original state. Hence, small to medium size rural catchments provide perhaps a better opportunity, as typically ownership is less complex, and opportunities for consensus and shared responsibility are greater than in large, urbanised catchments (Kumar et al., 2019; Lim et al., 2022).

Tools to support catchment management have been developed and are now widely adopted. For example, Integrated River Basin Management (IRBM) is one of the commonly used frameworks designed to support and coordinate the conservation of water, land, and related resources (Evers, 2016). It aims to maximise the economic and social benefits of water and catchment resources while preserving freshwater ecosystems. Thus, it is a critical tool to support many aspects of sustainability. In Malaysia, IRBM is guided by Integrated Water Resources Management (IWRM) principles but remains in its infancy despite being promoted for more than 20 years (Academy of Sciences Malaysia, 2015). Due to constraints on the development of water policy, notably non-uniform state legislation governing water allocation, separation of many relevant government departments, and inconsistent water resource assessment studies, IRBM management has not been rolled out nationally (Academy of Sciences Malaysia, 2014). Numerous studies have highlighted the need for and the importance of IRBM in certain basins (e.g. Langat and Muda Catchments), due to issues such as water shortages, flooding and river water pollution. However, implementation remains fragile and faces many challenges due to institutional capacity, financial support, and policy issues, and in particular the large and complex nature of these two basins (Elfithri et al., 2011; Mokhtar et al., 2011) as more broadly across Malaysia.

The starting point for effective management under IRBM is to understand catchment hydrological functioning. This understanding can be used to regulate the spatial distribution of human activities (i.e. regulate landuse), typically referred to as spatial planning. Several tools and models such as Soil and Water Assessment Tool (SWAT®), Precipitation Runoff Modelling System (PRMS®), and Hydrologic Modeling System (Hec-HMS®) are now available to help such planning (Markstrom et al., 2015; Scharffenberg et al., 2010). Among these tools, SWAT® is the most widely used model to simulate surface runoff and groundwater movement and predict the environmental impact of land management (Wang et al., 2019), as well as to help with spatial planning within the context of climate change (Brouziyne et al., 2022; Yang et al., 2022). It is recognised as a top hydrological model for its flexibility in simulating wide range of hydrological processes. Moreover, SWAT® database (e.g. soil characteristics) was extensively calibrated and validated using real-world data, which makes it a reliable tool for predicting the environmental impact of land management. SWAT® has been widely used in temperate regions, but less in the tropics (Strauch & Volk, 2013; Tan et al., 2019). However, it has great utility for helping understand hydrological functioning in tropical catchments experiencing deforestation and, in turn, informing decisions on spatial planning and catchment management.

This chapter applies SWAT® to understand the hydrological functioning of the Upper Trusan catchment, a small rural catchment (i.e. meso-scale) in Sarawak. Increased flooding has been reported by the local community living in the catchment. Concerns have been expressed about the possible influence of previous and ongoing uncontrolled deforestation on runoff and, hence, a cause of the flooding. Moreover, a government-sponsored agricultural strategy for the area raises concerns about the potential for increased flooding in the future. Against this background, this chapter aims to provide recommendations for land cover management in the catchment, to improve resilience and maintain river integrity. It applied SWAT® to address the following objectives:

i) Assess how historical land cover and land use change have affected the river's hydrological regime, specifically focusing on the incidence of high flows.

ii) Assess how future land cover and land use changes may alter flood frequency and magnitude.

iii) Provide spatially explicit recommendations for strategic forest protection, to limit future alterations to the river's hydrological regime.

The overarching goal was that this work could form the starting point for an IRBM plan for the Trusan. Because of the relatively small size of the area, its small population with similar water use priorities and relatively homogeneous land cover, the Trusan represents a tractable location for such a plan, which could help improve resilience in the future.

6.2 Study area

The study area (hereafter 'Upper Trusan') is an upper sub-catchment of the main Trusan catchment, in Sarawak (Figure 6.1). The sub-catchment is delimited by a downstream village, namely Long Semadoh, and the river extending upstream from here is approximately 10 km in length. Total catchment area of the Upper Trusan is 140 km^2. The Upper Trusan catchment is covered with a dense native rainforest. Large proportions of the forest within the catchment are made up of Hill Mixed Dipterocarp Mixed Dipterocarp Forest, with mountainous terrain ranging from 800 to 900 meters above mean sea level. These natural forests support rich biodiversity and ecosystems (Appanah & Turnbull, 1998). This rural area is also home to indigenous people, with low population densities (less than 1000 inhabitants based on local reports) compared to the other parts of Sarawak. Large forest areas and associated streams support hunting, foraging, and fishing which are important parts of community livelihoods.

The Upper Trusan catchment has been subjected to selective timber logging, that at a scale much smaller than elsewhere in Sarawak. This resulted in a change of land cover from forest cover to bare earth in some localised areas, mainly due to the logging trails created for vehicle access. However, logging activities were halted in 2000s and some of the lands were reforested naturally according to local communities (personal communications). Other changes are due to shifting agriculture, where the agricultural lands are migrated from one area to another. This is normally in hilly areas, away from the river floodplain. Areas close to the villages (villages are mostly located on lower hillslopes, just above the floodplain) are actively changed. Certain areas have been cleared in some years, but they have recovered to either grassland or forest again subsequently. Additionally, small portions of land have been cleared temporarily partly for storage and due to the migration of the communities. The associated expansion of road networks has also resulted in land cover change to bare earth and has contributed to issues such as landslides, increased fine sediment entering the river during rainfall, and riverbank erosion (Marteau et al., 2018). The major permanent land use change relates to the use of river floodplains as rice paddy cultivation land.

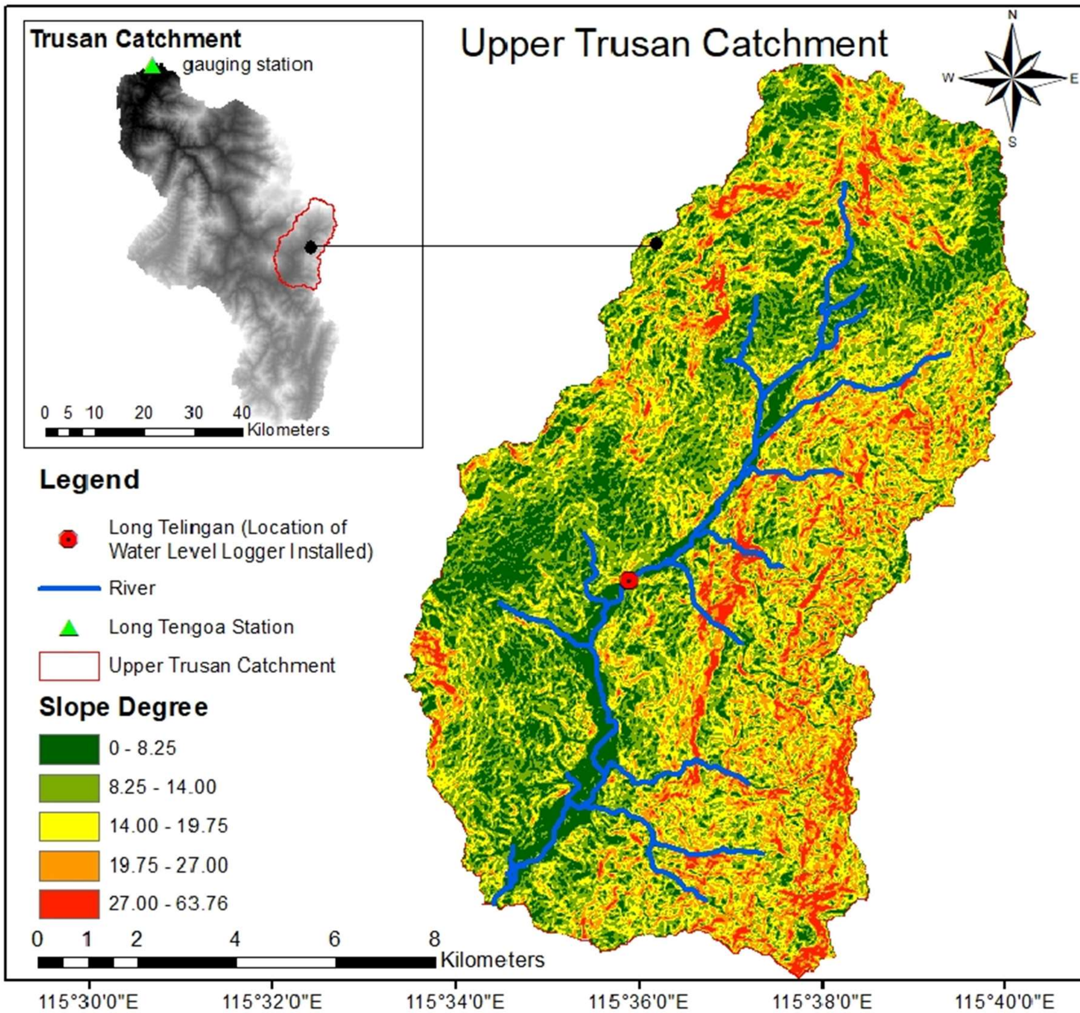

Figure 6.1: The Upper Trusan Catchment (right). The main Trusan Catchment (top left). The main Trusan Catchment was used to set up the initial model for calibration and validation in SWAT®.

Within the study area, river reaches are experiencing a high incidence of bank erosion due to high flows. Flooding has become a significant issue affecting the livelihood of the local community that relies on the nutrient-rich floodplain areas to cultivate rice. During the monsoonal rainy season, the magnitude of overbank flow is reportedly high and induces accelerated bank erosion. As detailed in earlier chapters, several local scale green measures such as live fencing, coconut geotextile matting, and brush mattress were installed at some selected sites in 2019 to reduce riverbank erosion (Chapter 4). Furthermore, flooding issues were addressed at the river corridor scale by assessing the potential flood reduction using floodplain as flood retention (Chapter 5).

In recent years, the Upper Trusan Catchment has seen increased demand for its rice, partly as a result of access to new markets, and agricultural activities have expanded and intensified. In addition, there is a regional strategy to increase agricultural productivity (Lyndon, 2018), and this includes proposals for further expansion of agriculture in the Trusan (Borneo Post Online, 2022; Khushiri, 2022). Assessing the impact of land use and land cover change on runoff characteristics at the catchment scale is essential to help ensure the community is resilient to future change, either due to large scale factors such as climate change or local changes in land use. No historical work has been done to address flooding issues at the catchment scale; thus, the SWAT® model, a spatially explicit hydrological model, was used to help inform decisions related to future land use management across the whole of the study area.

6.3 Methods

6.3.1 SWAT® Model description and future land cover scenarios

SWAT® is a comprehensive model capable of estimating the impact of land use change and management on water (Rufino et al., 2022), sediment (Akoko et al., 2021), and agricultural chemicals (Delgado et al., 2010) in catchments and helps inform management decisions (Samimi et al., 2020). It requires a variety of detailed input data representing the land use soil, topography, and climate to run the model. Good results from the model simulation depend on precipitation input and the abundance of observational data to calibrate and validate the water budget (Emam et al., 2017; Son et al., 2020)

In the Upper Trusan, no gauging station is available, which creates challenges for SWAT® modelling. The nearest gauging station is well downstream of the study area, located at Long Tengoa (see Figure 6.1 for the location). As discussed in Chapter 3, the long-term discharge data for Long Tengoa station contain extended gaps of missing data. Additionally, the discharge rating curve can only predict peak discharges up until 179.2 m^3/s. Hence, SWAT® calibration, validation and modelling is limited to these data conditions and need to be conducted with care. This is detailed further below.

The workflow developed for the study is shown in Figure 6.2, with the primary focus to understand how land use and land cover change could affect the hydrological functioning of the Upper Trusan catchment, particularly runoff and spatial variation in runoff. The initial run of the model simulated runoff at Long Tengoa (see Figure 6.1 for station location). Thus, the initial model included the whole area upstream of Long Tengoa. This set of simulations was used to set values for the hydrological parameters for all the sub-basins upstream from Long Tengoa, including the Upper Trusan Catchment. The model was simulated from 1998 to 2021 using 23 years of historical daily rainfall and climate data. It was set up to have 3 years warm up period, and simulated results are from 2002 to 2021 (20 years). Then, the daily flow data observed at Long Tengoa station were used to calibrate and validate the model using SWAT-CUP®. SWAT-CUP® is an open-source tool developed to calibrate and validate SWAT® hydrological model by automatically adjusting input parameters and providing statistical measures and graphical displays to evaluate the performance of the model (Abbaspour, 2015). Further details of calibration are given below. After the model was calibrated and validated to a satisfactory level, the parameterised model was used for the Upper Trusan Catchment to simulate the effects of various land cover scenarios (Figure 6.3).

For the first Scenario (Scenario 1), we simulated runoff across the Upper Trusan Catchment using historical land cover in 1988 and recent land cover in 2021. The runoff simulated for these two land covers was used to assess how observed land use change has affected the river's hydrological regime, specifically focusing on high flows.

For the second Scenario (Scenario 2), we simulated runoff for future changes in land cover and land use and assessed how this might alter flood frequency and magnitude. The future changes were represented by a future land use Master Plan proposed by Sarawak State Government. This future land use plan was created to accommodate local needs while enhancing sustainable agricultural practices and development. The planning encompasses road expansion that connects isolated rural areas and expands general agriculture zones to increase food production and potential natural capital revenue in the future.

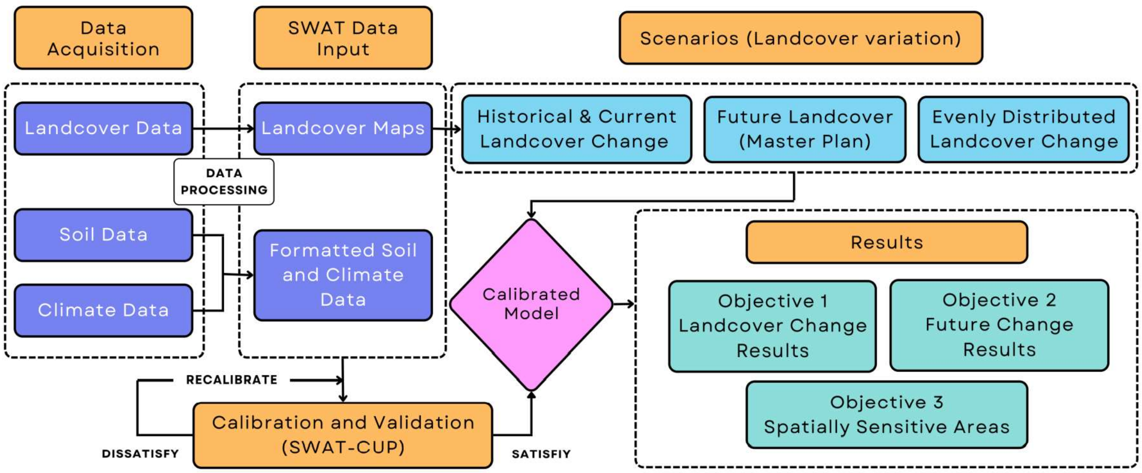

Figure 6.2: SWAT® modelling workflow.

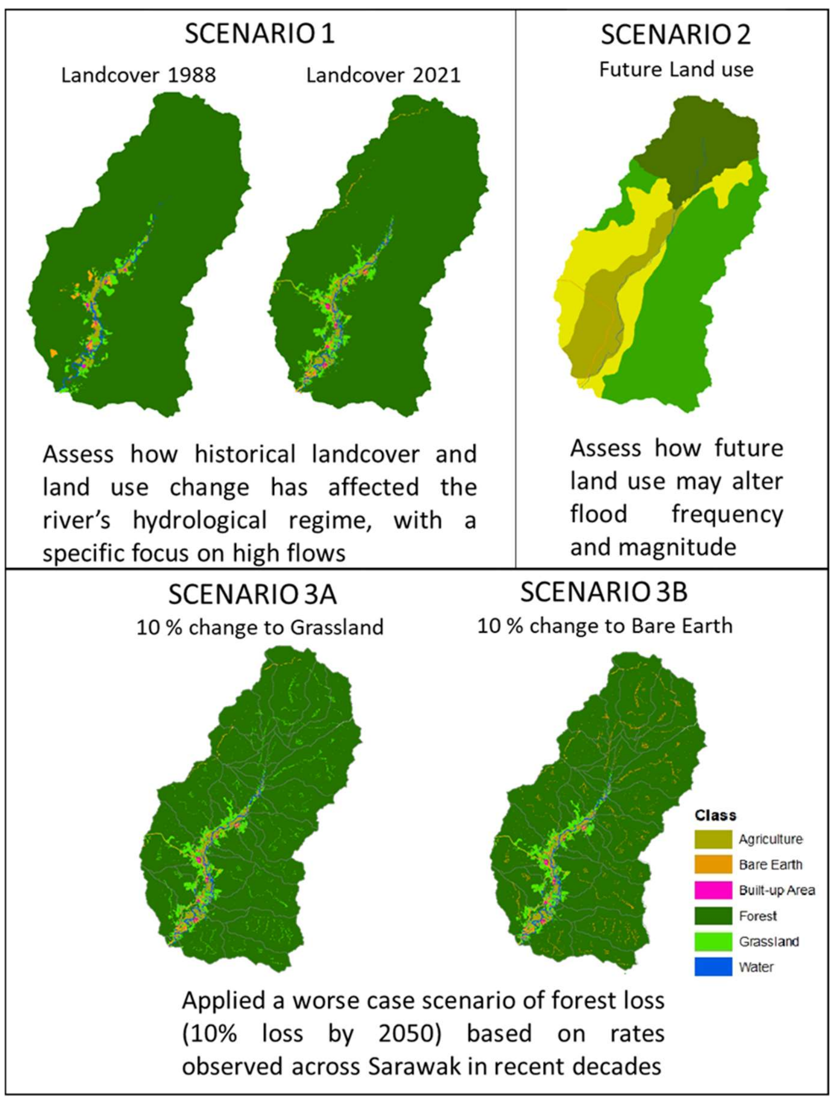

Figure 6.3: Scenarios simulated in SWAT® model.

For the third Scenario (Scenario 3), a worst-case scenario of 10 percent forest loss across the Upper Trusan catchment by 2050. This loss was chosen based on annual rates observed across Sarawak in recent decades. We simulated the conversion of 10 percent of current forest to grassland (Scenario 3A) and bare earth (Scenario 3B), to assess the contribution of different land uses to changes in river flow and flood frequency and magnitude. The forest loss was distributed evenly across the catchment to help identify areas sensitive to land cover change; thus, sensitive areas are defined as those that, for the same magnitude of forest loss, experience relatively high increases in runoff.

6.3.2 Data acquisition

SWAT® model requires at least four fundamental types of catchment data to use as spatial input for the model. These data consist of hydro-climatic characteristics, soils' distribution, land use and topography information. The data used in this study consisted of data collected from field sampling and various external sources, as shown in Table 6.1.

The ALOS PALSAR® Digital Elevation Model (DEM) was obtained from the Alaska Satellite Facility® and used for the topographic data input in SWAT®. ALOS PALSAR® DEM (Dataset: ASF DAAC, 2021) is radiometrically corrected model from Synthetic Aperture Radar (SAR) geometry and radiometry with a higher resolution (12.5 meter spacing) than many available data sets. The raw DEM was resampled to fill up voids using the interpolation method in ArcMap®. The DEM was used to generate percent slope values, to help delineate the catchment boundary, define the river network within the catchment and identify sub-basin outlet points.

Table 6.1: Summary of data used in the SWAT® model.

No	Data	Data Format	Source
1	Digital Elevation Model	Cell size 12.5 x 12.5 m	ALOS PALSAR®
2	Soil Map of Sarawak (1968)	Scale 1:500,000	Department of Agriculture Sarawak
3	Sentinel Satellite Imagery (2021)	10 x 10 m	Copernicus Sentinel 2

4	Landsat 5 Satellite Imagery (1988)	30 x 30 m	Google Earth Engine® LANDSAT 5
5	Upper Trusan Master Plan Land Use Map		Sarawak State Government
6	Soil Database	Non-US study areas	MWSWAT®
7	Long Tengoa Discharge	1999-2010 (daily)	DID Malaysia
8	Rainfall Data	1999-2021 (daily)	DID Malaysia
9	Water Level Data	2020-2021 (15 min interval)	Field Data (Water level logger installed at Long Telingan)
10	Climate Data	1999-2013 (CFSR), 2008-2018 (CMAD)	SWAT® Climate Forecast System Reanalysis (CFSR) and China Meteorological Assimilation Driving Dataset (CMAD)

The soil map of Sarawak was obtained from the European Soil Data Centre (ESDAC) and used as soil data in the model. The map was originally published by the land and survey department, Sarawak, in 1968. The other soil map available is FAO-UNESCO soil map, but it has only two soil classes for the Upper Trusan. In comparison, the local soil map has up to 5 soil classes for the study area. However, the classes from both sources are consistent (i.e. the distribution of the two types shown in FOA-UNESCO is the same as in the ESDAC data base. The soil map acquired was classified through supervised classification and used as SWAT® input data. In the SWAT® soil database, the data for soil properties are only applicable to the United States. Hence, the global soil database was acquired from MWSWAT® (SWAT, 2022), to matching the regional soil map applied in the model so that appropriate soil properties could be applied in the Trusan Model.

Satellite imagery was acquired from Google Earth Engine® (GEE) to produce land cover maps. The oldest satellite image available was captured in 1988 from Landsat 5; the current satellite image dated 2021 was taken from Sentinel-2. Both these satellite images were processes and classified to different land use classes (see section below). Landsat 5 satellite image has a resolution of 30 x 30m, while Sentinel-2 satellite image has a resolution of 10 x 10m. The future land use map proposed by Sarawak State Government was obtained from WWF Malaysia.

Daily rainfall data from 1998-2021 were obtained from the Department of Irrigation and Drainage (DID) Malaysia for four rainfall stations as shown in Table 6.2. All four rainfall stations are in the Trusan Catchment and were used for the initial model setup to calibrate and validate the model. The long-term daily flow data at Long Tengoa was obtained from DID Malaysia from 1998 to 2010. Water level data was obtained from mini diver installed at Long Telingan. This logger was installed in September 2020 and the water level was recorded for a period of 14 months. It was then extracted and removed in November 2021 due to the large flood occurred in September 2021 that damaged the logger cable. The recorded data was in sub-daily (15 minutes' interval) time-step which represented the instantaneous flow that allow us to identify the duration for certain flood peaks.

Table 6.2: Rainfall station used in SWAT® model.

Rainfall station	Station code	Latitude	Longitude	Elevation (meter)
Long Tengoa	4553001	4.589851	115.336103	111
Long Merarap	4354001	4.360139	115.458944	515
Long Semadoh	4255006	4.218972	115.587528	832
Bakelalan	3956001	3.975361	115.615583	1001

The climate data (i.e. daily minimum and maximum temperature, relative humidity, wind speed and solar radiation) were acquired from the NCEP Climate Forecast System Reanalysis (CFSR) available on the SWAT® official website. CFSR is generated by reanalysing meteorological model data using field, surface observations and remote sensing data. It is global data that provides the most accurate assessment of the state of the atmosphere, ocean, land surface, and sea ice over the estimation period (Saha et al., 2010). However, the CFSR dataset was available until 2014, which was not long enough for the simulation period. Datasets from the China Meteorological Assimilation Driving Datasets (CMADs) were used as the climate data for the remaining period. These two sets of data from CSFR and CMAD have high linear correlation, and both are suitable inputs for hydrological simulations (Zhang et al., 2020).

6.3.3 Satellite Imagery and cloud masking

Information on the spatial distribution of Land Use and Land Cover (LULC) over expansive areas is crucial for numerous environmental and monitoring tasks. Satellite imagery is widely employed to generate LULC maps as an essential data source for assessing regional and temporal land cover change patterns (Liping et al., 2018) and have been used extensively in hydrological modelling (e.g. remote sensing based) to quantify the impact of LULC change on the hydrological regime (Barreto-Martin et al., 2021; Sertel et al., 2019). LULC that governs the runoff coefficients is particularly useful to predict the impact of different LULC scenarios on flood frequency and magnitude and, thus, helps to inform decisions about catchment scale land management.

In this study, Google Earth Engine® (GEE), a cloud-based platform, was utilised to access and process numerous freely available satellite images, including those acquired by the Sentinel-2 and Landsat-5 remote sensing satellites. As a result of atmospheric impurities such as cloud cover and haze, the pixel values that represent the geographical information in satellite imagery captured by Sentinel-2 and Landsat-5 were affected. Hence, cloud detection and image compositing methods were essential to generate accurate LULC maps. In order to create a cloud-free composite for that period based on the specified summary statistic, a cloud masking algorithm in GEE® was used. This algorithm applied filtered through a collection of images for the catchment area with a maximum of one-year period, removed identified cloud pixels, and selected the clearest pixel in the collection. Final cloud-free composite satellite images were produced for 1988 from Landsat-5 and 2021 from Sentinel-2.

6.3.4 Land use and soil map classification

The LULC maps for 1988 and 2021 were generated using supervised image classification. For the satellite image composites of the Trusan Catchment, training samples were created using ArcGIS® tools to acquire the most precise pixel signature for each of the LULC classes. In order to match the land use classes available in SWAT® database, six major land use classes were assigned to the LULC maps, as shown in Figure 6.4a. Additional training samples were repeatedly added at the areas with noise resulting from shadow pixels and no data gaps that could introduce errors in the LULC map and replaced with rectified pixels.

The accuracy assessment metrics were carried out for 1988 and 2021 land cover classification and the key outputs are summarised in Table 6.3. The classified map of 1988 and 2021 have an overall accuracy of 82.11% and 92.41% respectively. The kappa coefficient for both classified maps are higher than 0.75 which indicates good accuracy. However, the forest class for 1988 map has the largest commission error reaching 47%. This error was largely due to the coarse resolution of Landsat-5 satellite imagery which has caused confusion between grassland, water, and forest classes. The user's and producer's accuracy for the other classes are good, ranging from 70% to 100%.

Table 6.3: Summary of accuracy assessment metrics for 1988 and 2021 land cover classification. Overall accuracy for 1988 land cover is 82.11 %; and the overall accuracy for 2021 land cover is 92.41 %.

	1988 Land cover				**2021 Land cover**			
	Error (%)		**Accuracy (%)**		**Error (%)**		**Accuracy (%)**	
Class	**Commission**	**Omission**	**User**	**Producer**	**Commission**	**Omission**	**User**	**Producer**
Agriculture	17	5	82.61	95	12	12	88	88
Bare Earth	27	11	72.73	88.89	12	17	88.24	83.33
Built-up	0	29	100	71.43	9	5	91.30	95.45
Forest	47	0	53.33	100	0	0	100	100
Grassland	11	23	89.47	77.27	13	5	86.96	95.24
Water	6	27	94.12	72.73	5	13	95.24	86.96

The soil map obtained from European Soil Data Centre (ESDAC) was originally in image format. A similar method was used to classify the soil map into six distinct soil classes. The soil map is shown in Figure 6.4b, and the soil classes consist of gley soil, peat soil, alluvial soil, podzolic soil, skeletal soil, and composite soil of skeletal and podzolic soil. The assigned soil classes matched the database obtained from MWSWAT® that could be used in the SWAT® model.

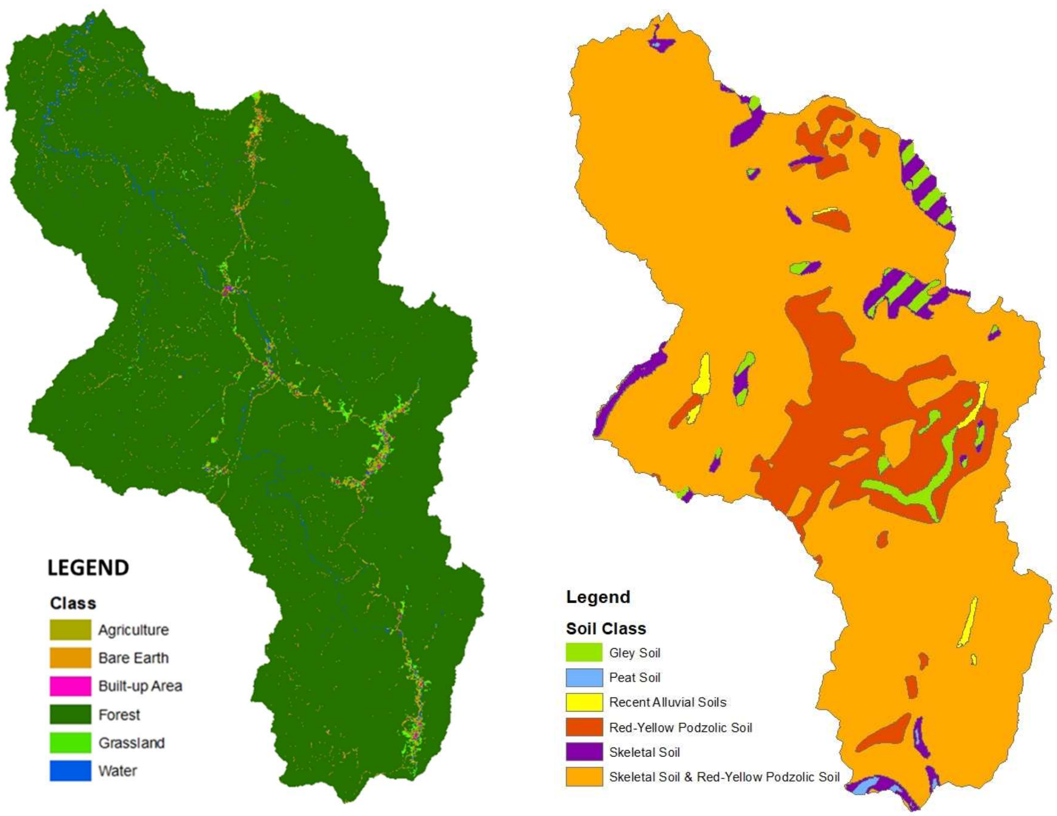

Figure 6.4: a) 2021 LULC map, b) Soil map of the Trusan Catchment upstream from the Long Tengoa Gauging station.

6.3.5 Model Calibration and Validation

The ArcSWAT® tool in ArcGIS® 10.7 was used to run SWAT® analysis. Fundamental processes such as watershed delineation, Hydrology Response Units (HRU) definition, database input, calibration, and validation were required in the SWAT® model. The first phase delineated the Trusan Catchment into 33 sub-catchments using the DEM. Subsequently, the HRUs were categorised and grouped according to the land uses, soil types, and slope characteristics. The initial SWAT® model was set up with meteorological data input for further calibration and validation stages.

The model calibration is a process of adjusting model input parameter values to provide simulated values of discharge, evapotranspiration, or sediment data that are as near to the measured data as possible. This step ensures that model parameters are optimal. In this study, SWAT-CUP® (Calibration and Uncertainty Procedures), a programme designed to calibrate SWAT® was used to calibrate the model setup for the Trusan Catchment. The software provides five calibration techniques in addition to validation and sensitivity analysis instruments (Abbaspour, 2015). Multiple studies have shown that the SUFI-2 (Sequential Uncertainty Fitting version 2) method performs well in tropical regions and is computationally efficient (Rafiei Emam et al., 2018; Shivhare et al., 2018). Hence, SUFI-2 was selected to perform calibration for the Trusan parameters.

The SUFI-2 method applied an algorithmic strategy to capture most observed data inside the model's 95% prediction uncertainty boundaries (95PPU). The 95 PPU computes the 2.5% and 97.5% levels of the cumulative distribution of an output variable generated by Latin hypercube sampling. Using two statistics, P-factor and R-factor, the calibration may be evaluated based on the goodness of fit between the two bands, which are 95PPU for model simulation and observed data (Khalid et al., 2016). P-factor goes from 0 to 1 and represents the proportion of measured data, including its error in the simulations; R-factor is the ratio of the standard thickness of the 995PU band to the standard deviation of the observed data ranging from 0 to infinity. A simulation with a P-factor of 1 and an R-factor of zero would perfectly match the measured data. Consequently, a robust calibration would exhibit a high P-factor and a low R-factor (Sao et al., 2020).

The calibration was carried out for the whole Trusan Catchment using the daily discharge gauged at Long Tengoa Station, which in this case is the outlet point (lowermost) of the catchment. This is the nearest station available within the catchment to the study area (Figure 6.1). The available discharge data range from 1999 to 2010 (station stopped operating in 2010), however, the data for the long-term period is incomplete and contains a substantial amount of missing data. As a result, calibrating the model poses significant challenges. To address this, the model was calibrated using the best continuous daily discharge data available, which was from 2006 to 2007. Subsequently, the model was validated using the daily discharge data from 2020. This approach was taken to mitigate the impact of the missing data and to ensure that the model was accurately calibrated and validate. There are 19 environmental parameters that govern the simulation outputs, and which were selected for the calibration (Table 6.4).

Figure 6.5 and Figure 6.6 show the calibration and validation results of the best estimated and observed daily discharge. The warm-up phase for the model was set as three years, from 1999 to 2001. The calibration and validation used the same input parameters shown in Table 6.4. The model performance for calibration and validation steps was assessed using Nash-Sutcliffe Efficiency (NSE) (Nash & Sutcliffe, 1970). Table 6.5 shows the value of deterministic parameters such as NSE, R2, and PBIAS. The validation at daily timestep was considered good with a NSE value of 0.44. In general, predictions of the timing and magnitude of low and moderate sized events and periods of low flow were good. However, as evident in Figure 6.5, the estimates of the magnitude of larger events (events greater that around 200 m^3/s) tended to be lower than observed; at the instantaneous scale it is possibly that differences could be even greater. Given that the rating curve can only estimate discharges up to 179.2 m^3/s, the significance of this underprediction and hence, the overall NSE value (which in part is driven by this underprediction) is hard to assess. Thus, rather than further model calibration work, altering model parameters to improve the fit to observed discharges was not undertaken, because these observed values are themselves uncertain.

Table 6.4: List of SWAT® parameters calibrated for the Trusan Catchment (runoff at Long Tengoa) SWAT® model.

Parameter Name	Description	Fitted Value	Min value	Max value
R_CN2.mgt	Initial SCS runoff curve number for moisture condition.	-1.438 **(Actual CN2 applied: 31 – 41)**	-5	5
V_ALPHA_BF.gw	Baseflow alpha factor for bank storage	0.992	0.75	1
V_GW_DELAY.gw	Groundwater delay time	366.875	0	500
V_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	1691.25	0	3000
V_CH_K2.rte	Effective channel hydraulic conductivity (mm/h)	36.9375	0	150
V_CH_N2.rte	Manning's n value for the main channel	0.022125	0	0.3

V_SURLAG.bsn	Surface runoff lag coefficient	10.3125	0	50
V_ESCO.bsn	Soil evaporation compensation factor (basin)	0.63125	0	1
V_EPCO.bsn	Plant uptake compensation factor (basin)	0.25125	0	1
V_REVAPMN.gw	Threshold depth of water in the shallow aquifer required for revap to occur (mm)	110.625	0	500
V_SOL_K.sol	Soil saturated hydraulic conductivity (mm/h)	36.625	-50	50
V_SOL_AWC.sol	Available water capacity of the soil layer (mm/mm)	25.125	-50	50
V_SOL_BD.sol	Moist bulk density	-25.375	-50	50
V_ESCO.hru	Soil evaporation compensation factor	0.01875	0	1
V_EPCO.hru	Plant uptake compensation factor	0.28375	0	1
V_GW_REVAP.gw	Groundwater revap coefficient	0.19525	0	0.2
V_HRU_SLP.hru	Average slope steepness (m/m)	1.3425	1	3
R_OV_N.hru	Manning's "n" value for overland flow	-0.07425	-0.2	0
R_SLSUBBSN.hru	Average slope length (m)	-0.11125	-0.2	0

Prefix R_ in SWATCUP multiplies the existing values by (1+ fitted value); Prefix V_ replaces existing values with fitted values.

Table 6.5: Statistics summary of calibration and validation in SWAT® model.

Time-step (daily)	NSE	R^2	PBIAS
2006 – 2007 (calibration)	0.49	0.5	5.8
2009 – 2010 (validation)	0.44	0.465	-

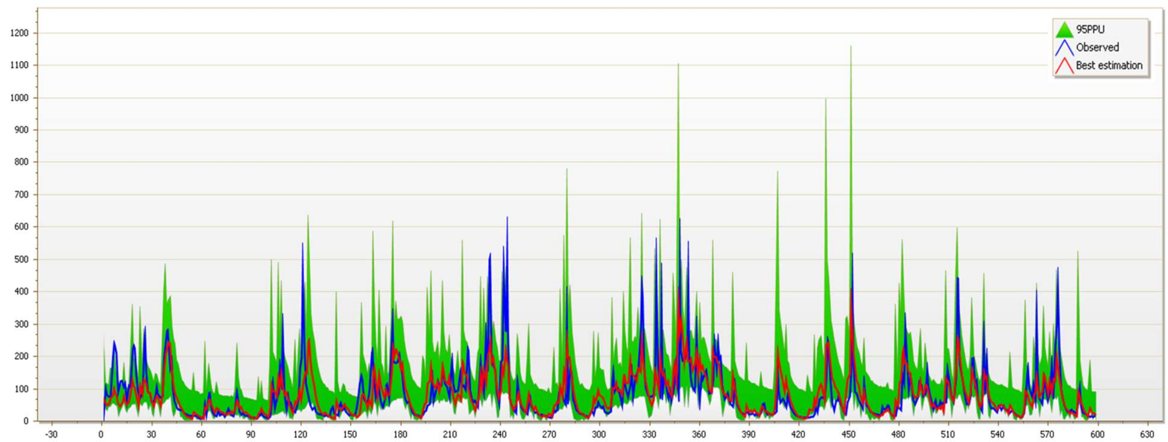

Figure 6.5: Calibrated outputs showing the comparison of observed and simulated (best estimated) discharge data at daily timestep.

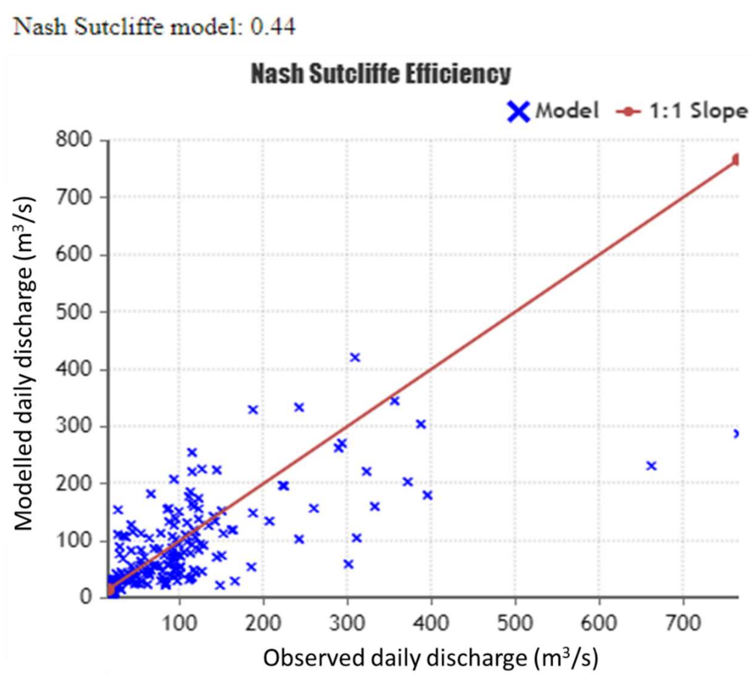

Figure 6.6: Validated outputs showing the comparison of observed and simulated (best estimated) discharge data at daily timestep.

