ARCADIS &

DELFT UNIVERSITY OF TECHNOLOGY

FINAL THESIS
MSC CIVIL ENGINEERING
WATERMANAGEMENT

Possibilities And Requirements For A Water Quality Monitoring System In The Ayeyarwady Basin

---

D.W.A. Spaans

July 12, 2021

The work in this thesis was created for the section:

Water Management
Hydrology & Water Resources
Civil, Engineering & Geosciences
Delft University of Technology

Supervisors TU Delft :	Dr. T. A. (Thom) Bogaard, Chairman (CEG)
	Dr. C. J. (Kees) Sloff, (CEG)
	Dr. M. M. (Martine) Rutten, (CEG)
Supervisor company :	T. (Tanya) Huizer, MSc. (ARCADIS)

Acknowledgements

This research was conducted as a graduation project for the Master Water Management at the Delft University of Technology. My interest in the field of international water management resulted in this thesis in which I investigated the possibilities and requirements for a water quality monitoring system in the Ayeyarwady Basin in Myanmar. The complete research was conducted from home due to covid pandemic. Even though this presented a number challenges, I feel the continued support of all involved helped me successfully complete this research.

I would like to thank my graduation committee from the TU Delft for their continued assistance throughout the research process. First of all, I would like to thank Thom Bogaard, chairman of the thesis committee. From the first time we spoke he was enthusiastic about Myanmar and the research into a water quality monitoring system in the Ayeyarwady Basin. During our video calls he provided me with insights that put me in the right direction. He kept me motivated, throughout the developments in Myanmar. Secondly, I would like to thank Kees Sloff, who provided me with technical feedback and experiences from his work in Myanmar. Thirdly, I would like to thank Martine Rutten for completing the committee and her help during the colloquia.

I would also like to thank Tanya Huizer for giving me the opportunity to extend my internship at Arcadis and perform my thesis research with the Myanmar team. I have thoroughly enjoyed working together and have learned so much from her experiences and projects in Myanmar. I would like to thank Johannes de Groot and the rest of the Arcadis Myanmar team for supporting me in finding and using available data for this research. I would also like to thank Arjon Buijert at Arcadis for his assistance with modelling in SOBEK.

Besides professional assistance I have been greatly helped by the moral support of my parents and my brothers. I would like to thank Elise for her patience and support. I am grateful for the experiences that I have gained during my study period and would like to thank all my friends for their involvement in this process.

Diederik Spaans
July 2021

Possibilities And Requirements For A Water Quality Monitoring System In The Ayeyarwady Basin

Diederik W. A. Spaans

Abstract

Myanmar lacks a water quality monitoring system to monitor changes in water quality in the Ayeyarwady Basin. This study aims to find to what extent changes in water quality can be measured in the Ayeyarwady basin and to identify requirements for a water quality monitoring system.

In this study, the current water quality monitoring systems of the Ayeyarwady, Mekong Chao Phraya and Hong (Red) River Basins were compared. Several contamination sources were used to identify contamination scenarios. A river model of the Ayeyarwady and its main tributary, the Chindwin, was made to understand the workings of the river system and the distribution of contaminants throughout the Basin after contamination events.

This study found that contamination is diluted to a high degree over long distances in the Ayeyarwady Basin. At low river discharge, the remaining contamination peak downstream of large contamination events like waste water treatment plant failure or tailings dam failures occurring upstream in the river near the limits of detection. During high river discharge these concentrations can be over 17 times smaller. The study showed that in case of pulse water quality incidents for most common water quality parameters, the monitoring system should have a temporal frequency of once per week with an analytical accuracy of around 0.1 $\mu g/l$. A high-quality monitoring station is required in both river branches just upstream of the confluence of the Ayeyarwady and Chindwin rivers as significant dilution occurs here. Finally, it is crucial to clearly define and distribute measurement responsibility.

Contents

List of Figures

List of Tables

List of Abbreviations

BOD	Biological Oxygen Demand
CS	Citizen Science
COD	Chemical Oxygen Demand
DEM	Digital Elevation Model
DON	Dissolved Organic Nitrogen
DO	Dissolved Oxygen
DWIR	Directorate of Water Resources and Improvement of River Systems (Myanmar)
EC	Electrical Conductivity
FCB	Fecal Coliform Bacteria
GDP	Gross Domestic Product
IWRM	Integrated Water Resource Management
MoNRE	Ministry of Natural Resources and Environment (Vietnam)
MoU	Memorandum of Understanding
NMN	National Monitoring Network
NWRC	National Water Resource Committee
PCD	Pollution Control Department
RMSE	Root Mean Square Error
SDG(s)	Sustainable Development Goal(s)
SOBA	State of the Basin Report
SRTM	Shuttle Radar Topography Mission
T-N	Total Nitrogen
T-P	Total Phosphorus
TSS	Total Suspended Solids
WB	World Bank
WQMN	Water Quality Monitoring Network
WWF	World Wide Fund
WWTP	Waste Water Treatment Plant
YRCC	Yellow River Conservancy Commission

1 Introduction

"The Ayeyarwady river is the lifeblood of Myanmar" [29] and it's importance to everyday life is widely acknowledged. Still, excessive utilisation of the natural resources provided by the river pose a threat to the sustainable development of the country. The Ayeyarwady and it's main tributary, the Chindwin River, are large and long rivers that have flowed through Myanmar for centuries and stretch respectively 2210 and 900 km through Myanmar [41]. With a combined catchment area of over 404,000 square kilometers, "the rivers lie at the economic, spiritual and cultural heart of the country" [42].

The scale of the river basin makes the river system susceptible to a wide variety of contamination sources. At the same time, millions of people rely on the river for irrigation, agriculture, fishing, drinking and transportation. The World Wide Fund (WWF) states that "Without the services provided by the river, Myanmar's economy would cease to exist as it does today, but activities on the river have many negative impacts" [69]. “Siltation from mining operations, results of deforestation, and lack of soil protection ranks the siltation rate in the Ayeyarwady the third highest in the world” [6][45]. The river has been ranked the 9th most polluting river in terms of plastic pollution to the world's oceans [32]. “High levels of arsenic and cyanide are found seasonally in the river” [6]. Reducing the river's exposure to pollution is an important part of achieving the countries SDGs [28] and monitoring the water quality in the river is crucial to be able to reach these. However, monitoring water quality is complex due to it's situational dependency and the multitude of quality parameters that need tracking [11].

Currently, "most countries in South-East Asia have no country-specific tools for monitoring river health" [49] and Myanmar is no exception. Following the Memorandum of Understanding (MoU) that was signed in 2013 by The Netherlands and the government of the Union of the Republic of Myanmar to cooperate on integrated water resource management (IWRM) [16], the National Water Resources Committee (NWRC) has developed a National Water Policy. Research was conducted to build a basis for the Myanmar National Water Master Plan to plan for sustainable water management. It was indicated by the Dutch consortium that there is a shortage of reliable data and knowledge and that "Water quality should be controlled based on set standards, and standards should be enforced" [46][48]

Research from The World Bank identified three major water quality indicators for SDG 6.3.2 (Proportion of bodies of water with good ambient water quality): "nitrogen, electrical conductivity (EC) as a measure of salinity in water; and biological oxygen demand (BOD)" [11][60]. In 2019 a low-cost water quality measurement system using a participatory approach was designed by researchers at the TU Delft [51]. The researchers concluded that the measurement results of the volunteers using the simple and low-cost measurement techniques were accurate for sensor-based EC measurement and transparency measurements. They found that the measurements taken by volunteers for these parameters were comparable to the measurements of experienced lab technicians that perform a yearly water quality survey whilst also having a higher frequency. Their findings indicated that a part of water quality parameters can be monitored in a way that is reliable and cost-effective. However, these measurements do not measure other water quality parameters such as pharmaceuticals, fertilizers, micro-organisms, oils, and heavy metals. Monitoring the change in concentrations of these substances throughout the river is crucial to identify environmental threats and maintain a safe and sustainable river system for the future.

To further increase the knowledge of the water quality in Myanmar's rivers and to decrease the deficit of reliable data as was advised by the Dutch consortium, a more comprehensive monitoring system is needed. The research objective is *'to find to what extent contamination events in the Ayeyarwady River system can be measured downstream and to find the requirements for a water quality monitoring system in the Ayeyarwady basin'.* Based on a literary study, the water quality monitoring systems of six rivers in South-East Asia are compared including the Ayeyarwady and Chindwin. A model of the Ayeyarwady and its main tributary, the Chindwin River, is created to model the river flow in the river basin. Using this model, the distribution of contaminants throughout the river system is modelled using artificial tracers. The results of this research can assist policy makers to determine requirements for a water quality monitoring system in the Ayeyarwady basin.