6.3.6 Assessing the flood frequency and magnitudes for future land cover change scenarios

Flood frequency was computed from the water surface runoff generated in each LULC Scenario to investigate how the change in peak flow magnitude affected flood frequency. The SWAT® model allowed of surface water runoff at the outlet node of each sub-basin across the

Upper Trusan study area. To assess the influence of different land cover scenarios, discharge was extracted at two points on the mainstream Trusan: one at the upstream Site B and the other at the downstream end of the study section (i.e. outlet point of the Upper Trusan Catchment (see Figure 6.7). These two locations were then the focal points to assess the frequency of events exceeding bankfull flow (i.e. flood frequency) for each LULC Scenario. The flood frequency was determined based on the number of events exceeding the bankfull flow estimated at key selected sites in Chapter 3. The HEC-RAS® model suggested that the overbank flow varies across the channel upstream but was approximately 30 m^3/s.

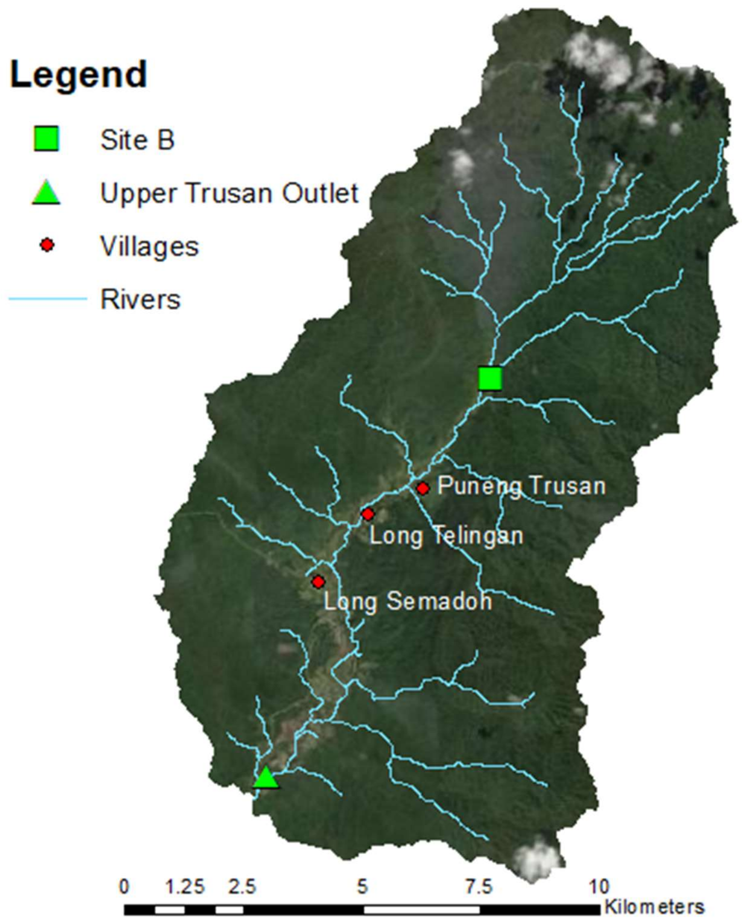

Figure 6.7: Map of Upper Trusan Catchment. Time-series runoff was extracted from Site B (green box) and outlet of the catchment (green triangle) to look at frequency of flood at these two sites.

The SWAT® simulated flow for the scenarios was at a daily time step (i.e. mean daily flow), and the instantaneous flood peaks could be higher than this. Hence, the sub-daily data from the water level logger installed at Long Telingan bridge site (see Figure 6.1 & Figure 6.7) was used to estimate the instantaneous flood magnitude associated with mean daily flows of certain magnitudes. On this basis, it was estimated that mean daily flows greater than 15 m^3/s result in instantaneous flows exceeding 30 m^3/s (i.e. exceeding bankfull). Hence, the mean daily discharge of 15 m^3/s was used as a discharge threshold to assess the frequency of events exceeding bankfull flow (i.e. flood frequency) for each LULC Scenario.

Also, these sub-daily (15 minutes' interval) time-step water level data allow us to identify the duration for certain flood peaks. These two types of flood peak events (from rising to falling limbs) did not last longer than one day.

6.4 Results and discussion

6.4.1 Historical LULC change

The land use and land cover maps for 1988 and 2021 are shown in Figure 6.8. The statistics of land use area and percentage change for 1998 and 2021 are summarised in Table 6.6. The total land area of the Upper Trusan Catchment is 140 km^2. Forest covered more than 90 % of the total area in each year. The forest was subjected to minor disturbance and loss and reduced from 95.21 % to 93.31 % over the 33-year period. The decline reflected increases in bare earth (mainly logging roads), built-up areas, grassland, and water (i.e. rice paddy). Of the 1.9% forest loss, most involved the conversion of forest cover to grassland (1.29 %). Bare earth increased by 0.41 % and built-up areas by 0.07 %. The agricultural area did not exhibit any major changes, with a 0.04 % of decline in the area. The change in water class was also small (0.16 %).

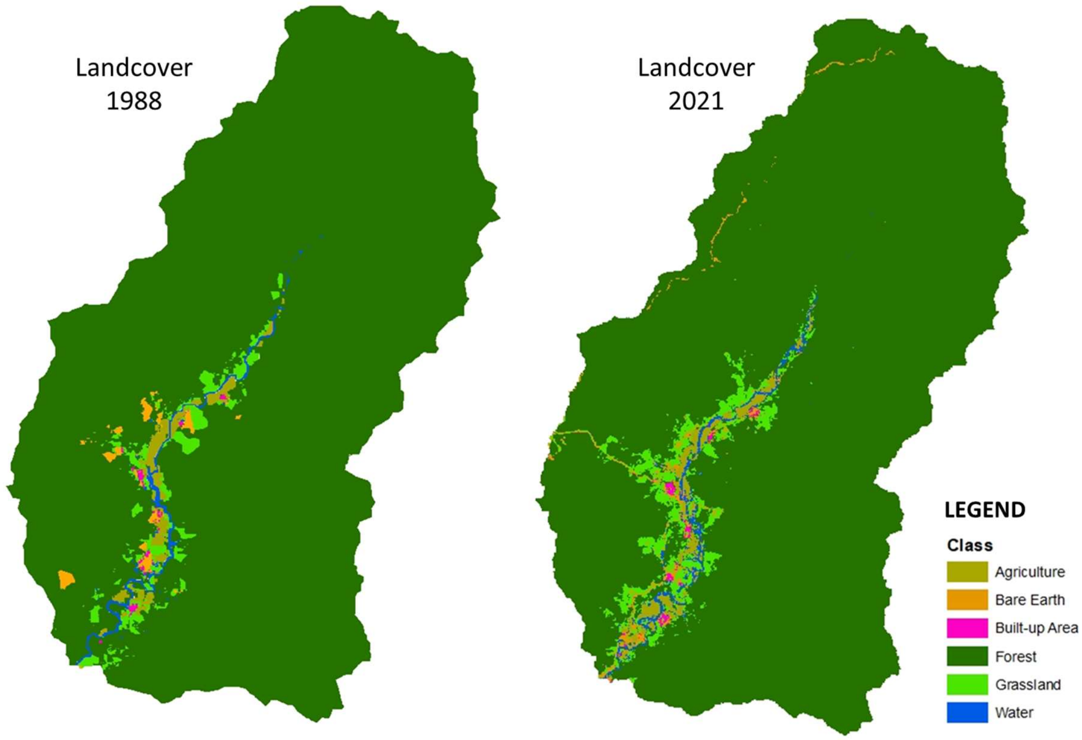

Figure 6.8: Classified land cover maps represent the historical (1988) and current 2021 land use.

Table 6.6: Statistics of area and percentage of the land use and land cover in 1988-2021.

Land use and land cover class	Area (km^2)		Percentage (%)		1988-2021
	1988	2021	1988	2021	Area changed (%)
Agriculture	1.73	1.67	1.25	1.21	-0.04
Bare Earth	0.78	1.36	0.57	0.98	+0.41
Built-up Area	0.21	0.30	0.15	0.22	+0.07
Forest	132.00	129.37	95.21	93.31	-1.90
Grassland	2.91	4.69	2.1	3.38	+1.29
Water	1.02	1.23	0.73	0.89	+0.16

6.4.2 Impacts of historical land cover change on runoff

The daily runoff simulated for the 1988 and 2021 land cover is shown in Figure 6.9, with respective Flow Duration Curves (FDCs) shown in Figure 6.10. The figures indicate that the change in runoff resulting from land cover change over the 33 years is hardly detectable, e.g. in terms of the overall hydrograph, runoff exceeding 75th or below the 25th percentile was the same for both LULCs. Regardless of the scale of the plot, runoff generated for 1988 and 2021 are almost identical. There are some small differences in the peak magnitude (typically less than 1% change), but this could not be visible due to the scale in these figures (Figure 6.9 & Figure 6.10).

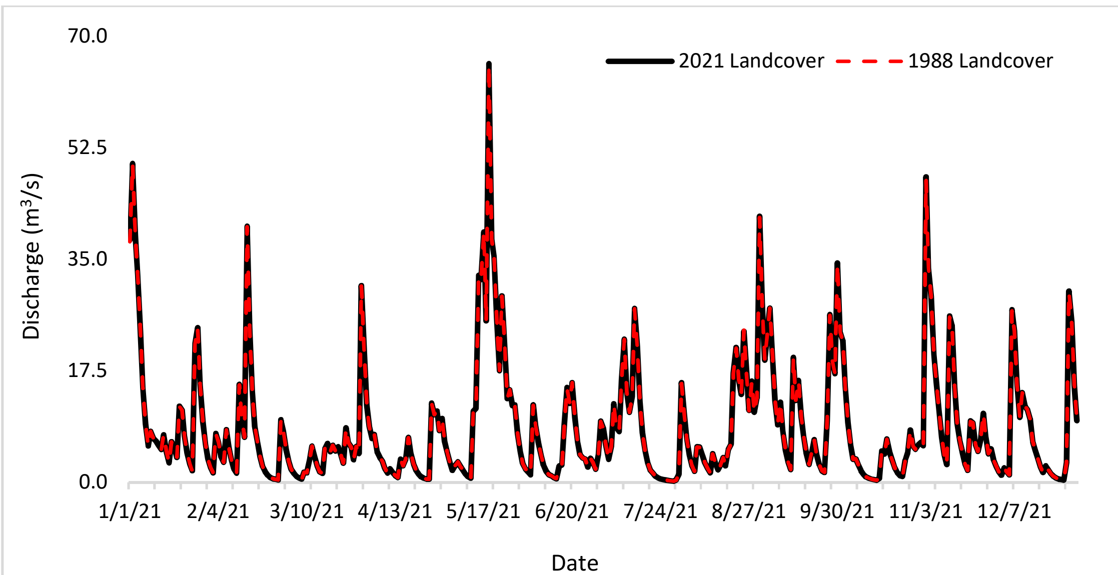

Figure 6.9: Daily runoff simulated for 1988 and 2021 land cover. The flow was simulated for Long Semadoh.

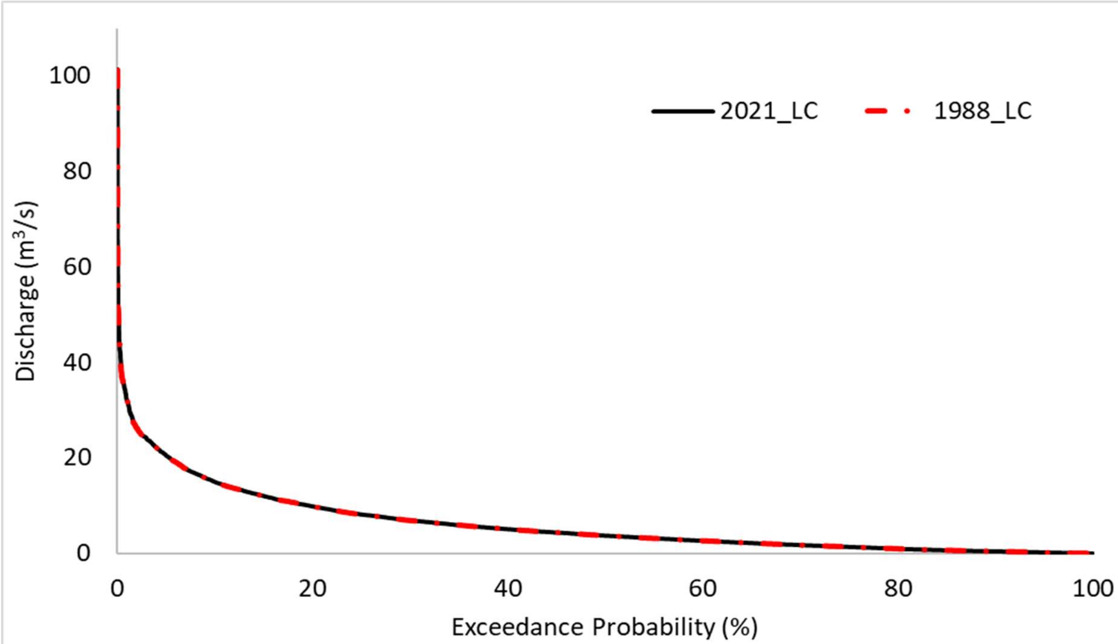

Figure 6.10: Flow Duration Curve (FDC) produced for 1988 and 2021 land cover. Simulated flow at Long Semadoh was used.

The change in the magnitude of peaks for events that exceeded 10 - and 50 - years return periods are shown in Figure 6.11 and Figure 6.12. These were plotted based on the events exceed the recurrence interval of 10 and 50, the peaking of the entire events was taken into account. The overall change in the peaks that exceed 10 – year return period is approximately 0.5 %; the average change in magnitude in the peaks that exceed 50 – year return period is approximately 0.4 %. There is no clear evidence of an increase in flood magnitude over the past 33 years. The maximum change for the peaks that exceed 10 and 50 – year return period was 4.25 % and 1.39 % respectively.

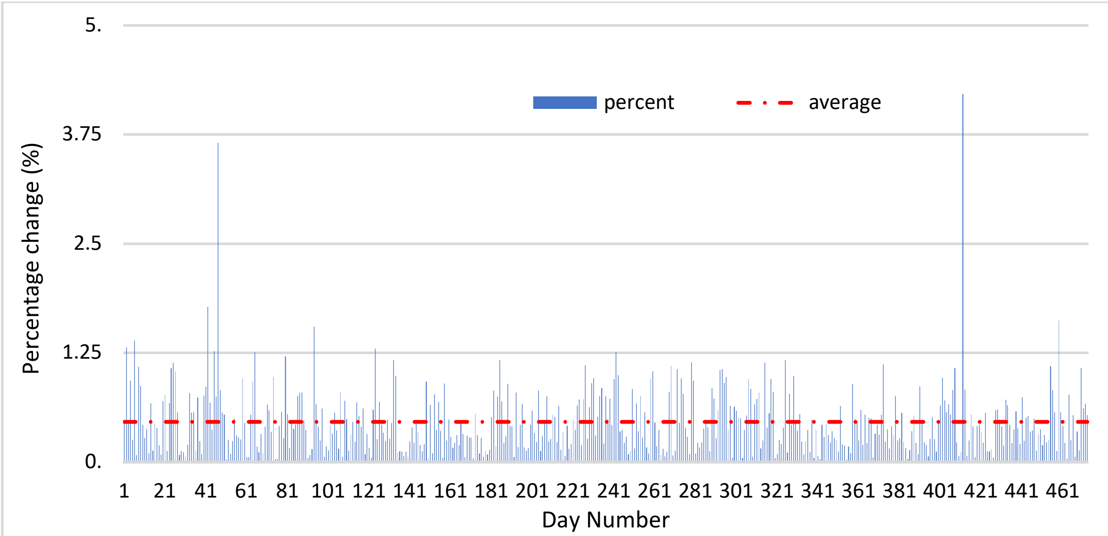

Figure 6.11: percent change in discharge magnitude for flows greater than 10-year return period.

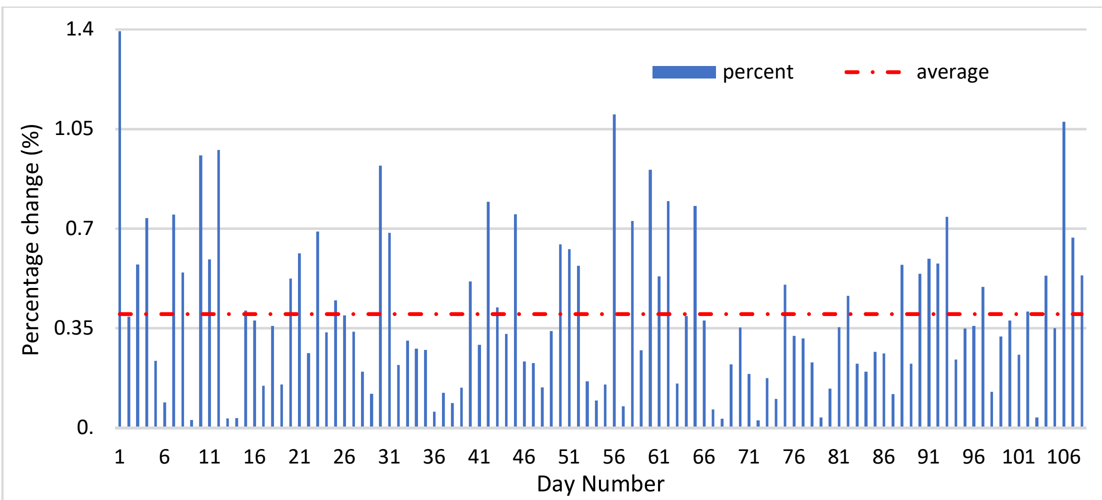

Figure 6.12: percent change in discharge magnitude for flow greater than 50-year return period.

6.4.3 Impacts of the future land use Master Plan (LULC Change Scenario 2)

The future land use proposed for the Upper Trusan Catchment is shown in Figure 6.13. The land use map is classed as elementary planning and consists of 4 main classes: forest, agriculture, road, and water. The forested area remains the biggest proportion of all land use that accounts for a total area of 87.45 km^2 (Figure 6.14). Approximately 30 % of the forested area was classified as environmentally sensitive (i.e. Forest 1), and the remaining was earmarked for selective reforestation via direct planting. (i.e. Forest 2). However, agricultural expansion is one of the main goals in future land use planning in the area. Hence, large proportion (50.12 km^2) of the area in the west part of the catchment was proposed as agricultural areas. This agricultural area is also the subject of more specific zoning (i.e. local zoning proposed by Sarawak State Government) such as Agriculture 1 and 2, that intends to protect farmland and farming activities from incompatible land uses. However, the authority has not yet specified the zoning criteria (e.g. farming type, lot size and buffer zone). In addition to agricultural expansion, a link road was proposed to connect isolated rural villages across the Trusan Catchment. This linear feature will have a total area of 0.31 km^2. The initial built-up area in the Upper Trusan Catchment was very limited, and the change in built-up area over 33 years period was almost negligible, with an area of 0.2 km^2 in 1988 to 0.3 km^2 in 2021. Additionally, the overall population in the Trusan Catchment is expected to remain the same; hence, the future land use did not include built-up area.

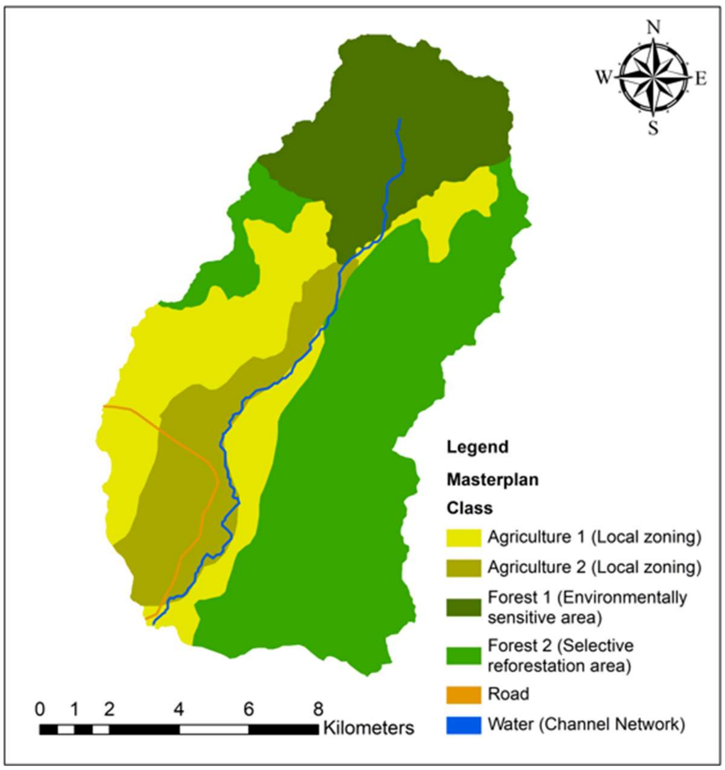

Figure 6.13: Future land use Master Plan for the Upper Trusan Catchment (Scenario 2) proposed by Sarawak State Government.

The future land use scenario proposed by the Sarawak State Government represents a major change (Table 6.7). An estimate of 30 % of forest loss is expected in future land use, where most of these areas will be converted to agricultural areas. Road expansion is classified as bare earth as most road networks across the Trusan Catchment were track road that left unpaved.

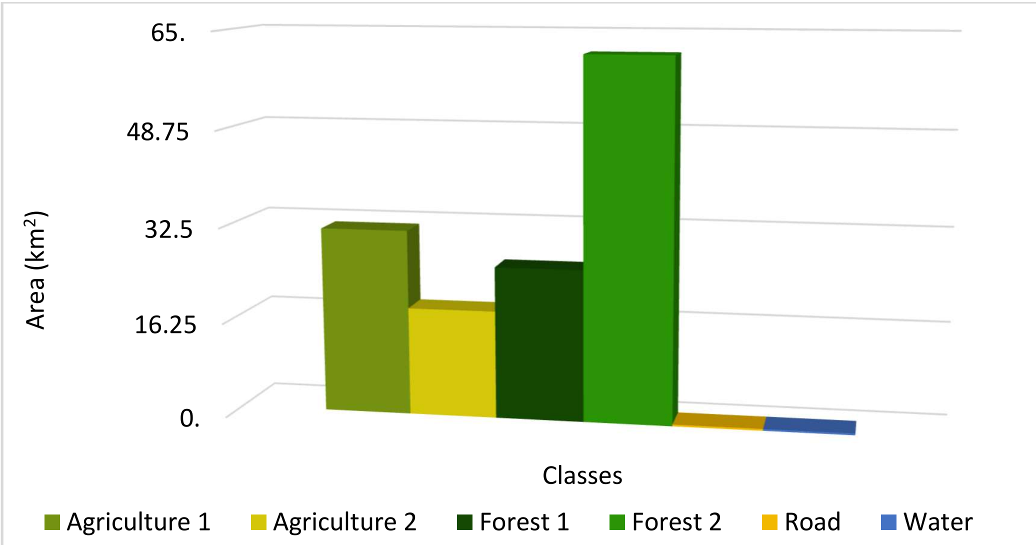

Figure 6.14: Scenario 2 representing the future land use map proposed by Sarawak State Government. The proposal distinguished agricultural and forested areas into two for zoning purposes.

Table 6.7: Statistics of area and percentage of the land use and land cover in 2021 and scenario 2 (Master Plan).

Land use and land cover class	Area (km^2)		Percentage (%)		Future Change
	2021	Scenario 2	2021	Scenario 2	Area changed (%)
Agriculture	1.67	50.12	1.21	36.27	+35.06
Bare Earth	1.36	0.31	0.98	0.23	-0.75
Built-up Area	0.30	0	0.22	0	-0.22
Forest	129.37	87.45	93.31	63.28	-30.04
Grassland	4.69	0	3.38	0	-3.38
Water	1.23	0.31	0.89	0.22	-0.67

6.4.4 Runoff in future land use scenarios

The daily runoff for various scenarios simulated from January 2021 to December 2021 is shown in Figure 6.15, relative to current land cover (2021, Scenario 1). The change scenarios are the Master Plan (Scenario 2), a 10% loss of forest and its conversion to grassland (#3A), and a 10% loss and conversion to bare earth (#3B). The SWAT® models indicated that 10 % forest loss to bare earth significantly changes the peak discharges, but the same loss and conversion to grassland has very little influence on the runoff. Land cover under the Master Plan (future land use of approximately 35 % of agricultural land throughout the catchment) showed signs of an increase in flood magnitude for some events. None of the future change scenarios perceptibly impacted on baseflow, the timing of peaking, or flow recession.

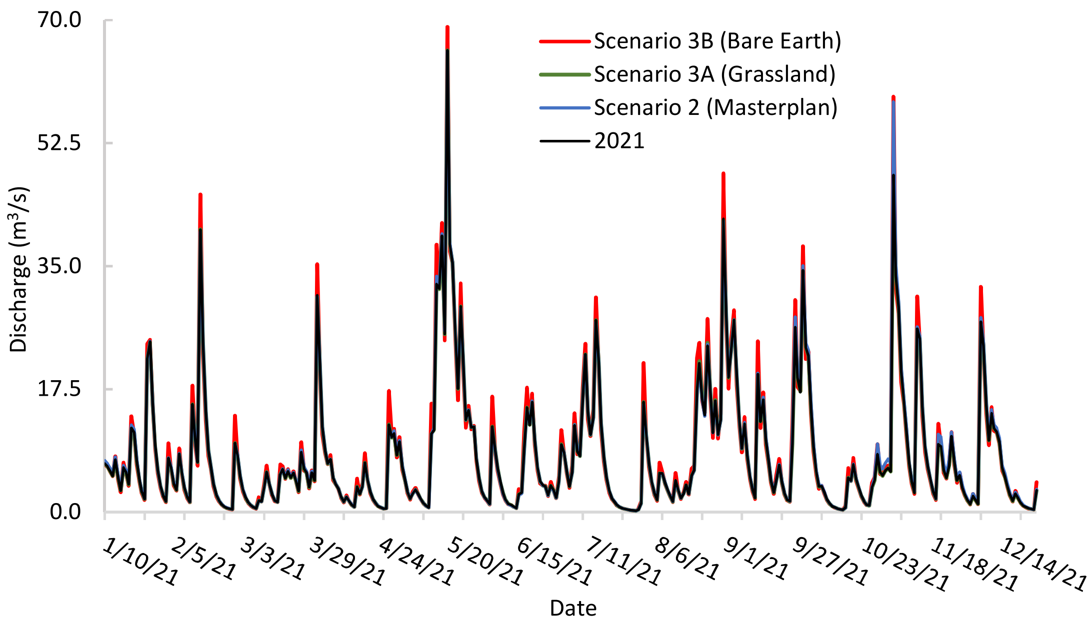

Figure 6.15: Daily runoff simulated for scenario 2, scenario 3A, Scenario 3B, and 2021 land cover. Runoff of 2021 land cover was illustrated as an initial Scenario as a comparison to the other scenarios.

The long-term Flow Duration Curve for the future change scenarios is shown in Figure 6.16. Notably, Scenario 3B (i.e. 10% forest loss to bare earth) most notably impacts the overall flow regime. The most marked changes associated with 3B occurred for flow magnitude greater than Q_{10} (15 m^3/s), with more pronounced changes for flow that ranged from $Q_{0.03}$ (65 m^3/s) to Q_1 (32 m^3/s). The flow magnitude that was below Q_{10} (15.42 m^3/s) was not predicted to change much. Conversely, Scenario 3A, with the same amount of forest loss converted to grassland across the catchment, did not appear to have such as marked impact on the flow regime - the overall flow regime for Scenario 3A (green dotted line) was similar to the flow regime of the 2021 land cover (solid black line).

For Scenario 2 (i.e. Master Plan), the flow regime was altered, but the change is less significant than Scenario 3B. The change was notable for flow that ranged from $Q_{0.05}$ (65 m^3/s) to Q_1 (32 m^3/s). Other than that, flow magnitude that is greater than $Q_{0.05}$ and flows lesser than Q_1 did not exhibit detectable change.

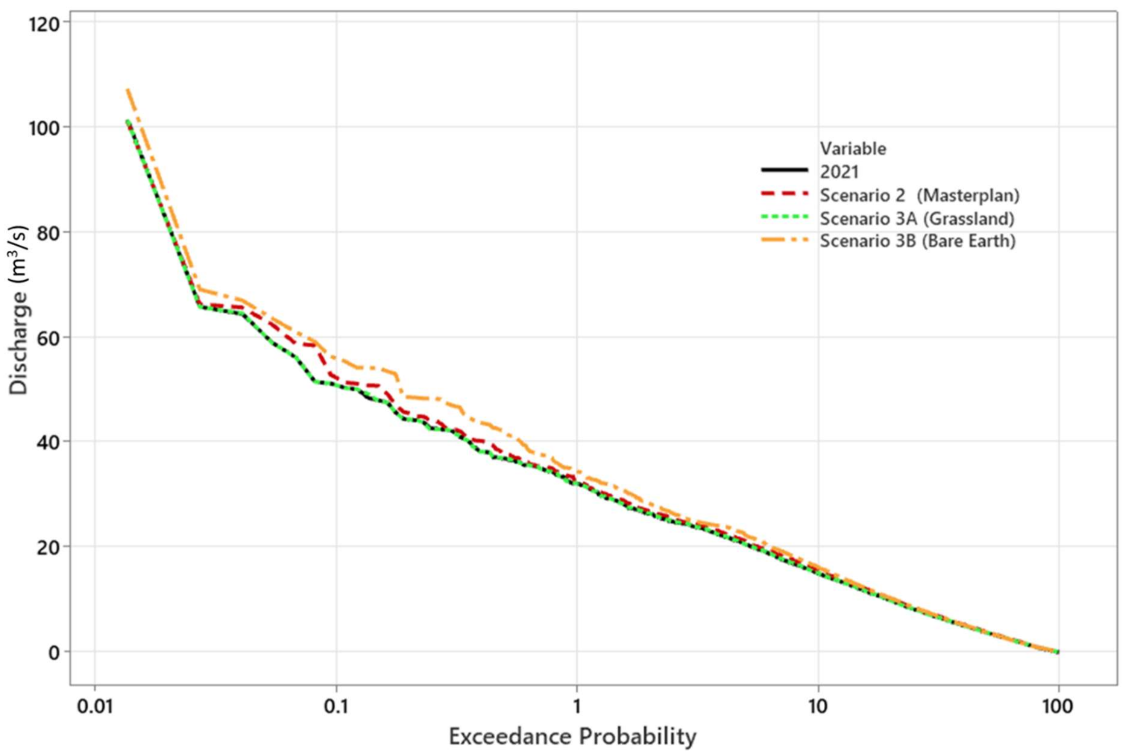

Figure 6.16: Flow Duration Curve (FDC) plotted for various land cover scenarios representing future change in land cover.

The average monthly discharge from August 2021 to December 2021 for the three scenarios is summarised in Table 6.8. The monthly discharge was used as it is indicative of a large flow volume that helps to identify the average surface runoff generated each month. According to the statistics, Scenario 2 and Scenario 3B result in a higher monthly discharge overall. The monthly discharge in Scenario 2A has little difference compared to the Scenario with current land cover (2021).

For wetter months, Scenario 3B results in a higher monthly discharge in August and September. However, except for the wet month in November, the monthly discharge for

Scenario 2 is higher than Scenario 3B. For the dryer months (i.e. October and December), Scenario 2 has a higher monthly discharge than Scenario 3B.

Table 6.8: Average monthly discharge (2021) of different land use scenarios.

Month (2021)	Average Discharge (m^3/s)			
	2021	Scenario 2	Scenario 3A	Scenario 3B
January	12.79	13.43	12.78	13.11
February	6.92	6.95	6.90	7.14
March	4.79	4.88	4.76	5.04
April	4.97	5.00	4.96	5.13
May	15.76	15.88	15.75	16.14
June	4.95	4.90	4.94	5.26
July	7.26	7.27	7.26	7.47
August	9.57	9.50	9.59	10.41
September	12.39	12.66	12.39	12.71
October	5.01	5.28	4.99	5.02
November	11.50	12.37	11.57	11.79
December	7.82	8.20	7.83	8.01

6.4.5 Overbank flows under land cover change scenarios

The frequency of events exceeding the bankfull discharge of 15 m^3/s for each Scenario at the outlet of the Upper Trusan Catchment are shown in Figure 6.17. It is shown that the number of events exceeds 15 m^3/s in the future LULC scenarios has increased as compared to the number of events recorded in the 2021 land cover scenario. For events exceeding 15 m^3/s, Scenario 3B has the highest number of annual flood frequency (20 events), followed by Scenario 2 (16 events) and Scenario 3A (15 events).

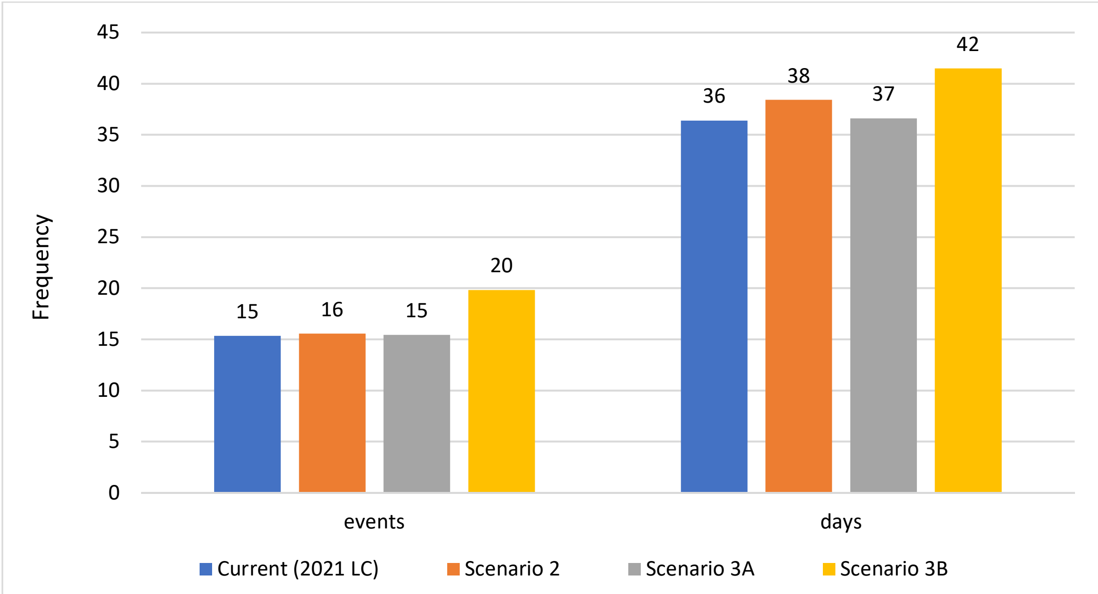

Figure 6.17: Annual frequency of events exceeding bankfull discharge at the outlet of the Upper Trusan Catchment.

It is shown that the total number of days that the flow exceeded 15 m^3/s has increased with the future land cover change scenarios. Annually, the total number of days that flow exceeded 15 m^3/s in 2021 LC was 36 days. With the land cover change in Scenario 3B, the total number of days that flow exceeded 15 m^3/s has increased to 42 days. While Scenario 2 and Scenario 3A recorded a total number of 38 days and 37 days exceeding 15 m^3/s.

For the three scenarios, the frequency of events exceeding the bankfull discharge of 15 m^3/s at the upstream site is shown in Figure 6.18. A smaller catchment area of upstream site resulted in lesser flood frequency compared to the downstream outlet Upper Trusan Catchment. Furthermore, the impact of land cover change scenarios on the upstream peak flow magnitude was not as marked as that at the downstream outlet. Scenario 3B, with the conversion of 10 % forest to bare earth, has the highest flood frequency overall and duration. While Scenario 2 and 3A have the least change in flood frequency and duration compared to current scenario with 2021 land cover.

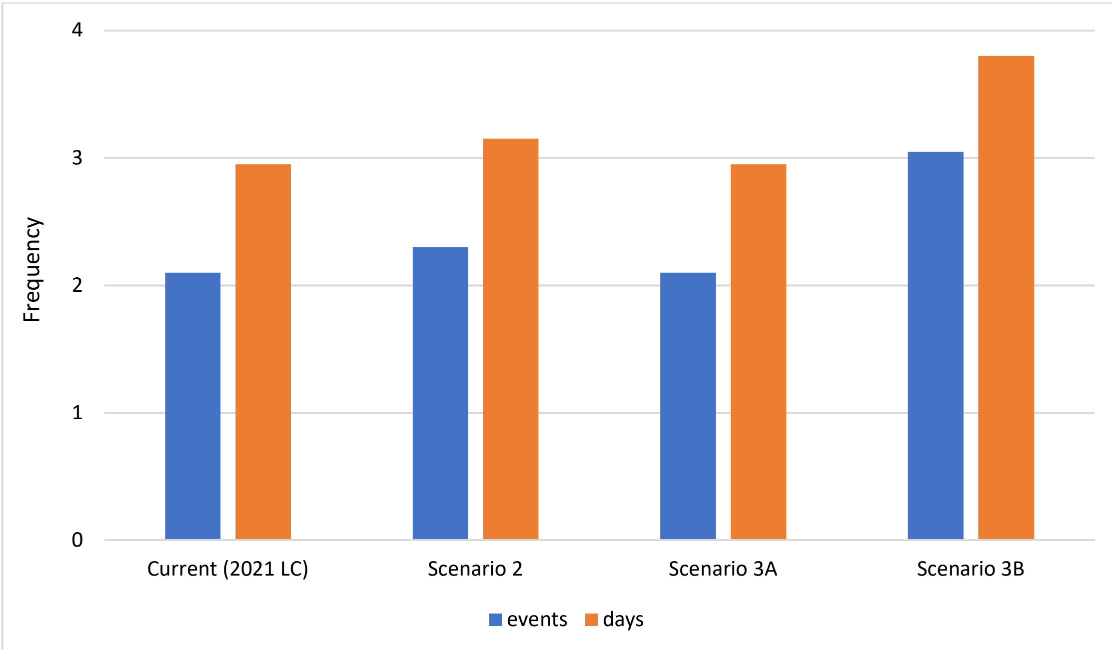

Figure 6.18: Annual frequency of events exceeding bankfull discharge at Site A and B (where bankfull is estimated to be the same for both sites).

6.4.6 Water Yield and spatially sensitive areas

The total specific water yield (annual) estimated for each scenario was shown in Figure 6.19. The result indicates that Scenario 3B has the highest specific water yield (354.72 $\mathrm{mm/km^2}$) among the others, followed by Scenario 2 (350.62 $\mathrm{mm/km^2}$) and 2021 land cover (340.29 $\mathrm{mm/km^2}$). Specific water yield generated for 2021 land cover and Scenario 3A are similar, while water yield for 1988 land cover remained the lowest.

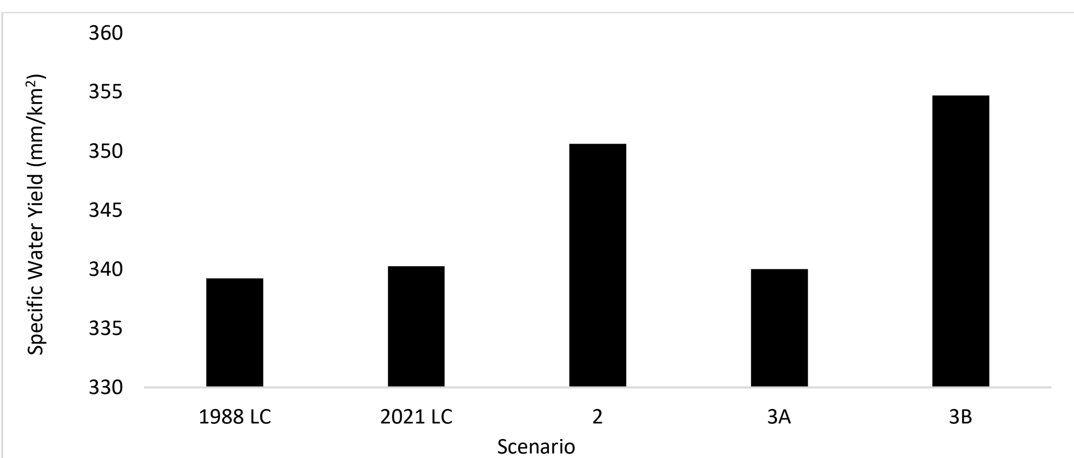

Figure 6.19: Total specific water yield estimated for each scenario. Scenario 2 = Future Land use Master Plan, Scenario 3A = 10% forest loss to grassland, Scenario 3B = 10% forest loss to bare earth.

The average annual specific water yield (from 2002 to 2021) generated for the sub-basins in each scenario was estimated by SWAT® (Figure 6.20). The maps in Figure 6.20 indicate that land cover change scares modelled would have complex and spatially variable effects on runoff and river discharge. Scenario 2 (Master Plan) results in the highest annual specific water yield, ranging across the sub-basins from 119.69 mm/km^2 to 14403.98 mm/km^2, and with an average of 1224.7 mm/km^2. This is followed by Scenario 3B with the second highest annual specific water yield, giving an average of 1214.05 mm/km^2, ranging from 124.16 mm/km^2 to 14054.41 mm/km^2. Average annual specific water yields for 2021 land cover (current) and Scenario 3A are lowest, at 1187.16 mm/km^2 and 1188.89 mm/km^2 respectively.

The change in average annual specific water yield (from 2002 to 2021) resulting from different land cover change scenarios is shown in Figure 6.21 for the subsist separately. More than half of the sub-basins in Scenario 3B appeared to have change greater than 16 mm/km^2 in water yield. For Scenario 2, the sub-basins in the western part subjected to agricultural land use exhibited higher water yield changes. Most sub-basins in this western area have a change in water yield that ranges from 3.61 mm/km^2 to 34.36 mm/km^2, while a few showed changes greater than 94.88 mm/km^2. The change in water yield for Scenario 1 (1988 -2021) and Scenario 2 is almost negligible, with most of the change in water yield close to 1 mm/km^2 to 9 mm/km^2.

Scenario 3B, with equal forest loss in each sub-basin spread randomly, was used to help identify areas most sensitive to land change (Figure 6.21- Scenario 3B). With the same amount of land cover conversion from forest to bare earth in each sub-basin, the model suggested that change in water yield varied substantially between sub-catchments; water yield increased by more than 140 mm/km^2 in some sub-catchments but by less than 10 mm/km^2 in others. This suggests that some sub-catchments are more sensitive to land cover change than others.

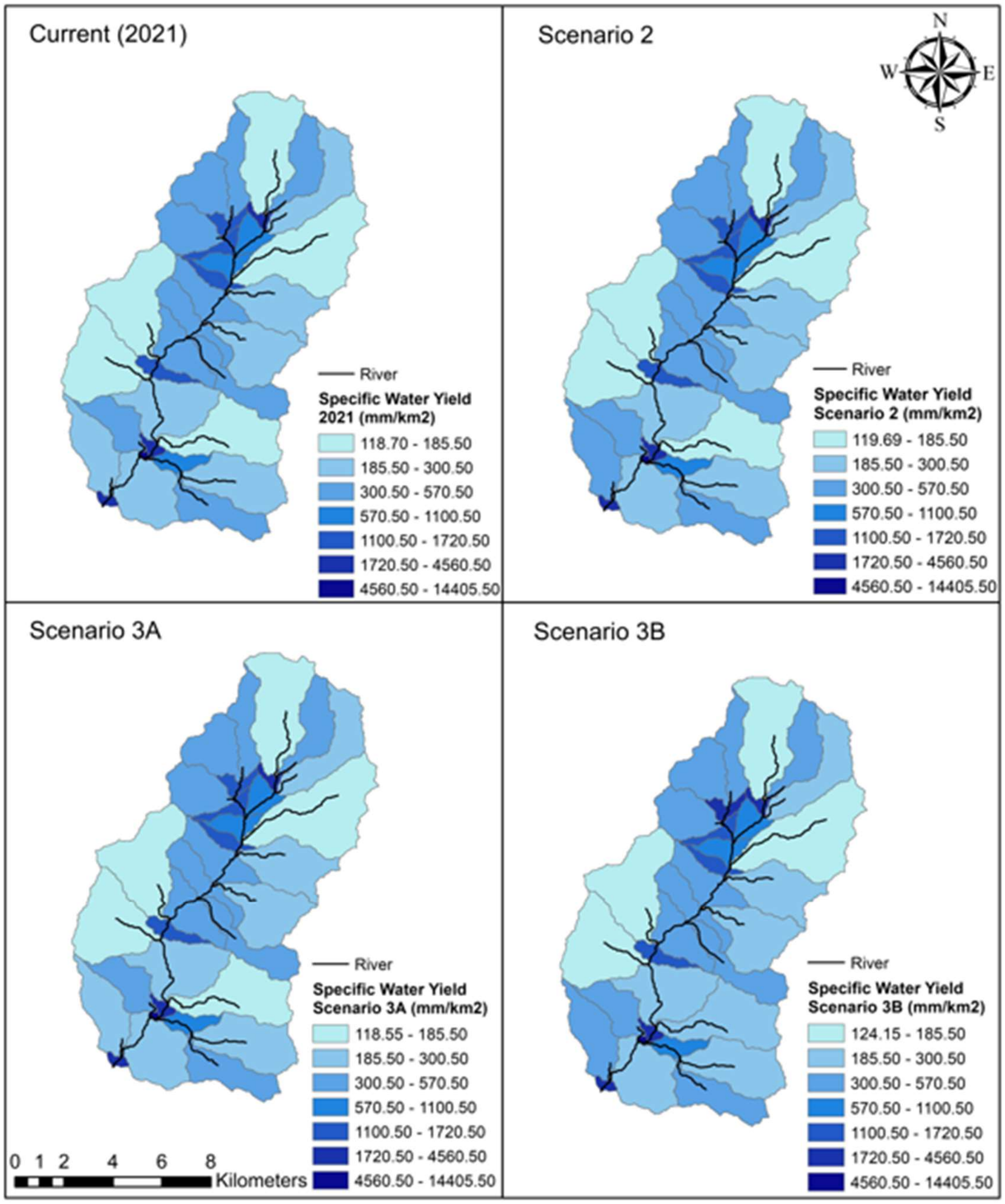

Figure 6.20: Annual specific water yield (mm/km^2) contributed from each sub-basins in Scenario 1, 2, 3A and 3B over the period of 20 years.

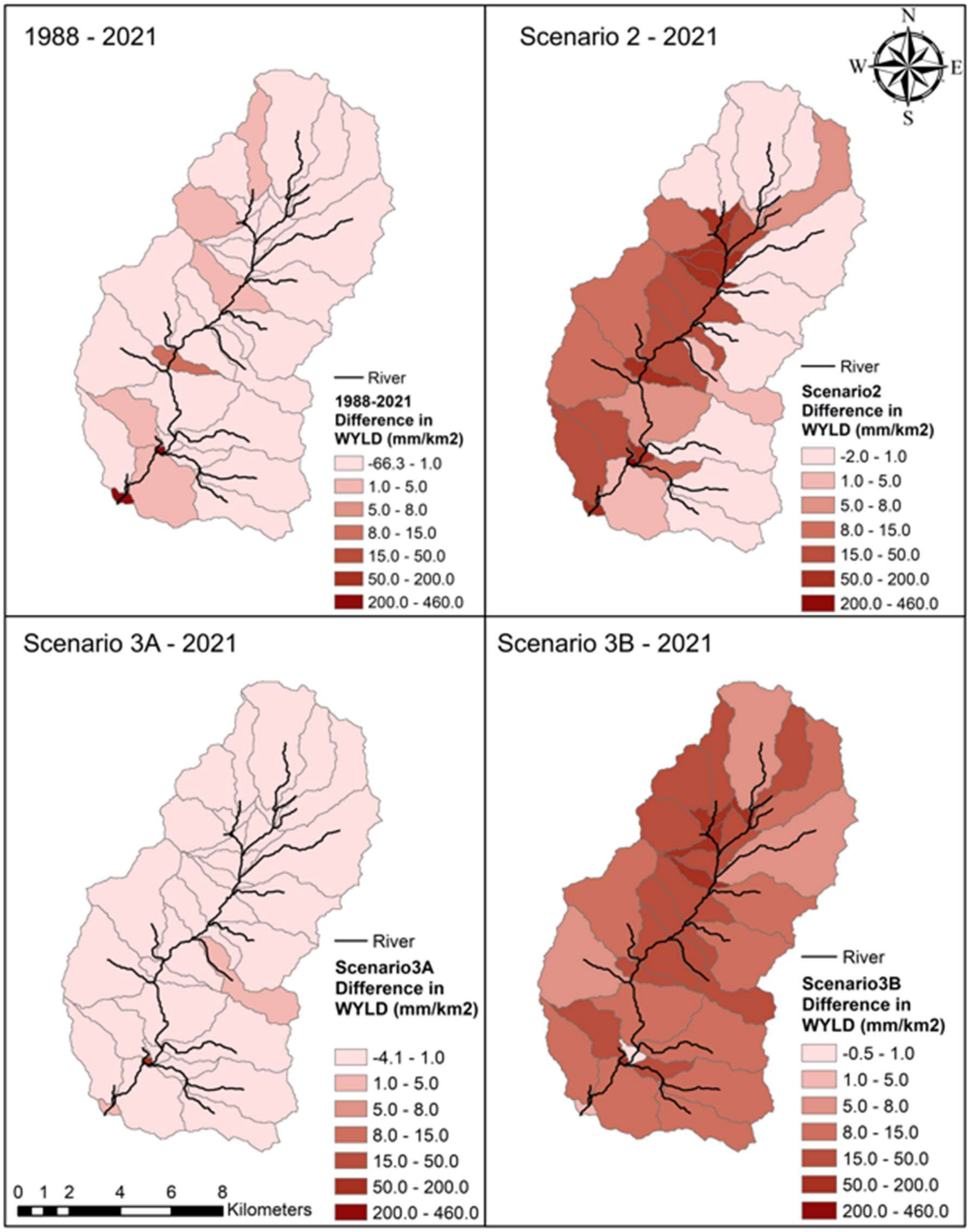

Figure 6.21: Results of SWAT® analysis of the effects of land cover change on annual specific water yield (runoff) from different sub-basins over the period of 20 years. The results show changes in runoff (mm/km^2) in different sub-basins resulting from Scenario 1 (1988-2021), Scenario 2, Scenario 3A and Scenario 3B. All the scenarios were compared with 2021 land cover.

6.5 Discussion

6.5.1. Key findings

This chapter focussed on understanding the implications of historical and plausible future land cover changes on runoff and the incidence of flooding in the Upper Trusan. The work had three objectives (as mentioned in section 6.1), and the following conclusions can be drawn with respect to each of these:

Objective 1. *Assess how historical land cover and land use change have affected the river's hydrological regime, specifically focusing on the incidence of high flows.*

The magnitude of historical land cover change in the Upper Trusan was not significant. The forest cover remained the largest percentage of the area, with more than 90 % of the total land cover in 2021. The small decline in forest loss (1.9%) reflected increases in tracks and access roads, built-up areas, grassland, and water (i.e. rice paddy); most of the change was conversion of forest cover to grassland (1.29 %). Bare earth increased by 0.41 % and built-up areas by 0.07 %. Due to the minimal clearance of forest, historical land cover change appears from the SWAT® modelling to have had only a limited impact on the river's hydrological regime.

Objective 2. *Assess how future land cover and land use changes may alter flood frequency and magnitude.*

35 % conversion from forest to agricultural land use, as expected under the Master Plan, could change the river's hydrological regime. The flow ranges from $Q_{0.05}$ (65 m^3/s) to Q_1 (32 m^3/s) would attain a higher magnitude than the flow regime in 2021. Flood events that fall within this range could potentially experience a higher magnitude. All the scenarios that represented the future land use showed an increase in monthly runoff. Scenario 3B has the highest monthly runoff, followed by Scenario 2 and Scenario 3A. With 10 % of forest converted to bare earth (Scenario 3B), flood event frequency increased significantly due to higher flood magnitude; most of the high flow events that did not exceed bankfull flow previously were predicted to be experiencing a higher magnitude and exceed the bankfull flow of 15 m^3/s at the site modelled.

Objective 3. *Provide spatially explicit recommendations for strategic forest protection, to limit future alterations to the river's hydrological regime.*

The land cover change for Scenarios 1 and 2 was concentrated at the middle and lower part of the catchment. This has resulted in a more significant change in runoff at the lower part of the river, which could increase the frequency of flood events; upstream from here the river above tends to experience less flooding. The water yield resulting from Scenario 2 was higher in the western region, where the forested areas were converted to agricultural land use. On the other hand, the change in runoff (water yield) resulting from the evenly distributed conversion of forest to bare earth (i.e. Scenario 3B) varied substantially between sub-catchment. The sub-catchments nearer to the river channel have higher water yield overall. This means that these areas were more sensitive to land cover change and the conservation of natural forests needs to be prioritised.

6.5.2. Land cover change in tropical regions

Magnitude and nature of observed land cover change

Most of the forested areas cleared in the Upper Trusan were cleared for livestock farming and agricultural purposes. The land use pattern is largely predictable, where most of the floodplain areas adjacent to the river channel were actively expanded as agricultural land to support community livelihoods. However, the local community did not have a clear land use plan for the Upper Trusan Catchment, resulting in a constant shift of land use between agriculture and grazing land over the years. The extension of road networks throughout the basin, harvesting of forests and storage land resulted in a slight rise in bare earth. As a result of higher rice production demand, transportation has become key to increasing productivity. Hence, road networks to access the paddy field areas were increased over the years. The old logging trails used to access the logging regions were still apparent in the northern part of the basin, where bare earth could be seen. Nevertheless, all logging operations ceased in the 2000s. The built-up area in the watershed remained the same during the study area as the population of the nearby settlements did not increase.

Over 33 years (i.e. 1988 – 2021), the magnitude of land cover change in the Upper Trusan was relatively small compared to other parts of Borneo, equating to 0.06 % per annum. In other parts of Sarawak, the annual deforestation rate from 1990 to 2010 was estimated at 0.64 %

(Satoshi Tsuyuki, 2011). Several studies have indicated that land use change in Sarawak was largely due to the expansion of agricultural land use (Hon & Shibata, 2013). Notably, forest degradation was mainly caused by large-scale expansion of oil palm plantations and farming areas across the state (Aik & Ismail, 2020). However, the land cover change rate across Sarawak, particularly forest loss or forest degradation, varies greatly. In urban areas such as Kuching, the catchment was subjected to 0.235 % of forest loss per year (from 2000 to 2020), according to Global Forest Watch (Global Forest Watch, 2022). This forest loss was largely due to rapid urban development, where urban areas increased by 104.13 km^2 between 1972 to 2018 (Kemarau & Eboy, 2018). Whereas the Baleh catchment, a less urbanised area compared to Kuching located at the south bank of Rajang River, has experienced a lesser forest loss with a change of 0.02 % per year from 2000 to 2020 (Global Forest Watch, 2022). A study has shown that the home of Iban in the North-Eastern region of Sarawak, a rural area, is changing more slowly than state land, with an expected annual rate of land use conversion under shifting agriculture zones of 0.2% over the next 100 years (Cramb, 2011). In rural areas similar to the Upper Trusan, for instance, Bario, Bakelalan, and Kapit, deforestation is not as severe as urban areas based on recent satellite images.

However, not all the rural areas in Sarawak have a low deforestation rate; some areas were subjected to large-scale clearance mainly caused by the hydropower dam projects (Alicia et al., 2020). Due to the pressure of sustaining industrial growth in Sarawak, large-scale reservoirs were built to provide sufficient electrical energy supply by using rivers as a source of energy. The construction of dams has flooded large forest areas, forcing the local communities and wildlife to displace from these habitats. Sarawak now has three big hydropower dams in operation, and a fourth dam (i.e. Baleh Dam) is being constructed (Tham, 2022). The Batang Ai Dam was the first dam project in Sarawak which was commenced in 1982, followed by Bakun Dam and Murum Damn in 1986 and 2008, respectively (Aiken & Leigh, 2015). Bakun Dam, which is the largest dam in Southeast Asia with an installed capacity of 2400 megawatts, has inundated a land area of 696.4 km^2 which is approximately five times the catchment size of the Upper Trusan (Ahsan & Ahmad, 2016). Furthermore, severe deforestation was seen at the Bakun water catchment, where access roads were built for access to dam constructions, logging, and palm oil plantations (Gaveau et al., 2016). Another twelve hydropower projects were planned for the period 2008 to 2020 to meet the demand for industrial economy expansion in the Sarawak region under an industrial development initiative called the Sarawak Corridor of Renewable Energy (SCORE) (Lee et al., 2014). It is estimated that 17000 km^2 of the forest will be impacted collectively by these dams (Alamgir et al., 2020), with major modification of the flow regimes in rivers likely as a result of hydropower operations (Chong et al., 2021). Thus, the hydrological change predicted here for the Trusan appears limited by comparison.

Impacts of land cover and land use change on the hydrology of tropical rivers

The simulated runoff from SWAT® indicated that a historical land cover change of 2% forest loss (i.e. 1988 versus 2021 land cover) has very little impact on the river's hydrological regime. Particularly, there was no clear evidence showing an increase in daily runoff and high flows. However, under the agricultural Master Plan which proposes 30 % of land use conversion from forest to agricultural land the flow ranges from $Q_{0.05}$ (65 m^3/s) to Q_1 (32 m^3/s) have a higher magnitude than the flow regime in simulated with 2021 land cover. For the worst-case Scenario 3A and 3B, the results indicated that land use change from forest to bare earth has the most impact on runoff. Scenario 3B has the highest monthly runoff, and the frequency of flood events increased significantly due to higher flood magnitude. With the same amount of forest loss converted to grassland, the change in runoff was almost negligible. Other than that, results also indicated that changes in runoff varied in different sub-basins despite the same amount of forest loss in each sub-basin. This suggested that some sub-basins are particularly vulnerable to land cover change; thus, protecting natural forests is a priority.

The runoff responses to varying land cover and land use changes predicted for the Trusan generally agree with other research literature. Most of these responses are driven by effects on hydrological processes such as soil interception, infiltration, evapotranspiration, soil recharge and ground water movement (Gashaw et al., 2018; Legesse et al., 2003; Silva et al., 2018).

In the context of tropical rivers, several studies reported increases in surface runoff when approximately 10 % of forest loss occurred in the catchment (Guzha et al., 2018; Lin et al., 2015; Shrestha et al., 2018). Sajikumar et al. (2015) reported that a reduction in forest area amounts to 60 % and 32 % resulting in an increase in surface runoff up to 20 %. However, the amount of increment in runoff largely depends on the type of land use change. Gashaw et al.

(2018) suggested that with a mixture of forest loss and decreased in shrublands being converted to built-up area (1.1 %) and agricultural land (76.8 %), the observed changes had increased the surface runoff, annual flow, and water yield by 9.3 %, 2.2%, and 2.4% respectively. Moreover, a study conducted by Silva et al. (2018) showed that when pastureland is replaced by bare soil, the runoff increases by 69 %. In contrast, conversion from pastureland to natural vegetation decreased the runoff by 42 %. Evidently, reafforestation by converting agricultural or grazing land to forest could help reduce the catchment runoff (Legesse et al., 2003). This corresponds to the case of the Upper Trusan Catchment, in which the simulated results from Scenario 3A show how important it is to keep native natural plants or regrown forests to help slow the erosion of soil caused by raindrops and surface water runoff.

Besides that, several studies illustrated water yield or surface runoff spatially (Chilagane et al., 2021; Gyawali et al., 2022; Silva et al., 2018). Notably, the contribution of water yield or runoff varies across the catchment, and the land use type is the main driver towards runoff generation. In areas subjected to forest clearance and disturbance, the runoff in respective sub-basins was particularly higher (Silva et al., 2018). Areas with a higher density of built-up areas also appeared to have higher runoff (Zhou et al., 2013). However, various spatial studies were conducted to look at sediment yield and loading (Gyawali et al., 2022; Tadesse et al., 2015), less were found to look at hydrological responses spatially.

It is widely acknowledged that land cover and land use change adversely impact runoff generation, but evidence and specific findings vary between studies. A study conducted by Sajikumar et al. (2015) in Southern India rivers highlighted that the changes in forested area would not influence changes in runoff directly. This coincides with the statement made by Malmer et al. (2010), who argued that relations between forest loss and runoff were not simple linear ones (Malmer et al., 2010; Sajikumar & Remya, 2015).

6.5.3 Implications for land use planning and catchment management

The historical land cover and land use change in the Upper Trusan Catchment was not enough to cause marked changes in the hydrological regime. In particular, there is no clear indication of alteration in high flows and so the simulations suggested that the land use change did not cause the increase in flooding reported by local communities. There are two issues that result from flooding – one is the inundation of and damage to rice paddies, and the other is the bank erosion that results from high flows. The erosion has local causes as previous work in the Trusan indicated that areas experiencing the most severed erosion have had riparian areas cleared of forest and no fencing to protect banks from poaching (trampling) by buffalo (Marteau et al., 2018). Given the modelling results together with the lack of trend in rainfall (Chapter 3) it is hard to support suggestions from the community that flooding has increased.

Regional or urban planners need to manage the development of floodplains, and this needs to be consisted explicitly as part of the Master Plan for the area. Floods pose personal and economic risks that must be weighed against the benefits of floodplains, such as good farmland and desirable places to live. In Chapter 5, we suggested agriculture zoning according to flood inundation map produced at corridor scale to help minimise losses. Good practices and management at the corridor scale could also help to enhance riverbank stability. Agricultural planning should consider dynamic agricultural land use and incorporate seasonal cropping, while proper drainage and terracing methods could further help delay surface water movement, reducing river channel runoff.

However, forest loss has an adverse impact on runoff generation. Strong evidence indicates that the conversion of forest to bare earth has the greatest impact on runoff in the Trusan, and expansion of agricultural land without proper management could lead to higher runoff and, thus, frequent flooding. Scenario 3B with extensive of forested areas being converted to bare earth (10% of the catchment area), was predicted to result in significant change in total water yield (354.72 $\mathrm{mm/km^2}$, which is 4% greater than the 2021 land cover; see Figure 6.22).

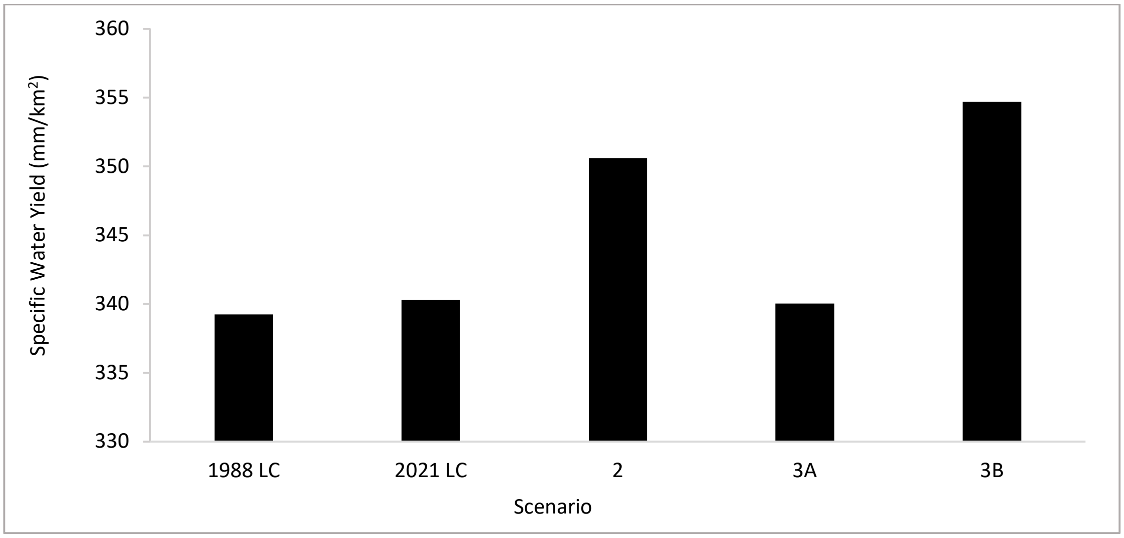

Figure 6.22: Total specific water yield estimated for each Scenario.

The land use Master Plan (Scenario 2) sets out that approximately 35 % of the forest areas in the Upper Trusan will be converted to agricultural land. This amount of land use conversion could lead to water scarcity issues as agricultural land could potentially affect evapotranspiration and groundwater recharge (Guzha et al., 2018; Owuor et al., 2016). Our results indicated that the baseflow under the Master Plan was slightly lower in dry months compared to the current land cover but also resulted in increased magnitude of peak discharge in the wet months. Furthermore, large-scale agricultural land use often leads to building of access road and expansion of built-up areas, all of which may contribute to further changes in runoff.

The SWAT® results suggested that some areas are sensitive to land cover change. This is one of very few studies that have used SWAT® to identify these areas, and it could be useful for us to avoid forest clearance in these areas. Furthermore, reforestation and conservation planning should prioritise these areas, certainly the sub-basins located in the middle part of the catchment with higher water yields. In the sensitive areas, the surface runoff will likely increase drastically under land use conversion to bare earth; hence, road expansion should be avoided in these sub-basins.

6.5.4. Limitations and future work

In ungauged catchments, data scarcity has been challenging for hydrological modelling applications, especially related to model performance and confidence. Obtaining long-term river discharge data in rural regions of Sarawak is challenging as the hydrometric network is limited and data often poor (long gaps in timeseries). No gauging station exists in the upper Trusan so data from the Long Tengoa gauging station at the far downstream (see Figure 6.1 for the location) was used to calibrate and validate the SWAT® model. This long-term discharge data for Long Tengoa station contained extended gaps of missing data, and the discharge rating curve can only predict peak discharges up until 179.2 $\mathrm{m^3/s}$. The autocalibration tool (i.e. SWAT-CUP®) forced the simulated peak to best match the unreliable observed peaks by adjusting the parameters in order to achieve goodness-of-fit.

The other limitation to note is that the smallest simulation timestep that SWAT® allows is in daily timestep. Although previous studies mostly focussed on runoff responses to land use change based on annual, seasonal, or monthly time frames, these time scales are no appropriate for flood analyses. Particularly, a sub-daily time step is required to estimate the instantaneous flow and to assess the impact of LULC on flood magnitude. The daily mean flow is the average streamflow, while instantaneous peak flow is the maximum flow, typically recorded at 15-minute intervals. As a result of intense rainfall, instantaneous flows during flood events can peak above daily mean flows. We attempted to deal with this by relating daily means to peaks during a few flood events that we have high resolution data for, but nevertheless it is important to note that analysis of changes in flood frequency and magnitude are based on less than ideal data.

Much previous work has shown that LULC change result in increases in rivers fine sediment loads and concentration (Chilagane et al., 2021; Gyawali et al., 2022; Norazhar et al., 2013). However, due to the complete absence of sediment data for the river, we did not simulate sediment despite SWAT's capability to predict sediment load.

For future work, we suggest looking at the impact of climate change on water surface runoff for the Upper Trusan Catchment. Previous work has suggested that the effect of climate change on hydrological components is more significant than the impact of land cover change (Son et al., 2020). Tan et al. (2017) reported increases in annual streamflow (14.6–27.2%), evapotranspiration (0.3–2.7%), surface runoff (46.8–90.2%) and water yield (14.2–26.5%) when the annual rainfall and maximum temperature were projected to increase by 1.2 – 8.7 % and 0.6 – 2.1 °C, respectively, in Kelantan River Basin, Malaysia (Tan et al., 2017). Previously, Marteau et al. (2018) showed that there was no trend in rainfall up to 2019. However, several big floods occurred in Malaysia in 2020 and 2021, and more intense rainfall events were reported in recent years. Thus, a more extensive and up-to-date study on the impact of climate change on hydrology is required to inform decisions for integrated land use and water management practices in the Upper Trusan Catchment. The issue of climate change is considered more in Chapter 7.

6.6 Final remarks

Despite the challenges of calibrating and validating SWAT® in data poor catchments such as the Trusan, the modelling presented in this chapter provided some important insights into how land cover change has affected flood frequency and magnitude and how further changes might affect the river's hydrology in the future. The work suggests that, due to the very limited clearance of forest, historical land cover change has had only a limited impact on the river's hydrological regime. Although it represents quite a major change in land cover, the agricultural Master Plan is predicted to have minimal impact on flooding in the Trusan in future years. However, what is clear from the work is that forest clearance, where cleared land is left as bare earth, has the potential to increase flood frequency and magnitude. Most such clearance related to the expansion of roads and tracks, and this practice should be avoided, unless great care is taken with surfacing, adopting best practice in drainage etc. The SWAT® modelling that used a 10% forest loss applied evenly to all sub-basins indicated that, by virtue of their intrinsic properties, some areas are more sensitive than others. It is proposed that these areas should be prioritised for forest protection, to preserve the hydrological integrity of the basin in general and limit localised flooding in these areas.

This study has highlighted several limitations such as the uncertainty in runoff modelling, catchment data extrapolation (larger to smaller catchment) and data scarcity. Particularly, a sub-daily time step is required to estimate the instantaneous flow and to assess the impact of LULC on flood magnitude. To address these limitations, the recommendation for future work is to have continuous monitoring of catchment data (e.g. precipitation, evapotranspiration, infiltration, runoff etc.) to improve our understanding of catchment behaviour and help to develop accurate catchment hydrological models for catchments such as the Trusan. Furthermore, continuous monitoring should be designed to capture a comprehensive picture of catchment behaviour that involves collecting data at multiple spatial and temporal scales (e.g. instantaneous flow) and including data on groundwater levels and recharge. Lastly, there is also a need for ongoing data analysis that help to identify the hydrological trends and patterns for the catchment and use these data to evaluate and improve the performance of catchment models.

CHAPTER 7: SYNTHESIS

photo taken at Long Telingan showing channel re-alignment undertaken by the local following a large flood
Photo: Yih Yoong Lip, February 2023

7.1 Main findings

The Trusan River, located in the rural heartland of Sarawak, is a highly dynamic river that has experienced significant historical planform changes due to high flows. The impact of flooding has been particularly severe for the local communities here who rely on rice paddy farming. Despite years of research and the establishment of national standards, the issue of flooding in rural areas remains a significant challenge in Malaysia. Moreover, the magnitude of the problem has grown in recent decades due to climate change, population growth, and the increasing pressure to balance environmental, social, and economic needs and priorities in rural areas.

In the Upper Trusan, to deal with the flooding issues, in the past communities have used gabions and other forms of protective revetment, along with channelisation, to protect their properties and livelihoods. However, these traditional engineering approaches can lead to disturbance in natural flow conditions and instream habitat, with negative impacts on aquatic ecosystems and biodiversity. These approaches have resulted in changes in sediment transport and erosion patterns in the river and have led, for example, to issues of a bridge being undermined. Hence, sustainable management to deal with flooding and erosion was suggested as alternative to these failed hard-engineering approaches.

The overall aim of the research presented in this thesis was to **assess the feasibility of using sustainable management to help solve flooding and erosion problems in the Trusan River**. The thesis evaluated opportunities for management at three scales: (i) Green measures for local bank protection (Chapter 4), (ii) floodplain retention for corridor scale flood risk reduction (Chapter 5), and (iii) watershed management (e.g. preservation of natural land cover) for controlling hydrological change (Chapter 6). The main findings with respect to each of the four research objectives (which were set out in Chapter 1) are summarised below:

Objective 1: ***Assess the opportunities and constraints for local measures to protect riverbanks from erosion.***

The green measures used in the Upper Trusan were partially successful but had limitations. Living materials worked well, but the experience gained from installation in the Trusan suggests that design and management should focus on ensuring measures are robust in the first few months of life and are maintained well to ensure they remain in place for as long as possible. Poor materials selection and failure to follow proper installation procedures can contribute to failure, and frequent high flows in the Upper Trusan leave only a short time window for installation. In future, banks need to be graded before installation, live materials should be used, and toe protection is needed. Failings of some measures in the Trusan relate to incomplete installation, not following the initial design, and lack of maintenance. Thus, all installation should be completed fully before moving to the next site or section, and time should be given for checks and maintenance of existing measures.

Objective 2: ***Assess the potential of using floodplain as flood retention in high-energy river and its associated benefits , in terms of reducing flood peaks and flood risk downstream.***

Floodplain retention may not be effective in reducing extreme flood peaks in the Upper Trusan due to the small size of floodplains – the floodplains are simply too small to store sufficient floodwater. A strategic zoning map is recommended to reallocate paddy fields to lower flood risks areas and a programme of managed retreat or abandonment of higher risk areas is suggested for effective flood risk management.

Objective 3: ***Assess the impact of land use change on runoff generation and its contribution to increased flood risk, and identify contribution that catchment management could have in reducing erosion and flood risk.***

This SWAT® model used to help address this objective provided a good insight on how land cover change affects flood frequency and magnitude. The study found that historical land cover change has had a limited impact on the hydrological regime of Trusan river, due to the small scale of the deforestation. Very few hillslope areas (i.e. areas away from the floodplain) have been completely deforested, with the change mainly being small areas being cleared for agricultural crops such as pineapples or cattle grazing. The proposed agricultural Master Plan is also expected to have minimal impact on flooding. However, more extensive clearance of forests, especially when land is left bare, has the potential to increase flood frequency and magnitude. This type of clearance is often due to the expansion of roads and tracks, so new roads should be kept to a minimum and caution should be exercised with surfacing and drainage to avoid this effect. The modelling also shows that some areas are more sensitive to forest loss than others, and priority should be given to protecting these areas to preserve the hydrological integrity of the basin and reduce localised flooding.

7.2 A sustainable future for the Upper Trusan

7.2.1 Future scenarios

As indicated above, floodplain inundation offers little hope of being able to solve the challenges faced by the communities in the Upper Trusan. Moreover, while local measures if well-designed and maintained can help prevent erosion in selected sections of channel, in extremely high energy systems such as the Trusan they should not be seen as a long-term solution to the problems caused by high flows. Although historic land cover change has not been great, the future is likely to be rather different. For example, the local government Master Plan suggested that up to 35 % of the Upper Trusan is to be converted to agricultural land use. There are also overarching pressures posed by climate change. The analysis of historical rainfall contained in Marteau et al. (2018) suggested that there is no clear evidence of increased rainfall in the Trusan. However, this was based on data only up to 2015. The eight years since this point (i.e. 2015 to 2023) have seen many large floods in the Upper Trusan and communities are reporting more intense rainfall now than in living memory. It is therefore possible that a more complete (up to the present time) and thorough sub-daily time interval rainfall data may show evidence of climate change impacts in the Trusan. Thus, there is a need to think about adaptation to future land cover and climate scenarios that are quite different to the present. This adaptation also requires a longer-term perspective and looking for solutions focussed on wider aspects of livelihoods rather than simply flood prevention or protection.

7.2.2 Broader perspectives on the future of the Trusan

The research presented in the thesis has primarily focussed on hydrological issues, particularly flooding and erosion, and proposed solutions to mitigate these. However, the results suggest that on their own hydrological measures may not provide sufficient resilience to deal with future climate and land cover changes, which could lead to increased incidence of damaging events such as one that occurred in 2021. This flood event caused major changes throughout the Upper Trusan River. Figure 7.1 shows its effects at Site A, where a channel evulsion occurred – the channel switched from occupying the left bank to the right bank as a result of blockage cause by major deposition of sediments in the upper part of the section. As a result of the evulsion, the previously eroding bank (true left) was no longer part of the main flow path; in effect the green measures installed are not currently needed as this bank is now not exposed to flow. Given the potential for more frequent and severe events such as this in the future, it is unrealistic to expect that the local and corridor scale measures described in the thesis are likely to be able to cope.

Alternative approaches are needed to support communities in this high energy upland catchment. Work presented in chapter 4 indicated the scale and extent of long-term erosion along the study section. If such rates of bank retreat continue for the coming decades, communities will face ongoing problem of land loss. It is therefore timely to consider abandoning the areas at most risk of erosion. Such areas are shown in Figure 7.2 (approximately 10 kilometers section of the Upper Trusan River). Figure 7.3 to Figure 7.5 show the areas at local scale anticipated to be lost as a result of bank erosion, based on rates observed over the 1988-2021 period projected forward the next 30 years; i.e. width of the shaded areas plotted show expected extent of lateral erosion if historic rates continue. These areas can be considered at risk and so ones where abandonment should be to consider as part of resilience planning.

As part of such planning, a full socioeconomic analysis is recommended in the future to assess the livelihoods of local communities in the Upper Trusan catchment, particularly their dependence on rice production and the significance of this for income. It is possible that the main driver for rice production is increasing income rather than solely providing food for the community, but there is currently no data on this. There may be possibilities for diversifying income through ecotourism, agroforestry and change in farming practices to provide a sustainable transformative economy for the communities. For instance, Kim et al. (2019) studied the potential of implementing ecotourism as a transformative economy in a rural community in Cambodia (Kim et al., 2019). Ngan et al., (2016) and Tran et al. (2021) recognised that rice-based agricultural in Vietnam that has been heavily reliant on the delta and floodplain has to adapt to changes (Ngan et al., 2018; Tran et al., 2021). Agroforestry systems that integrate woody perennials with arable crops, livestock, or fodder also help to promote more efficient utilisation of resources as compared to monocropping alone (Fahad et al., 2022). Thus, a full socio-economic study is proposed as a priority for the Upper Trusan, to better understand the potential for income streams from alternative sources that would reduce reliance on rice production.