The research design and methods used in this research are presented in chapter 2. Here, four research components are identified. Chapter 3 presents the results for the first component: 'comparing water quality monitoring systems in comparable rivers'. Chapter 4 presents the results of the second component: 'identifying contamination scenarios in the Ayeyarwady basin'. Chapter 5 presents the third component: 'river system model of the Ayeyarwady Basin'. Chapter 6 presents the results for the fourth components: 'Ayeyarwady Basin Measurement System Performance'. In chapter 7 the research limitations and opportunities are discussed. Conclusions into what extent contamination events in the Ayeyarwady River system can be measured downstream and requirements for a water quality monitoring system in the Ayeyarwady basin are presented in chapter 8.

2 Research Design & Methods

This research was divided in four research components: comparing water quality monitoring systems for five different river systems in Southeast Asia, identification of contamination scenarios for the Ayeyarwady and Chindwin rivers, building a model of the Ayeyarwady and Chindwin rivers system and an analysis of the monitoring system performance. This chapter describes the design of the four research components and the methods that were used during the research. Figure 1 shows an overview of the four components that forms the basis for this research and the way in which the four components are structured. The research objective is to find to what extent contamination events in the Ayeyarwady River system can be measured downstream and to find the requirements for a water quality monitoring system in the Ayeyarwady basin.

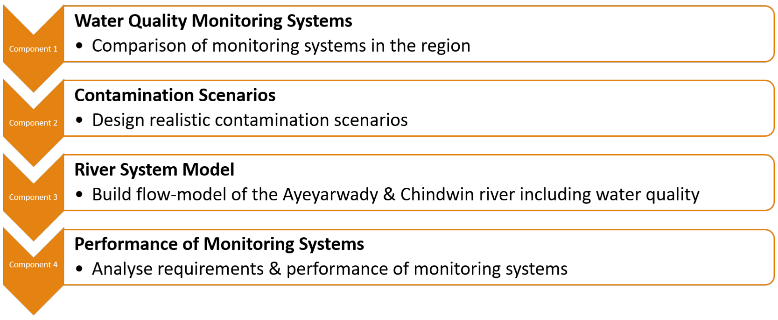


Figure 1: Research structure: four consecutive research components. *First, an analysis on water quality monitoring systems in the region is performed followed by the identification of contamination scenarios in the Ayeyarwady river. Consecutively, a flow and water quality model is built of the Ayeyarwady basin. Finally, the scenarios are implemented in the model to find to what extent a monitoring system can measure contamination in the Ayeyarwady basin.*

The first of the research components aims to get an understanding of water quality monitoring systems in the region (chapter 2.1). By means of a literature research of existing water quality monitoring systems in four river systems, water quality monitoring practices and current water quality monitoring systems in river systems in South-East Asia were compared. The second component is the identification of contamination scenarios to model sources of contamination in the river system (chapter 2.2). The third component consists of the building of a model of the Ayeyarwady and Chindwin river systems and is described in chapter 2.3. A river flow model was built and combined with a water quality module to enable the modelling of tracers in the river system. The fourth component is the analysis of the performance of a water quality monitoring system. Using the contamination scenarios identified in research component two, the distribution of contamination in the Ayeyarwady basin was modelled with the river model that was built for component three. Based on the results, requirements for a water quality monitoring system in the Ayeyarwady and Chindwin were identified. The analysis of the monitoring system performance is described in chapter 2.4.

2.1 Component 1: Comparing Water Quality Monitoring Systems in Comparable Rivers

The first research component of this research is to identify what kinds of water quality monitoring systems are present in four geographically comparable river systems. This part of the research compares the current water quality monitoring system in the Ayeyarwady basin to the water quality monitoring systems that are currently implemented and used in three other river systems in Southeast Asia. This analysis of monitoring systems provides a first insight into the possibilities and requirements regarding a water quality monitoring system in the Ayeyarwady Basin.

In this component of the research project, water quality monitoring systems in the Ayeyarwady Basin and three other river systems in the Southeast Asia region were analysed and compared. The following rivers were part of this research:

- Ayeyarwady & Chindwin (main tributary)
- Mekong
- Chao Prahya
- Hong River (Red River)

The aim of analysing the water quality monitoring systems in these rivers was to get a general understanding of the water quality monitoring system needed. It was established what monitoring systems are currently in place to measure and monitor water quality. When this was determined these systems are analysed in more depth. Firstly, it was determined where these measurements are taken. Secondly, it was determined what the monitoring system measures. What kind of parameters are measured and with what accuracy are they measured? Thirdly, it was determined when and with what frequency the measurements are taken. Finally, it was determined who takes these measurements and who is responsible for taking these measurements. To summarise: to get an understanding of the monitoring systems, the monitoring systems were analysed on these factors:

- Where is it measured?
- What is measured?
- When is it measured?
- Who measures it?

2.2 Component 2: Identifying Contamination Scenarios in the Ayeyarwady Basin

The second research components aims to identify realistic contamination scenarios that can be modelled to show to what extent contamination events occurring in the Ayeyarwady river basin can be measured downstream. The scale and importance of the river basin for livelihood makes the river system susceptible to a wide variety of contamination sources. This underlines the importance that the water quality of the rivers is monitored. To know what kind of monitoring is effective in the river system, it is crucial to know what potential sources cause contamination in the rivers. In this research component, scenarios of river contamination will be identified. To be able to compare the performance of water quality monitoring systems, these scenarios need to be realistic. The research on contamination scenarios was divided into several tasks:

1. Identification of contamination sources
2. Identification of required measurements
3. Determination of scenarios

2.3 Component 3: River System Model of the Ayeyarwady and Chindwin Rivers

For the third research component a model of the river system was produced to provide insight in the workings of the river system. To be able to identify an effective monitoring system for the Ayeyarwady and Chindwin rivers, it is crucial to understand the workings of the river system. The model gives insight in processes like advection and diffusion that affect contaminant distribution in the river. At present, some models already exist for parts of the Ayeyarwady river. Most of these models cover parts of the Ayeyarwady Delta and focus mainly on river flow, flooding, and morphology. Some of the models were made of areas in the Ayeyarwady north of the Delta. One of these models covers an area from Mandalay southward to the confluence of the Ayeyarwady and Chindwin. one of these models covers an area from Mandalay southward to the confluence of the Ayeyarwady and Chindwin. Possibly additional models were created of the Ayeyarwady basin for private project purposes by the other companies or institutions, but these were expected to be created at a similar spatial scale as the models described before and focus on morphology and flooding. A model combining river flow and river quality on a larger spatial scale has not yet been created for the Ayeyarwady basin.

The building of the model is divided into several tasks:

1. Building of the river flow model
2. Expanding the model with water the quality module

The model was made in the modelling suite SOBEK. SOBEK is a modelling suite developed by Deltares that is "an integrated software package for river, urban or rural management" [12] and is used to model "flood forecasting, optimization of drainage systems, control of irrigation systems, sewer overflow design, river morphology, salt intrusion and surface water quality" [13]. A SOBEK model was made that models the river flow and the distribution of several water quality parameters in the river. The model provides quantitative data that was used to identify to what extent contamination is measurable downstream and the requirements for the water quality monitoring system in the Ayeyarwady Basin.

The water quality module of SOBEK was used to integrate the water quality parameters into the model. The contamination was modelled in the form of tracers. Primarily, this prevented the model from being excessively complex from the start. To make the modelled contamination substance represent more processes and therefore approach a better representation of reality, reactive tracers were also released in the model. Observation locations and contamination scenarios were implemented into the model. The performance of the water quality monitoring system can be assessed for each of the observation locations.

2.4 Component 4: Ayeyarwady Basin Monitoring System Performance

In the final component of this research the different contamination scenarios were implemented in the model to compare to what extent contamination is measurable at the different observation locations in the Ayeyarwady Basin. The performance of the water quality monitoring system was assessed by its respective ability to measure contamination in the river. It was assessed to which extent the contamination caused by the contamination scenarios is present in the river at the measurement locations. When contamination is present in the river it was assessed what kind of measurement equipment would be needed to monitor the contamination there. This was done in terms of measurement accuracy as well as measurement frequency.

3 Comparing Water Quality Monitoring Systems in Comparable Rivers

This chapter describes the results from the first of the research components. As discussed in chapter 2.4, the first component is the analysis of water quality monitoring systems in the Ayeyarwady and its main tributary the Chindwin, as well as the Mekong, Chao Prahya and Hong (Red) rivers. All rivers are geographically located in Southweast Asia. The water quality monitoring systems of these rivers that are currently implemented and used were analysed and compared. It was determined where measurements are taken, what kind of parameters are measured and with what accuracy they are measured, with which frequency the measurements are taken and who is responsible for taking these measurements. To summarise: to get an understanding of the monitoring systems, the monitoring systems were analysed on these factors:

- Where is it measured?
- What is measured?
- When is it measured?
- Who measures it?

Results for the analysis of the monitoring system of the Ayeyarwady and Chindwin rivers are shown in chapter 3.1. Results for the analysis of the Mekong, Chao Phraya and Hong River are shown in respectively chapter 3.2, 3.3, 3.4. Chapter 3.5 presents the similarities and differences between the compared monitoring systems.