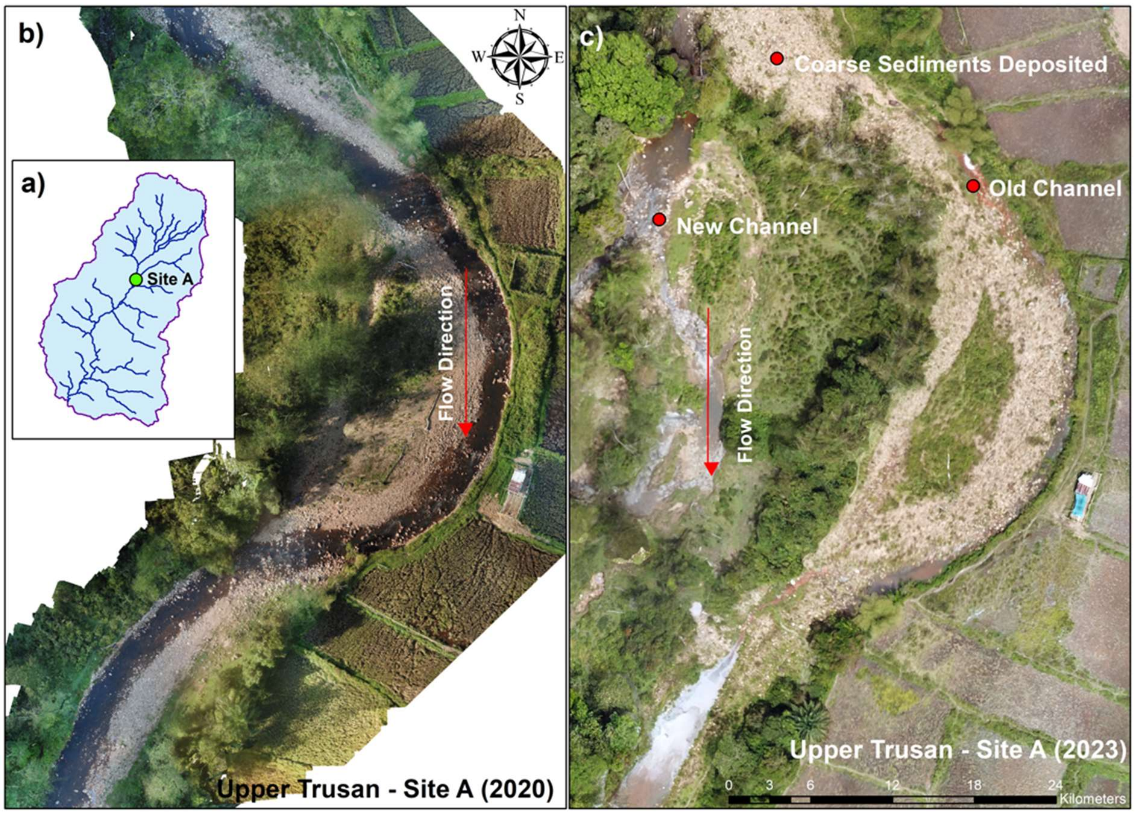

Figure 7.1: a) Location of Site A, b) Orthomosaic of Site A surveyed in 2020 and c) 2023 before and after a large flood.

Such a rounded assessment would provide a model for future land use management and social-economic development that is not reliant on intensive use of the floodplain. This would enable the potential return of land to the river, as advocated in scientific literature. Conversations with the local community suggest that the income generated from a single rice paddy range from 100 to 2000 Ringgit per year, compared to the cost of building riverbank protection at 200,000 Ringgits. Therefore, to support proposed changes in farming practices, a proper cost-benefit analysis is needed to assess the merits of investing in local measures, given the income generated by rice production.

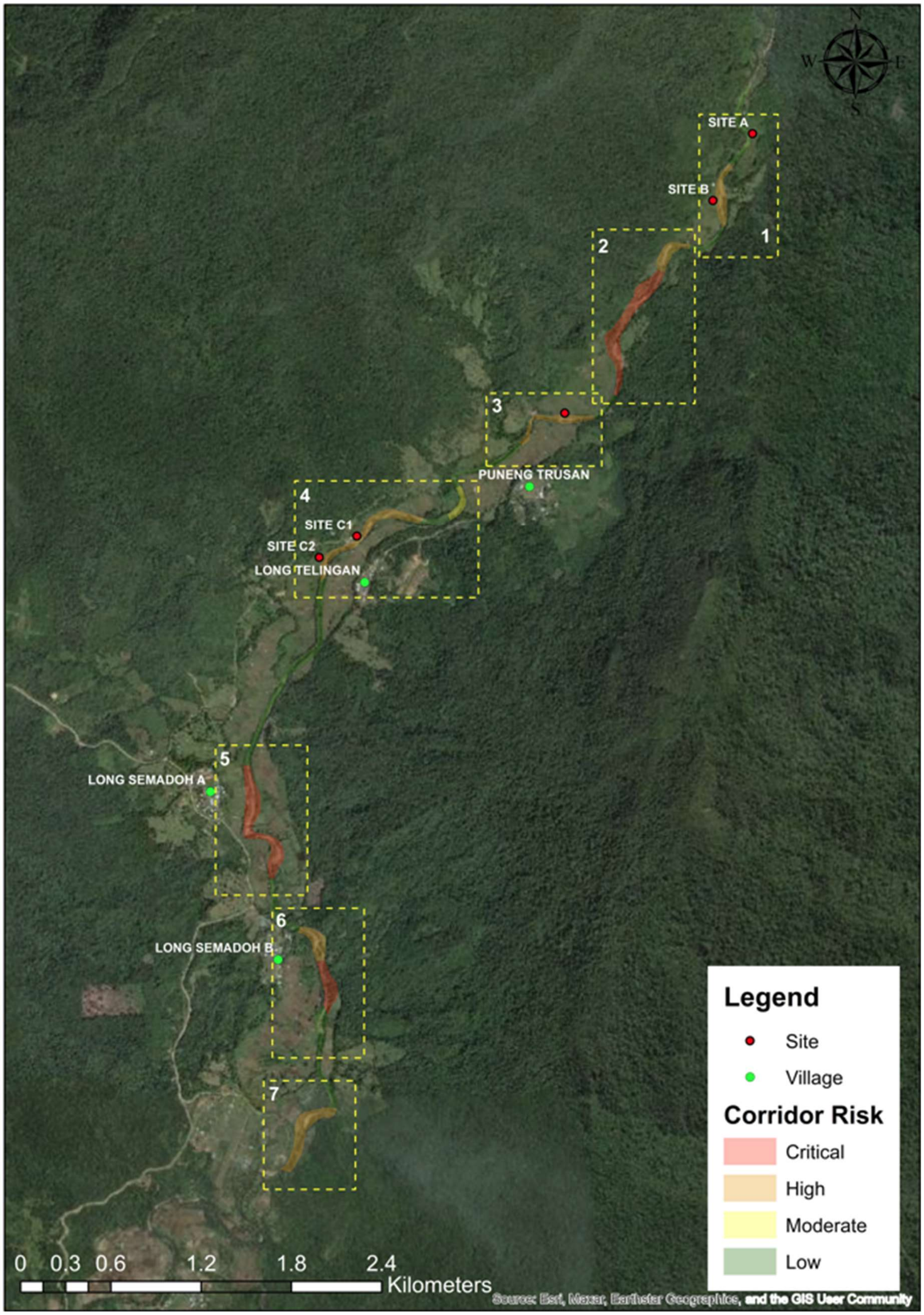

Figure 7.2: Estimated corridor risk based on the historical planform changes over 33 years (1988 -2021). The level of corridor risk is classified based on the magnitude of historical observed erosion rate.

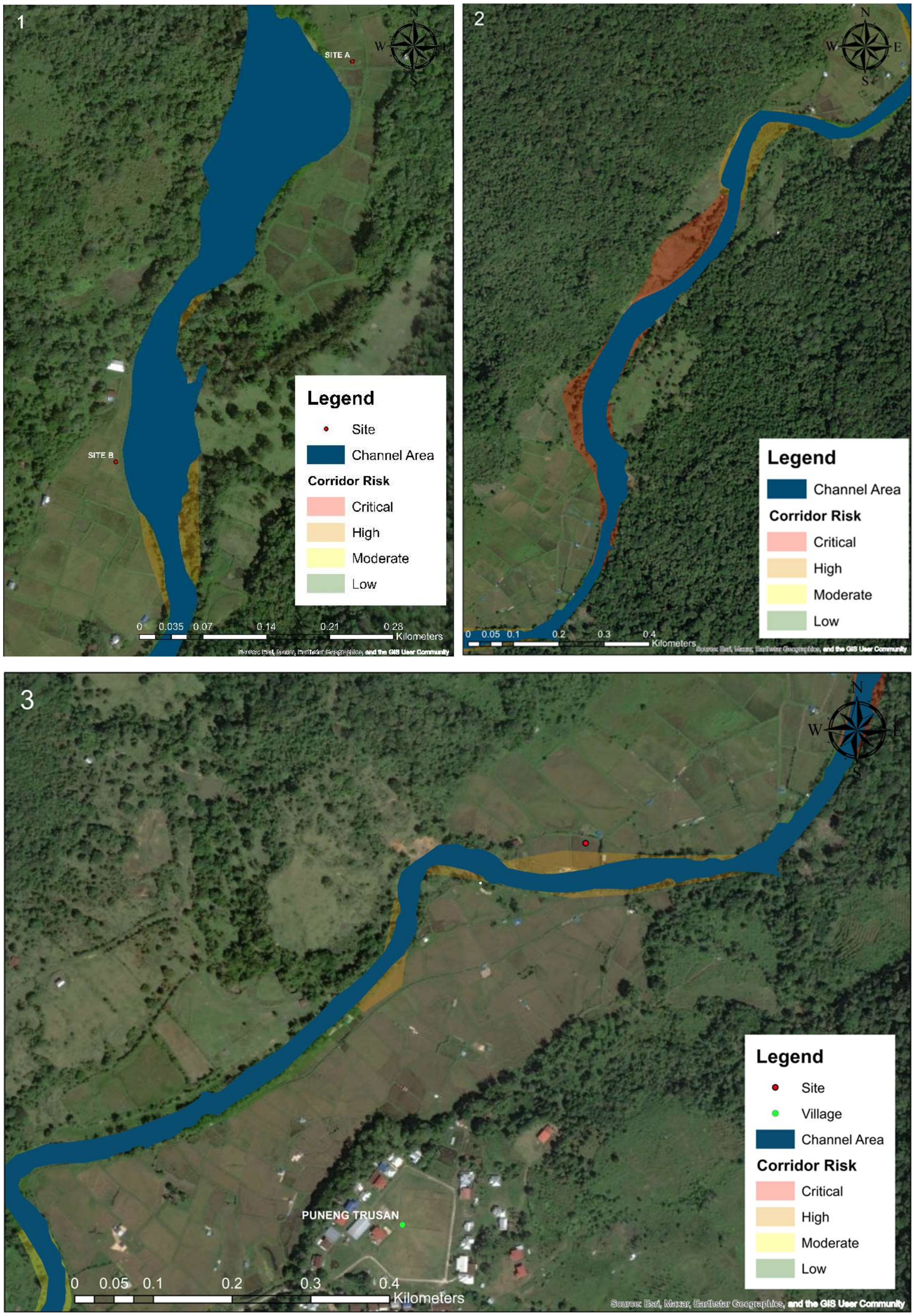

Figure 7.3: Estimated corridor risk at local scale (focus frame 1,2 & 3 extracted from Figure 7.2).

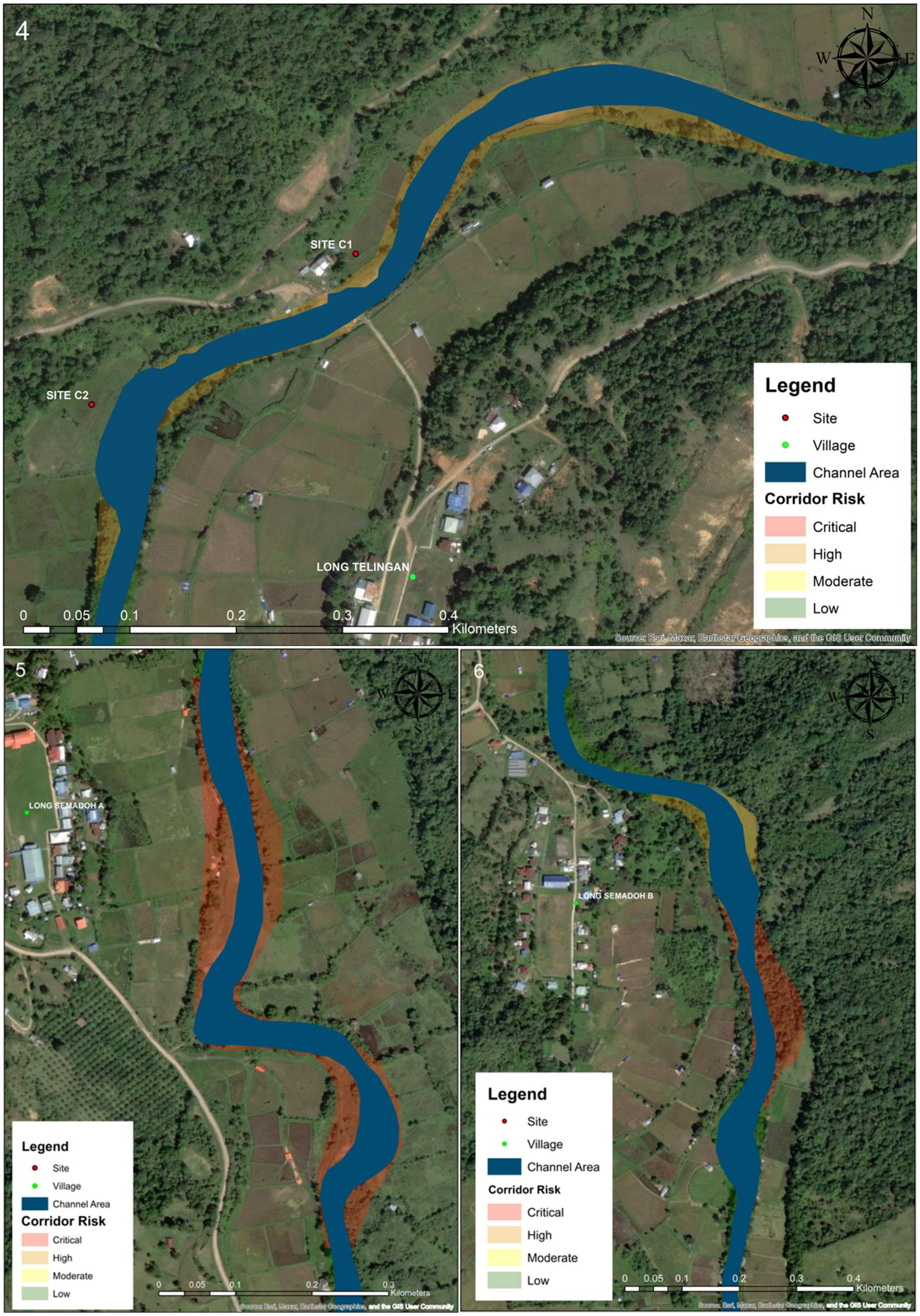

Figure 7.4: Estimated corridor risk at local scale (focus frame 4,5 & 6 extracted from Figure 7.2).

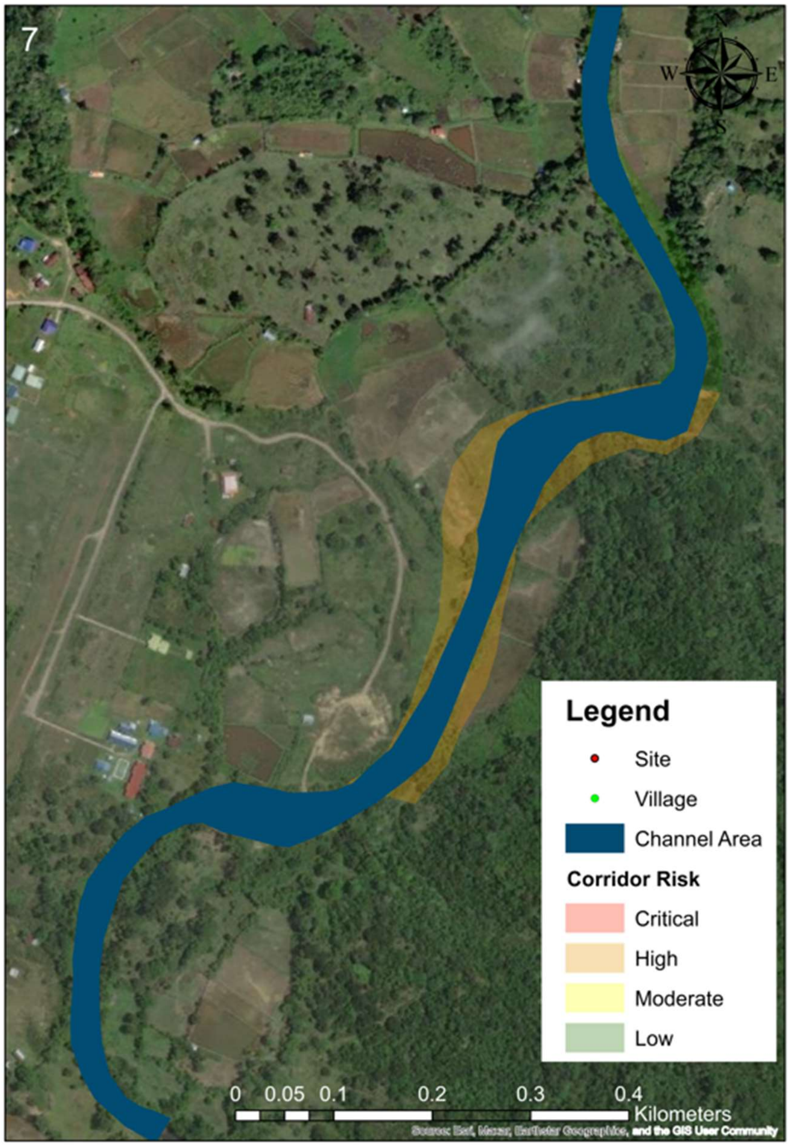

Figure 7.5: Estimated corridor risk at local scale (focus frame 7 extracted from Figure 7.2).

The overall conclusion of this work is that, as observed elsewhere, the demands of food production and economic growth set against climate change and land cover change create challenges for water resources management (Dagar et al., 2020; Power, 2010; Vijulie et al., 2019). Instead of having intensive water infrastructure to protect floodplains, a longer-term sustainability strategy should be considered. Thus, alternatives to sustain the livelihood of rural communities are required to make space for river as part of flood risk management to reduce and avoid flood damage. This alternative model for the valley may be critical to improving resilience.

7.3 Limitations

7.3.1 Limitations in the current thesis

In its original conception, this thesis was focussed solely on evaluation of constraints on using local green measures in high energy rivers. To this end, various monitoring programmes were set in place at the very start of the project, to understand in much more detail the fluvial dynamics (erosion, sediment transport etc) in the Upper Trusan. For instance, (i) tracers were installed to track changes in the riverbed, and (ii) baseline surveys were initiated to assess rates of bank erosion as well as the effectiveness of bank protection measures. However, due to travel restrictions imposed by the COVID-19 pandemic, it was not possible to conduct the repeat survey fieldwork needed to track changes for each of these things in the way needed to understand the river's dynamics and evaluate changes in green measures after a series individual high flow events. Consequently, the work was reorientated, so that the thesis was much less dependent on empirical sedimentary and fluvial geomorphic field data but on modelling using hydrological data and satellite imagery, and topographic information that could be collected using the drone. Thus, while the thesis has addressed opportunities for sustainable management in the Trusan, it has done this in a different way (at different scales and different methods) than originally planned.

Another factor that affected the work presented in the thesis was the lack of a flow gauge in the Upper Trusan. Moreover, data quality for the gauge that is located much further down the river is poor, with long data gaps and a stage discharge relationship that is unreliable at the high flows that were the main focus of this work. The lack of empirical flow data for the study section made it hard to assess long-term changes in river’s hydrology, and data reliability made it difficult to validate hydrological models. Finally, although the analysis of satellite images provided valuable insights into the river's dynamics over an extended time period, the resolution of the satellite imagery was relatively low and so the magnitude of changes from some of the older satellite images should be interpreted with caution.

7.3.2 Limitation of Sustainable Green Approaches in Erosion and Flood Management

This study recognised that sustainable green approaches could not possibly eliminate all erosion and flood issues, especially in the context of tropics region with high rainfall associated climate change and intensification and increased frequency of extreme events.

Given that the Upper Trusan Catchment is subjected to dynamic seasonality due to the monsoon, the rainfall intensity and frequency of extreme rainfall events are particularly high. Through the historical study looking at the changes of river planform, it is evident that the Upper Trusan River is highly dynamic morphologically. Over the course of the study period, the river was frequently subjected to extreme events that changes the entire river channel alignment and we witnessed extremely high sediment mobility associated with one or two extremely large events (see Figure 7.1).

This study recognised that the causes of failures for green measures are very diverse, ranging from its built structure integrity, maintenance, slope failure, and the magnitude of extreme flood events. The phenomenon of frequent flood events may mean that the local scale green bank protection measures are constantly subjected to extreme flow forces limiting their use in such settings. Furthermore, frequent flooding in the Upper Trusan makes the dry season window for the installation, growth, and stabilisation of green measures on the riverbank very short. This affects the resistance capacities of the measures that were applied in our study, with field evidence and observation indicating that scouring and uplifting of green measures occurred before the plants and bamboo shoots bedded-in to the riverbank. During the course of the study period, several large flood events were observed, and these caused major damage to the riverbank and nearby infrastructure. The magnitude was enough to change the geomorphology of the entire river system, and hence, green measures have self-evident limitations in morphologically dynamic areas.

For corridor scale measures, the main limitation in the Trusan is that the floodplain storage capacity is relatively small compared to other areas in which such measures are typically employed (typically more lowland rivers). Given that the floodplains are mostly occupied by paddy fields area, the areas that were allowed to flood is limited. After the discussion with the local communities, we recognised that land ownership could make it hard to have reserve floodplain retention areas for storage of larger floods. However, that floodplain retention could be a solution to reduce the flood impact for small and moderate floods. The analysis shows that the flood frequency for small to moderate flood is high and the magnitude of high and extreme flood events could get up to 325 m^3/s and 425 m^3/s respectively. For the magnitude of high and extreme flood, the storage capacity has very little impact on the flood reduction at the downstream, because under natural conditions this magnitude will flood most of the area. Furthermore, due to the steep slope nature of the geometry in the Upper Trusan valley, the energy of the river system is relatively high. Water moves through very quickly from upstream to downstream, making the floodplain redundant in propagating flood waves and hence, magnitude of flood peaks can hardly be reduced. Overall, the results show that using floodplains as retention area could help to reduce the flooding in downstream areas but the reduction achieved largely depends on the magnitude of the flood events.

A general limitation of catchment scale management is the engagement of stakeholders in to get them to embrace good land use management planning and strategies. The study found that as long as the land use was maintained with agricultural or grassland, there will be little impact on the river hydrology (e.g. flood frequency and magnitude remain the same across the simulated scenarios). However, efforts to engage them are challenged by difficulty of communicating how land use management to reduce runoff generation. Due to the nature of high energy river system in the Upper Trusan, flood frequency and magnitude are naturally high. The relative contribution of catchment land use management may be hindered by this. Hence, the long-term benefits could hardly be evident here, and this undermines efforts to communicate and ‘sell’ the benefits of good land use management in reducing runoff. There are also limitations in using modelling results to help with such communications, due to model input data quality and setup (e.g. inadequate rainfall data, limited numerical information about field drainage systems, poor knowledge of the underlying geology, limited information on the hydraulic structures and soil characteristics).

Although there are limitations for sustainable approaches in river erosion and flood management the integrated approaches of local-scale rehabilitation measures, effective river-floodplain management, and catchment management should not be abandoned altogether, since collectively they could make a significant contribution to effective erosion risk reduction and flood prevention. This study highlighted the significant contribution of local scale bank protection measures in reducing bank erosion if done correctly, how corridor scale measures can reduce certain magnitude flood peaks and alter wave propagation, and effective land use management can be in reducing runoff generation.

7.4 Concluding remarks

The work presented in this thesis is quite unusual, in that it applies multiple spatial scale hydrological analyses to address problems faced by communities living in an upland tropical river. A series of complementary approaches was used to better understand the causes, consequences, and possible solutions to flooding – from using drones to build DEMs to look at channel change, to the use of hydraulic models to understand corridor scale flooding (HEC-RAS®) and catchment scale hydrological models to assess implications of land cover change (SWAT®).

The study emphasised the need for sustainable management solutions. Findings indicated that while green measures for local bank protection had some success, they are challenged by the need for careful (locale-specific) design, maintenance, and short time windows for installation. Floodplain retention was found useful to reduce small or moderate flood events, but limited in its ability to reduce extreme flood peaks due to the small size of floodplains in the Upper Trusan. Hence, the suggestion is to practice land use reallocation to reduce flood risk. Furthermore, the research suggested that land use change had a relatively small impact on hydrology but emphasised the importance of protecting sensitive areas to maintain basin integrity. In conclusion, the research supports the feasibility of sustainable approaches within a comprehensive, multi-scale adaptive strategy to address the complex challenges in the Trusan River; to achieve this, a multifaceted and long-term strategies are required.

The work also provided important new insights into the hydrology of this river, but it is suggested now that a much broader perspective needs to be taken to try and secure a resilient future for the people living in this remote area. This broader perspective should consider the social, economic, and environmental factors that contribute to their vulnerabilities, as well as the potential impacts of climate change on the hydrology and flood regime of this remote area. This requires engagement with local communities to understand their needs and priorities, as well as working with government agencies and other stakeholders to develop policies and strategies that address these issues. It is important to consider approaches that prioritize resilience and adaptation, such as incorporating ecosystem-based approaches to flood management, managed retreat from high-risk areas, building more resilient infrastructure, and supporting sustainable livelihoods through diversification.

REFERENCES

Abbaspour, K. C. (2015). SWAT-CUP-2015. SWAT Calibration and Uncertainty program - A User Manual.

Abdullah, K. bin. (2017). Building Resilience for Sustainable ASEAN from Water-Related Disasters. *Executive Summary Report: Asia and The Pacific ASEAN*.

Academy of Sciences Malaysia. (2014). Strategic plan for Integrated River Basin Management (IRBM). In *Malaysia Volume 2 a study on the status and issues on*.

Academy of Sciences Malaysia. (2015). Strategic plan for Integrated River Basin Management (IRBM) in Malaysia.

Acreman, M. C., Riddington, R., & Booker, D. J. (2003). Hydrological impacts of floodplain restoration: A case study of the River Cherwell, UK. *Hydrology and Earth System Sciences*, *7*(1), 75–85. https://doi.org/10.5194/hess-7-75-2003

Aguiar Jr., T. R., Rasera, K., Parron, L. M., Brito, A. G., & Ferreira, M. T. (2015). Nutrient removal effectiveness by riparian buffer zones in rural temperate watersheds: The impact of no-till crops practices. *Agricultural Water Management*, *149*, 74–80. https://doi.org/10.1016/j.agwat.2014.10.031

Ahsan, R., & Ahmad, M. H. (2016). Development, displacement and resettlement a challenge for social sustainability: A Study on mega development project (Bakun Dam) in Sarawak. *International Journal of Advances in Agricultural and Environmental Engineering*, *3*(1). https://doi.org/10.15242/ijaaee.er0116020

Aik, D. H. J., & Ismail, M. H. (2020). Detection of deforestation and analysis land conversion from high resolution satellite imageries in Bintulu District, Serawak, Malaysia. *IOP Conference Series: Earth and Environmental Science*, *561*(1). https://doi.org/10.1088/1755-1315/561/1/012010

Aiken, S. R., & Leigh, C. H. (2015). Dams and indigenous peoples in Malaysia: development, displacement resettlement. *Source: Geografiska Annaler. Series B, Human Geography* (Vol. 97, Issue 1).

Akoko, G., Le, T. H., Gomi, T., & Kato, T. (2021). A Review of SWAT Model Application in Africa. *Water*, *13*(9), 1313. https://doi.org/10.3390/w13091313

Alamgir, M., Campbell, M. J., Sloan, S., Engert, J., Word, J., & Laurance, W. F. (2020). Emerging challenges for sustainable development and forest conservation in Sarawak, Borneo. *PLoS ONE*, *15*(3). https://doi.org/10.1371/journal.pone.0229614

Alicia, J., Blandoi, J., Azizul Hafiz Jamian, M., & Mohd-Azlan, J. (2020). An assessment of land use surrounding hydropower reservoirs using remote sensing in Sarawak, Malaysia. In *Journal of Sustainability Science and Management* (Vol. 15).

Allan, J. D. (2004). Landscapes and Riverscapes: The influence of land use on stream ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, *35*(1), 257–284. https://doi.org/10.1146/annurev.ecolsys.35.120202.110122

Allen, H. H., & Leech, J. R. (1997). Bioengineering for Streambank Erosion Control. *Report 1 Guidelines*.

Anstead, L., Boar, R. R., & Tovey, N. K. (2012). The effectiveness of a soil bioengineering solution for river bank stabilisation during flood and drought conditions: Two case studies from East Anglia. *Area*, *44*(4), 479–488. https://doi.org/10.1111/j.1475-4762.2012.01132.x

Apel, H., Merz, B., & Thieken, A. H. (2009). Influence of dike breaches on flood frequency estimation. *Computers and Geosciences*, *35*(5), 907–923. https://doi.org/10.1016/j.cageo.2007.11.003

Appanah, S., & Turnbull, J. M. (1998). A Review of Dipterocarps: Taxonomy, ecology and silviculture. *Center of International Forestry Research*.

Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., Van Griensven, A., Liew, M. W. Van, Kannan, N., Jha, M. K., Harmel, D., Member, A., Liew, M. W. Van, & Arnold, J.-F. G. (2012). Swat: Model Use, Calibration, And Validation. *American Society of Agricultural and Biological Engineers*, *55*(4), 1491–1508. http://swatmodel.tamu.edu

Asdak, C. (2014). Hydrology and watershed management. *Third publish. Gajah Mada University Press.* Yogyakarta.

ASDSO. (2014). From response to recovery - The story of the 2013 Colorado floods as experienced by the Colorado Division of Water Resources Dam Safety Branch. *Colorado Division of Water Resources*

Baharom, A., Shah Habibullah, M., & Padli, J. (2013). Determinants of flood fatalities: evidence from a panel data of 79 countries determinants of halal food export performance: the impact of Halal certification, oic trade-cooperation, and the level of restriction on religion view project. In *Article* *in Pertanika Journal of Social Science and Humanities*. https://www.researchgate.net/publication/260096101

Baker, V. R. (1994). Geomorphological understanding of floods. *Geomorphology*, *10*(1–4), 139–156. https://doi.org/10.1016/0169-555X(94)90013-2

Barkdoll, B. D., Vittilam, S., Bennett, S. J., & Alonso, C. v. (2004). Flow resistance of emergent vegetation. *Proceedings of the 2004 World Water and Environmetal Resources Congress: Critical Transitions in Water and Environmetal Resources Management*, 1398–1406. https://doi.org/10.1080/00221686.2004.9641206

Barreto-Martin, C., Sierra-Parada, R., Calderón-Rivera, D., Jaramillo-Londono, A., & Mesa-Fernández, D. (2021). Spatio-temporal analysis of the hydrological response to land cover changes in the sub-basin of the Chicú river, Colombia. *Heliyon*, *7*(7). https://doi.org/10.1016/j.heliyon.2021.e07358

Barrett, K. R. (1999). Ecological engineering in water resources: The benefits of collaborating with nature. *Water International*, *24*(3), 182–188. https://doi.org/10.1080/02508069908692160

Bates, P. D., & De Roo, A. P. J. (2000). A simple raster-based model for flood inundation simulation. *Journal of Hydrology*, *236*(1–2), 54–77. https://doi.org/10.1016/S0022-1694(00)00278-X

Beechie, T. J., Sear, D. A., Olden, J. D., Pess, G. R., Buffington, J. M., Moir, H., Roni, P., & Pollock, M. M. (2010). Process-based principles for restoring river ecosystems. *BioScience*, *60*(3), 209–222. https://doi.org/10.1525/bio.2010.60.3.7

Begum, R. A., Raihan, A., & Said, M. N. M. (2020). Dynamic impacts of economic growth and forested area on carbon dioxide emissions in malaysia. *Sustainability (Switzerland)*, *12*(22), 1–15. https://doi.org/10.3390/su12229375

Bent, G. C., & Waite, A. M. (2013). Equations for estimating bankfull channel geometry and discharge for streams in Massachusetts. *U.S. Geological Survey Scientific Investigations Report 2013-5155*, 62. https://doi.org/http://dx.doi.org/10.3133/ sir20135155.

Bernhardt, E. S., Palmer, M. A., Allan, J. D., Alexander, G., Barnas, K., Brooks, S., Carr, J., Clayton, S., Dahm, C., Follstad-Shah, J., Galat, D., Gloss, S., Goodwin, P., Hart, D., Hassett, B., Jenkinson, R., Katz, S., Kondolf, G. M., Lake, P. S., … Sudduth, O. (2005). Synthesizing U.S. river restoration efforts. In *Science (Vol. 308, Issue 5722, pp. 636–637).* https://doi.org/10.1126/science.1109769

Biron, P. M., Buffin-Bélanger, T., Larocque, M., Choné, G., Cloutier, C. A., Ouellet, M. A., Demers, S., Olsen, T., Desjarlais, C., & Eyquem, J. (2014). Freedom space for rivers: a sustainable management approach to enhance river resilience. *Environmental Management*, *54*(5), 1056–1073. https://doi.org/10.1007/s00267-014-0366-z

Black, A., Peskett, L., MacDonald, A., Young, A., Spray, C., Ball, T., Thomas, H., & Werritty, A. (2021). Natural flood management, lag time and catchment scale: Results from an empirical nested catchment study. *Journal of Flood Risk Management*, *14*(3). https://doi.org/10.1111/jfr3.12717

Blackburn, J., Marteau, B., Vericat, D., Batalla, R. J., Comte, J.-C., & Gibbins, C. (2023). Long-term geomorphic adjustments following the recoupling of a tributary to its main-stem river. *Geomorphology*, *424*, 108561. https://doi.org/10.1016/j.geomorph.2022.108561

Blöschl, G. (2005). Rainfall-runoff modeling of ungauged catchments. In *Encyclopedia of Hydrological Sciences*. John Wiley & Sons, Ltd. https://doi.org/10.1002/0470848944.hsa140

Borneo Post Online. (2022). Sarawak to come up with master plan to develop agriculture industry, enhance food security. https://www.theborneopost.com/2022/08/10/sarawak-to-come-up-with-master-plan-to-develop-agriculture-industry-enhance-food-security/

Boulton, A. J., Boyero, L., Covich, A. P., Dobson, M., Lake, S., & Pearson, R. (2008). Are tropical streams ecologically different from temperate streams? In *Tropical Stream Ecology* (pp. 257–284). Elsevier. https://doi.org/10.1016/B978-012088449-0.50011-X

Brookes, A. (1985). Downstream morphological consequences of river channelization in England and Wales. In *Source: The Geographical Journal* (Vol. 151, Issue 1). https://about.jstor.org/terms

Brouziyne, Y., Belaqziz, S., Benaabidate, L., Aboubdillah, A., Bilali, A. el, Elbeltagi, A., Tzoraki, O., & Chehbouni, A. (2022). Modeling long term response of environmental flow attributes to future climate change in a North African watershed (Bouregreg watershed, Morocco). *Ecohydrology and Hydrobiology*, *22*(1), 155–167. https://doi.org/10.1016/j.ecohyd.2021.08.005

Bryan, J. E., Shearman, P. L., Asner, G. P., Knapp, D. E., Aoro, G., & Lokes, B. (2013). Extreme Differences in Forest Degradation in Borneo: Comparing Practices in Sarawak, Sabah, and Brunei. *PLoS ONE*, *8*(7), e69679. https://doi.org/10.1371/journal.pone.0069679

Buchanan, B. P., Walter, M. T., Nagle, G. N., & Schneider, R. L. (2012). Monitoring and assessment of a river restoration project in central New York. *River Research and Applications*, *28*(2), 216–233. https://doi.org/10.1002/rra.1453

Buffin-Bélanger, T., Biron, P. M., Larocque, M., Demers, S., Olsen, T., Choné, G., Ouellet, M. A., Cloutier, C. A., Desjarlais, C., & Eyquem, J. (2015). Freedom space for rivers: An economically viable river management concept in a changing climate. *Geomorphology*, *251*, 137–148. https://doi.org/10.1016/j.geomorph.2015.05.013

Buuren, A. van, Lawrence, J., Potter, K., & Warner, J. F. (2018). Introducing Adaptive Flood Risk Management in England, New Zealand, and the Netherlands: The Impact of Administrative Traditions. *Review of Policy Research*, *35*(6), 907–929. https://doi.org/10.1111/ropr.12300

Campbell, I. C. (2016). Integrated management in the Mekong River Basin. *Ecohydrology & Hydrobiology*, *16*(4), 255–262. https://doi.org/10.1016/j.ecohyd.2016.09.003

Carone, M. T., Greco, M., & Molino, B. (2006). A sediment-filter ecosystem for reservoir rehabilitation. *Ecological Engineering*, *26*(2), 182–189. https://doi.org/10.1016/j.ecoleng.2005.09.002

Castellarin, A., Di Baldassarre, G., & Brath, A. (2011). Floodplain management strategies for flood attenuation in the river Po. *River Research and Applications*, *27*(8), 1037–1047. https://doi.org/10.1002/rra.1405

Cater, T. C., Jorgenson, M. T., Bishop, S. C., & Rea, C. L. (2007). Erosion control and restoration of a sand dune on the Colville River Delta, northern Alaska. In *Ecological Restoration* (Vol. 25, Issue 4, pp. 238–246). https://doi.org/10.3368/er.25.4.238

Cavaillé, P., Dommanget, F., Daumergue, N., Loucougaray, G., Spiegelberger, T., Tabacchi, E., & Evette, A. (2013). Biodiversity assessment following a naturality gradient of riverbank protection structures in French prealps rivers. *Ecological Engineering*, *53*, 23–30. https://doi.org/10.1016/j.ecoleng.2012.12.105

Chen, S., Zhang, J., Jia, P., Xu, J., Wang, G., & Xiao, S. (2010). Effects of size variation and spatial structure on plastic response of plant height to light competition. *Chinese Science Bulletin*, *55*(12), 1135–1141. https://doi.org/10.1007/s11434-010-0107-5

Chilagane, N. A., Kashaigili, J. J., Mutayoba, E., Lyimo, P., Munishi, P., Tam, C., & Burgess, N. (2021). Impact of Land Use and Land Cover Changes on Surface Runoff and Sediment Yield in the Little Ruaha River Catchment. *Open Journal of Modern Hydrology*, *11*(03), 54–74. https://doi.org/10.4236/ojmh.2021.113004

Chong, X. Y., Vericat, D., Batalla, R. J., Teo, F. Y., Lee, K. S. P., & Gibbins, C. N. (2021). A review of the impacts of dams on the hydromorphology of tropical rivers. In *Science of the Total Environment* (Vol. 794). Elsevier B.V. https://doi.org/10.1016/j.scitotenv.2021.148686

Chuan, G. K. (2005). The climate of Southeast Asia. *The Physical Geography of Southeast Asia.* Oxford, 2005; [online] Oxford Academic 2020, https://doi.org/10.1093/oso/9780199248025.003.0015.

Clilverd, H. M., Thompson, J. R., Heppell, C. M., Sayer, C. D., & Axmacher, J. C. (2016). Coupled Hydrological/Hydraulic Modelling of River Restoration Impacts and Floodplain Hydrodynamics. *River Research and Applications*, *32*(9), 1927–1948. https://doi.org/10.1002/rra.3036

CloudCompare v2.12. (2022). *3D point cloud and mesh processing software*. Retrieved from http://www.cloudcompare.org/.

Coe, M. T., Latrubesse, E. M., Ferreira, M. E., & Amsler, M. L. (2011). The effects of deforestation and climate variability on the streamflow of the Araguaia River, Brazil. *Biogeochemistry*, *105*(1–3), 119–131. https://doi.org/10.1007/s10533-011-9582-2

Cole, L. J., Stockan, J., & Helliwell, R. (2020). Managing riparian buffer strips to optimise ecosystem services: A review. *Agriculture, Ecosystems & Environment*, *296*, 106891. https://doi.org/10.1016/j.agee.2020.106891

Collison, A. J. C., & Anderson, M. G. (1996). Using a combined slope hydrology/stability model to identify suitable conditions for landslide prevention by vegetation in the humid tropics. *Earth Surface Processes and Landforms*, *21*(8), 737–747. https://doi.org/10.1002/(SICI)1096-9837(199608)21:8<737::AID-ESP674>3.0.CO;2-F

Consoer, M., & Milman, A. (2018). Opportunities, constraints, and choices for flood mitigation in rural areas: perspectives of municipalities in Massachusetts. *Journal of Flood Risk Management*, *11*(2), 141–151. https://doi.org/10.1111/jfr3.12302

Cooper, M. M. D., Patil, S. D., Nisbet, T. R., Thomas, H., Smith, A. R., & McDonald, M. A. (2021). Role of forested land for natural flood management in the UK: A review. In *Wiley Interdisciplinary Reviews: Water* (Vol. 8, Issue 5). John Wiley and Sons Inc. https://doi.org/10.1002/wat2.1541

Cramb, R. A. (2011). Agrarian Transitions in Sarawak: Intensification and Expansion Reconsidered. *Singapore: National University of Singapore Press. Page 44-93.* http://www.caac.umontreal.ca/en/chatsea_intro.html

Curado, G., Grewell, B. J., Figueroa, E., & Castillo, J. M. (2014). Effectiveness of the aquatic halophyte Sarcocornia perennis spp. perennis as a biotool for ecological restoration of salt marshes. *Water, Air, and Soil Pollution*, *225*(9). https://doi.org/10.1007/s11270-014-2108-5

Czech, W., Radecki-Pawlik, A., Wyżga, B., & Hajdukiewicz, H. (2016). Modelling the flooding capacity of a Polish Carpathian river: A comparison of constrained and free channel conditions. *Geomorphology*, *272*, 32–42. https://doi.org/10.1016/j.geomorph.2015.09.025

Dagar, J. C., Gangaiah, B., & Gupta, S. R. (2020). Agroforestry to Sustain Island and Coastal Agriculture in the Scenario of Climate Change: Indian Perspective. In *Agroforestry for Degraded Landscapes* (pp. 367–424). Springer Singapore. https://doi.org/10.1007/978-981-15-4136-0_13

Darus, A., Ghani, A. A., Zakaria, N. A., Abdullah, R., & Kiat, C. C. (2004). River Restoration Through Bank Stabilization Using FLUVIAL-12: Case Study of Raia River, Ipoh, Perak. *1st International Conference on Managing RIvers in the 21st Century: Issues and Challenges*.

Dataset: ASF DAAC. (2021). ALOS PALSAR Radiometric Terrain Corrected high_res. In *Includes Material © JAXA/METI 2007*. ASF DAAC.

De Santoli, L., Astiaso Garcia, D., & Violante, A. C. (2008). Planning of flood defence management and rehabilitation of the natural habitat in the downstream part of the river Tiber. *WIT Transactions on the Built Environment*, *100*, 25–34. https://doi.org/10.2495/GEO080031

de Vriend, H. J., van Koningsveld, M., Aarninkhof, S. G. J., de Vries, M. B., & Baptist, M. J. (2015). Sustainable hydraulic engineering through building with nature. *Journal of Hydro-Environment Research*, *9*(2), 159–171. https://doi.org/10.1016/j.jher.2014.06.004

Dechmi, F., & Skhiri, A. (2013). Evaluation of best management practices under intensive irrigation using SWAT model. *Agricultural Water Management*, *123*, 55–64. https://doi.org/10.1016/j.agwat.2013.03.016

Delgado, J. A., Gross, C. M., Lal, H., Cover, H., Gagliardi, P., McKinney, S. P., Hesketh, E., & Shaffer, M. J. (2010). A New GIS Nitrogen Trading Tool Concept for Conservation and Reduction of Reactive Nitrogen Losses to the Environment (pp. 117–171). https://doi.org/10.1016/S0065-2113(10)05004-2

Department of Irrigation and Drainage Malaysia. (2015). Estimation of design rainstorm in Peninsular Malaysia. *Hydrological Procedure 1 (HP1)*, 103.

Department of Irrigation and Drainage Malaysia. (2018). Design flood hydrograph estimation for rural catchments in Malaysia. *Hydrological Procedure 11 (HP11)*, 97.

Der Sarkissian, R., Al Sayah, M. J., Abdallah, C., Zaninetti, J. M., & Nedjai, R. (2022). Land Use Planning to Reduce Flood Risk: Opportunities, Challenges and Uncertainties in Developing Countries. *Sensors*, *22*(18). https://doi.org/10.3390/s22186957

Dhital, Y. P., Kayastha, R. B., & Shi, J. (2013). Soil bioengineering application and practices in Nepal. *Environmental Management*, *51*(2), 354–364. https://doi.org/10.1007/s00267-012-0003-7

DID. (2009). Government of malaysia department of irrigation and drainage. *Volume 2-River Management*.

Dixon, S. J., Sear, D. A., Odoni, N. A., Sykes, T., & Lane, S. N. (2016). The effects of river restoration on catchment scale flood risk and flood hydrology. *Earth Surface Processes and Landforms*, *41*(7), 997–1008. https://doi.org/10.1002/esp.3919

Douglas, F., Pezeshki, S. R., Wilson, G. v, Wu, W., & Dabney, S. M. (2008). Rehabilitation of an Incised Stream Using Plant Materials: the Dominance of Geomorphic Processes. *And Society*, *13*(2). https://doi.org/10.2307/26267985

Dufty, N., Dyer, A., & Golnaraghi, M. (2020). *Flood Risk Management in Australia: Building flood resilience in a changing climate*.

Dutta, D., Teng, J., Vaze, J., Lerat, J., Hughes, J., & Marvanek, S. (2013). Storage-based approaches to build floodplain inundation modelling capability in river system models for water resources planning and accounting. *Journal of Hydrology*, *504*, 12–28. https://doi.org/10.1016/j.jhydrol.2013.09.033

Eccles, R., Zhang, H., & Hamilton, D. (2019). A review of the effects of climate change on riverine flooding in subtropical and tropical regions. In *Journal of Water and Climate Change* (Vol. 10, Issue 4, pp. 687–707). IWA Publishing. https://doi.org/10.2166/wcc.2019.175

Edwards, D. P., Larsen, T. H., Docherty, T. D. S., Ansell, F. A., Hsu, W. W., Derhé, M. A., Hamer, K. C., & Wilcove, D. S. (2011). Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. *Proceedings of the Royal Society B: Biological Sciences*, *278*(1702), 82–90. https://doi.org/10.1098/rspb.2010.1062

Edwards, D. P., Socolar, J. B., Mills, S. C., Burivalova, Z., Koh, L. P., & Wilcove, D. S. (2019). Conservation of Tropical Forests in the Anthropocene. In *Current Biology* (Vol. 29, Issue 19, pp. R1008–R1020). Cell Press. https://doi.org/10.1016/j.cub.2019.08.026

Elfithri, R., Toriman, M. E. B., Mokhtar, M. B., & Juahir, H. B. (2011). Perspectives and initiatives on integrated river basin management in Malaysia: A review. *Social Sciences*, *6*(2), 169–176. https://doi.org/10.3923/sscience.2011.169.176

Elliott, J. C., Olin, L., Novak, M., Wiescher, P., Riley, C., & Reiter, M. (2016). *Habitat Restoration and Environmental Remediation Success at a National Wildlife Refuge Wetland*.

Emam, A. R., Kappas, M., Linh, N. H. K., & Renchin, T. (2017). Hydrological modeling and runoff mitigation in an ungauged basin of central Vietnam using SWAT model. *Hydrology*, *4*(1). https://doi.org/10.3390/hydrology4010016

Erős, T., Kuehne, L., Dolezsai, A., Sommerwerk, N., & Wolter, C. (2019). A systematic review of assessment and conservation management in large floodplain rivers – Actions postponed. In *Ecological Indicators* (Vol. 98, pp. 453–461). Elsevier B.V. https://doi.org/10.1016/j.ecolind.2018.11.026

Evers, M. (2016). Integrative river basin management: challenges and methodologies within the German planning system. *Environmental Earth Sciences*, *75*(14). https://doi.org/10.1007/s12665-016-5871-3

Fahad, S., Chavan, S. B., Chichaghare, A. R., Uthappa, A. R., Kumar, M., Kakade, V., Pradhan, A., Jinger, D., Rawale, G., Yadav, D. K., Kumar, V., Farooq, T. H., Ali, B., Sawant, A. V., Saud, S., Chen, S., & Poczai, P. (2022). Agroforestry Systems for Soil Health Improvement and Maintenance. In *Sustainability (Switzerland)* (Vol. 14, Issue 22). MDPI. https://doi.org/10.3390/su142214877

Fang, T., Bao, S., Sima, X., Jiang, H., Zhu, W., & Tang, W. (2016). Study on the application of integrated eco-engineering in purifying eutrophic river waters. *Ecological Engineering*, *94*, 320–328. https://doi.org/10.1016/j.ecoleng.2016.06.003

Feldman, A. D. (2000). Hydrologic Modelling System HEC-HMS: Technical Reference Manual. *U.S. Army Corps of Engineers*, 3–142.

Ferguson, C., & Fenner, R. (2020). Evaluating the effectiveness of catchment-scale approaches in mitigating urban surface water flooding. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2168). https://doi.org/10.1098/rsta.2019.0203

Fischenich, J. C. (2000). Impacts of Streambank Stabilization Structures.

Fischenich, J. C. (2001). Stability Thresholds for Stream Restoration Materials. *EMRRP Technical Notes Collection, U.S. Army Engineer Research and Development Center, Vicksburg, MS.*

Florineth, F. (1982). Greening of erosion zones in areas above the tree line. *Journal of Vegetation Engineering*, *5*, 20–24 (translated from German).

Frothingham, K. M. (2008). Evaluation of stability threshold analysis as a cursory method of screening potential streambank stabilization techniques. *Applied Geography*, *28*(2), 124–133. https://doi.org/10.1016/j.apgeog.2007.07.006

Galicia, S., Navarro-Hevia, J., Martínez-Rodríguez, A., Mongil-Manso, J., & Santibáñez, J. (2019). 'Green', rammed earth check dams: A proposal to restore gullies under low rainfall erosivity and runoff conditions. *Science of the Total Environment*, *676*, 584–594. https://doi.org/10.1016/j.scitotenv.2019.04.189

Gall, M., & Friedland, C. J. (2020). If Mitigation Saves $6 Per Every $1 Spent, Then Why Are We Not Investing More? A Louisiana Perspective on a National Issue. *Natural Hazards Review*, *21*(1). https://doi.org/10.1061/(ASCE)NH.1527-6996.0000342

Gashaw, T., Tulu, T., Argaw, M., & Worqlul, A. W. (2018). Modeling the hydrological impacts of land use/land cover changes in the Andassa watershed, Blue Nile Basin, Ethiopia. *Science of the Total Environment*, *619–620*, 1394–1408. https://doi.org/10.1016/j.scitotenv.2017.11.191

Gaveau, D. L. A., Sheil, D., Husnayaen, Salim, M. A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P., & Meijaard, E. (2016). Rapid conversions and avoided deforestation: Examining four decades of industrial plantation expansion in Borneo. *Scientific Reports*, *6*. https://doi.org/10.1038/srep32017

Gerstgraser, C. (1998). Bioengineering methods of bank stabilisation. *Garten & Landschaft*, *9*, 35–37.

Giupponi, L., Bischetti, G. B., & Giorgi, A. (2017). A proposal for assessing the success of soil bioengineering work by analysing vegetation: results of two case studies in the Italian Alps. *Landscape and Ecological Engineering*, *13*(2), 305–318. https://doi.org/10.1007/s11355-016-0323-5

Global Forest Watch. (2022). Net Change In Tree Cover. *Global Forest Watch*. https://www.globalforestwatch.org/dashboards/country/MYS/14

Golden, H. E., & Hoghooghi, N. (2018). Green infrastructure and its catchment-scale effects: an emerging science. *WIREs Water*, *5*(1). https://doi.org/10.1002/wat2.1254

Gray, D. H., & Sotir, R. B. (1996). Biotechnical and soil bioengineering: A practical guide for erosion control. *John Wiley and Sons, New York*.

Guzha, A. C., Rufino, M. C., Okoth, S., Jacobs, S., & Nóbrega, R. L. B. (2018). Impacts of land use and land cover change on surface runoff, discharge and low flows: Evidence from East Africa. In *Journal of Hydrology: Regional Studies* (Vol. 15, pp. 49–67). Elsevier B.V. https://doi.org/10.1016/j.ejrh.2017.11.005

Gyawali, B., Shrestha, S., Bhatta, A., Pokhrel, B., Cristan, R., Antonious, G., Banerjee, S., & Paudel, K. P. (2022). Assessing the Effect of Land-Use and Land-Cover Changes on Discharge and Sediment

Yield in a Rural Coal-Mine Dominated Watershed in Kentucky, USA. *Water (Switzerland)*, *14*(4). https://doi.org/10.3390/w14040516

Habersack, H., Schober, B., & Hauer, C. (2015). Floodplain evaluation matrix (FEM): An interdisciplinary method for evaluating river floodplains in the context of integrated flood risk management. *Natural Hazards*, *75*(S1), 5–32. https://doi.org/10.1007/s11069-013-0842-4

Halajova, D., Halaj, P., Macura, V., & Skrinar, A. (2019). Urban River Design: A River Restoration Case Study. *IOP Conference Series: Materials Science and Engineering*, *471*(9). https://doi.org/10.1088/1757-899X/471/9/092090

Hammersmark, C. T., Rains, M. C., & Mount, J. E. (2008). Quantifying the hydrological effects of stream restoration in a Montane meadow, northern California, USA. *River Research and Applications*, *24*(6), 735–753. https://doi.org/10.1002/rra.1077

Hansen, M. C., Potapov, P. v., Moore, R., Hancher, M., Turubanova, S. A., Tyukavina, A., Thau, D., Stehman, S. v., Goetz, S. J., Loveland, T. R., Kommareddy, A., Egorov, A., Chini, L., Justice, C. O., & Townshend, J. R. G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science*, *342*(6160), 850–853. https://doi.org/10.1126/science.1244693

Hanspeter, L., & Godert, van L. (2008). A Framework for Documentation and Evaluation of Sustainable Land Management - Technologies. Centre for Development and Environment (CDE). *Bern, Switzerland; Food and Agriculture Organization of the United Nations (FAO), Rome, Italy; International Soil Reference and Information Centre (ISRIC), Wageningen, Netherlands*.

Hazell, D., Lensch, B., & King, M. (2007). *Channel Stabilisation, Habitat Restoration, and Realignment Feasibility Study for Class 1 Trout Stream in Wisconsin*.

Hemmati, M., Mahmoud, H. N., Ellingwood, B. R., & Crooks, A. T. (2021). Unraveling the complexity of human behavior and urbanization on community vulnerability to floods. *Scientific Reports*, *11*(1), 20085. https://doi.org/10.1038/s41598-021-99587-0

Henderson, J. E., & Shields Jr., F. D. (1984). *Environmental Features for Streambank Protection Projects*.

Hon, J., & Shibata, S. (2013). A Review on Land Use in the Malaysian State of Sarawak, Borneo and Recommendations for Wildlife Conservation Inside Production Forest Environment. In *Borneo Journal of Resource Science and Technology* (Vol. 3, Issue 2).

Hook, P. B., Salsbury, K. M., & Klausmann, J. M. (2009). Revegetation of reed canarygrass infested riparian areas: Performance of pre-vegetated coir after 3 to 6 years. *26th Annual Meetings of the*

American Society of Mining and Reclamation and 11th Billings Land Reclamation Symposium 2009, *2*, 591–623. https://doi.org/10.21000/jasmr09010597

Horton, M., Keys, A., Kirkwood, L., Mitchell, F., Kyle, R., & Roberts, D. (2015). Sustainable catchment restoration for reintroduction of captive bred freshwater pearl mussels Margaritifera margaritifera. *Limnologica*, *50*, 21–28. https://doi.org/10.1016/j.limno.2014.11.003

Hu, S., Fan, Y., & Zhang, T. (2020). Assessing the effect of land use change on surface runoff in a rapidly Urbanized City: A case study of the central area of Beijing. *Land*, *9*(1). https://doi.org/10.3390/land9010017

Iacob, O., Brown, I., & Rowan, J. (2017). Natural flood management, land use and climate change trade-offs: the case of Tarland catchment, Scotland. *Hydrological Sciences Journal*, *62*(12), 1931–1948. https://doi.org/10.1080/02626667.2017.1366657

Janssen, P., Cavaillé, P., Bray, F., & Evette, A. (2019). Soil bioengineering techniques enhance riparian habitat quality and multi-taxonomic diversity in the foothills of the Alps and Jura Mountains. *Ecological Engineering*, *133*, 1–9. https://doi.org/10.1016/j.ecoleng.2019.04.017

Jones, C. M. (2008). Dry Creek-The Removal of a Barrier to Fish Passage and Restoration of a Stream in Napa County, California Written for presentation at the 2008 ASABE Annual International Meeting Sponsored by ASABE Rhode Island Convention Center Providence, Rhode Island. *2008 ASABE Annual International Meeting*.

Jonoski, A., Popescu, I., Zhe, S., Mu, Y., & He, Y. (2019). Analysis of flood storage area operations in Huai River using 1D and 2D river simulation models coupled with global optimization algorithms. *Geosciences (Switzerland)*, *9*(12). https://doi.org/10.3390/geosciences9120509

Jude Toyat. (2019). Bio-engineering key to restoring eroded riverbanks in highlands. *Borneo Post Online*. https://www.theborneopost.com/2019/12/22/bio-engineering-key-to-restoring-eroded-riverbanks-in-highlands

Junger, L., Hohensinner, S., Schroll, K., Wagner, K., & Seher, W. (2022). Land Use in Flood-Prone Areas and Its Significance for Flood Risk Management—A Case Study of Alpine Regions in Austria. *Land*, *11*(3). https://doi.org/10.3390/land11030392

Kail, J., Hering, D., Muhar, S., Gerhard, M., & Preis, S. (2007). The use of large wood in stream restoration: Experiences from 50 projects in Germany and Austria. *Journal of Applied Ecology*, *44*(6), 1145–1155. https://doi.org/10.1111/j.1365-2664.2007.01401.x

Karim, F., Marvanek, S., Merrin, L. E., Nielsen, D., Hughes, J., Stratford, D., & Pollino, C. (2020). Modelling flood-induced wetland connectivity and impacts of climate change and dam. *Water (Switzerland)*, *12*(5). https://doi.org/10.3390/W12051278

Kashaigili, J. J. (2008). Impacts of land-use and land-cover changes on flow regimes of the Usangu wetland and the Great Ruaha River, Tanzania. *Physics and Chemistry of the Earth*, *33*(8–13), 640–647. https://doi.org/10.1016/j.pce.2008.06.014

Kemarau, R. A., & Eboy, O. V. (2018). Land Cover Change Detection in Kuching, Malaysia Using Satellite Imagery. *Borneo Journal of Sciences & Technology*, *3*, 61–65. https://doi.org/10.3570/bjost.2021.3.1-09

Khalid, K., Ali, M. F., Rahman, N. F. A., Mispan, M. R., Haron, S. H., Othman, Z., & Bachok, M. F. (2016). Sensitivity Analysis in Watershed Model Using SUFI-2 Algorithm. *Procedia Engineering*, *162*, 441–447. https://doi.org/10.1016/j.proeng.2016.11.086

Khushiri, F. (2022). *Master plan to develop Sarawak's agriculture sector*. New Sarawak Tribune. https://www.newsarawaktribune.com.my/master-plan-to-develop-sarawaks-agriculture-sector/

Kiehl, K., Kirmer, A., Donath, T. W., Rasran, L., & Hölzel, N. (2010). Species introduction in restoration projects – Evaluation of different techniques for the establishment of semi-natural grasslands in Central and Northwestern Europe. *Basic and Applied Ecology*, *11*(4), 285–299. https://doi.org/10.1016/j.baae.2009.12.004

Kim, M., Xie, Y., & Cirella, G. T. (2019). Sustainable transformative economy: Community-based ecotourism. *Sustainability (Switzerland)*, *11*(18). https://doi.org/10.3390/su11184977

Kironoto, B. A. and Yulistiyanto, B. (2000). Land conservation. *Journal of Postgraduate Programme Civil Engineering Department UGM.* Yogyakarta.

Koenker, R. (2005). *Quantile Regression*. Cambridge University Press. https://doi.org/10.1017/CBO9780511754098

Koepke, J. (2020). Urban stream restoration and applied practices in northeast illinois. www.isws.illinois.edu

Kondolf, G. M. (2006). River restoration and meanders. *Ecology and Society*, *11*(2). https://doi.org/10.5751/ES-01795-110242

Korpak, J., Lenar-Matyas, A., Radecki-Pawlik, A., & Plesiński, K. (2021). Erosion irregularities resulting from series of grade control structures: The Mszanka River, Western Carpathians. *Science of the Total Environment*, *799*. https://doi.org/10.1016/j.scitotenv.2021.149469

Kreienkamp, F., Philip, S. Y., Tradowsky, J. S., Kew, S. F., Lorenz, P., Arrighi, J., Belleflamme, A., Bettmann, T., Caluwaerts, S., Chan, S. C., Ciavarella, A., de Cruz, L., de Vries, H., Demuth, N., Ferrone, A., Fischer, E. M., Fowler, H. J., Goergen, K., Heinrich, D., Otto, F. E. L. (2021). Rapid attribution of heavy rainfall events leading to the severe flooding in Western Europe during Jul 2021. In *Royal Netherlands Meteorological Institute (KNMI)* (Vol. 13). Deutscher Wetterdienst. https://www.meteo.be/fr/infos/actualite/ce-que-lon-sait-sur-les-pluies-

Krymer, V., & Robert, A. (2014). Stream restoration and cribwall performance: A case study of cribwall monitoring in Southern Ontario. *River Research and Applications*, *30*(7), 865–873. https://doi.org/10.1002/rra.2684

Kumar, M., Denis, D. M., Kundu, A., Joshi, N., & Suryavanshi, S. (2022). Understanding land use/land cover and climate change impacts on hydrological components of Usri watershed, India. *Applied Water Science*, *12*(3). https://doi.org/10.1007/s13201-021-01547-6

Kumar, P., Liu, W., Chu, X., Zhang, Y., & Li, Z. (2019). Integrated water resources management for an inland river basin in China. *Watershed Ecology and the Environment*, *1*, 33–38. https://doi.org/10.1016/j.wsee.2019.10.002

Kundzewicz, Z. W., Kanae, S., Seneviratne, S. I., Handmer, J., Nicholls, N., Peduzzi, P., Mechler, R., Bouwer, L. M., Arnell, N., Mach, K., Muir-Wood, R., Brakenridge, G. R., Kron, W., Benito, G., Honda, Y., Takahashi, K., & Sherstyukov, B. (2014). Le risque d'inondation et les perspectives de changement climatique mondial et régional. *Hydrological Sciences Journal*, *59*(1), 1–28. https://doi.org/10.1080/02626667.2013.857411

Lambin, E. F., Geist, H. J., & Lepers, E. (2003). Dynamics of land-use and land-cover change in tropical regions. *Annual Review of Environment and Resources*, *28*, 205–241. https://doi.org/10.1146/annurev.energy.28.050302.105459

Larsen, E. W., Girvetz, E. H., & Fremier, A. K. (2007). Landscape level planning in alluvial riparian floodplain ecosystems: Using geomorphic modeling to avoid conflicts between human infrastructure and habitat conservation. *Landscape and Urban Planning*, *79*(3–4), 338–346. https://doi.org/10.1016/j.landurbplan.2006.04.003

Lashford, C., Lavers, T., Reaney, S., Charlesworth, S., Burgess-Gamble, L., & Dale, J. (2022). Sustainable Catchment-Wide Flood Management: A Review of the Terminology and Application of

Sustainable Catchment Flood Management Techniques in the UK. *Water*, *14*(8), 1204. https://doi.org/10.3390/w14081204

Lavers, T., Charlesworth, S. M., Lashford, C., Warwick, F., & Fried, J. (2022). The Performance of Natural Flood Management at the Large Catchment-Scale: A Case Study in the Warwickshire Stour Valley. *Water (Switzerland)*, *14*(23). https://doi.org/10.3390/w14233836

Lee, T., Jalong, T., & Meng-Chuo, W. (2014). *Indigenous Peoples' Rights Violations At The Proposed Baram Dam In Sarawak A Fact-Finding Mission Report*.

Legesse, D., Vallet-Coulomb, C., & Gasse, F. (2003). Hydrological response of a catchment to climate and land use changes in Tropical Africa: Case study south central Ethiopia. *Journal of Hydrology*, *275*(1–2), 67–85. https://doi.org/10.1016/S0022-1694(03)00019-2

Li, M. H., & Eddleman, K. E. (2002). Biotechnical engineering as an alternative to traditional engineering methods A biotechnical streambank stabilization design approach. In *Landscape and Urban Planning* (Vol. 60).

Li, X., Zhang, L., & Zhang, Z. (2006). Soil bioengineering and the ecological restoration of riverbanks at the Airport Town, Shanghai, China. *Ecological Engineering*, *26*(3), 304–314. https://doi.org/10.1016/j.ecoleng.2005.10.011

Liao, K.-H. (2019). The socio-ecological practice of building blue-green infrastructure in high-density cities: what does the ABC Waters Program in Singapore tell us? *Socio-Ecological Practice Research*, *1*(1), 67–81. https://doi.org/10.1007/s42532-019-00009-3

Lim, C. H., Wong, H. L., Elfithri, R., & Teo, F. Y. (2022). A Review of Stakeholder Engagement in Integrated River Basin Management. In *Water (Switzerland)* (Vol. 14, Issue 19). MDPI. https://doi.org/10.3390/w14192973

Lim, H. S., & Lu, X. X. (2016). Sustainable urban stormwater management in the tropics: An evaluation of Singapore's ABC Waters Program. In *Journal of Hydrology* (Vol. 538, pp. 842–862). Elsevier B.V. https://doi.org/10.1016/j.jhydrol.2016.04.063

Limerinos, J. T. (1970). Determination of Manning's Coefficient for Measured Bed Roughness in Natural Channels.

Lin, B., Chen, X., Yao, H., Chen, Y., Liu, M., Gao, L., & James, A. (2015). Analyses of landuse change impacts on catchment runoff using different time indicators based on SWAT model. *Ecological Indicators*, *58*, 55–63. https://doi.org/10.1016/j.ecolind.2015.05.031

Liping, C., Yujun, S., & Saeed, S. (2018). Monitoring and predicting land use and land cover changes using remote sensing and GIS techniques—A case study of a hilly area, Jiangle, China. *PLoS ONE*, *13*(7). https://doi.org/10.1371/journal.pone.0200493

Liu, J., Li, Z., Shao, W., Yan, Di., & Mei, C. (2020). Urban flood modelling in Qiqihar city based on MIKE flood. *Proceedings of the International Association of Hydrological Sciences*, *383*, 185–192. https://doi.org/10.5194/piahs-383-185-2020

Liu, W. Z. (1999). Study on rainfall erosion and soil erodibility in the Zhaotong Basin in Yunnan Province. *Yunna Geographic Environment Research 11 (2), 76-82 (in Chinese, translated to English).*

Luke, S. H., Barclay, H., Bidin, K., Chey, V. K., Ewers, R. M., Foster, W. A., Nainar, A., Pfeifer, M., Reynolds, G., Turner, E. C., Walsh, R. P. D., & Aldridge, D. C. (2017). The effects of catchment and riparian forest quality on stream environmental conditions across a tropical rainforest and oil palm landscape in Malaysian Borneo. *Ecohydrology*, *10*(4). https://doi.org/10.1002/eco.1827

Lulloff, A. R. (2013). *The Floodway Encroachment Standard: Minimizing Cumulative Adverse Impacts.*

Lyn, D., & Newton, J. (2015). *Approaches to the Design of Biotechnical Streambank Stabilization: Volume I—A Guide to the Literature*. https://doi.org/10.5703/1288284315998

Lyndon, N. (2018). Strengthening Rural Economy through Regional Development Planning Approach in Sarawak. *International Journal of Academic Research in Business and Social Sciences*, *8*(13), 122–129. https://doi.org/10.6007/IJARBSS/v8-i13/4816

Malmer, A., Murdiyarso, D., Sampurno Bruijnzeel, L. A., & Ilstedt, U. (2010). Carbon sequestration in tropical forests and water: A critical look at the basis for commonly used generalizations. *Global Change Biology*, *16*(2), 599–604. https://doi.org/10.1111/j.1365-2486.2009.01984.x

Markstrom, S. L., Regan, R. S., Hay, L. E., Viger, R. J., Webb, R. M. T., Payn, R. A., & Lafontaine, J. H. (2015). PRMS-IV, the Precipitation-Runoff Modeling System, Version 4. *USGD Techniques and Methods, Book6, Chap. B7*. https://doi.org/10.3133/tm6B7

Marteau, B., Gibbins, C. N., Batalla, R., Vericat, D. (2018). Hydrological and geomorphological analysis of the Uppre Trusan River to assess remediation for riverbank integrity. *WWF-Malaysia Project Report.*

Marteau, B., Vericat, D., Gibbins, C., Batalla, R. J., & Green, D. R. (2017). Application of Structure-from-Motion photogrammetry to river restoration. *Earth Surface Processes and Landforms*, *42*(3), 503–515. https://doi.org/10.1002/esp.4086

Martin, P. A., Newton, A. C., Pfeifer, M., Khoo, M. S., & Bullock, J. M. (2015). Impacts of tropical selective logging on carbon storage and tree species richness: A meta-analysis. *Forest Ecology and Management*, *356*, 224–233. https://doi.org/10.1016/j.foreco.2015.07.010

Maxwell, C. M., Fernald, A. G., Cadol, D., Faist, A. M., & King, J. P. (2021). Managing flood flow connectivity to landscapes to build buffering capacity to disturbances: An ecohydrologic modeling framework for drylands. *Journal of Environmental Management*, *278*. https://doi.org/10.1016/j.jenvman.2020.111486

Mazzoleni, M., Mård, J., Rusca, M., Odongo, V., Lindersson, S., & Di Baldassarre, G. (2021). Floodplains in the Anthropocene: A Global Analysis of the Interplay Between Human Population, Built Environment, and Flood Severity. *Water Resources Research*, *57*(2). https://doi.org/10.1029/2020WR027744

Meals, D. W. (2001). Water quality response to riparian restoration in an agricultural watershed in Vermont, USA.

Miguez, M. G., Veról, A. P., de Sousa, M. M., & Rezende, O. M. (2015). Urban floods in lowlands-levee systems, unplanned urban growth and river restoration alternative: A case study in Brazil. *Sustainability (Switzerland)*, *7*(8), 11068–11097. https://doi.org/10.3390/su70811068

Mihu-Pintilie, A., Cîmpianu, C. I., Stoleriu, C. C., Pérez, M. N., & Paveluc, L. E. (2019). Using high-density LiDAR data and 2D streamflow hydraulic modeling to improve urban flood hazard maps: A HEC-RAS multi-scenario approach. *Water (Switzerland)*, *11*(9). https://doi.org/10.3390/w11091832

Mohamed, I., Othman, F., Ibrahim, A. I. N., Alaa-Eldin, M. E., & Yunus, R. M. (2015). Assessment of water quality parameters using multivariate analysis for Klang River basin, Malaysia. *Environmental Monitoring and Assessment*, *187*(1), 4182. https://doi.org/10.1007/s10661-014-4182-y

Mohammed, T. A., Ghazali, A. H., Noor, M. J. M., & Yusuf, B. (2009). Environmental consideration in flood mitigation and river restoration. *Alam Cipta*, 67–74.

Mokhtar, M. Bin, Toriman, M. E. H., Hossain, M. A. A., & Tan, K. W. (2011). Institutional challenges for integrated river basin management in Langat River Basin, Malaysia. *Water and Environment Journal*, *25*(4), 495–503. https://doi.org/10.1111/j.1747-6593.2010.00245.x

Moses, T., & Gorman, D. (1998). Brookside Channel and Floodplain Improvements. *Engineering Approaches to Ecosystem Restoration*, 728–733. https://doi.org/10.1061/40382(1998)124

Muhammad, M. M., Alias, M. N., Yusof, K. W., Mustafa, M. R. U., & Ghani, A. A. (2016). Suitability of bioengineering channels in erosion control: Application to urban stormwater drainage systems. *Advances and Applications in Fluid Mechanics*, *19*(4), 765–785. https://doi.org/10.17654/FM019040765

Muhammad, M. M., Raza, M., Mustafa, U., & Ghani, A. A. (2015). Vegetated Open Channel Flow For Urban Stormwater Management: A Review. https://www.researchgate.net/publication/283976569

Muhammad, M. M., Yusof, K. W., Mustafa, M. R. U., & Ghani, A. A. (2016). Velocity Distributions in Grassed Channel. *4th Annual International Conference on Architecture and Civil Engineering (ACE 2016)*. https://doi.org/10.5176/2301-394X_ACE16.39

Muhammad, M. M., Yusof, K. W., Mustafa, M. R. U., Zakaria, N. A., & Ghani, A. A. (2018). Artificial Neural Network Applications for Predicting Drag Coefficient in Flexible Vegetated Channels. *Article in Journal of Electrical and Computer Engineering*. https://www.researchgate.net/publication/324820433

Nakamura, K., Tockner, K., & Amano, K. (2006). River and Wetland Restoration_Lessons from Japan. *Bioscience*, *56*(5), 419–429.

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology*, *10*(3), 282–290. https://doi.org/10.1016/0022-1694(70)90255-6

Newton, J., & Lyn, D. (2015). Approaches to the design of biotechnical streambank stabilization: Volume II—A field assessment. https://doi.org/10.5703/1288284315999

Ngan, L. T., Bregt, A. K., van Halsema, G. E., Hellegers, P. J. G. J., & Nguyen, L. D. (2018). Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta. *Land Use Policy*, *73*, 269–280. https://doi.org/10.1016/j.landusepol.2018.01.030

NIBS, N. I. of B. S. (2019). Mitigation saves: Federal grants provide a $6 benefit for each $1 invested. www.nibs.org/mitigationsaves.

Nichols, R., & Leiser, A. T. (1998). Biotechnical bank stabilization on the Petaluma river, California.

Norazhar, A., Yatim, M., Keniin, D., Anis, F., Adnan, F., & Payus, C. M. (2013). An analysis of land use/land cover changes using remote sensing data and its impacts towards sediment loading in padas river sub-catchment.

O'Callaghan, P., Kelly-Quinn, M., Jennings, E., Antunes, P., O'Sullivan, M., Fenton, O., & hUallacháin, D. Ó. (2019). The environmental impact of cattle access to watercourses: A review. *Journal of Environmental Quality*, *48*(2), 340–351. https://doi.org/10.2134/jeq2018.04.0167

Omar, S. R., & Sohaili, J. (2015). River reserves: Understanding its significance as a prevention measure of river pollution measure of river pollution. https://www.researchgate.net/publication/312492515

Opperman, J. J., Galloway, G. E., & Duvail, S. (2013). The multiple benefits of river-floodplain connectivity for people and biodiversity. In *Encyclopedia of Biodiversity: Second Edition* (pp. 144–160). Elsevier Inc. https://doi.org/10.1016/B978-0-12-384719-5.00325-7

Orr, H. G., Wilby, R. L., Hedger, M. M. K., & Brown, I. (2008). Climate change in the uplands: A UK perspective on safeguarding regulatory ecosystem services. In *Climate Research* (Vol. 37, Issue 1, pp. 77–98). https://doi.org/10.3354/cr00754

Osawa, T. (2022). Evaluating the effectiveness of basin management using agricultural land for ecosystem-based disaster risk reduction. *International Journal of Disaster Risk Reduction*, 103445. https://doi.org/10.1016/j.ijdrr.2022.103445

Ourloglou, O., Stefanidis, K., & Dimitriou, E. (2020). Assessing nature-based and classical engineering solutions for flood-risk reduction in urban streams. *Journal of Ecological Engineering*, *21*(2), 46–56. https://doi.org/10.12911/22998993/116349

Owuor, S. O., Butterbach-Bahl, K., Guzha, A. C., Rufino, M. C., Pelster, D. E., Díaz-Pinés, E., & Breuer, L. (2016). Groundwater recharge rates and surface runoff response to land use and land cover changes in semi-arid environments. In *Ecological Processes* (Vol. 5, Issue 1). Springer Verlag. https://doi.org/10.1186/s13717-016-0060-6

Parrott, A., Brooks, W., Harmar, O., & Pygott, K. (2009). Role of rural land use management in flood and coastal risk management. *Journal of Flood Risk Management*, *2*(4), 272–284. https://doi.org/10.1111/j.1753-318X.2009.01044.x

Patel, D. P., Ramirez, J. A., Srivastava, P. K., Bray, M., & Han, D. (2017). Assessment of flood inundation mapping of Surat city by coupled 1D/2D hydrodynamic modeling: a case application of the new HEC-RAS 5. *Natural Hazards*, *89*(1), 93–130. https://doi.org/10.1007/s11069-017-2956-6

Petrone, A., & Preti, F. (2010). Soil bioengineering for risk mitigation and environmental restoration in a humid tropical area. *Hydrology and Earth System Sciences*, *14*(2), 239–250. https://doi.org/10.5194/hess-14-239-2010

Piégay, H., Cuaz, M., Javelle, E., & Mandier, P. (1997). Bank erosion management based on geomorphological, ecological and economic criteria on the Galaure River, France. *Regulated Rivers: Research & Management*, *13*(5), 433–448. https://doi.org/10.1002/(SICI)1099-1646(199709/10)13:5<433::AID-RRR467>3.0.CO;2-L

Piégay, H., Darby, S. E., Mosselman, E., & Surian, N. (2005). A review of techniques available for delimiting the erodible river corridor: A sustainable approach to managing bank erosion. In *River Research and Applications* (Vol. 21, Issue 7, pp. 773–789). https://doi.org/10.1002/rra.881

Pinto, A. A. S., Fernandes, L. F. S., & de Oliveira Maia, R. J. F. (2019). A method for selecting suitable technical solutions to support sustainable riverbank stabilisation. *Area*, *51*(2), 285–298. https://doi.org/10.1111/area.12488

Pinto, A., Fernandes, L. F. S., & Maia, R. (2016). Monitoring methodology of interventions for riverbanks stabilization: assessment of technical solutions performance. *Water Resources Management*, *30*(14), 5281–5298. https://doi.org/10.1007/s11269-016-1486-4

Pinto, I., Zachariah, M., Wolski, P., Landman, S., Phakula, V., Maluleke, W., Bopape, M.-J., Engelbrecht, C., Jack, C., Mcclure, A., Bonnet, R., Vautard, R., Philip, S., Kew, S., Heinrich, D., Vahlberg, M., Singh, R., Arrighi, J., Thalheimer, L., … Dipura, R. (2022). Climate change exacerbated rainfall causing devastating flooding in Eastern South Africa.