3.1 Ayeyarwady Basin

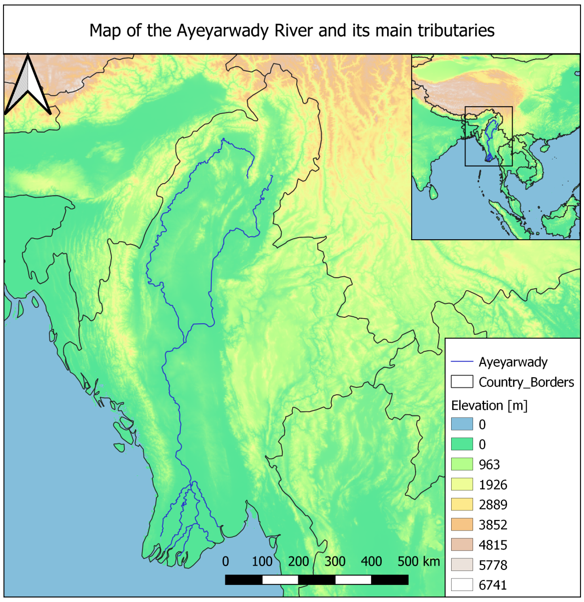


Figure 2: Map of Ayeyarwady and Chindwin rivers *The Ayeyarwady flows from the northeast towards the Ayeyarwady Delta in the south. The Chindwin flows from the north and joins the Ayeyarwady at the confluence in the center.* [2][38]

First, an analysis was carried out on the water quality monitoring system of the Ayeyarwady and it's largest tributary: the Chindwin river. To draft requirements for a future water quality monitoring system it is crucial to understand what monitoring systems are already in place and to identify what parameters are and are not measured regularly. Both the Ayeyarwady and Chindwin river are shown in figure 2. The Ayeyarwady springs from the north of Myanmar in the Himalayan mountains and flows towards the south. The main tributary of the Ayeyarwady, the Chindwin river, flows west of the Ayeyarwady from the northern part of the country towards the middle, where it joins with the Ayeyarwady. From here, the combined Chindwin and Ayeyarwady rivers flow, named as the Ayeyarwady, towards the south until it splits into multiple branches, becoming the Ayeyarwady Delta. Eventually the river branches of the delta discharge into the Andaman Sea. One of the main interesting features of the Ayeyarwady river basin is that almost all of the drainage basin lies within the borders of Myanmar.

Ayeyarwady

The Ayeyarwady river is called the life-blood of Myanmar and flows through the heart of the country. Interestingly the river's economic, spiritual and cultural importance to the people that make use of the river's water, is not resembled by the countries ability to monitor the water quantity and quality that flow through the river basin. Though a multitude of (governmental) organizations have taken up the task of monitoring water quality, most only measure on behalf of their own objectives. This was observed by Thatoe Nwe Win, Bogaard and van de Giesen as: "The monitoring is haphazard, short term and based on individual interest and the available equipment" [50]. Most of the measurements are taken in the delta by and at locations where an office of the Directorate of Water Resources and improvement of River Systems (DWIR) is present. Some basic monitoring is performed in the Ayeyarwady river. Annually basic water quality parameters are measured by DWIR. The extent of the measured parameters is shown in table 1 and appendix A.

Chindwin

The Chindwin river is the largest tributary of the Ayeyarwady river and joins the river south-east of the city of Mandalay. The river is an important source of (drinking) water for domestic use and agriculture. The river is also used for logging and mining activities along the river's shores [40]. Because of the active use of land around the Chindwin river some measurements have been performed on the water quality in the river. As the Chindwin is part of the Ayeyarwady basin, the same organizations perform and are responsible for taking measurements as in the Ayeyarwady River. The measurements performed annually by DWIR are presented in table 1 and appendix A.

3.2 Mekong Basin

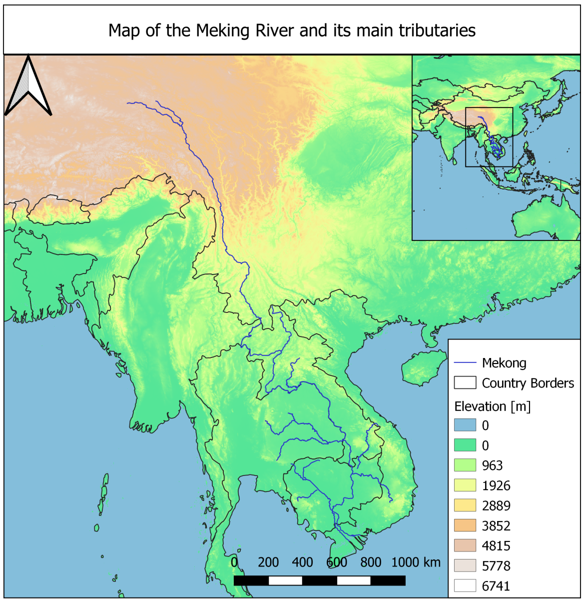


Figure 3: Map of the Mekong river [2][38].

The Mekong river is a trans-boundary river that flows from the Tibetan Plateau through China, Myanmar, Laos and Thailand until it reaches it's delta in Vietnam and flows into the South China Sea. With it's length of 4880 km it is the world's twelfth longest river. The Mekong River Commission member countries established a Water Quality Monitoring Network (WQMN) in 1985 "to be able to detect changes in water quality and take preventive and remedial actions" [52]. Up to 90 stations have provided a continuous (bi-)monthly record of water quality parameters of which 48 stations have been classified as primary stations. Because the Mekong river is a trans-boundary river, responsibility for water quality measurements is divided between the member countries where each country is responsible for routine water quality monitoring, data management in accordance with the agreed format and publishing an annual water qualityn data assessment report. Sample handling (sampling, preservation, transportation and storage) is done in "accordance with methods from the 'Standard Methods for the Examination of Water and Wastewater' or complying with the requirements of method validation of ISO/IEC 17025-2005".[52]

Table 1 shows the different analytical parameters that are monitored at the different locations in the Mekong river. The recommended analytical methods for each of the measured parameters is presented in appensix A.

3.3 Chao Phraya Basin

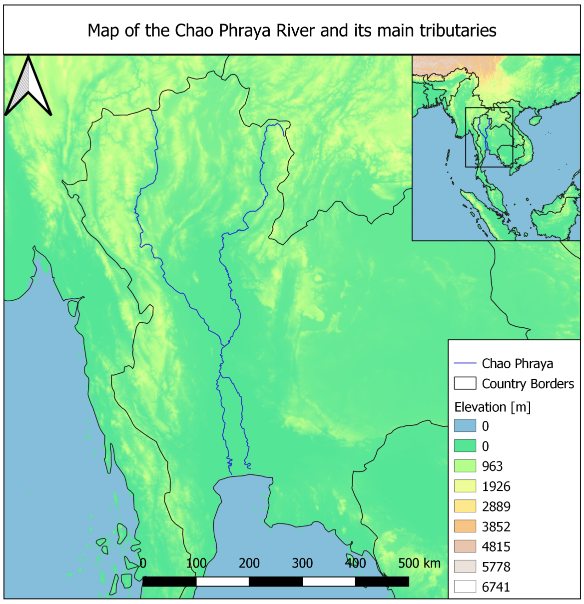


Figure 4: Map of Chao Phraya river and main tributaries [2][38].

The Chao Phraya is the main river in Thailand. The river's main tributaries are the Pa Sak river, Sakae river, Nan river, Ping river and the Tha Chin river. The river flows from the north of the country through the city of Bangkok after which it discharges into the Gulf of Thailand. Simmilar to Myanmar, the tributaries of and the Chao Phraya river itself do not cross the borders of the country. The old name for the river '*Mae*' (mother) '*Nam*' (river), signifies the importance of the river to the country. Because of this the river is referred to as the 'river of kings'. Different to the largely unmodified Ayeyarwady river is that the the lower Chao Phraya has been modified by the creation of man-made shortcut channels. The channels have changed and shortened the course of the river and were constructed between 1538 and 1722.

Water quality monitoring is performed in the Chao Phraya river since 1981 by the Pollution Control Department (PCD). There are 16 monitoring stations along the river that measure approximately 2-4 times a year. "Samples are collected using the stratified random sampling method, preserved, and sent for laboratory analysis following Standard Methods for the Examination of Water and Wastewater" [47]. Table 1 and appendix A show the parameters that are monitored by the PCD in the Chao Phraya river.

3.4 Hong (Red) River Basin

The Hong river, also known as the Red river, is the second largest rivers in Vietnam. Its main tributaries are the Black (Da) river and Lô river. It stretches 1149 km from South-West China an flows mainly southeastwards through Vietnam. Eventually the river forms the Hong River Delta where it flows past the city of Hanoi and into the Gulf of Tonkin.

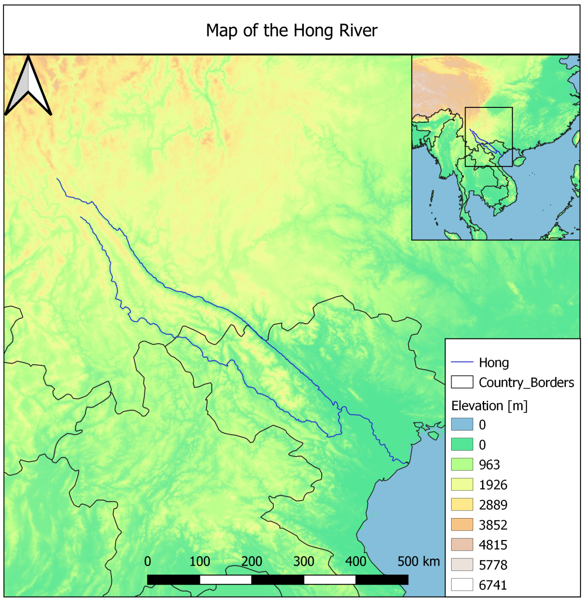


Figure 5: Map of Hong river and main tributaries [2][38].

The government of Vietnam set up the National (Environmental) Monitoring Network (NMN) in 1995 to measure water quality parameters in four rivers in Vietnam (Red River, Cam river, Huong river and Saigon river) under supervision of the Ministry of Natural Resources and Environment (MoNRE). MoNRE is "responsible for water resource management, water environment protection and pollution control" and the NMN established up to 21 monitoring stations up to 2002 [10]. This network was expanded to 45 stations in later years that monitors water quality every month. Table 1 and appendix A shows the parameters that are being monitored by the National Monitoring Network. Though basic measurements are performed, quality and access to information are still considered poor. [17][53].

Table 1: Overview of annual measurements in the different river systems. *Basic water quality parameters are measured annually by the responsible entities.*

Parameters	Measuring Unit	Ayeyarwady Basin	Mekong Basin	Chao Phraya Basin	Hong Basin
Alkalinity	mg/L	x	x		
Ammonia	mg/L	x	x		x
Bicarbonate	mg/L				x
Biological Oxygen Demand	mg/L		x	x	x
Calcium (Ca)	mg/L		x		x
Chemical Oxygen Demand	mg/L		x		
Chloride	mg/L	x	x		x
Chlorine	mg/L	x			
Dissolved oxygen	mg/L	x	x	x	
Electrical conductivity	mS/m		x	x	
Faecal Coliform	mg/L		x	x	
Fluoride	mg/L	x			
Hardness	mg/L	x			
Iron	mg/L	x			x
Lead	mg/L			x	
Magnesium (Mg)	mg/L	x			x
Mercury	mg/L			x	
Nitrate	mg/L	x		x	
Nitrite	mg/L	x			
pH	mg/L	x	x	x	x
Phosphate	mg/L	x			
Potassium	mg/L		x		x
Salinity	mg/L			x	
Silicon Dioxide	mg/L				x
Sodium	mg/L		x		x
Sulphate	mg/L		x		x
Temperature	C^o		x	x	x
Total Nitrite and Nitrate	mg/L		x		
Total Nitrogen	mg/L		x		
Total phosphorous	mg/L		x	x	
Total Suspended Solid	mg/L		x		
Turbidity	NTU	x			x

3.5 Measurement Systems: Similarities And Differences

Monitoring, Responsibility and data accessibility
In the Mekong, Chao Phraya and the Hong (Red) River, the water quality is monitored by an organized monitoring network. In these organized systems, a single entity has the final responsibility that the water quality (and quantity) are monitored. Though lower responsibilities can be distributed or delegated among other (smaller) entities, the single entity tries to ensure and check that monitoring is done. In most of these river systems, the amount of monitoring locations have increased over time. Often, water quality is monitored at least on a (bi-)monthly basis. The results of the monitoring are published in yearly water quality progress reports. This kind of collaboration is often arranged in river systems where the main river flows through a multitude of countries.

Interestingly, measurements and monitoring of water quality is arranged differently in Myanmar. One major difference between Ayeyarwady Basin and other large scale basins is that the Ayeyarwady, except for some smaller reaches upstream, is completely located within the countries borders, which reduces the need for international collaboration. Still, responsibilities for water quality measurements and monitoring in Myanmar are fragmented. Most measurements are collected project-based and in-situ by a department that needs the measurements. Accessibility and sharing of measurement data between different departments or external parties is often poor and limited due to interdepartmental competition and bureaucracy.

Alternative Measurement Methods
Besides traditional water measurement systems, another kind of data collection has gained renewed and increased scientific interest since the 1990s: Citizen Science (CS). The term citizen science was termed by Alan Irwin and defined as "developing concepts of scientific citizenship which foregrounds the necessity of opening up science and science policy to the public". [23][43].

Multiple studies on citizen science and participatory approaches have been performed to this date. On of which studied the "spatial distribution of nitrogen solutes, namely, nitrate, ammonium and dissolved organic nitrogen (DON), in German surface waters". They found crowdsourcing to be "a useful method to assess the spatial distribution of stream solutes, as considerable amounts of samples were collected with comparatively little effort" [7]. Buytaert et al. describe water resources as "one of the most fundamental ecosystem services and a significant bottleneck for sustainable development and poverty alleviation" and note that citizen science could have "large potential in data collection due to the availability of inexpensive, robust and highly automated sensors", but also identified that several major research and implementation challenges exist when implementing citizen science. [8].

In Myanmar, a first step in implementing citizen science was made by Thatoe Nwe Win et al. in their research on using a participatory approach for measuring water quality in the Ayeyarwady river [51]. They found that for basic water quality measurement like sensor-based EC measurements and transparency measurements, the measurements taken by local stakeholders were of comparable quality to the measurements taken by government appointed professionals.

4 Identifying Contamination Scenarios in the Ayeyarwady Basin

This chapter describes the results from the second research component. As discussed in chapter 2, the second components is the determination and quantification of different contamination scenarios. The scenarios are implemented in the system model to simulate contamination events in the river to gain insight in the dispersion of contaminant particles downstream. First, chapter 4.1 describes the projection for the country of Myanmar for population growth and economic development. Subsequently, this chapter describes the scenarios for urbanisation (chapter 4.2), industry (chapter 4.3), and agriculture (chapter 4.4).

Contamination scenarios were based on realistic contamination sources along the stretches of the Ayeyarwady and the Chindwin Rivers. Based on the available data these scenarios were quantified and prepared to be implemented in the system model. Though the scenarios determined and used in this research are based on realistic sources of pollution they serve the purpose to give an initial sense for contamination concentrations along the river from these sources. If at all possible to measure, the insights gained from this analysis are to determine to what extent contamination is expected to be measured and to find initial requirements for a monitoring system in the Ayeyarwady and Chindwin river.

Scenarios were determined for different sources of pollution that were identified in this research. For each type of contamination source, a short term as well as long term scenarios were determined. Short term scenarios were drafted to resemble a relatively local and source specific event. These events result in the release of large quantities of contaminants into the river in a relatively short period of time. Long term scenarios were drafted to resemble the expected long term development of the country and the accompanied change in contaminant production and water pollution. The particle dispersion was modeled for the short term scenarios for low river discharge that typically occurs around March.

4.1 Myanmar Future Projections

Due to the coronavirus pandemic, as well as the coup d'état by the Myanmar military that took place in the morning of February 1st 2021, the future of Myanmar is uncertain. The country has shifted to a controversial military leadership which was internationally criticized and nationally contested by large scale protests. Due to the uncertainty that is the result of the coup, (international) businesses, institutions and investors have expressed their concerns and projects have been halted. This chapter describes the projections for Myanmar based on reports in which the effects of the pandemic and the military coup have not been taken into account due to its recent occurrence. To be able to determine scenarios, it is important to understand the current state and the expected developments of the country in the future. It is crucial to realize that the projections are now subject to an even larger degree of uncertainty than they were in the past since its reopening to the world in recent years.

Currently, the population of Myanmar is about 54.4 million people (2020). In the past 20 years, the country experienced an annual population growth rate of 0.6 - 0.8%. The population of Myanmar is expected to continue to grow at a decreasing rate of approximately 0.7% a year to about 58.5 million people in 2030 after which it will grow at a rate of around 0.35% to 62.3 million in 2050. It is also expected that the percentage of population living in urban areas will increase significantly in the future because more people will move away from rural areas and into urban areas. The proportion of people living in urban areas is expected to rise from about 30% in 2020 to almost 50% in 2050. [15][22][57][58][61][62].

The economy of Myanmar was classified as an emerging market and developing economy by the World Bank's Global Economic Prospects report. In the last 20 years, the country has experienced an average yearly GDP growth rate of over 8%. The countries economy is expected to continue to grow in the coming years at a average rate around 6% [3][22][54].

Generally, a growing economy is initially accompanied by negative side-effects including increasing emissions of pollution [31][71]. Pollution in the Ayeyarwady basin has increased due to long-term neglect, over-exploitation, deforestation, urbanisation and industrialisation. The increasing industrial and agricultural production also cause an increase in pollution from these sectors. Industrial pollution is emitted to the air and discharged through industrial waste and waste water. Growth of the agricultural sector generally results in intensification of fertiliser use that can be followed by increase of pesticide use depending on the type of crops cultivated. Overuse of either of these substances increases the amount of contamination present in agricultural run-off. To gain insights in the rate that pollution is expected to increase in the future, scenarios for urbanisation, industrialisation and agriculturalization are drafted below.