Plesiński, K., Radecki-Pawlik, A., & Galia, T. (2021). Block ramp hydraulic structures in mountain streams and rivers: Design considerations, flow hydraulics and eco-geomorphic processes view project. https://www.researchgate.net/publication/351590942

Poff, N. L., Brown, C. M., Grantham, T. E., Matthews, J. H., Palmer, M. A., Spence, C. M., Wilby, R. L., Haasnoot, M., Mendoza, G. F., Dominique, K. C., & Baeza, A. (2016). Sustainable water management under future uncertainty with eco-engineering decision scaling. In *Nature Climate Change* (Vol. 6, Issue 1, pp. 25–34). Nature Publishing Group. https://doi.org/10.1038/nclimate2765

Power, A. G. (2010). Ecosystem services and agriculture: Tradeoffs and synergies. In *Philosophical Transactions of the Royal Society B: Biological Sciences* (Vol. 365, Issue 1554, pp. 2959–2971). Royal Society. https://doi.org/10.1098/rstb.2010.0143

Powers, P. D., Helstab, M., & Niezgoda, S. L. (2019). A process-based approach to restoring depositional river valleys to Stage 0, an anastomosing channel network. *River Research and Applications*, *35*(1), 3–13. https://doi.org/10.1002/rra.3378

Provan, M., & Murphy, E. (2021). Nature-based solutions for coastal and riverine flood and erosion risk management. https://www.researchgate.net/publication/355649746

PUB. (2018). *Singapore water guideliness*.

Pumo, D., Viola, F., & Noto, L. (2016). Generation of Natural Runoff Monthly Series at Ungauged Sites Using a Regional Regressive Model. *Water*, *8*(5), 209. https://doi.org/10.3390/w8050209

Putz, F. E., Sist, P., Fredericksen, T., & Dykstra, D. (2008). Reduced-impact logging: Challenges and opportunities. *Forest Ecology and Management*, *256*(7), 1427–1433. https://doi.org/10.1016/j.foreco.2008.03.036

Quinn, J. M. (2000). Effects of pastoral development In New Zealand stream invertebrates: ecology and implications for management. *(K. J. Collier & Winterbourn M. J., Eds.). NZ: Caxton.*

Rafiei Emam, A., Kappas, M., Fassnacht, S., & Linh, N. H. K. (2018). Uncertainty analysis of hydrological modeling in a tropical area using different algorithms. *Frontiers of Earth Science*, *12*(4), 661–671. https://doi.org/10.1007/s11707-018-0695-y

Rak, G., Kozelj, D., & Steinman, F. (2016). The impact of floodplain land use on flood wave propagation. *Natural Hazards*, *83*(1), 425–443. https://doi.org/10.1007/s11069-016-2322-0

Ramey, T. L., & Richardson, J. S. (2017). Terrestrial Invertebrates in the Riparian Zone: Mechanisms Underlying Their Unique Diversity. *BioScience*, *67*(9), 808–819. https://doi.org/10.1093/biosci/bix078

Raymond, P., & Smestad, T. (2008). TECK COMINCO RIVERBANK RESTORATION PROJECT: CASE STUDY, TRAIL, BRITISH COLUMBIA.

Ree, W. O., & Crow, F. R. (1977). Friction factors for vegetated waterways of small slope: . *Agricultural Research Service, U.S. Department of Agriculture*, *ARS-S-151*, 56.

Rey, F., & Burylo, M. (2014). Can bioengineering structures made of willow cuttings trap sediment in eroded marly gullies in a Mediterranean mountainous climate? *Geomorphology*, *204*, 564–572. https://doi.org/10.1016/j.geomorph.2013.09.003

Ritchie, H., & Roser, M. (2021). Forests and Deforestation. *Our World in Data*. https://ourworldindata.org/forests-and-deforestation

Roessner, U., Nahid, A., Chapman, B., Hunter, A., & Bellgard, M. (2011). Metabolomics – The Combination of Analytical Biochemistry, Biology, and Informatics. In *Comprehensive Biotechnology* (pp. 435–447). Elsevier. https://doi.org/10.1016/B978-0-444-64046-8.00027-6

Rogers, J., & Doeing, B. (2009). A stream restoration case study in the California Central Coast - PDF Free Download. *International Erosion Control Association*.

Roslan, Z. A., Naimah, Y., & Roseli, Z. A. (2013). River bank erosion risk potential with regards to soil erodibility. *WIT Transactions on Ecology and the Environment*, *172*, 289–297. https://doi.org/10.2495/RBM130241

Rouillard, J. J., & Spray, C. J. (2017). Working across scales in integrated catchment management: lessons learned for adaptive water governance from regional experiences. *Regional Environmental Change*, *17*(7), 1869–1880. https://doi.org/10.1007/s10113-016-0988-1

Rufino, P. R., Gücker, B., Faramarzi, M., Boëchat, I. G., Cardozo, F. da S., Santos, P. R., Zanin, G. D., Mataveli, G., & Pereira, G. (2022). Evaluation of the SWAT model for the simulation of flow and water balance based on orbital data in a poorly monitored basin in the Brazilian Amazon. *Geographies*, *3*(1), 1–18. https://doi.org/10.3390/geographies3010001

Russo, R. C., Rashleigh, & Ambrose R. B. (2008). Watershed management in the United States. In *Sustainable Use and Development of Watersheds* (pp. 173–198). Springer.

Sa'adi, Z., Shahid, S., Ismail, T., Chung, E.-S., & Wang, X.-J. (2017). Distributional changes in rainfall and river flow in Sarawak, Malaysia. *Asia-Pacific Journal of Atmospheric Sciences*, *53*(4), 489–500. https://doi.org/10.1007/s13143-017-0051-2

Saadatkhah, N., Tehrani, M. H., Mansor, S., Khuzaimah, Z., Kassim, A., & Saadatkhah, R. (2016). Impact assessment of land cover changes on the runoff changes on the extreme flood events in the Kelantan River basin. *Arabian Journal of Geosciences*, *9*(17). https://doi.org/10.1007/s12517-016-2716-z

Saha, S., Moorthi, S., Pan, H. L., Wu, X., Wang, J., Nadiga, S., Tripp, P., Kistler, R., Woollen, J., Behringer, D., Liu, H., Stokes, D., Grumbine, R., Gayno, G., Wang, J., Hou, Y. T., Chuang, H. Y., Juang, H. M. H., Sela, J., … Goldberg, M. (2010). The NCEP climate forecast system reanalysis. *Bulletin of the American Meteorological Society*, *91*(8), 1015–1057. https://doi.org/10.1175/2010BAMS3001.1

Sajikumar, N., & Remya, R. S. (2015). Impact of land cover and land use change on runoff characteristics. *Journal of Environmental Management*, *161*, 460–468. https://doi.org/10.1016/j.jenvman.2014.12.041

Samimi, M., Mirchi, A., Moriasi, D., Ahn, S., Alian, S., Taghvaeian, S., & Sheng, Z. (2020). Modeling arid/semi-arid irrigated agricultural watersheds with SWAT: Applications, challenges, and solution strategies. In *Journal of Hydrology* (Vol. 590). Elsevier B.V. https://doi.org/10.1016/j.jhydrol.2020.125418

Sao, D., Kato, T., Tu, L. H., Thouk, P., Fitriyah, A., & Oeurng, C. (2020). Evaluation of different objective functions used in the sufi-2 calibration process of Swat-Cup on water balance analysis: A Case Study Of The Pursat River Basin, Cambodia. *Water (Switzerland)*, *12*(10), 1–22. https://doi.org/10.3390/w12102901

Satoshi Tsuyuki, M. H. G. S. T. K. U. K. M.-H. P. (2011). Monitoring Deforestation In Sarawak Malaysia Using Multitemporal Landsat Data. *Asia-Pacific Network for Global Change Research*.

Sauquet, E., & Catalogne, C. (2011). Comparison of catchment grouping methods for flow duration curve estimation at ungauged sites in France. *Hydrology and Earth System Sciences*, *15*(8), 2421–2435. https://doi.org/10.5194/hess-15-2421-2011

Schagrin, A., Makowski, P., & Scaffidi, R. (1998). Urban stream restoration on tributaries of Accotink Creek. *Engineering Approaches to Ecosystem Restoration*, 24–29. https://doi.org/10.1061/40382(1998)3

Scharffenberg, W., Ely, P., Daly, S., Fleming, M., & Pak, J. (2010). Hydrologic Modeling System (Hec-Hms): Physically-Based Simulation Components. *2nd Joint Federal Interagency Conference*.

Schiechtl, H. M., & Stern, R. (1996). Water bioengineering techniques for watercourse bank and shoreline protection. *Blackwell Science*, 224.

Schmitt, K., Schäffer, M., Koop, J., & Symmank, L. (2018). River bank stabilisation by bioengineering: potentials for ecological diversity. *Journal of Applied Water Engineering and Research*, *6*(4), 262–273. https://doi.org/10.1080/23249676.2018.1466735

Schober, B., Hauer, C., & Habersack, H. (2020). Floodplain losses and increasing flood risk in the context of recent historic land use changes and settlement developments: Austrian case studies. *Journal of Flood Risk Management*, *13*(3). https://doi.org/10.1111/jfr3.12610

Schoklitsch, A. (1937). Hydraulic structures: A text and handbook (translated by Samuel Shulits). *The American Society of Mechanical Engineers, New York*.

Selvakumar, A., O'Connor, T. P., & Struck, S. D. (2010). Role of stream restoration on improving benthic macroinvertebrates and in-stream water quality in an urban watershed: Case study. *Journal of Environmental Engineering*, *136*(1), 127–139. https://doi.org/10.1061/(asce)ee.1943-7870.0000116

Serra-Llobet, A., Jähnig, S. C., Geist, J., Kondolf, G. M., Damm, C., Scholz, M., Lund, J., Opperman, J. J., Yarnell, S. M., Pawley, A., Shader, E., Cain, J., Zingraff-Hamed, A., Grantham, T. E., Eisenstein, W., & Schmitt, R. (2022). Restoring rivers and floodplains for habitat and flood risk reduction: Experiences in multi-benefit floodplain management from California and Germany. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.778568

Sertel, E., Imamoglu, M. Z., Cuceloglu, G., & Erturk, A. (2019). Impacts of land cover/use changes on hydrological processes in a rapidly urbanizing mid-latitudewater supply catchment. *Water (Switzerland)*, *11*(5). https://doi.org/10.3390/w11051075

ShahiriParsa, A., Noori, M., Heydari, M., & Rashidi, M. (2016). Floodplain zoning simulation by using HEC-RAS and CCHE2D models in the Sungai Maka river. *Air, Soil and Water Research*, *9*, 55–62. https://doi.org/10.4137/ASWR.S36089

Shields Jr., F. D., Bowie, A. J., & Cooper, C. M. (1995). Control of streambank erosion due to bed degradation with vegetation and structure. *Water Resources Bulletin*.

Shields Jr., F. D., Pezeshki, S. R., Wilson, G. V, Wu, W., & Dabney, S. M. (2008). Rehabilitation of an incised stream using plant materials: the dominance of geomorphic processes. *Ecology and Society*, *13*(2). https://doi.org/10.2307/26267985

Shih, C.-H., Chu, T.-J., & Lee, Y.-C. (2010). Environmental pre-evaluation for eco-leisure: A case study of a restored stream system in Hofanchuken creek of Taipei county, Taiwan. https://www.researchgate.net/publication/260320438

Shivhare, N., Dikshit, P. K. S., & Dwivedi, S. B. (2018). A comparison of SWAT model calibration techniques for hydrological modeling in the Ganga River watershed. *Engineering*, *4*(5), 643–652. https://doi.org/10.1016/j.eng.2018.08.012

Shrestha, J., Niklaus, P. A., Pasquale, N., Huber, B., Barnard, R. L., Frossard, E., Schleppi, P., Tockner, K., & Luster, J. (2014). Flood pulses control soil nitrogen cycling in a dynamic river floodplain. *Geoderma*, *228–229*, 14–24. https://doi.org/10.1016/j.geoderma.2013.09.018

Shrestha, M. S. (2013). Impacts of flood in South Asia. https://www.researchgate.net/publication/259484329

Shrestha, S., Bhatta, B., Shrestha, M., & Shrestha, P. K. (2018). Integrated assessment of the climate and landuse change impact on hydrology and water quality in the Songkhram River Basin, Thailand. *Science of the Total Environment*, *643*, 1610–1622. https://doi.org/10.1016/j.scitotenv.2018.06.306

Shustikova, I., Neal, J. C., Domeneghetti, A., Bates, P. D., Vorogushyn, S., & Castellarin, A. (2020). Levee breaching: A new extension to the LISFLOOD-FP model. *Water*, *12*(4), 942. https://doi.org/10.3390/w12040942

Silva, V. de P. R., Silva, M. T., Singh, V. P., de Souza, E. P., Braga, C. C., de Holanda, R. M., Almeida, R. S. R., de Assis Salviano de Sousa, F., & Braga, A. C. R. (2018). Simulation of stream flow and hydrological response to land-cover changes in a tropical river basin. *Catena*, *162*, 166–176. https://doi.org/10.1016/j.catena.2017.11.024

Smith, M. W., & Vericat, D. (2015). From experimental plots to experimental landscapes: topography, erosion and deposition in sub-humid badlands from Structure-from-Motion photogrammetry. *Earth Surface Processes and Landforms*, *40*(12), 1656–1671. https://doi.org/10.1002/esp.3747

Snyder, F. F. (1938). Synthetic unit-graphs. *Transactions, American Geophysical Union*, *19*(1), 447. https://doi.org/10.1029/TR019i001p00447

Sokolova, G. v., Verkhoturov, A. L., & Korolev, S. P. (2019). Impact of deforestation on streamflow in the amur river basin. *Geosciences (Switzerland)*, *9*(6). https://doi.org/10.3390/geosciences9060262

Son, N. T., Hoang, L. H. V., Phuong Tran, T., Duc Loc, N., Le Huong, H., & Thanh Son, N. (2020). Response of Streamflow and Soil Erosion to Climate Change and Human Activities in Nam Rom River Basin, Northwest of Vietnam. *Environment and Natural Resources Journal*, *18*(4), 411–423. https://doi.org/10.20944/preprints202001.0362.v1

Sotir, R. B. (2001). Integration of soil bioengineering techniques for watershed management. *Wetlands Engineering & amp; River Restoration 2001*, 1–8. https://doi.org/10.1061/40581(2001)56

Strauch, M., & Volk, M. (2013). SWAT plant growth modification for improved modeling of perennial vegetation in the tropics. *Ecological Modelling*, *269*, 98–112. https://doi.org/10.1016/j.ecolmodel.2013.08.013

Sudduth, E. B., & Meyer, J. L. (2006). Effects of bioengineered streambank stabilization on bank habitat and macroinvertebrates in urban streams. In *Environmental Management* (Vol. 38, Issue 2, pp. 218–226). https://doi.org/10.1007/s00267-004-0381-6

Suman, A., & Akther, F. (2014). D2D inundation modelling using SOBEK-Rural: A measure for flood risk management. *International Journal of Advanced Engineering Research and Science (IJAERS)*, *1*(5).

SWAT. (2022). *MWSWAT 2012*. Soil and Water Assessment Tool. https://swat.tamu.edu/software/mwswat/

Tabari, H. (2020). Climate change impact on flood and extreme precipitation increases with water availability. *Scientific Reports*, *10*(1). https://doi.org/10.1038/s41598-020-70816-2

Tadesse, W., Whitaker, S., Crosson, W., & Wilson, C. (2015). Assessing the impact of land-use land-cover change on stream water and sediment yields at a watershed level using SWAT. *Open Journal of Modern Hydrology*, *05*(03), 68–85. https://doi.org/10.4236/ojmh.2015.53007

Tan, M. L., Gassman, P. W., Srinivasan, R., Arnold, J. G., & Yang, X. (2019). A Review of SWAT Studies in Southeast Asia: Applications, Challenges and Future Directions. *Water*, *11*(5), 914. https://doi.org/10.3390/w11050914

Tan, M. L., Ibrahim, A. L., Yusop, Z., Chua, V. P., & Chan, N. W. (2017). Climate change impacts under CMIP5 RCP scenarios on water resources of the Kelantan River Basin, Malaysia. *Atmospheric Research*, *189*, 1–10. https://doi.org/10.1016/j.atmosres.2017.01.008

Tan, M. L., Liang, J., Samat, N., Chan, N. W., Haywood, J. M., & Hodges, K. (2021). Hydrological Extremes and Responses to Climate Change in the Kelantan River Basin, Malaysia, Based on the CMIP6 HighResMIP Experiments. *Water (Switzerland)*, *13*(11). https://doi.org/10.3390/w13111472

Tardio, G., Mickovski, S. B., Stokes, A., & Devkota, S. (2017). Bamboo structures as a resilient erosion control measure. *Proceedings of the Institution of Civil Engineers: Forensic Engineering*, *170*(2), 72–83. https://doi.org/10.1680/jfoen.16.00033

Tariq, M. A. U. R., Rajabi, Z., & Muttil, N. (2021). An evaluation of risk-based agricultural land-use adjustments under a flood management strategy in a floodplain. *Hydrology*, *8*(1). https://doi.org/10.3390/hydrology8010053

Tate, E., Strong, A., Kraus, T., & Xiong, H. (2016). Flood recovery and property acquisition in Cedar Rapids, Iowa. *Natural Hazards*, *80*(3), 2055–2079. https://doi.org/10.1007/s11069-015-2060-8

Tayefi, V., Lane, S. N., Hardy, R. J., & Yu, D. (2007). A comparison of one- and two-dimensional approaches to modelling flood inundation over complex upland floodplains. *Hydrological Processes*, *21*(23), 3190–3202. https://doi.org/10.1002/hyp.6523

Tham. (2022). Hydropower development in Sarawak: Sensitivities over sustainability and China's involvement. *Yusof Ishak Institute*, *2022 No. 45*. https://www.facebook.com/IEEE.CurtinMalaysia/photos/a.558865270846311/5054565917942868

The Nature Conservancy. (2009). *Indicators of Hydrologic Alteration (Version 7.1) - User's Manual*.

Tran, D. D., Huu, L. H., Hoang, L. P., Pham, T. D., & Nguyen, A. H. (2021). Sustainability of rice-based livelihoods in the upper floodplains of Vietnamese Mekong Delta: Prospects and challenges. *Agricultural Water Management*, *243*. https://doi.org/10.1016/j.agwat.2020.106495

Tripathy, Dr. B., & Mondal, T. (2019). Impact of Riverbank erosion on Human life. *Thematics Journal of Geography*, *8*(9), 53–56. https://doi.org/10.26643/tjg.v8i9.8101

TXDOT. (1997). Field performance testing of selected erosion control products. *TXDOT/ TTI Hydraulics and Erosion Control Laboratory, Bryan, TX.*

U.S. Army Corps of Engineers. (2012). *HEC-HMS Hydrologic Modeling System - User's Manual (Version 4.0)*.

Umar, D. A., Ramli, M. F., Aris, A. Z., Jamil, N. R., & Abdulkareem, J. H. (2018). Runoff irregularities, trends, and variations in tropical semi-arid river catchment. *Journal of Hydrology: Regional Studies*, *19*, 335–348. https://doi.org/10.1016/j.ejrh.2018.10.008

USACE. (2004). The role of the U.S. Army Corps of Engineers in environmental restoration and stewardship. In *River Basins and Coastal Systems Planning Within The U.S. Army Corps of Engineers* (pp. 63–80).

Verdi, D. A. (1998). Stream restoration and streambank protection using soil bioengineering measures in Massachusetts. *Engineering Approaches to Ecosystem Restoration*, 1064–1069. https://doi.org/10.1061/40382(1998)174

Vergani, C., Chiaradia, E. A., & Bischetti, G. B. (2012). Variability in the tensile resistance of roots in Alpine forest tree species. *Ecological Engineering*, *46*, 43–56. https://doi.org/10.1016/j.ecoleng.2012.04.036

Vijulie, I., Preda, M., Lequeux-Dincă, A. I., Cuculici, R., Matei, E., Mareci, A., Manea, G., & Tudoricu, A. (2019). Economic productivity vs. ecological protection in Danube floodplain. Case study: Danube's sector between olt and vedea. *Sustainability (Switzerland)*, *11*(22). https://doi.org/10.3390/su11226391

Voicu, R., Radecki-Pawlik, A., Tymiński, T., Mokwa, M., Sotir, R., & Voicu, L. (2020). A potential engineering solution to facilitate upstream movement of fish in mountain rivers with weirs: Southern Carpathians, the Azuga River. *Journal of Mountain Science*, *17*(3), 501–515. https://doi.org/10.1007/s11629-019-5572-y

Wang, S., Meng, X., Chen, G., Guo, P., Xiong, M., & Zeng, R. (2017). Effects of vegetation on debris flow mitigation: A case study from Gansu province, China. *Geomorphology*, *282*, 64–73. https://doi.org/10.1016/j.geomorph.2016.12.024

Wang, Y., Jiang, R., Xie, J., Zhao, Y., Yan, D., & Yang, S. (2019). Soil and Water Assessment Tool (SWAT) Model: A systemic review. In *Journal of Coastal Research* (Vol. 93, Issue sp1, pp. 22–30). Coastal Education Research Foundation Inc. https://doi.org/10.2112/SI93-004.1

Weng, C. N. (2005). Sustainable management of rivers in malaysia: Involving all stakeholders. *International Journal of River Basin Management*, *3*(3), 147–162. https://doi.org/10.1080/15715124.2005.9635254

Weng, C. N., Lee, A. A., Ibrahim, A. L., & Ghazali, S. (2003). River pollution and restoration towards sustainable water resources management in Malaysia Machine Translation and CAT View project Topophilia and topophobia: Place, identity and Imagination of "urban villagers" View project. *Society, Space and Environment in a Globalised World: Challenges and Prospect*, 208–219. https://www.researchgate.net/publication/279495316

Wilkinson, M. E., Quinn, P. F., Barber, N. J., & Jonczyk, J. (2014). A framework for managing runoff and pollution in the rural landscape using a Catchment Systems Engineering approach. *Science of the Total Environment*, *468–469*, 1245–1254. https://doi.org/10.1016/j.scitotenv.2013.07.055

Wing, O. E. J., Lehman, W., Bates, P. D., Sampson, C. C., Quinn, N., Smith, A. M., Neal, J. C., Porter, J. R., & Kousky, C. (2022). Inequitable patterns of US flood risk in the Anthropocene. *Nature Climate Change*, *12*(2), 156–162. https://doi.org/10.1038/s41558-021-01265-6

Wingfield, T., Macdonald, N., Peters, K., & Spees, J. (2021). Barriers to mainstream adoption of catchment-wide natural flood management: A transdisciplinary problem-framing study of delivery practice. *Hydrology and Earth System Sciences*, *25*(12), 6239–6259. https://doi.org/10.5194/hess-25-6239-2021

WMO. (2021). *State of the Climate in Asia 2020*.

Wohl, E., Lane, S. N., & Wilcox, A. C. (2015). The science and practice of river restoration. *Water Resources Research*, *51*(8), 5974–5997. https://doi.org/10.1002/2014WR016874

Wood, A. D. (1998). Stream Restoration with Soil Bioengineering: Making Believers. *Engineering Approaches to Ecosystem Restoration*, 1070–1074. https://doi.org/10.1061/40382(1998)175

Wu, L., Liu, X., Chen, J., Yu, Y., & Ma, X. (2022). Overcoming equifinality: time-varying analysis of sensitivity and identifiability of SWAT runoff and sediment parameters in an arid and semiarid watershed. *Environmental Science and Pollution Research*, 29(21), 31631–31645. https://doi.org/10.1007/s11356-022-18573-9

Wu, W., Switala, B. M., Acharya, M. S., Tamagnini, R., Auer, M., Graf, F., te Kamp, L., & Xiang, W. (2015). Effect of vegetation on stability of soil slopes: Numerical aspect. *Springer Series in Geomechanics and Geoengineering*, *2015*, 163–177. https://doi.org/10.1007/978-3-319-11053-0_15

Yang, K., Chen, T., Ao, T., Zhang, X., Zhou, L., & Gao, D. (2022). Response of runoff in the upper reaches of the Minjiang River to climate change. *Journal of Water and Climate Change*, *13*(1), 260–273. https://doi.org/10.2166/wcc.2021.038

Yusoff, N., & Abidin, R. Z. (2013). RIVER BANK EROSION RISK WITH REGARDS TO RAINFALL EROSIVITY. In *Infrastructure University Kuala Lumpur Research Journal* (Vol. 1, Issue 1).

Zafirah, N., Nurin, N. A., Samsurijan, M. S., Zuknik, M. H., Rafatullah, M., & Syakir, M. I. (2017). Sustainable ecosystem services framework for tropical catchment management: A review. In *Sustainability (Switzerland)* (Vol. 9, Issue 4). MDPI. https://doi.org/10.3390/su9040546

Zhang, C., Li, S., Qi, J., Xing, Z., & Meng, F. (2017). Assessing impacts of riparian buffer zones on sediment and nutrient loadings into streams at watershed scale using an integrated REMM-SWAT model. *Hydrological Processes*, *31*(4), 916–924. https://doi.org/10.1002/hyp.11073

Zhang, L., Meng, X., Wang, H., Yang, M., & Cai, S. (2020). Investigate the applicability of CMADS and CFSR reanalysis in Northeast China. *Water (Switzerland)*, *12*(4). https://doi.org/10.3390/W12040996

Zhang, Z., Cao, L., Zhu, Z., He, C., Xiang, H., Xu, L., Sun, C., Lin, C., Yang, H., & Li, K. (2019). Evaluation on soil bioengineering measures in agricultural areas: Poorer durability of wooden structures and better aboveground habitat improvements. *Ecological Engineering*, *129*, 1–10. https://doi.org/10.1016/j.ecoleng.2019.01.004

Zhou, F., Xu, Y., Chen, Y., Xu, C. Y., Gao, Y., & Du, J. (2013). Hydrological response to urbanization at different spatio-temporal scales simulated by coupling of CLUE-S and the SWAT model in the Yangtze River Delta region. *Journal of Hydrology*, *485*, 113–125. https://doi.org/10.1016/j.jhydrol.2012.12.040

Zuquette, L. V., Dos Santos Collares, J. Q., & Pejon, O. J. (2007). Proposal for selection of control, preventive and rehabilitation measures based on degradation land level and geoindicators in the fortaleza metropolitan region, State of Ceará, Brazil. *Environmental Geology*, *52*(5), 899–922. https://doi.org/10.1007/s00254-006-0533-5

APPENDIX A: LIST OF REVIEWED LITERATURE

Table A.1: Scopus Papers

Country	Location	References	Methods	Composite	Goals
Applications					
France	Mountainous	Weissgerber et al. (2019)	Revegetation, check dam, seedlings	-	Erosion and recreating ecosystem
Swizerland	Mountainous	Janssen et al. (2019)	willow fascine, vegetated crib wall, native pioneer species	-	Bank stabilisation and habitat
Spain	Highland	Galicia et al. (2019)	green check dam, composite	-	Control flood and reservoir
Germany	Lowland urban	Schmitt et al. (2018)	Planting, revegetation	Riprap	Habitat, ecological improvement
China	Highland	Wang et al. (2017)	Revegetation, plant trees	-	Morphological changes, ecosystem, flow debris, flood
Spain	Hill slope	Tardio et al. (2017)	Check dam, live fencing, palisade	Rock wall	Bank stability, alter flow, trap sediment
Portugal	Highland non-urban	Pinto et al. (2016)	Revegetation, live stake, live crib wall, live slope grid	Rock toe, riprap, gabions	Stabilisation
Canada	Lowland semi-urban	Krymer et al. (2014)	Crib wall	Rock toe	Erosion, sediment, geomorphology
Spain	Lowland wetland (Delta)	Curado et al. (2014)	Specific plant (aquatic halophyte)	-	Nutrients, ecological
Czech Republic	Mountainous	Kovar et al. (2014)	Chute pool, step-pool	-	Biota, stable flow, geomorphological
France	Mountainous	Rey et al. (2014)	Brush layer, wooden sill weir, brush mat, vegetation	-	Trap sediment (geomorphology)
France	Lowland non-urban	Breton et al. (2014)	Revegetation, species survivorship	-	Ecological role, revegetate riparian zone, erosion, survivorship

Canada	Lowland Urban	Bariteau et al. (2013)	Rounded granular (not bioengineering)	-	Bank stabilisation
France	Mountainous	Cavaillé et al. (2013)	Willow fascine, brush layer, seedlings	Riprap, rock toe	Bank stabilisation, ecological and biodiversity, fauna, eliminate invasive species
Taipei	Highland semi-urban	Shih et al. (2010)	Wood revetment	Masonry, concrete	Habitat, water quality, biological
Nicaragua	Highland semi-urban	Petrone et al. (2010)	Live crib wall, live palisade, live fascine mattress	Drainages, bamboo, species survival rate	Bank erosion
USA	Lowland non-urban	Rogers et al. (2009)	Vegetated rock riprap, brush layering, willow planting, reseeded	Composite, grade control structure, rock toe, channelisation, fish passage	Bank stabilisation, habitat
USA	Lowland non-urban	Shields et al. (2008)	Willow planting, large wood	Drainage, dewatering pumps	Bank stabilisation, habitat
Canada	Highland	Raymond et al. (2008)	Woody vegetation, live cutting, brush layer, willow, fascines, sill planted	Drainage, machine-assist, regrade slope, trench, riprap, rock toe	Fish habitat, shade, bank stabilisation
USA	Lowland non-urban	Jones C.M. (2008)	Brush mattress, willow fascine, willow brush, riparian vegetation	Rock toe, vane, riprap, weir, boulder pools, salmon passage, remove dam	Fish habitat, bank stabilisation, riparian corridor,
USA	Lowland (river delta)	Cater et al. (2007)	Vegetation, seedlings, live stake	-	Stabilisation, ecological restoration
USA	Lowland Urban	Barrett et al. (2006)	Live brush, live poles, brush layers with geogrid-wrapped soil lifts, live stakes through coir blanket, brush fascine	Rock toe	Erosion, stabilise the bank, create dense vegetation
China	Lowland Urban	Li et al. (2006)	Live staking, live fascines, brush layer, vegetated geo-grids, geo-gabions	-	Erosion, habitat, water quality
USA	Lowland non-urban	Schaff et al. (2003)	Willow cuttings, survival growth rate, use this as support	-	Stabilise bank, willow survival at different soil conditions
France	Lowland delta	Suanez et al. (1999)	Fence (soft engineering)	-	Reduce shore erosion, control sediment transport
USA	Lowland urban	Nichols et al. (1999)	Coconut fibre roll, live willow stake, planting shrubs, live fascine	gradual slope, temporary drainage, remove invasive species	Stabilise bank, sediment trap, habitat, aesthetic

USA	Lowland non-urban	Shields et al. (1995)	Joint planting, live stakes, seedlings, willow cuttings	gradual slope, rock toe, riprap	Reduce erosion
USA	Highland	Newbury et al. (1993)	Riffle and pool (not so bioengineering)	-	Habitat, natural condition
Experimental					
France	Experimental	Dommanget et al. (2014)	Planting tree cut	-	Ecological, riparian invasive species
China	Experimental	Li et al. (2005)	Not restoration but support willow as bioengineering	-	Evaluate the photosynthetic and growth response of willow
Review					
Worldwide	Review	Nagayama et al. (2010)	Log deflectors, log dams	-	Habitat restoration, fish mobility
USA	N/A	Hook et al. (2009)	Willow cuttings, pre-vegetated coir mats, soil lifts	-	Evaluate the effectiveness of revegetation to eliminate invasive plant species
Germany & Austria	N/A	Kail et al. (2007)	Wood restoration	-	Evaluate effectiveness, state-of-art of wood in river restoration and summarises experiences gained
Worldwide	N/A	Kuzovkina et al. (2005)	Willow	-	Water quality, habitat, reduce erosion
Framework & proposal					
Portugal	Mountainous	Pinto et al. (2019)	Green measures and hard engineering	-	Selecting suitable methods for bank stabilisation
Slovakia	Lowland Urban	Halajova et al. (2019)	Revegetation and apply biotechnical measures	-	Reduce flood and improve the ecological status
Spain	Lowland urban	Maroto et al. (2017)	Live crib wall, organic mats, reinforced earth structure, live slope grids	Gabion wall	Slope stability
Italy	Lowland urban	Carone et al. (2003)	Study the quality state of fluvial ecosystems to support ecological restoration at sensible site using bioengineering measures	-	Preliminary analysis, biological condition
UK	N/A	Ellis J.B. (1995)	Framework, awareness, planning and guidelines	-	Developed integrated design approaches to enhance the environmental values of floodways and corridors

Table A.2: Web of Science Papers

Country	Location	References	Methods	Composite	Goals
Applications					
China	Lowland non-urban	Zhang et al. (2019)	willow cuttings	timber piles, riprap	bank stabilisation, wooden structure durability, willow survivability
Italy	Mountainous	Giupponi et al. (2017)	live slope, live cutting, brush layer fence, biomat blanket, live crib wall	riprap, drainage, regrading	ecological value, plant community, plant species
Nepal	Mountainous	Dhital et al. (2013)	brush layering, palisades, live check dams, fascines, vegetative stone pitching	N/A	slope stability, bank erosion
USA	Lowland urban	Frothingham, Kelly M. (2008)	wattles, coir roll, brush mattress, brush layering, live fascine, live willow stakes	rock toe	bank stabilisation
USA	Lowland urban	Piper et al. (2000)	willow cutting, brush mattress, brush layering, tree revetment	rock toe, stone dike, bank regrading, erosion fabric	bank stabilisation
Experimental					
Netherland	Experimental	Saaltink et al. (2018)	vegetation	N/A	effects of hydrological regime and sediment type on nutrient availability
Europe (Mediteranean)	Experimental	Fernandes et al. (2016)	log-crib wall, live log grid, live stake	gabion, riprap, drainage	short and long-term efficacy, factor of safety, Columb model, slope stability
USA	Experimental	Pezeshki et al. (1998)	willow cuttings	N/A	effects of various soil moisture conditions on willow cuttings growth

Review					
USA	Review	Li et al. (2002)	all	all	Strengths and weaknesses of bioengineering, cost, and design approaches
Canada	Review	Polster, D. F. (2002)	Wattle fences, live fencing, brush mattress, live palisades, live gravel bar staking, live shade (fish habitat), brush layers, live stake, live pole drains	N/A	reduce erosion, slope stability

Table A.3: Additional unpublished reports and papers

Country	Location	References	Methods	Composite	Goals	Other approaches
Applications						
Nepal	Lowland urban	Tamrakar, N, K. (2010)	Live Stakes, wattle fence, live palisade, bamboo planting and brush layering	Retaining wall and rip-rap toe	Reduce erosion	N/A
Vietnam	Lowland non-urban	Matsuki, H. (2014)	Bamboo planting, bamboo gabion, grassing and vegetation	groyne, revetment foundation, stone box, gabion	Reduce erosion	N/A
Report						
USA	Lowland urban (18), non-urban (6), Semi-urban (2)	Newton and Lyn (2015)	Live stakes, Vegetated Coir Roll, Rootwads, Tree Revetment, Crib wall, Live Fascines, Joint Planting	Regrading, Rock Toe	Reduce erosion and bank stabilisation	Hard armouring was needed, permanent mat and articulated concrete mat were used
China (2), South Korea (3), Japan (3)	Lowland urban (7), Lowland non-urban (1)	Asian River Restoration Network (ARRN: 2012)	Revegetation, plant trees	N/A	groundwater recharge, water quality (BOD), environmental values	Rehabilitate floodplain, reconstruct meanders, sewage and drainage systems
Japan (5)	Lowland urban (5)	Japanese River Restoration Network (JRRN: 2015)	Revegetation, green-rock vane, log groyne	rock ramp, rock vane, weir	Water quality, environmental values, ecological integrity, habitat	fish passage, good practice, floodplain connectivity
Singapore	Lowland urban	Public Utilities Board (PUB) Singapore (2018)	Revegetation, bioretention, vegetative swale	canal wall, gradual slope, elevated footpath	Water quality, habitat, aesthetic, environmental value	freshwater forest wetlands, sedimentation basins

APPENDIX B: PRIMARY DATA

JABATAN PENGAIRAN DAN SALIRAN SARAWAK,
(Department of Irrigation and Drainage Sarawak)
Tingkat 9 & 10, Wisma Saberkas,
Jalan Tun Abang Haji Openg,
Peti Surat No. 1230,
93626 Kuching,
Sarawak.

Telefon Am:082 – 243 241 Faks: 082 – 426400

Ruj. Tuan :
Ruj. Kami : (18) DID3/600-21 VOL.55

Tarikh : 8 January 2021

Lip Yih Yoong
University of Nottingham Malaysia,
Jalan Broga 43500 Semenyih, Selangor.
Tel: 016-9188739

Dear Sir,

REQUEST FOR HYDROLOGICAL DATA FOR RESEARCH PURPOSE
Project Title : River Morphodynamics and Green Engineering in River Trusan, Sarawak.

Reference is made to your Hydrological Data Request Form dated 30th December 2020 and also the letter from University of Nottingham Malaysia dated 9th October 2020 concerning the above subject.

2. Attached herewith are the hourly total rainfall, daily mean stage and hourly water level data for the stations as listed in Appendix A.

3. Please be informed that the data/information is provided with the following conditions:

i. that the data/information shall not be utilized for any other project or study,
ii. that acknowledgement for the use of the data provided will be suitably made in the report/paper/publication and a copy of such report/paper/publication be extended to the Department of Irrigation and Drainage (DID), Sarawak free of charge, and
iii. that DID, Sarawak shall not be liable for any loss or damages caused by the usage of any information provided.

Thank you.

"BERSATU BERUSAHA BERBAKTI"
"AN HONOUR TO SERVE"

(Ir. NORMAHYUSNI BT MOHD ANNUAR)
b.p. Pengarah Pengairan dan Saliran
Sarawak

TSV/SNU/JK

c.c.: Head of Student Registry, Student Registry Office
University of Nottingham, Malaysia

Figure B.1: Rainfall and runoff data acquisition form (Page 1).