4.2 Waste Water Treatment Plant Failure

As discussed above, the population of Myanmar is expected to continue to grow in the future. It is also expected that the percentage of people living in urban areas will increase. The increase of urban population will increase the amount of urban waste water that is produced in cities and towns. Economical growth further drives the increased production of pollution [71] in urban areas. Together, the increase in (urban) population and the countries economical growth can increase the influx of pollution in the river and other (surface) water bodies through the discharge of domestic and industrial waste water.

Water from the river is often used by the Myanmar population for drinking and bathing. A major contamination concern is associated with the use of unfiltered water from the river. E. coli or coliform bacteria can cause serious health related issues to people. In Myanmar, only the largest cities have advanced waste water treatment plants (WWTP) to treat the urban waste water before it is discharged into the river. Because of the generally poor waste water treatment, high levels of pollutants are discharged into receiving waters from urban centres [28].

In the long term, it is expected that urbanisation will increase the amount of waste water that is produced in urban areas. When only population growth is taken into account, the increase of urban population is expected to have a positive linear relationship with the increase in urban waste water produced. The same holds for the rate of urbanisation. The rate of urbanisation has a positive linear relationship with the increase in urban waste water produced. Together these processes increase the amount of urban waste water produced. The development of WWTPs in urban areas can reduce the amount of untreated domestic and industrial waste water that is directly discharged into the river. Table 2 shows the expected increase in population, rate of urbanisation and the resulting expected increase in urban waste water produced in urban areas in relation to 2020.

Year	Population growth	Rate of urbanisation	Increase in urban waste water
2020	0 %	0 %	0 %
2030	8 %	22 %	31 %
2050	15 %	67 %	91 %

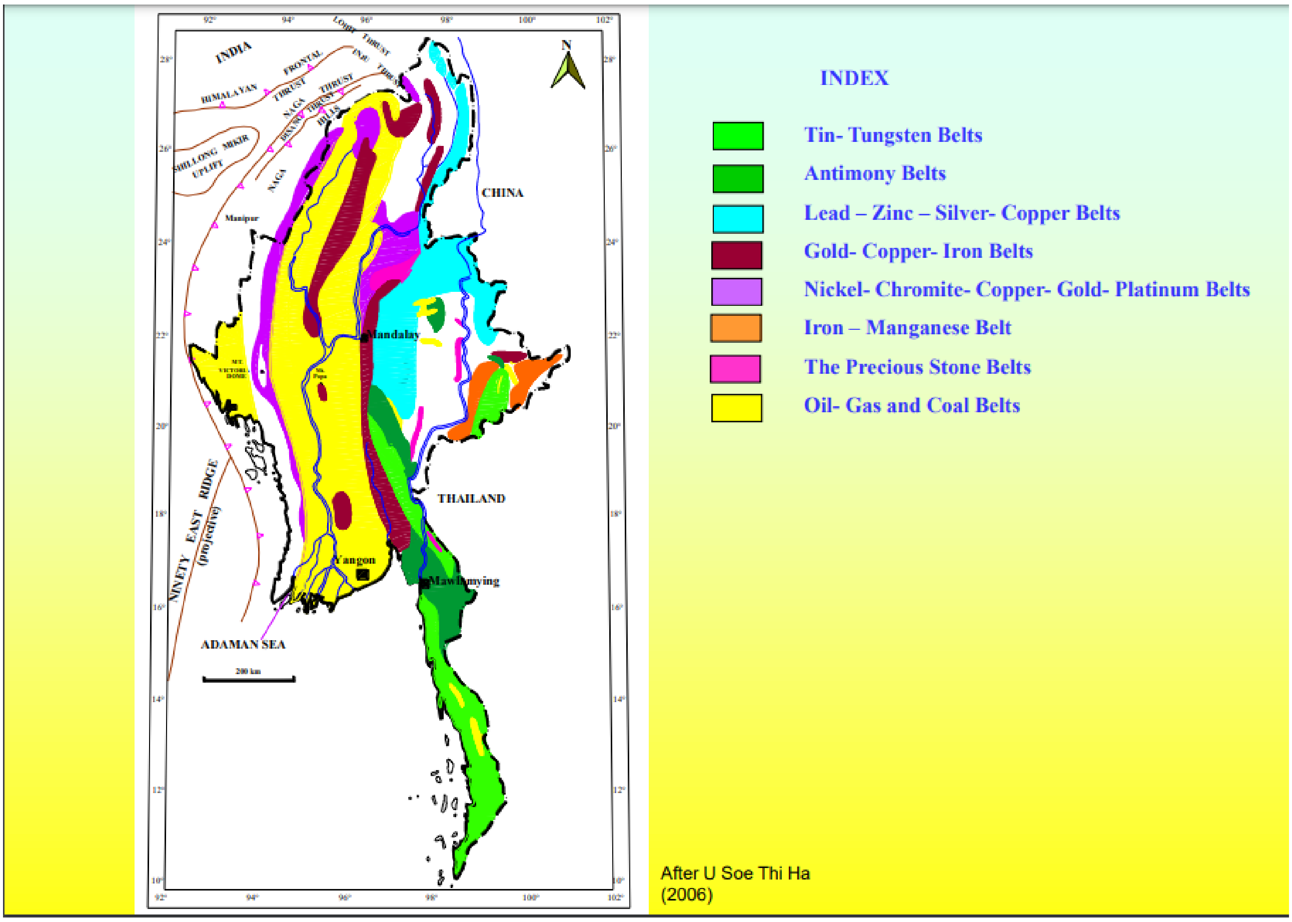
Table 2: Long term expected increase in urban waste water in relation to 2020. *The population of Myanmar is expected to grow in the future at a high rate. It is also expected that a larger portion of the population will be living in urban areas. These effects result in a significant increase in urban waste water in the coming 30 years.*

A short term pollution scenario that could occur in urban areas is a power outage in one of the major cities. A possible consequence of a power outage is failure of the cities Waste Water Treatment Plants (WWTP) resulting in the discharge of untreated waste water into the river. Failure of the WWTP's in large cities along the Ayeyarwady and Chindwin like Yangon (5.1 million people) or Mandalay (1.3 million people) could result in large quantities of untreated waste water being discharged into the river.

Mandalay is the largest city that is in the project area of this research. One of the WWTP's, '*No. 8 Water Treatment Plant*', is located along the river banks in the north west of the city. The treatment plant is the first to use water from the Ayeyarwady River and has a maximum capacity of 45.000 m^3/day [37]. For this research, the plant will stop working for a duration of 1 hour, 1 day and 1 week. The plant will discharge the untreated water directly into the Upper Ayeyarwady River.

4.3 Tailings Dam Failure

In the State of the Basin report (SOBA) 1.3, it was determined that "loads of biological oxygen demand (BOD), total suspended solids (TSS), lead, toxic chemicals (mainly ammonia, ethylene glycol and formaldehyde) and metals were identified as issues of concern originating from industries". [28]. Increased economic activity can result in an increase of pollution that is released into the river and other water bodies. In urban areas the rise of new or larger industrial areas will increase pollution from those areas. Also several mining locations are present in northern Myanmar. Increase of industrial activity could increase demand for products produced by the mining industry and therefor increase mining activity. The increase in mining activities can result in more pollution reaching the river. Win and Myint determined the mining potential for Myanmar and found that important deposits in Myanmar consist of "tin, tingsten, copper, gold, gemstones, zinc, lead, nickel and silver" [65]. In other research, Robb and Searle "built a Geographic Information System database of known Myanmar deposits, outcrops and mineral occurences", determining the provinces where deposits are present [44]. The extent of mining activities and expansion has been assessed by LaJeunesse Connette et al. in 2016 [30]. Figure 6 shows where the different mineral belts of Myanmar are located. Mining activities are most present in northern Myanmar in Kachin state, where the Ayeyarwady river and Chindwin river spring and Sagaing state, which is intersected by the majority of the Chindwin river. Mining is often performed by means of open pit mining [14]. In some cases the mining activities are illegal which means that the activity is not monitored and that regard for water quality and ecology is possibly reduced.



INDEX

🟩 Tin- Tungsten Belts
🟩 Antimony Belts
🟦 Lead – Zinc – Silver- Copper Belts
🟥 Gold- Copper- Iron Belts
🟪 Nickel- Chromite- Copper- Gold- Platinum Belts
🟧 Iron – Manganese Belt
🟪 The Precious Stone Belts
🟨 Oil- Gas and Coal Belts

After U Soe Thi Ha
(2006)

Figure 6: Mineral belts in Myanmar. *Mineral belts in Myanmar as depicted in a slide of the presentation "Database building in ministries, Myanmar" by the Department of Geological Survey and Mineral exploration [14]. Large mineral belts are present and exploited along the river. Contamination of the river is a serious threat to the water quality.*

In the long term, the increase in economic activity is expected to increase pollution in the river. In industrial areas the increase of pollution is associated with the type of industries that experience growth or that is engaged in. The increase in pollutants from mining activities are expected to occur at a similar rate to the economic growth and occur along the tributaries of the upper Ayeyarwady and Chindwin rivers. The long term scenario for industrialisation are presented in table 3.