Appendix A

LIST OF DATA PROVIDED (PDF FORMAT) FOR

RIVER MORPHODYNAMICS AND GREEN ENGINEERING IN RIVER TRUSAN, SARAWAK

A) Rainfall Station (Hourly Total)

NO.	STATION NAME	STATION NUMBER	DURATION OF DATA
			Logger
1	Long Tengoa	4653001	22.06.1998-13.10.2020
2	Kuala Lawas	4954001	01.08.2012-03.12.2020
3	Sundar	4852002	01.09.1998-03.12.2020
4	Long Semado	4255006	08.06.1998-25.11.2020
5	Ba Kelalan	3956001	02.12.1998-26.11.2020
6	Long Merarap	4354001	26.06.1998-24.11.2020

B) Water Level Station

NO.	STATION NAME	STATION NUMBER	DURATION OF DATA	
			Manual (Daily Mean Stage)	Logger (Hourly Water Level)
1	Long Tengoa	4653401	-	15.03.1984-04.02.1985
2	Kuala Lawas	4954401	02.08.2000-31.10.2020	-

Figure B.2: Rainfall and runoff data acquisition form (Page 2).

~~~ NIWA Tideda ~~~ JPS Ampang 22-MAR-2021 14:40
~~~ PDAY ~~~ VER 1.9
Source is Z:\rainfall.mtd
24 hour periods beginning at 8:00:00am each day.
Daily totals Year 2010 site 4658001 BAKUKU at SABAH
Rainfall mm

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1	?	?	?	?	?	?	?	?	?	?	?	0.5	
2	?	?	?	?	?	?	?	?	?	?	?	0.0	
3	?	?	?	?	?	?	?	?	?	?	?	14.5	
4	?	?	?	?	?	?	?	?	?	?	?	0.5	
5	?	?	?	?	?	?	?	?	?	?	?	0.0	
6	?	?	?	?	?	?	?	?	?	?	6.5	2.0	
7	?	?	?	?	?	?	?	?	?	?	2.0	15.0	
8	?	?	?	?	?	?	?	?	?	?	68.5	10.0	
9	?	?	?	?	?	?	?	?	?	?	48.5	0.0	
10	?	?	?	?	?	?	?	?	?	?	39.5	5.0	
11	?	?	?	?	?	?	?	?	?	?	0.0	0.5	
12	?	?	?	?	?	?	?	?	?	?	0.5	0.0	
13	?	?	?	?	?	?	?	?	?	?	2.0	11.0	
14	?	?	?	?	?	?	?	?	?	?	7.5	0.0	
15	?	?	?	?	?	?	?	?	?	?	0.0	0.0	
16	?	?	?	?	?	?	?	?	?	?	0.0	1.0	
17	?	?	?	?	?	?	?	?	?	?	30.0	5.0	
18	?	?	?	?	?	?	?	?	?	?	5.0	5.5	
19	?	?	?	?	?	?	?	?	?	?	0.0	6.0	
20	?	?	?	?	?	?	?	?	?	?	0.0	0.0	
21	?	?	?	?	?	?	?	?	?	?	0.0	11.5	
22	?	?	?	?	?	?	?	?	?	?	9.5	7.0	
23	?	?	?	?	?	?	?	?	?	?	0.5	0.5	
24	?	?	?	?	?	?	?	?	?	?	3.5	15.0	
25	?	?	?	?	?	?	?	?	?	?	0.0	3.0	
26	?	?	?	?	?	?	?	?	?	?	21.5	21.5	
27	?	?	?	?	?	?	?	?	?	?	0.0	5.0	
28	?	?	?	?	?	?	?	?	?	?	0.5	1.0	
29	?		?	?	?	?	?	?	?	?	14.5	11.5	
30	?		?	?	?	?	?	?	?	?	1.5	5.0	
31	?		?		?		?	?		?		0.5	
Min	?	?	?	?	?	?	?	?	?	?	0.0	0.0	0.0
Tot	?	?	?	?	?	?	?	?	?	?	261.5	158.0	419.5
Max	?	?	?	?	?	?	?	?	?	?	68.5	21.5	68.5
NO>0.0	0	0	0	0	0	0	0	0	0	0	17	24	41

Figure B.3: Example of raw daily rainfall data recorded at Bakuku (Sabah).

~~~ NIWA Tideda ~~~ JPS Ampang 22-MAR-2021 15:20
~~~ PDAY ~~~ VER 1.9
Source is Z:\WaterLevel.mtd
24 hour periods beginning at 8:00:00am each day.
Daily means Year 1990 site 4959401 SG. PADAS at KEMABONG, SABAH
Flow m3/sec

Day	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1	45.4	164.5	26.4	58.6	48.9	?	13.6	43.5	12.4	44.9	32.0	33.6	
2	38.0	200.9	46.0	71.0	58.7	?	12.4	29.8	22.3	38.5	26.4	28.0	
3	33.8	105.2	33.4	53.5	110.6	?	12.7	53.0	25.4	72.6	23.8	23.0	
4	32.8	75.5	26.5	40.1	110.7	?	16.8	49.9	27.3	66.3	55.2	19.9	
5	78.5	65.6	33.8	34.2	174.8	?	21.0	39.6	18.7	46.2	39.3	18.8	
6	124.0	66.8	86.7	74.7	156.5	?	30.6	39.2	17.3	33.5	43.4	27.6	
7	130.8	61.5	43.3	72.9	112.3	?	26.2	38.5	18.0	31.0	41.3	55.2	
8	89.2	51.5	30.9	41.4	105.7	?	18.8	37.3	28.4	35.9	30.1	33.5	
9	123.6	47.5	25.3	33.1	68.6	?	15.1	50.8	34.5	44.4	26.5	25.7	
10	73.0	47.0	22.6	29.1	51.3	?	19.2	49.2	27.1	36.3	25.3	21.9	
11	50.8	41.3	21.3	26.6	46.0	?	24.4	73.7	38.0	?	23.0	20.0	
12	42.6	35.5	20.6	26.4	64.0	?	54.4	68.3	36.7	?	22.2	19.5	
13	37.6	33.1	31.8	48.5	49.8	?	69.6	43.6	39.5	?	24.6	19.2	
14	33.9	45.6	26.6	137.3	54.1	?	65.2	31.1	23.4	?	33.5	18.1	
15	31.3	62.0	29.0	180.6	58.4	?	40.0	25.7	19.7	?	30.1	16.9	
16	30.8	38.9	47.8	157.7	42.4	28.1	25.3	24.3	15.7	?	30.1	17.9	
17	30.9	48.9	55.1	92.0	58.1	24.9	23.3	21.9	14.6	?	26.1	21.8	
18	53.8	44.2	39.2	58.9	56.4	22.5	27.5	18.9	17.4	?	29.6	83.8	
19	64.3	36.2	30.4	57.2	136.7	20.7	21.0	16.9	161.1	?	23.9	79.1	
20	200.8	36.8	70.4	74.1	72.6	19.5	17.8	14.9	209.5	?	21.5	35.8	
21	438.5	31.8	128.9	50.5	49.0	18.9	15.4	13.0	121.8	?	57.6	43.8	
22	156.4	27.7	?	43.3	45.8	18.2	15.4	12.0	61.5	?	81.0	28.1	
23	87.3	25.8	?	50.8	44.6	17.4	15.2	11.2	161.4	?	56.6	22.9	
24	71.8	25.0	?	116.8	42.7	15.9	14.6	10.3	150.1	27.4	40.8	19.9	
25	153.1	24.6	?	153.0	?	27.9	14.6	11.8	320.1	24.1	38.6	18.3	
26	218.5	22.6	?	178.2	?	27.8	13.7	10.4	171.0	21.8	98.8	17.6	
27	225.4	21.5	?	86.0	?	22.4	19.9	10.0	109.5	29.6	58.1	16.3	
28	167.8	22.8	?	61.5	?	18.8	16.8	9.7	129.2	42.3	37.7	15.9	
29	102.0		62.1	63.6	?	16.8	13.8	9.3	72.8	92.4	72.0	21.5	
30	85.0		106.1	45.4	?	14.9	18.0	8.8	56.0	52.7	46.3	23.9	
31	87.3		89.7		?		55.6	8.5		35.2		18.8	
Min	30.8	21.5	20.6	26.4	42.4	14.9	12.4	8.5	12.4	21.8	21.5	15.9	8.5
Mean	101.3	53.9	47.2	73.9	75.8	21.0	24.8	28.5	72.0	43.1	39.8	27.9	52.0
Max	438.5	200.9	128.9	180.6	174.8	28.1	69.6	73.7	320.1	92.4	98.8	83.8	438.5

Figure B.4: Example of raw daily discharge data recorded at Sungai Padas, Bakuku (Sabah).

Hourly Rainfall Data at Station 4255006 Long Semadoh

```
4255006, 18.00,19980608 1700, 0.0, 1
4255006, 18.00,19980608 1800, 0.0, 1
4255006, 18.00,19980608 1900, 2.0, 1
4255006, 18.00,19980608 2000, 0.0, 1
4255006, 18.00,19980608 2100, 0.0, 1
4255006, 18.00,19980608 2200, 0.0, 1
4255006, 18.00,19980608 2300, 0.0, 1
4255006, 18.00,19980609 0000, 0.0, 1
4255006, 18.00,19980609 0100, 0.5, 1
4255006, 18.00,19980609 0200, 0.0, 1
4255006, 18.00,19980609 0300, 0.0, 1
4255006, 18.00,19980609 0400, 0.0, 1
4255006, 18.00,19980609 0500, 0.0, 1
4255006, 18.00,19980609 0600, 0.0, 1
4255006, 18.00,19980609 0700, 0.0, 1
4255006, 18.00,19980609 0800, 0.0, 1
4255006, 18.00,19980609 0900, 0.0, 1
4255006, 18.00,19980609 1000, 0.0, 1
4255006, 18.00,19980609 1100, 0.0, 1
4255006, 18.00,19980609 1200, 0.0, 1
4255006, 18.00,19980609 1300, 0.0, 1
4255006, 18.00,19980609 1400, 0.0, 1
4255006, 18.00,19980609 1500, 0.0, 1
4255006, 18.00,19980609 1600, 0.5, 1
4255006, 18.00,19980609 1700, 0.0, 1
4255006, 18.00,19980609 1800, 0.0, 1
4255006, 18.00,19980609 1900, 0.0, 1
4255006, 18.00,19980609 2000, 0.0, 1
4255006, 18.00,19980609 2100, 0.0, 1
4255006, 18.00,19980609 2200, 0.0, 1
4255006, 18.00,19980609 2300, 0.5, 1
4255006, 18.00,19980610 0000, 0.5, 1
4255006, 18.00,19980610 0100, 0.0, 1
4255006, 18.00,19980610 0200, 0.0, 1
4255006, 18.00,19980610 0300, 0.5, 1
4255006, 18.00,19980610 0400, 0.0, 1
4255006, 18.00,19980610 0500, 0.0, 1
4255006, 18.00,19980610 0600, 0.0, 1
4255006, 18.00,19980610 0700, 0.0, 1
4255006, 18.00,19980610 0800, 0.0, 1
4255006, 18.00,19980610 0900, 0.5, 1
4255006, 18.00,19980610 1000, 0.0, 1
4255006, 18.00,19980610 1100, 0.0, 1
4255006, 18.00,19980610 1200, 0.0, 1
4255006, 18.00,19980610 1300, 0.0, 1
4255006, 18.00,19980610 1400, 0.0, 1
4255006, 18.00,19980610 1500, 0.0, 1
4255006, 18.00,19980610 1600, 2.0, 1
4255006, 18.00,19980610 1700, 2.0, 1
4255006, 18.00,19980610 1800, 2.0, 1
4255006, 18.00,19980610 1900, 1.5, 1
4255006, 18.00,19980610 2000, 1.0, 1
4255006, 18.00,19980610 2100, 1.0, 1
4255006, 18.00,19980610 2200, 1.0, 1
4255006, 18.00,19980610 2300, 0.5, 1
4255006, 18.00,19980611 0000, 0.0, 1
4255006, 18.00,19980611 0100, 0.5, 1
4255006, 18.00,19980611 0200, 0.0, 1
4255006, 18.00,19980611 0300, 0.0, 1
4255006, 18.00,19980611 0400, 0.0, 1
4255006, 18.00,19980611 0500, 0.0, 1
4255006, 18.00,19980611 0600, 0.0, 1
4255006, 18.00,19980611 0700, 0.0, 1
4255006, 18.00,19980611 0800, 0.0, 1
4255006, 18.00,19980611 0900, 0.0, 1
4255006, 18.00,19980611 1000, 0.0, 1
4255006, 18.00,19980611 1100, 0.0, 1
4255006, 18.00,19980611 1200, 0.0, 1
4255006, 18.00,19980611 1300, 0.0, 1
4255006, 18.00,19980611 1400, 0.0, 1
4255006, 18.00,19980611 1500, 0.0, 1
4255006, 18.00,19980611 1600, 0.0, 1
4255006, 18.00,19980611 1700, 0.0, 1
4255006, 18.00,19980611 1800, 0.0, 1
4255006, 18.00,19980611 1900, 0.0, 1
4255006, 18.00,19980611 2000, 0.0, 1
4255006, 18.00,19980611 2100, 0.0, 1
4255006, 18.00,19980611 2200, 0.0, 1
4255006, 18.00,19980611 2300, 0.0, 1
4255006, 18.00,19980612 0000, 0.0, 1
4255006, 18.00,19980612 0100, 0.0, 1
4255006, 18.00,19980612 0200, 0.0, 1
4255006, 18.00,19980612 0300, 0.0, 1
4255006, 18.00,19980612 0400, 0.0, 1
4255006, 18.00,19980612 0500, 0.0, 1
4255006, 18.00,19980612 0600, 0.0, 1
4255006, 18.00,19980612 0700, 0.0, 1
4255006, 18.00,19980612 0800, 0.0, 1
4255006, 18.00,19980612 0900, 0.0, 1
4255006, 18.00,19980612 1000, 0.0, 1
4255006, 18.00,19980612 1100, 0.0, 1
4255006, 18.00,19980612 1200, 0.0, 1
4255006, 18.00,19980612 1300, 0.0, 1
4255006, 18.00,19980612 1400, 0.0, 1
4255006, 18.00,19980612 1500, 0.0, 1
4255006, 18.00,19980612 1600, 0.0, 1
4255006, 18.00,19980612 1700, 0.0, 1
4255006, 18.00,19980612 1800, 0.0, 1
4255006, 18.00,19980612 1900, 0.0, 1
4255006, 18.00,19980612 2000, 0.0, 1
4255006, 18.00,19980612 2100, 0.0, 1
4255006, 18.00,19980612 2200, 0.0, 1
4255006, 18.00,19980612 2300, 0.0, 1
4255006, 18.00,19980613 0000, 0.0, 1
4255006, 18.00,19980613 0100, 0.0, 1
4255006, 18.00,19980613 0200, 0.0, 1
4255006, 18.00,19980613 0300, 0.0, 1
4255006, 18.00,19980613 0400, 0.5, 1
4255006, 18.00,19980613 0500, 0.0, 1
4255006, 18.00,19980613 0600, 0.0, 1
4255006, 18.00,19980613 0700, 0.0, 1
4255006, 18.00,19980613 0800, 1.0, 1
4255006, 18.00,19980613 0900, 0.0, 1
4255006, 18.00,19980613 1000, 0.0, 1
4255006, 18.00,19980613 1100, 0.0, 1
4255006, 18.00,19980613 1200, 0.0, 1
```

Figure B.5: Example of raw hourly rainfall data recorded at Long Semadoh (Sarawak).

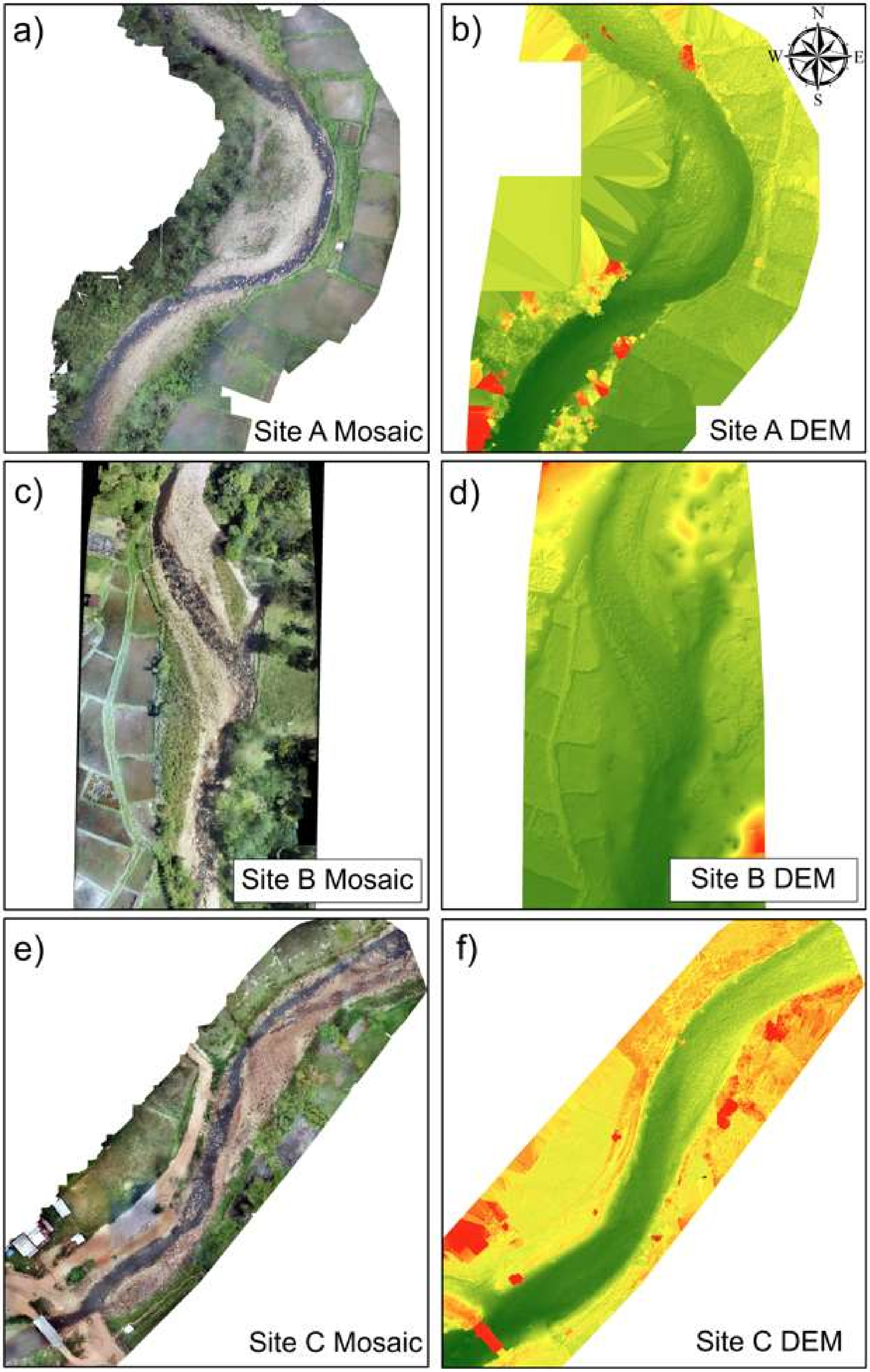

Figure B.6: Orthomosaic and DEM produced from aerial survey for Site A, B, and C.

APPENDIX C: HEC-HMS AND HEC-RAS MODEL

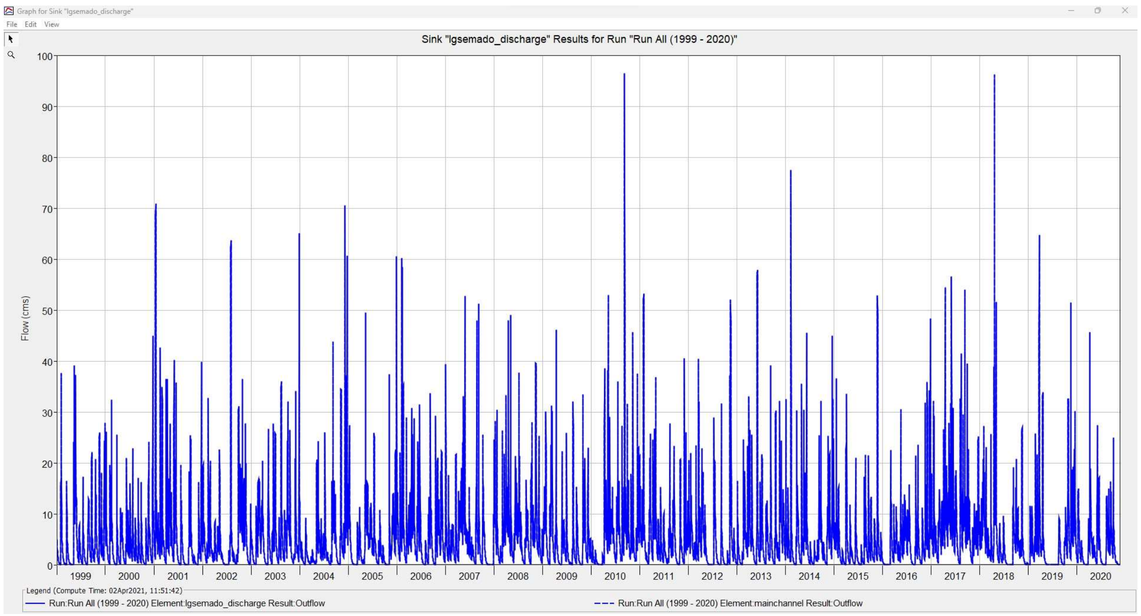

Figure C.1: Long-term hydrograph simulated for the Upper Trusan Catchment using HEC-HMS®.

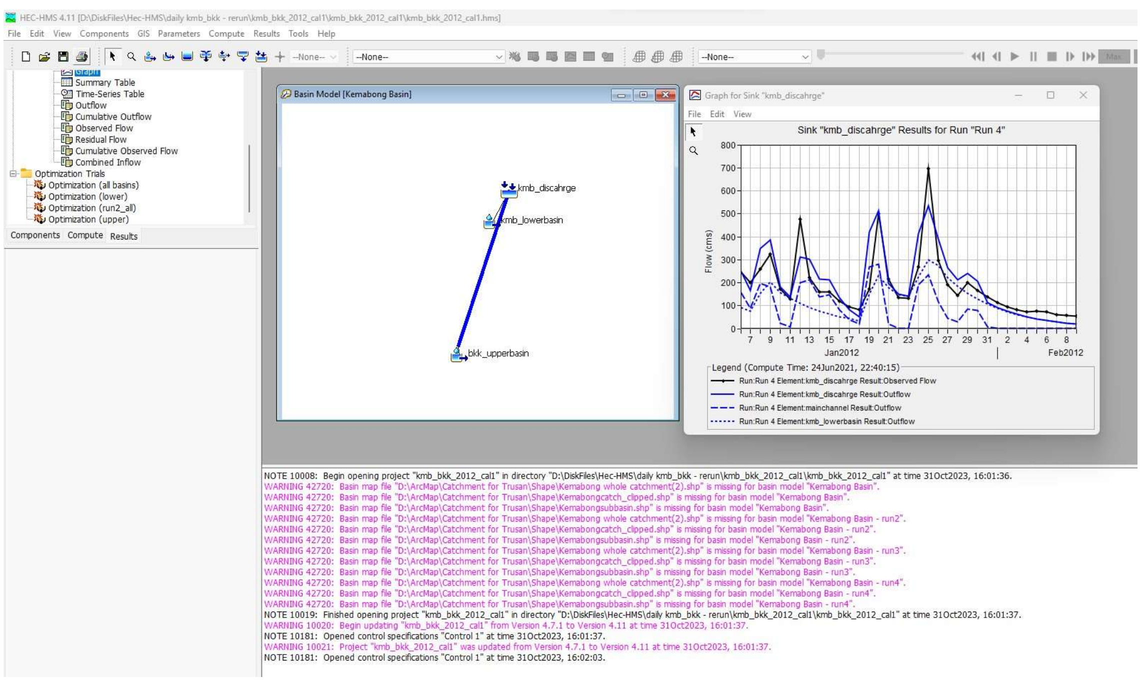

Figure C.2: HEC-HMS® calibration windows and interface.

Table C.1: Optimised hydrological parameters for Bakuku catchment (HEC-HMS®).

Parameters	Unit	Fitted Value	
		Upper Basin	Lower Basin
Initial and Constant - Constant Rate	mm/hr	0.79442	0.18183
Initial and Constant - Initial Loss	mm	15.6048	5.03837
Recession - Initial Discharge	m^3/s	106.3	80.0341
Recession - Ratio to Peak	-	0.75185	0.62926
Recession - Recession Constant	-	0.9	0.67368
Snyder Unit Hydrograph - Peaking Coefficient	-	0.54072	0.34548
Snyder Unit Hydrograph - Standard lag	hr	5.04342	7.15812

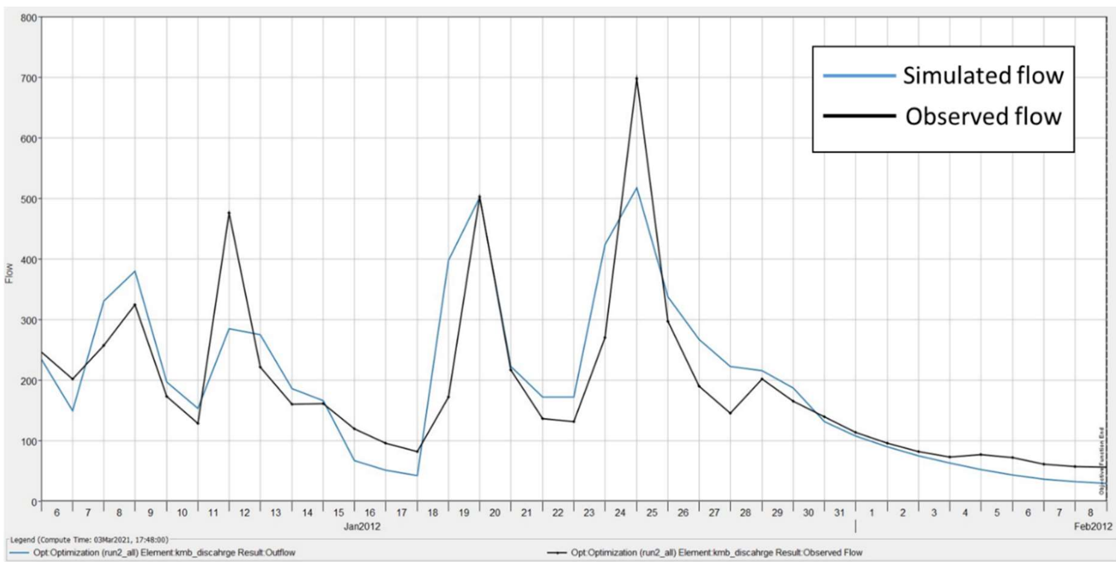

Figure C.3: HEC-HMS® calibration from January 2012 to February 2012 (Calibration 1 – NSE 0.711).

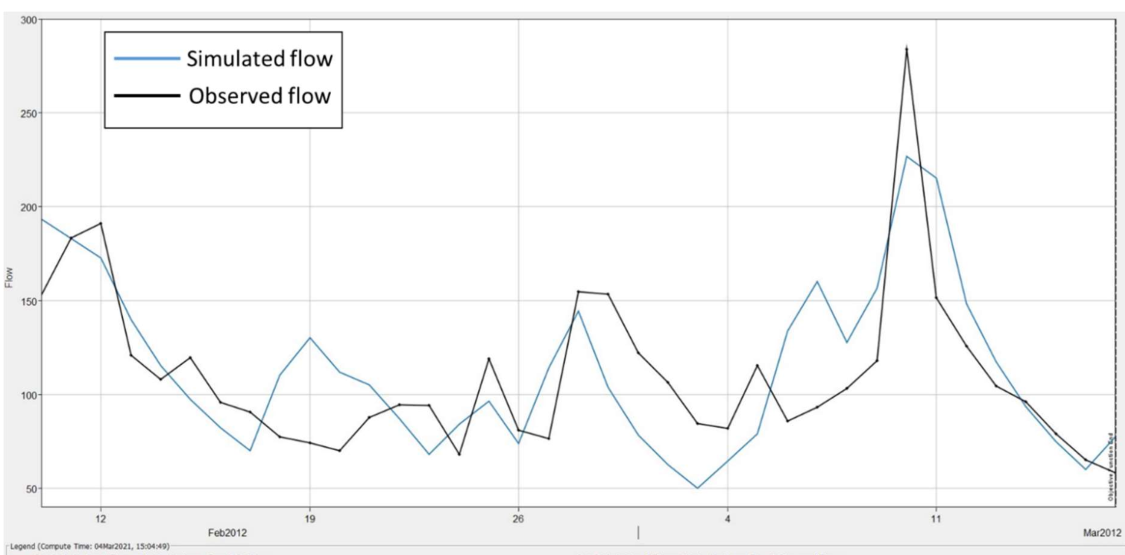

Figure C.4: HEC-HMS® calibration from February 2012 to March 2012 (Calibration 2 – NSE 0.423).

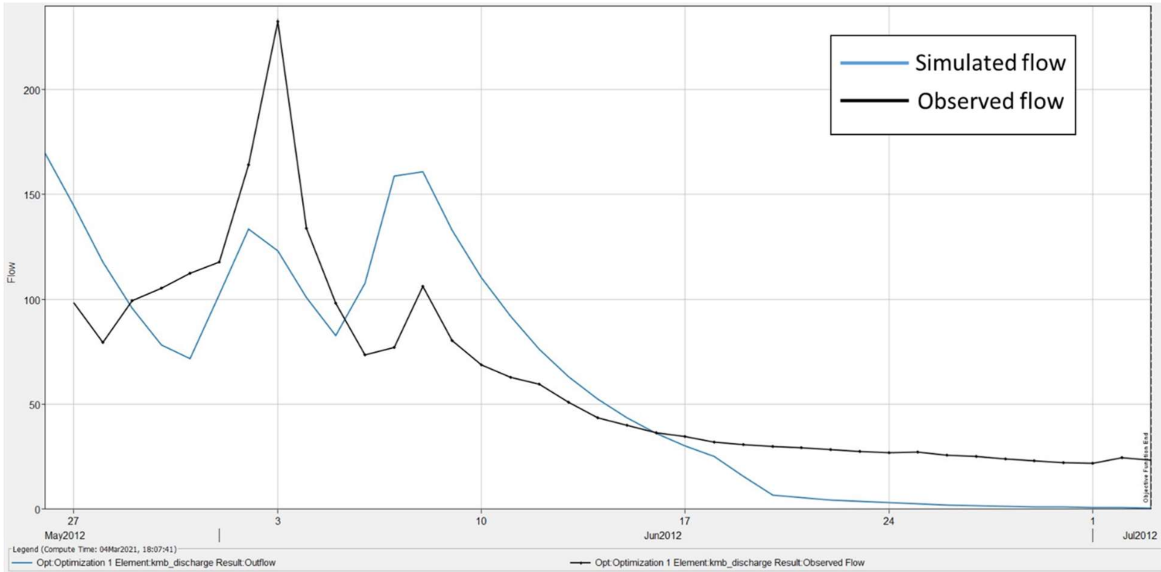

Figure C.5: HEC-HMS® calibration from May 2012 to July 2012 (Calibration 5 – NSE 0.453).

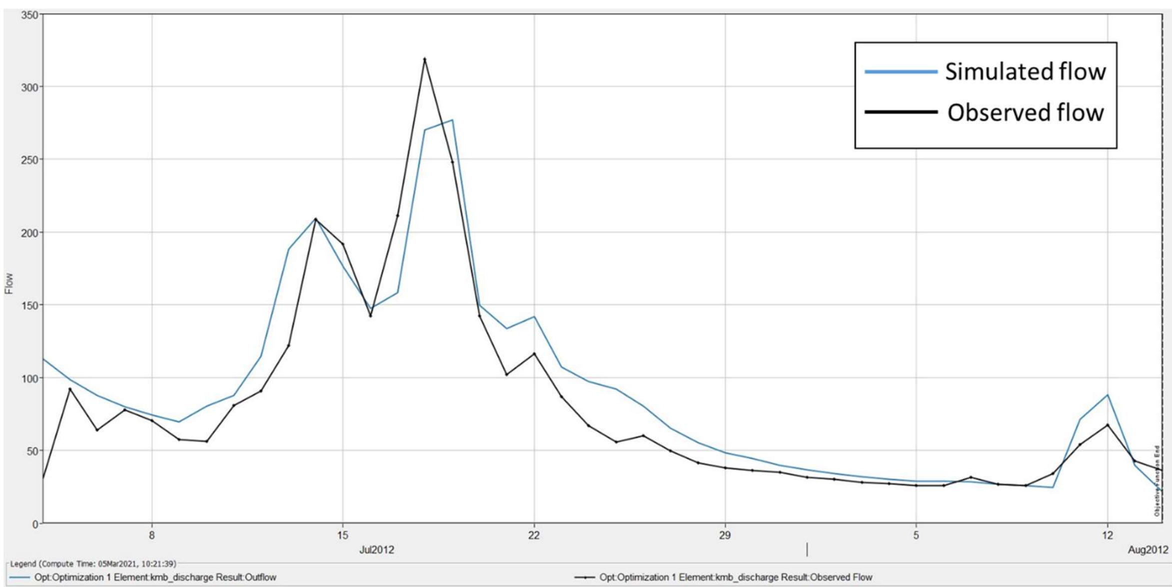

Figure C.6: HEC-HMS® calibration from July 2012 to August 2012 (Calibration 6 – NSE 0.861).

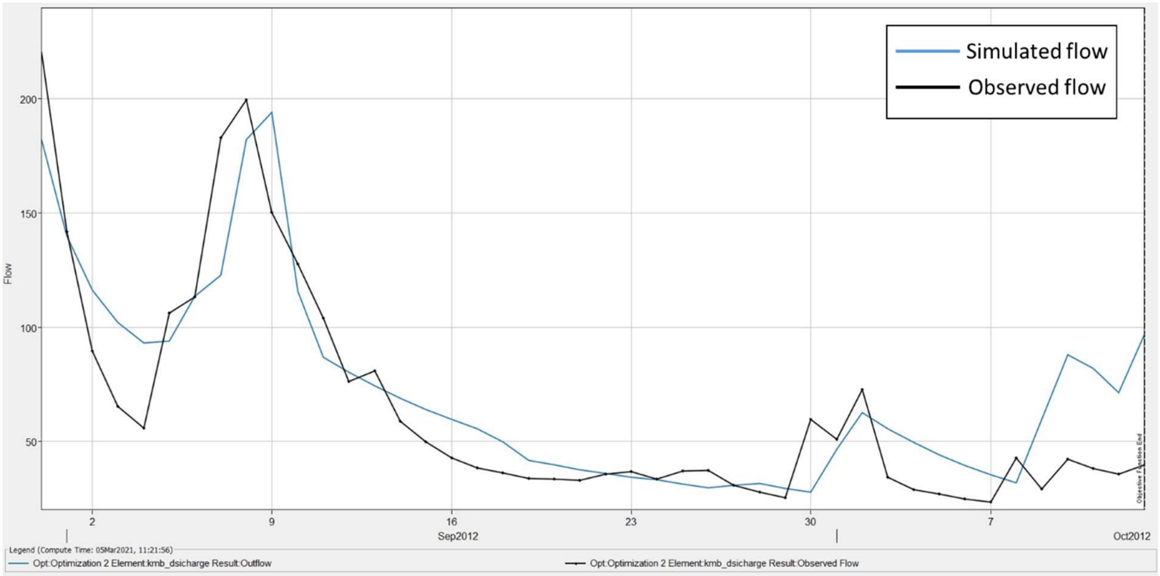

Figure C.7: HEC-HMS® calibration from August 2012 to October 2012 (Calibration 7 – NSE 0.763).

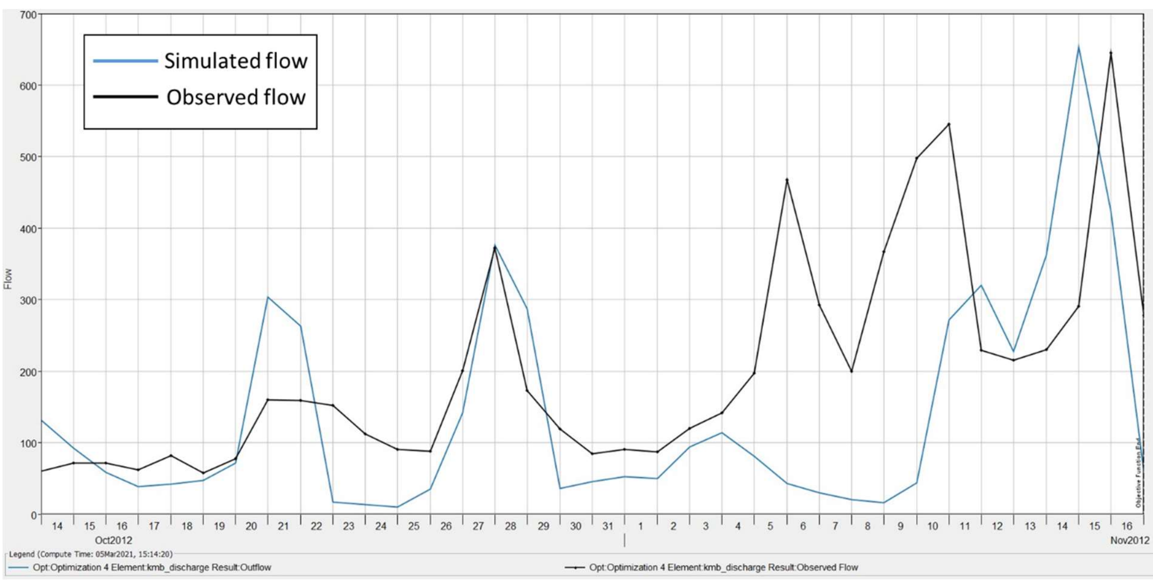

Figure C.8: HEC-HMS® calibration from October 2012 to November 2012 (Calibration 8 – NSE 0.370).

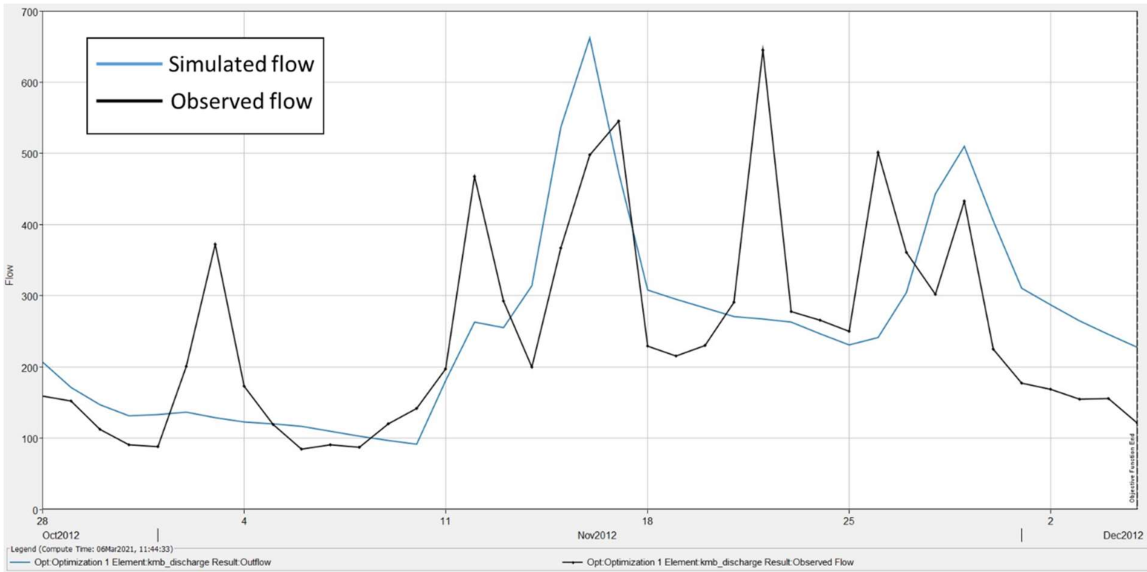

Figure C.9: HEC-HMS® calibration from November 2012 to December 2012 (Calibration 9 – NSE 0.291).