A short term pollution scenario that could occur in mining areas is the failure of a tailings dam of a mining waste water reservoir resulting in the release of large amounts of acid and heavy metals into the river. Tailings dam failures are not an uncommon disaster to occur in areas where mining activities take place. Unfortunately, several failures have occurred in Myanmar in recent years. A waste heap failure at a jade mine in Kachin State, Myanmar, killed at least 172 miners and caused the discharge of large quantities of contaminants and dirt into the nearby lake as recent as 2020. Since 1960 at least 135 major tailings dam failures have been reported from all around the world [66]. An increasing trend in greater consequence tailings dam failures is observed since 1990 [39]. Most failures occur in dams "up to 30 meters high with a maximum tailings volume of $5x10^6m^3$. One-fifth of the total amount of tailings that is contained by the dam is generally released during a tailings dam failure [4]. Fine and course tailings can have a natural water content of about 50% and a specific gravity of over 3.0 [20].

Based on the above, the following short term scenarios for industrialisation were determined and are presented in table 3. The scenarios are based on a the maximum size tailings dam presented above. The first short term scenario is failure of a tailings dam at a mine in Kachin state along the Uyu river, a tributary of the Ayeyarwady river. Tailings from the mining location are released into the river and 1 million m^3 of tailings reach the Ayeyarwady river. The mine is located in an area with coal, copper, gold, iron, nickel and jade mines. Therefor, the released tailings can consist of coal refuse, silicate minerals, cyanide, and dissolved metals like aluminium, copper, nickel, iron, gold and manganese. A second scenario is the failure of a tailings dam in the Chindwin river. Here, accounting for the resources present in the region, 1 million m^3 of tailings consisting of coal refuse, silicate minerals, and dissolved metals like iron and copper are discharged into the Chindwin river.

Scenario	Rate of contaminant increase
Long term	6 % annually

Scenario	Mining type	amount of tailings released $[m^3]$	Contaminants
Upper Ayeyarwady	Antimony, coal, copper, gold, iron, limestone, nickel and jade	1 million	Coal refuse, silicate minerals, cyanide and dissolved metals like aluminium, copper, nickel, iron, gold, and manganese
Chindwin	Chromite, coal, copper	1 million	Coal refuse, silicate minerals, and dissolved metals like iron and copper

Table 3: Scenario details for long term industrialization and short term tailings dam failure in both the Ayeyarwady and the Chindwin. *Significant amounts of heavy-metals and minerals are expected to contaminate the river in case of a talings dam failure.*

4.4 Agriculturalization

Agriculture is a crucial source of livelihood in Myanmar. 70% of the population relies on agricultural products for livelihood and 85% of the rural population lives in households that work in agriculture. With agriculture accounting for 30% of national GDP, the agricultural sector is a significant part of the Myanmar economy. [55]. Economical growth and thus the increase in GDP, as well as population growth, combined with international development aid [56] could result in an increased demand for food. This development can drive an increase in agricultural productivity and shift towards agricultural produce with higher associated costs [18]. Whilst growth of the agricultural sector in the country and the increase of agricultural products provides an increasing part of the population with basic livelihood and income, the sector's growth is expected to be accompanied by an increase in the use of fertilisers and pesticides as it did in recent years. "Between 2011 and 2018, the import of legal pesticides gradually increased by around 81% from 11,000 tons to 20,000 tons" [9] and increased the average consumption of fertilizer per hectare of arable land to about 20 kilograms between 2011 and 2016. These include "nitrogenous, potash, and phosphate fertilizers [25].

In the long term, it is expected that the growth of the agricultural sector will continue. Globally, the consumption of fertilizers have increased from less than 110 to more than 140 kilograms per hectare of arable land [59]. At the same time, the use of pesticides will increase. Misuse of pesticides can cause pollution in water bodies and soil and can result in deterioration of food production by the agricultural sector as well as rice-fish aquaculture systems. Contamination of water bodies can eventually cause deterioration of ecological systems and cause human health issues.

In the short term, it is expected that the use of fertilizers will increase. Fertilizer compounds enter the river through run-off. A significant part of the country's agriculture is located in the Dry zone. In this scenario, fertilizer use in Dry Zone increases with 50 %. The fertilizer is absorbed and discharged into the river. For this scenario all of the fertilizer is entering the river in the dry zone, contaminating it with nitrogen, potassium and phosphate.

Though contamination from agriculture can potentially be a large factor in future contamination in the Ayeyarwady Basin, it is complex to model. This research focuses on point contamination events. Because of the diffuse nature of agricultural contamination sources, the growth of the agricultural sector of Myanmar is not modelled in this research.

5 River System Model of the Ayeyarwady and Chindwin River

The third research component is the building of a quantitative model of the Ayeyarwady river and the Chindwin river, its main tributary. At present, some models exist for parts of the Ayeyarwady river. Most of these models cover parts of the Ayeyarwady Delta and focus mainly on river flow, flooding, and morphology. Some models were made of areas in the Ayeyarwady north of the Delta. One of these models covers an area from Mandalay southward to the confluence of the Ayeyarwady and Chindwin. A model combining river flow and river quality on a larger spatial scale had not yet been created for the Ayeyarwady basin.

Both the Ayeyarwady flow and water quality model are built in the one-dimensional modelling suite SOBEK 3.7.13.40404 by Deltares and was chosen for its suitability to model and analyze river systems and for its ability to implement a water quality module. The flexible modular structure of the model in SOBEK opens the opportunity to expand the functionalities of the river model for future applications.

A new model had to be built from scratch to be able to understand river dynamics and to gain insight in the propagation of contamination throughout the Ayeyarwady river system at the basin-scale. Herewith we can find initial requirements and possibilities for a water quality monitoring system in the Ayeyarwady. This chapter describes the model of the Ayeyarwady and Chindwin that was created for the purposes of this study. The model is composed of two main parts: the river flow model and the river quality model. Chapter 5.1 describes the modelling area and the topographical boundaries of the model. Chapter 5.2 describes the steps taken to construct the river flow model. Chapter 5.3 describes the building of the river quality model.

5.1 Modelling Area

To be able to model the river course it is crucial to define the spatial scope of the model. For this research, the model area includes most of the Ayeyarwady and Chindwin rivers. The research area stretches from the origin of the Ayeyarwady at the confluence of the Mai Kha and Mali Kha to the start of the Ayeyarwady Delta near Chaung Gyi (figure 7). The main tributary of the Ayeyarwady river, the Chindwin River, was also included in the research area. The Chindwin river was modelled from the confluence of the Tagarkha and Chindwin rivers to the confluence of the Chindwin and the Ayeyarwady river. The research area was divided into three distinct river branches: The Upper Ayeyarwady, the Lower Ayeyarwady, and the Chindwin river. The Ayeyarwady delta was not included in the research area. The tidal dynamics and its effects like salt intrusion would make the model unnecessarily complex. Tributaries to the Ayeyarwady, other than the Chindwin were not modelled in detail, but were incorporated into the model exclusively as river inflow.

5.2 Ayeyarwady Flow Model

The river flow model was constructed in a series of modelling steps. Table 4 shows an overview of the modelling steps and the data sources used to perform the steps.

Table 4: Modelling steps for the Ayeyarwady basin flow model. *Four modelling steps of the Ayeyarwady basin flow model are shown in combination with the source of the data that is used to perform the modelling steps.*

	Modelling Step	Data Source
1	Tracing the river course(s)	Map tracing
2	River slope & channel bathymetry	SRTM DEM 1-arcsecond (30m * 30m), River depth measurements
3	River discharge estimation	River discharge measurements, River catchment area determination
4	Boundary & initial conditions	SRTM DEM 1-arcsecond (30m * 30m), River discharge estimations, River depth measurements

First, the river course was defined. By tracing the river over a projected map, the river course can be identified and defined in the flow model. After the tracing of the river course the bed level was identified using the Digital Elevation Model (DEM) by SRTM with a resolution of 1 arcsecond (30m * 30m). Together with the available river depth measurements the river bathymetry was added to the model. The third step was the river discharge estimation. Using available river discharge measurements and estimations of the catchment areas the river discharge was implemented in the model. The last step was the implementation of initial and boundary conditions based on the DEM, river discharge and river depth measurements.

River Course

Figure 7: River course included in the flow model. *The blue lines show the traced river courses. The green-white dots show the boundaries of the different river courses, the filled green dot shows the confluence of the Upper Ayeyarwady and Chindwin Rivers. A total of 2319 km of the rivers was traced.*

The foundation for the river flow model is the determination and tracing of the river course. Three distinct river branches were identified and traced in SOBEK 3 using satellite imagery from 2021: the Upper Ayeyarwady, the Lower Ayeyarwady and the Chindwin River. The Upper Ayeyarwady was traced from the origin of the Ayeyarwady river, at the confluence of the Mai Kha and Mali Kha in the east of Kachin State in northern Myanmar, southwards to the confluence of the Ayeyarwady and the Chindwin rivers. The Chindwin river was traced from the confluence of the Tagarkha river and the Chindwin river in the west of Kachin State to the confluence of the Ayeyarwady and Chindwin rivers. The Lower Ayeyarwady was traced from the confluence of the Ayeyarwady river and the Chindwin river to the beginning of the Ayeyarwady Delta near the town of Chaung Gyi. A total of around 2319 kilometers of the Ayeyarwady and Chindwin rivers were traced and added to the model. Figure 7 shows the three river branches as they are modelled in SOBEK. The blue lines represent the different branches, whilst the green-white nodes represent the boundaries of the river branches. The Upper Ayeyarwady (east) and Chindwin (west) rivers were modelled towards their confluence where they join and continue southwards together as the Lower Ayeyarwady. The confluence is represented by the filled green node.

Bathymetry and River Slope

The second part of the modelling process is to determine the river slope and the river bathymetry. To model the different river bathymetries along the river branches, every 9 kilometers a cross-section was determined. This cross-section frequency was chosen because of the large scale of the model and the goal of this research. As the river model is made at the basin scale and data availability is limited, an increase in cross-section frequency could give a false sense of model accuracy. For the indicative nature of the research goal, the cross-section frequency is sufficient to model river flow. A total of 259 locations were identified along the three river branches where cross-sections can be identified. For every of these locations, the geographical coordinates were determined and exported to QGIS. A sample of the Digital Elevation Model (DEM) was taken perpendicular to the rivers flow direction and of equal length in both directions with a total length of 10 kilometers for all locations. The DEM is a high-resolution digital topographic database and is measured by the Shuttle Radar Topography Mission (SRTM). The DEM was used with a resolution of 1-arcsecond (30m * 30m). The geographical elevation was measured by the SRTM in February 2000. The height profiles extracted from the DEM were exported from QGIS. Figure 2 shows a cross-section in the Ayeyarwady near the confluence of the Ayeyarwady and the Chindwin as it was extracted from the DEM.

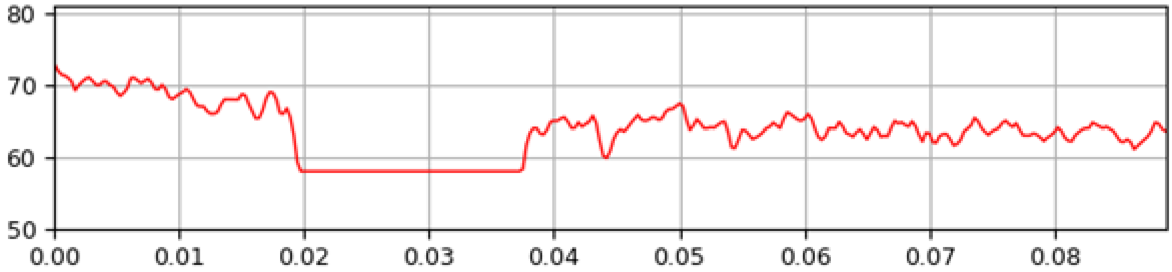


Figure 8: Cross-section 'UA77' from the Upper Ayeyarwady near the confluence with the Chindwin river. *The red line shows the measured surface height by the SRTM. The horizontal segment of the cross-section shows the water level that is measured by the SRTM in February 2020. The total width of the cross-section is 10km. Height is shown in [m].*

The DEM measures the height of the terrain at locations where no surface water is present but is unable to measure the bed level at locations where surface water is present. This is because the height that is measured by the SRTM at locations with surface water is the water level. This means that the shape of the channel under the water level cannot be determined by the SRTM measurements. To realistically model the river, the underwater profile needs to be estimated. Several shapes can be implemented below the measured water level to estimate and model the shape of the river channel. Importantly, the elevation is measured by the DEM in February, which is the Ayeyarwady dry season. Even during the low river discharge of the dry season, the width of the river upstream in the river system exceeds 100 meters. At these upstream locations, the measured water depth does not typically exceed 2 meters. Using Gauckler-Manning (formula 1) for river discharge it was determined that the modelled difference in river discharge and thus the modelled water levels are small due to the scale of the Ayeyarwady river.

$$Gauckler - Manningformula : V = \frac{k}{n} R_h^{2/3} S^{1/2} \tag{1}$$

Modelled differences in discharge are $< 1\%$ between a rectangular channel shape and a trapezoidal channel shape with an assumed 1:1 slope of the riverbanks. In the first set of upstream cross-sections in the river model where the river width does not exceed 100 meters, the discharge is relatively small and effects on the model's results are negligible. Due to the small differences, a rectangular channel shape was assumed below the water level at every cross-section. The width of the channel is equal to the width of the measured water level for that cross-section. In cross-sections where multiple channels in the river are presents, a rectangular channel shape was added to each of the channels that are present at low river discharge.

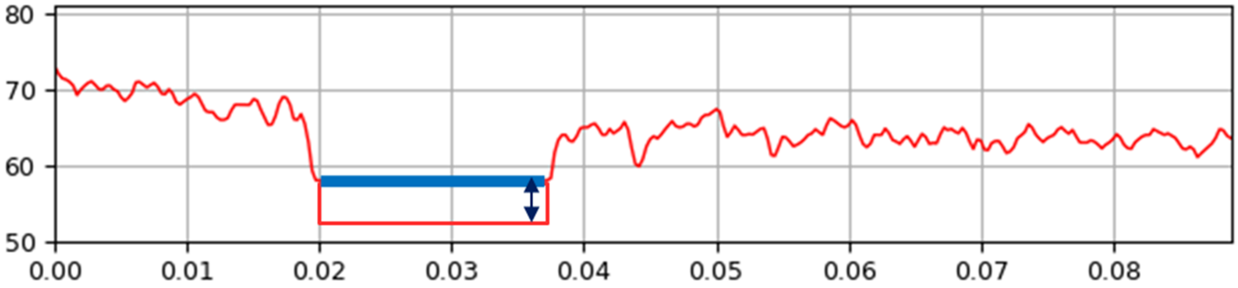


Figure 9: Cross-section 'UA77' with added channel. *An underwater rectangular channel was added to the cross-section based on the interpolated water depth measurements available. The red line shows the new surface height, the blue line shows the water level measured by the SRTM.*

In addition to the channel shape, a channel depth is necessary to model the river flow. Data availability for water level measurements in the Ayeyarwady river system is limited. Moreover, the quality of the depth measurements and the way the measurements were performed cannot be verified. Water level measurements at time of the DEM measurements were available for nine locations: Myitkyina, Katha and Sagaing (all Upper Ayeyarwady), NyaungU, Chauk, Magway, Aunglan and Pyay (all Lower Ayeyarwady) and Monywa (Chindwin). The water level measurements give an estimation of the channel depth at low discharge. The available measured water levels were interpolated and implemented into the model as the channel depth. The rectangular channel was added to the cross-sections below the measured water level as shown in Figure 9. The width of the channel was set equal to the width of the measured water levels by the DEM. The depth of the channel was determined to be the interpolated measured channel depth. The measured water level by the DEM subtracted by the channel depth is used as the bed level for the cross-sections. A natural slope is created by the new bed levels in the river system.

River Discharge

The availability of river discharge measurements in the Ayeyarwady river system is also limited. Discharge measurements at time of the measured elevation were available at nine locations. As well as with the river depth measurements, the quality of the discharge measurements available cannot be verified. Significantly higher discharge relative to measurement locations downstream were observed in two locations: NyaungU and Magway. This significant difference in discharge rates could be explained by high evaporation rates or groundwater recharge. It can also be explained by measurement errors due to a change in the gauge reference to prevent negative water levels. The Q-h relation used to estimate these discharges could be outdated whilst the real Q-h relation has changed. Due to the significant errors in discharge data, the measurement from NyaungU and Magway were not used in this study. Besides the discharge data in the Ayeyarwady and Chindwin, discharge data from the Myitgne and Myittha rivers were available. The discharge data from the main rivers was supplemented by the two discharge measurements from the Myitgne and Myittha rivers.

The catchment areas were determined using QGIS for every of the 259 locations along the river branches using the DEM. A large increase in discharge area was observed at several locations. This sudden increase in catchment size are due to the confluence of tributary rivers. The increase of catchment area at the Myitgne en Myittha rivers, for which discharge data are available, were used to identify the discharge relation. By plotting the known discharge measurements against their respective increase in catchment area, a discharge relation was estimated. A best fit was achieved using a linear interpolation. The resulting linear estimated discharge vs. catchment area relation (figure 10) was used to estimate the low discharge for the 259 model cross-sections for the dry season.