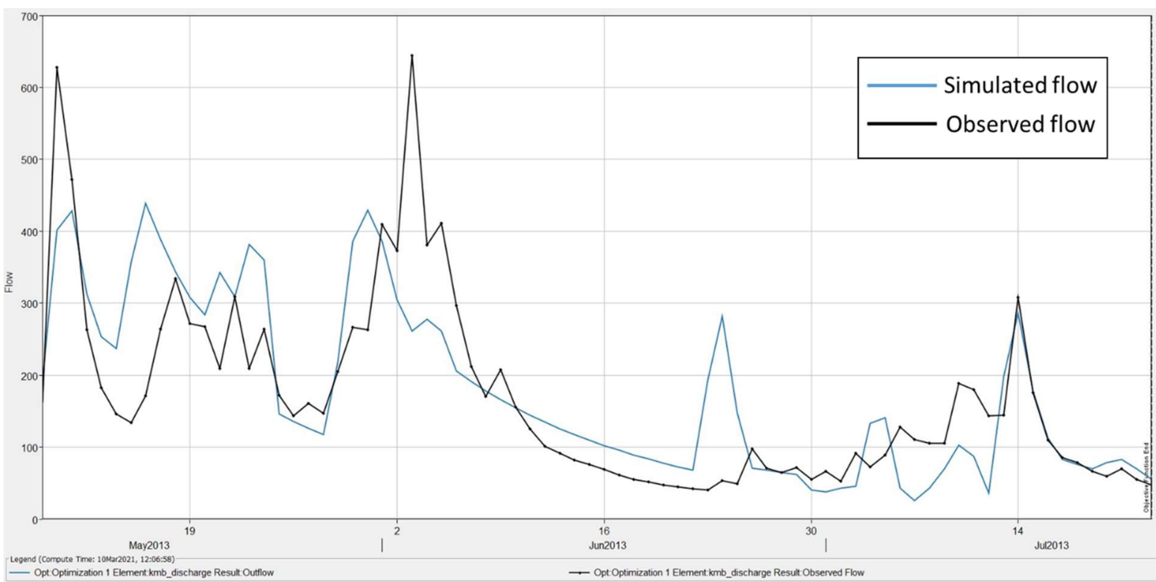

Figure C.10: HEC-HMS® validation from May 2013 to July 2013 (Validation 1 – NSE 0.328).

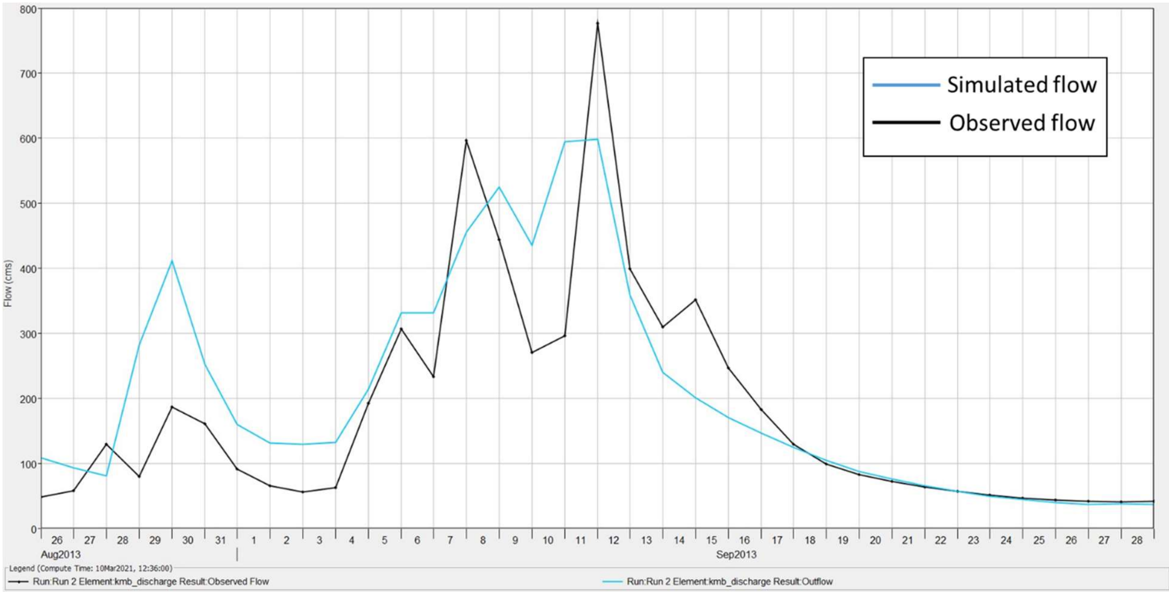

Figure C.11: HEC-HMS® validation from August 2013 to September 2013 (Validation 2 – NSE 0.653).

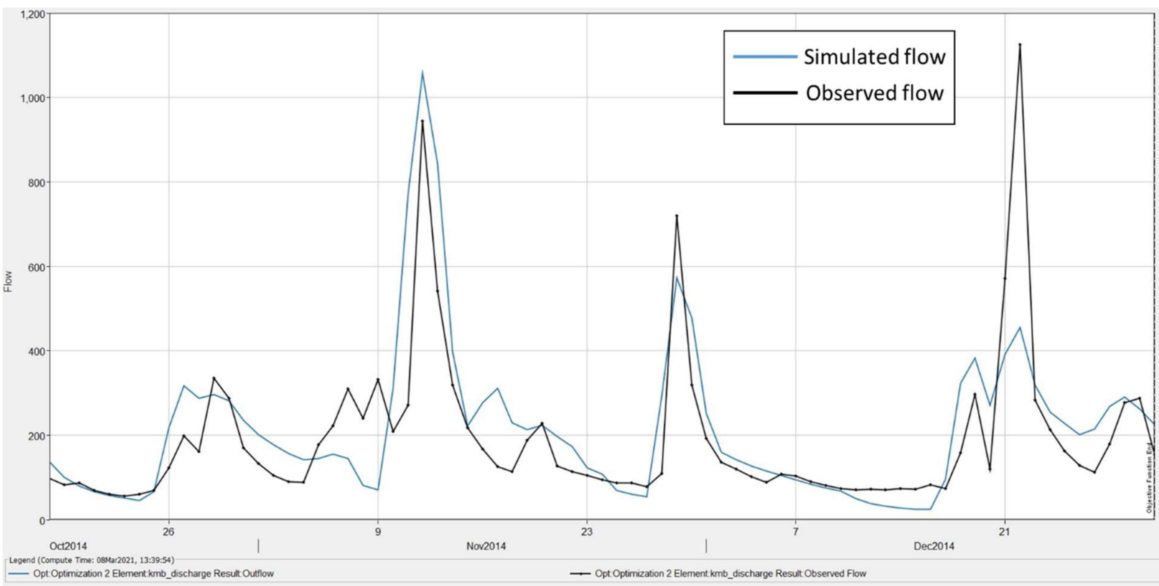

Figure C.12: HEC-HMS® validation from October 2014 to December 2014 (Validation 4 – NSE 0.424).

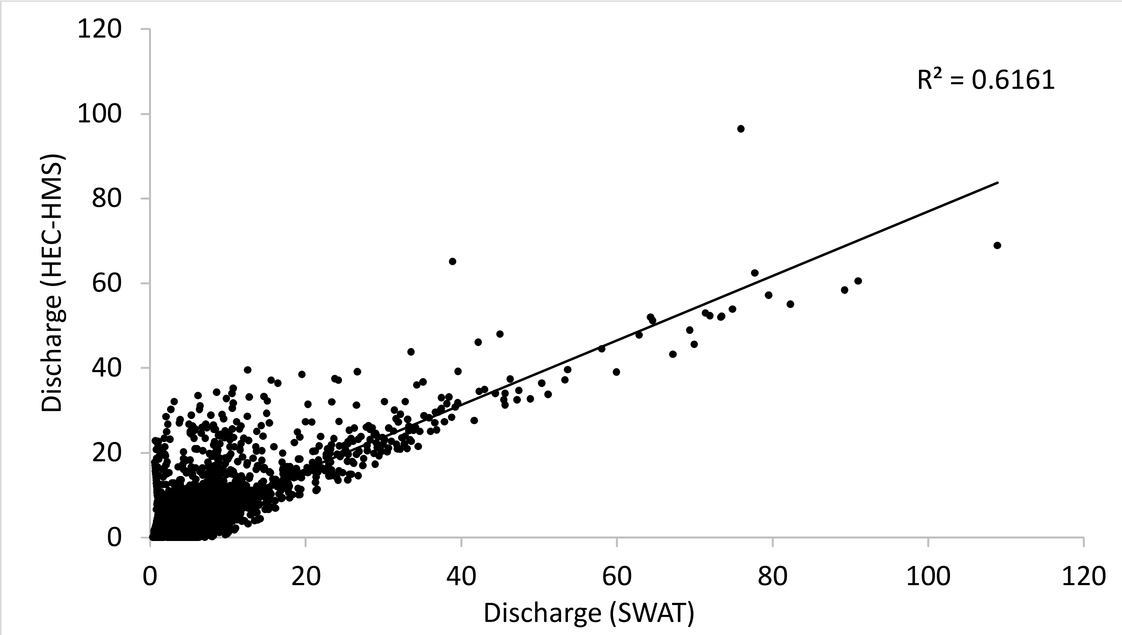

Figure C.13: Simulated runoff comparison between HEC-HMS® and SWAT® (2002-2013).

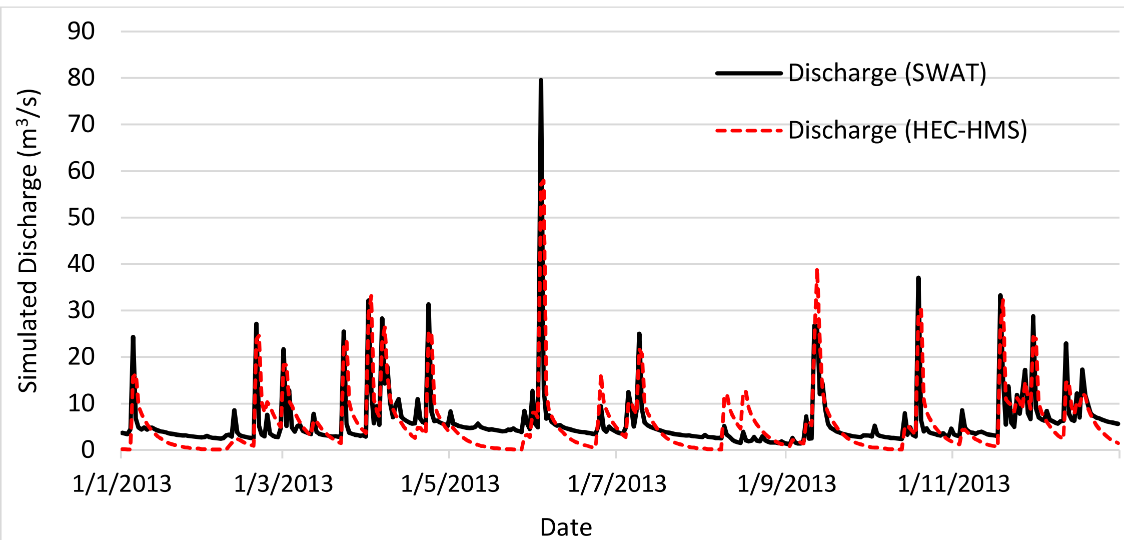

Figure C.14: Long-term runoff simulated using HEC-HMS® and SWAT®.

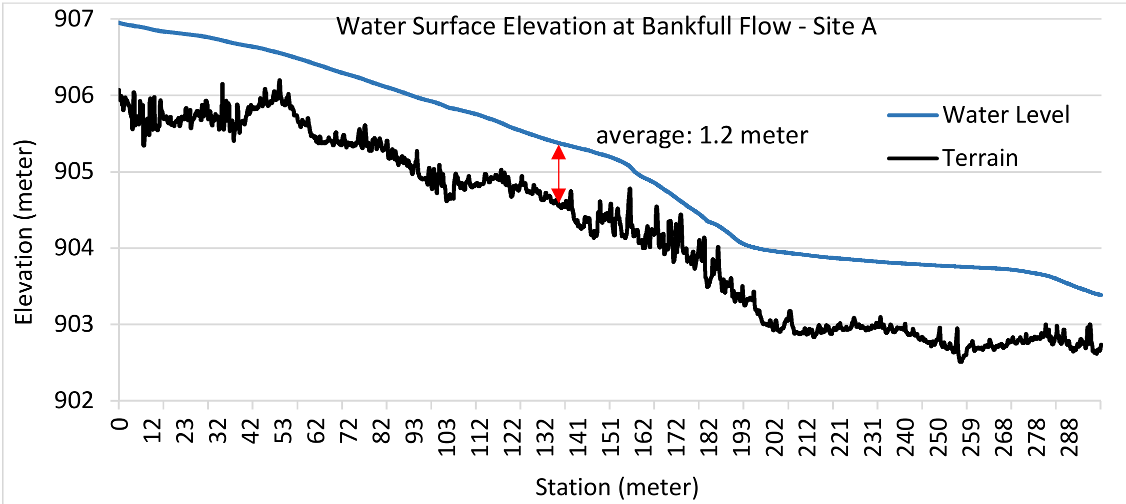

Figure C.15: Estimated water level at bankfull flow at Site A (HEC-RAS®).

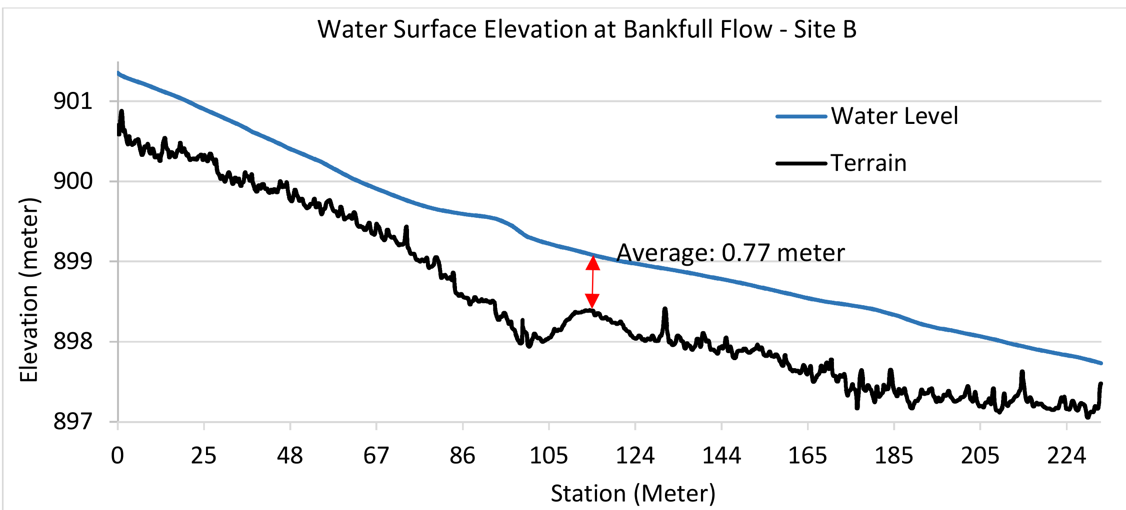

Figure C.16: Estimated water level at bankfull flow at Site B (HEC-RAS®).

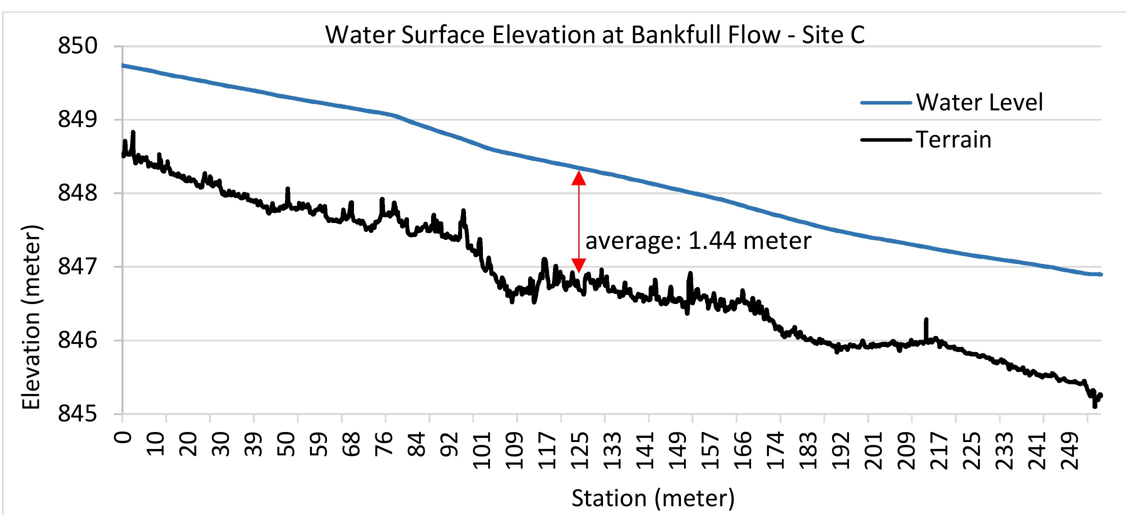

Figure C.17: Estimated water level at bankfull flow at Site C (HEC-RAS®).

APPENDIX D: CORRIDOR SCALE FLOOD MODELLING

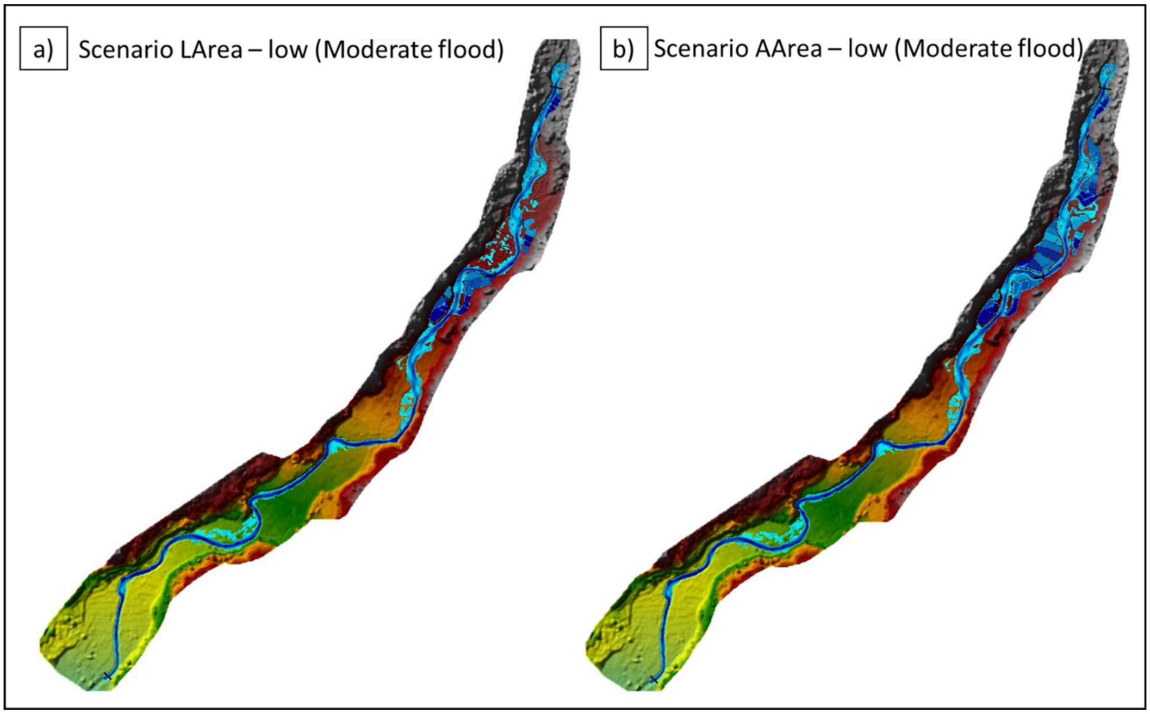

Figure D.1: a) Flood Scenarios LArea – low, and b) AArea - low with moderate flood (HEC-RAS®).

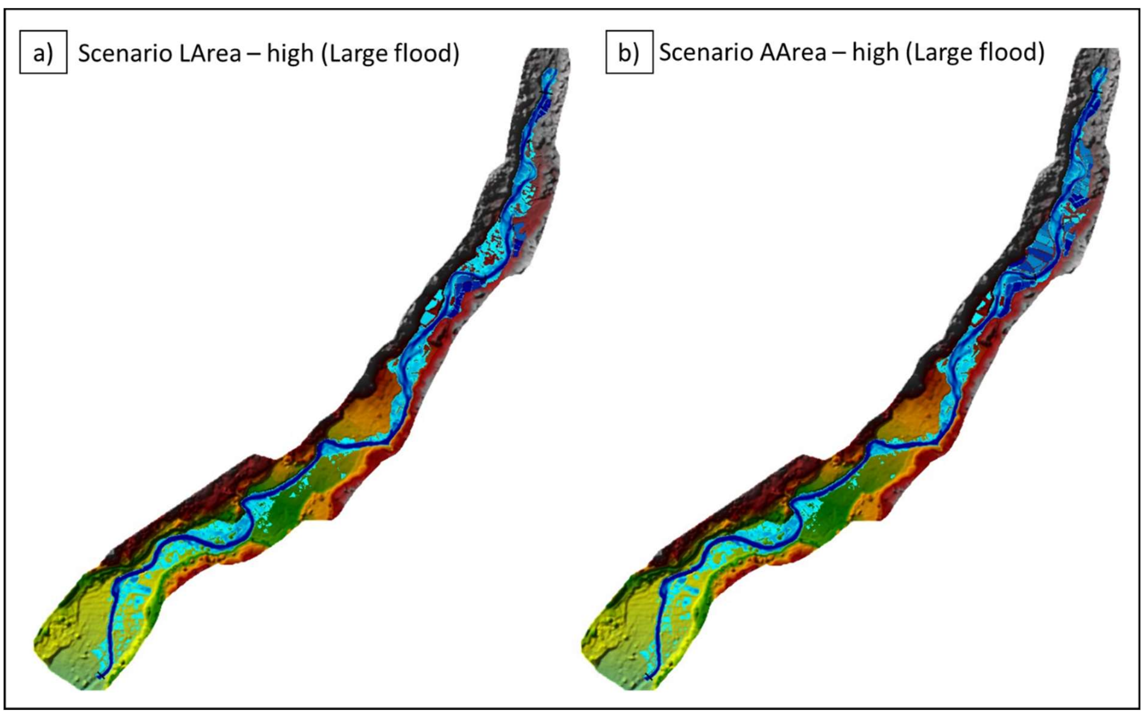

Figure D.2: a) Flood Scenarios LArea – high, and b) AArea – high with large flood (HEC-RAS®).

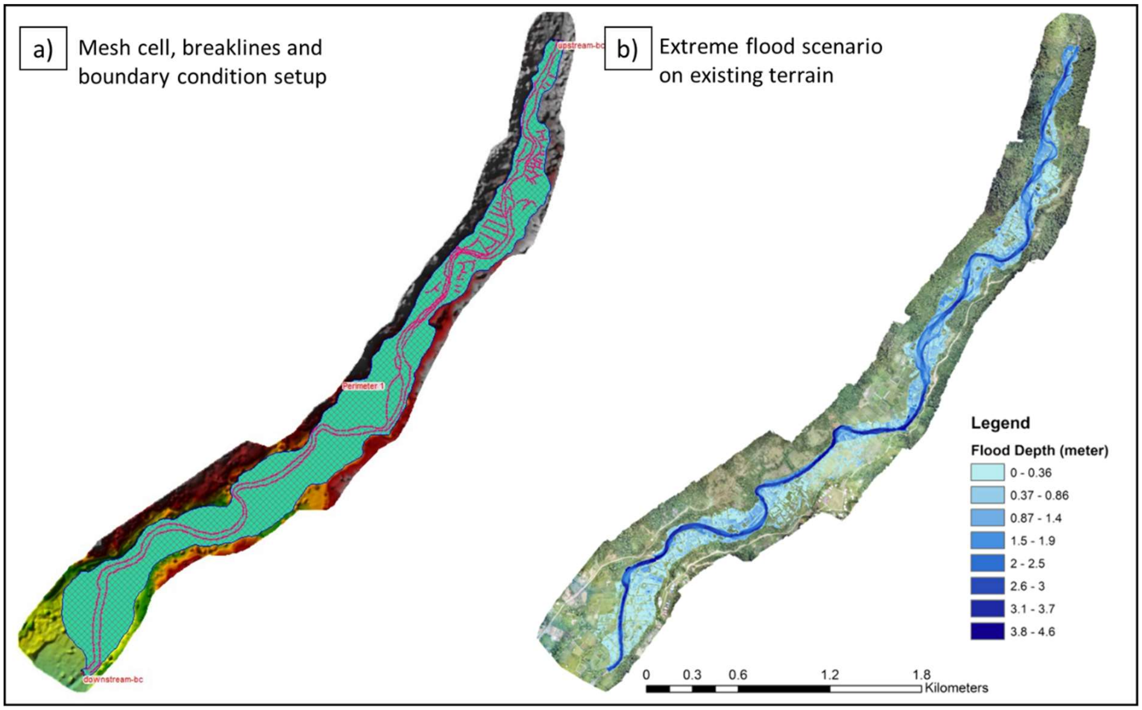

Figure D.3: a) 2D hydrodynamic model setup, and b) Extreme flood scenario (HEC-RAS®).

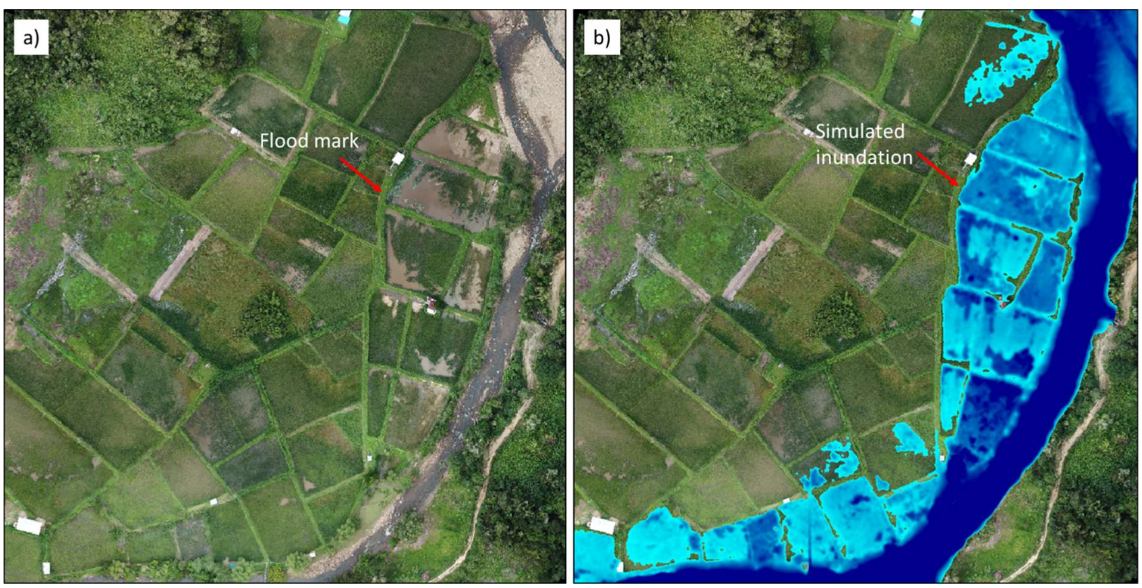

Figure D.4: a) Flood mark captured during aerial survey, b) simulated inundation at extreme flood.

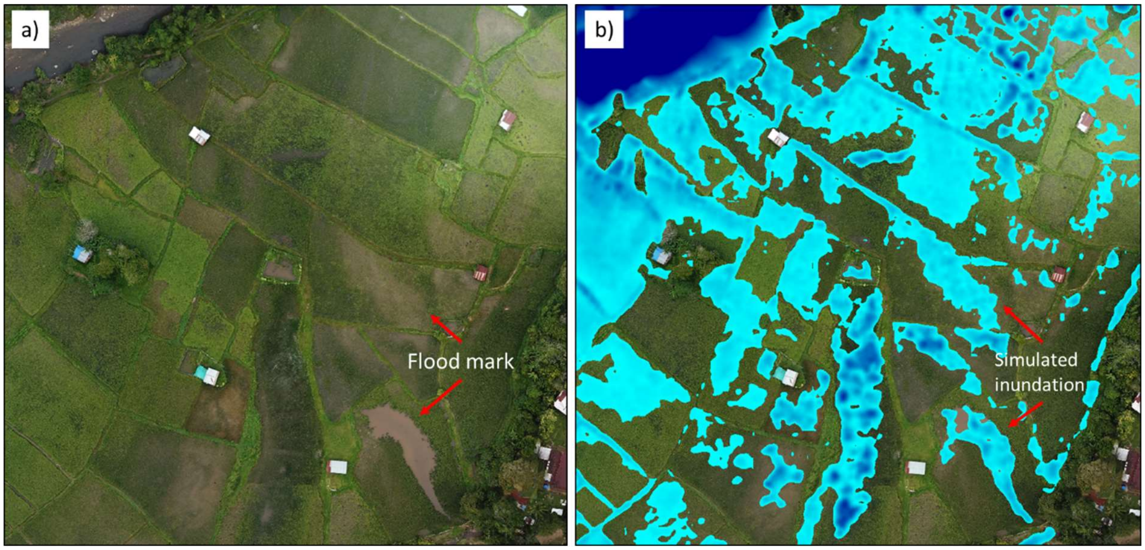

Figure D.5: a) Flood mark captured during aerial survey, b) simulated inundation at extreme flood.

```
                                        HEC-RAS - River Analysis System

 Project File:  e:\Hec-Ras\trusanflood-plot-dem\trusanflood-abandon-low - manning 0.04\trusanflood-abandon.prj
 Project Name:  trusanflood-abandon-low

Plan Name:     plan12-free-lowg-medf

Short ID:      plan12

Starting Time:   05Sep2010 2400

Ending Time:     06Sep2010 2300

                ################################################
                #                                              #
                #                                              #
                #       1D and 2D Unsteady Flow Module         #
                #                                              #
                #                                              #
                #          HEC-RAS 6.2 March 2022              #
                #                                              #
                #             28JUL22 at 20:26:23              #
                #                                              #
                ################################################


                 ***   Volume Accounting for 2D Flow Area in 1000 m^3   ***

           2D Area    Starting Vol     Ending Vol     Cum Inflow    Cum Outflow       Error   Percent Error
           *******    ************     **********     **********    ***********       *****   *************

       Perimeter 1           97.27          267.7          5336.          5165.      0.1772        0.003321


                 ***  Total Volume Accounting (for the entire model) in 1000 m^3   ***

Total Boundary Flux of Water In            5336.
Total Boundary Flux of Water Out           5165.

Starting Volume                            97.27
Ending Volume                              267.7


                             Error   Percent Error
                             *****   *************
                            0.1772        0.003261
```

Figure D.6: Model computational log file generated from HEC-RAS®.

APPENDIX E: LAND COVER CONSERVATION AND MANAGEMENT

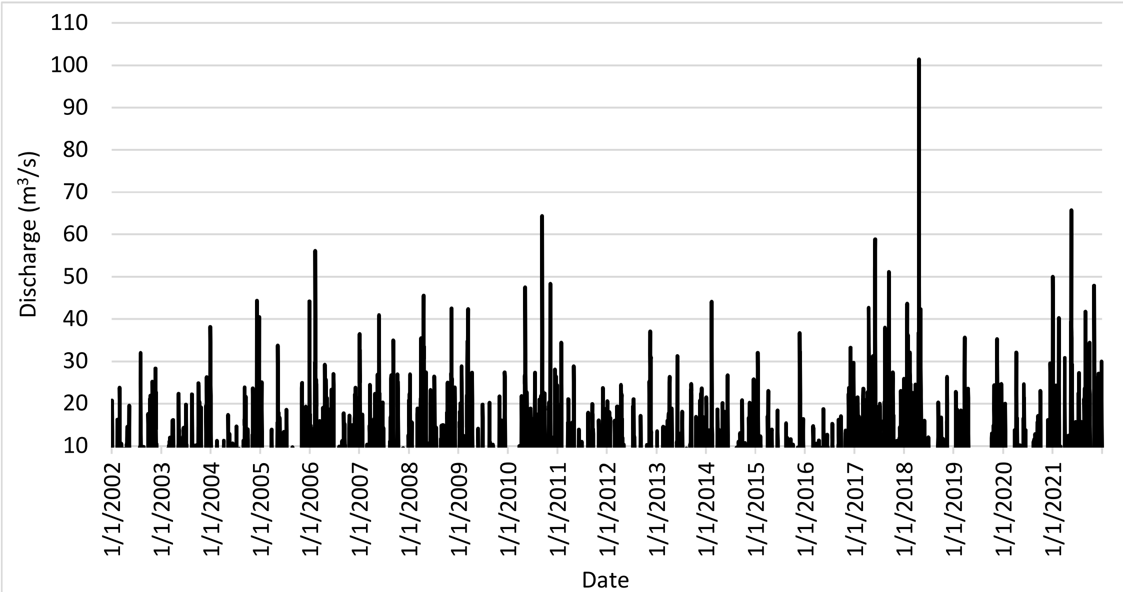

Figure E.1: Long-term hydrograph simulated for the Upper Trusan Catchment (2021 LC) using SWAT®.

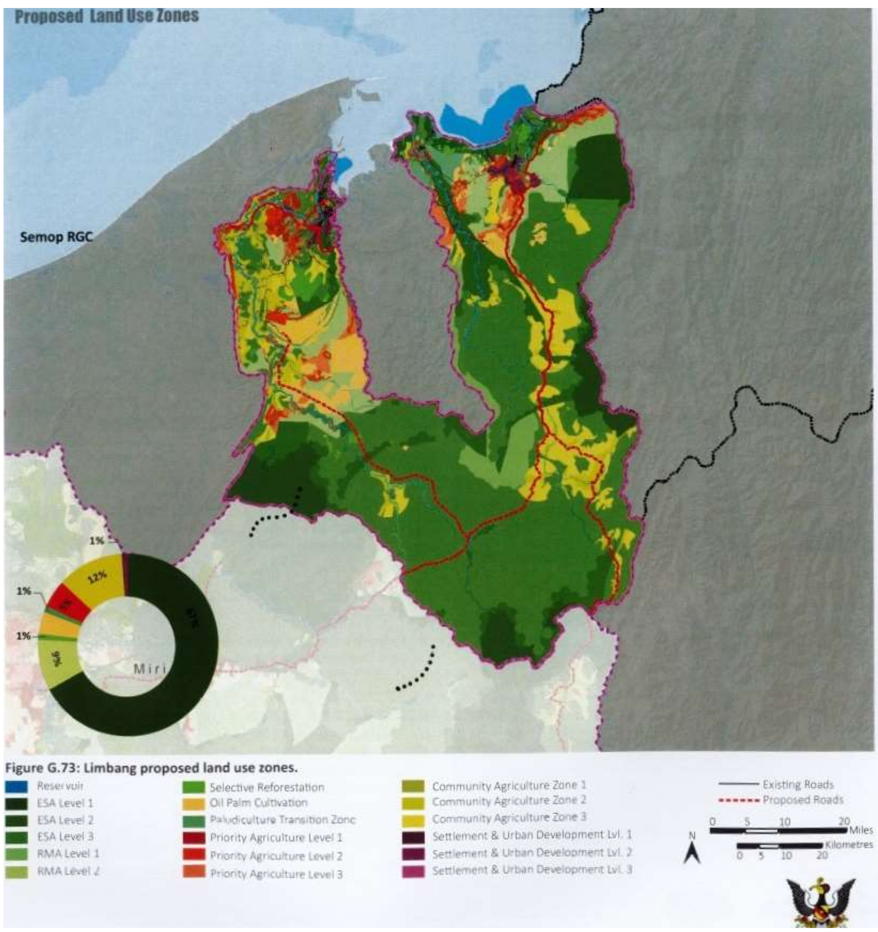

Figure E.2: Proposed Land Use Master Plan for the Limbang district.

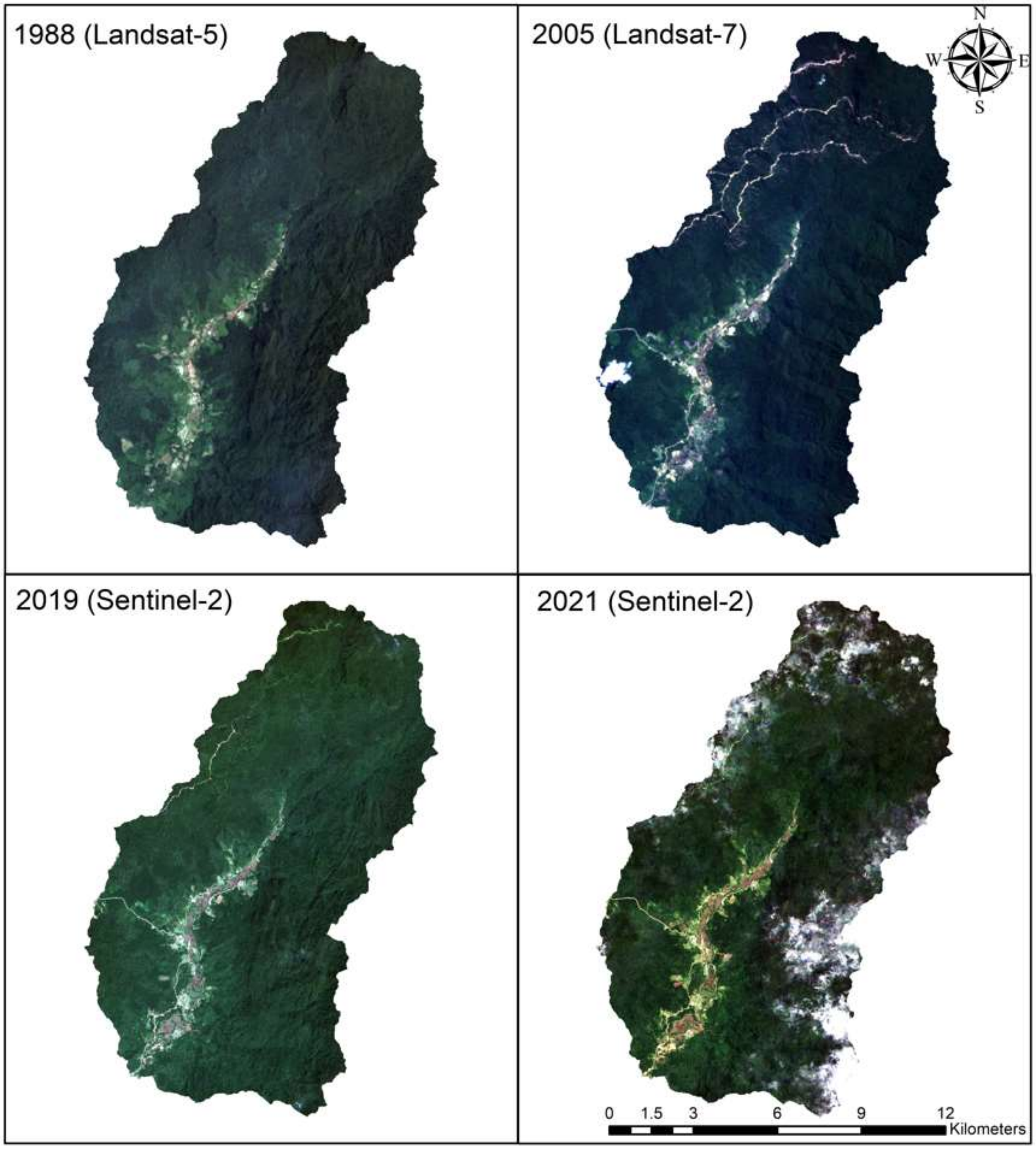

Figure E.3: Satellite images of the Upper Trusan Catchment.