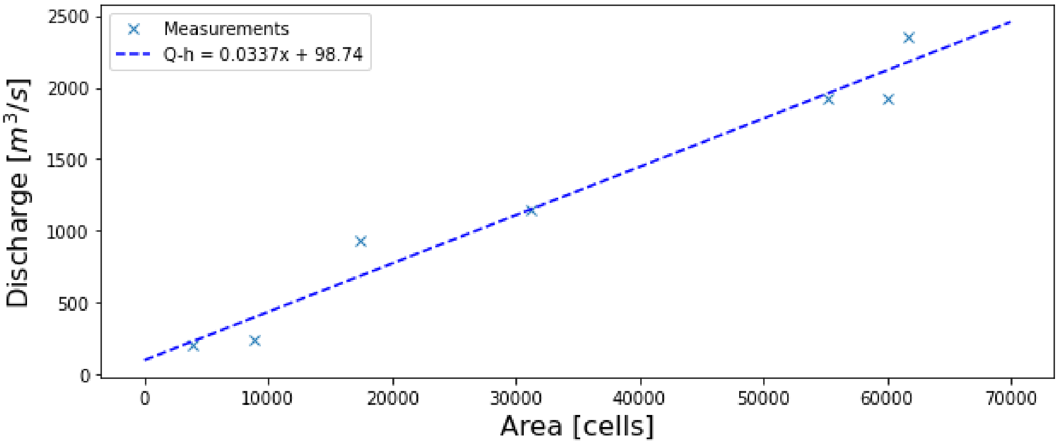


Figure 10: The Q-A relation used in the model for low discharge. *Using linear interpolation between the available discharge data, the Q-A relation for low river discharge was found and implemented into the model. The resulting Q-A relation:* $Q = 0.0337A + 98.74$.

Channel roughness was determined using a geological map of Myanmar. Every stretch between two cross-sections was analysed and assigned a soil type using the geological map of Myanmar presented in appendix D. For every soil type the manning roughness was assumed to be between 0.035 and 0.05 $s/m^{1/3}$. These values were tested and tuned in such a way that the modelled water levels in the model approached the water levels measured by the SRTM.

Boundary and Initial Conditions

Identifying and implementing boundary and initial model conditions is an important part of the modelling process. To identify the boundary conditions, the estimated river discharge relation was used. During the process of determining the discharge relation, the catchment areas of all cross-sections was identified. The catchment-area at the upper boundary nodes for the Upper Ayeyarwady and Chindwin rivers is the area that is upstream of the nodes. The relation between the catchment-area and the discharge resulted in an estimated initial discharge at the boundary nodes. This discharge was determined to be 277.26 m^3/s for the Upper Ayeyarwady and 153.55 m^3/s for the Chindwin river boundary nodes. For the downstream end of the model the initial condition as identified using the measured water level by the DEM. The water level at the downstream node was determined to be 0 meters for low discharge. A constant water level of 0 meters was implemented into the model at the downstream boundary node.

Initial conditions were identified using an initial water level. For the Chindwin and Upper Ayeyarwady the initial water level was estimated to be 2 meters. For the Lower Ayeyarwady the initial water level was estimated to be 5 meters. These initial conditions make that the model reaches an equilibrium state after approximately two months of running.

5.3 Ayeyarwady Water Quality Model

The quantitative flow model and particularly its modelled discharge and bathymetry form the basis for the water quality model. The water quality module is configured to be able to model artificial tracers. The "tracer techniques are a useful tool in understanding the transport processes and quantifying their parameters" [34] which will increase the understanding of the river system's workings regarding water quality. The water quality module in SOBEK enables the modelling of conservative and decaying tracers throughout the river system. The conservative tracers represent contamination transported by the river without intervention of any physical or chemical process that alters their composition. Unlike the conservative tracers, the decaying tracers are subject to a decay rate that can be set to any value that can represent a range of physical or chemical processes that alter the contamination's composition. Initially, no contamination of any kind is present in the rivers. The tracers representing contamination are released during later stages of the model runs after the model has reached an equilibrium state. The contamination is released into the river by means of a load. Several different tracer compositions are tested to provide understanding of the transportation of contaminants throughout the river system.

Selection of contaminant loads and location

The final step in the modelling process is the implementation of the contamination loads. The contamination loads are defined as point pollutions. So, for every contaminant composition, the contamination originates from a single location along the rivers. The goal of this research is to find to what extent contamination in the Ayeyarwady and Chindwin rivers can be measured and if so, what measurement frequency and accuracy is required to measure the contamination. To be able to find the requirements for a monitoring system, conservative as well as decaying contaminant transport is modelled. No specific contamination substances, physical processes or chemical processes were modelled in this research. Some physical and chemical processes can be approximated by implementing tracer decay rates. The advection and dispersion of the tracers throughout the river system will provide insight into the extent to which contamination is transported by the system. To represent different contamination and system behavior, tracer decay rates are varied during the implementation of contamination scenarios.

5.4 Ayeyarwady Model Validation

Validation of the Ayeyarwady river flow model is cumbersome. As the data that was available to build the model was already limited and its quality could not be verified, little data remains to validate the model. Due to the current political situation (2021) in Myanmar, it is not expected that additional measurements will become available for this study. There will also be no opportunity to take in-situ measurements during this study to use for model validation. Because of this information deficit, a proper model validation will not be possible at this time. Using the data that is available, a first effort is made to verify that the model performs in a way that is expected.

A first step in the validation process of the model is to try and find to what extent the model represents real-world physical processes. To do this, several model inputs and outputs were tested. First, the river discharge was compared to the region's water balance.

River Discharge

The key model variable is the river discharge. To make a first validation of the river discharge, the discharge that is based on the available measurements is compared to the expected output. The average discharge varies between a low of 2300 m^3/s and a high of 32600 m^3/s with the average annual river discharge around 13000 m^3/s at the head of the delta [5]. Therefore, the expected output for the model's low river discharge is in the order of 2300 m^3/s. The observation point in Pyay is located most to the south of the observation points modelled and is located more than 200 kilometers north from the head of the delta. The steady-state low discharge modelled at the observation point in Pyay is 2264 m^3/s. As the model is made to model low river discharge, this indicates that the modelled river discharge is comparable to the expected real-world low river discharge.

The low river discharge is also compared to the expected base flow. The total catchment area of the Ayeyarwady basin is estimated to be around 404,000 km^2 [24]. The catchment area of the Ayeyarwady delta is estimated to be around 118,000 km^2 [27]. The total catchment area of the area modelled area can therefor be estimated to be 286,000 km^2. The model is based on the low discharge of the Ayeyarwady river which occurs in the dry season. During this time, it can be assumed that the river discharge is mostly base flow. The average annual rainfall in the Myanmar Central Dry Zone is less than 1000 mm/year. The modelled equilibrium discharge at the head of the Ayeyarwady delta is 2280 m^3/s. Converting the modelled discharge and dividing by the rivers catchment area results in a runoff of about 0.7 mm/day. Discharge for several Asian rivers (Amur, Ganges, Indus, Mekong, Brahmaputra and the Ayeyarwady itself) is estimated between 0.66 and 1.67 mm/day [35][67]. The modelled discharge is a low estimation of the river's discharge based on one of the driest times of the year. Comparing the modelled discharge with the expected discharge indicated that the modelled low river discharge is comparable to the expected discharge.

6 Ayeyarwady Basin Monitoring System Performance

The goal of this research is to find to what extent contamination in the Ayeyarwady and Chindwin rivers can be measured and if so, what measurement frequency and accuracy is required to measure the contamination. First, a sensitivity analysis is performed on the model. Several input parameters for the model are varied to see to what extent the model outputs are sensitive to the variations. Chapter 6.1 describes the results of the sensitivity analysis. Secondly, contamination loads consisting of conservative tracers are modelled and released at several locations in the model. This analysis will show how contamination peaks move through the river model. The distribution of conservative tracers that is found downstream will show to what extent contamination can be measured in the Ayeyarwady basin. Lastly, the contamination scenarios that are identified in chapter 4 are modelled using a combination of conservative and reactive tracers and released in the model. Chapter 6.3 describes the results of the contamination scenario experiments. These experiments will give insight to what extent contamination is transported by the river system and to what extent contamination is at different downstream locations. It will provide information into what extent the contamination can be measured and what measurement frequency and accuracy is needed to measure the contamination in the Ayeyarwady and Chindwin rivers.

6.1 River System Model: Sensitivity Analysis

To test the model for the Ayeyarwady and Chindwin rivers. A sensitivity analysis was performed. This analysis tests to what extent target model outputs are affected by adjusting model input parameters. The sensitivity analysis gives insight in the behaviour of the Ayeyarwady and Chindwin River model.

River Discharge

First the model is tested for sensitivity to changes in river discharge. Initially the model was built to model low flows in the Ayeyarwady catchment. For a low flow regime, typical river discharge into the Andaman Sea is between 2500 and 3500 m^3/s but can be as low as 2300 m^3/s. High discharge for the Ayeyarwady river can exceed 40.000 m^3/s. To test the model sensitivity, discharges are varied between the low discharge of 2300 m^3/s and 40.000 m^3/s. Table 5 shows the results at the different observation locations along the Ayeyarwady and Chindwin rivers. For every location, the modelled water level is shown. The table also shows the total average and maximum cross-sectional flow velocities.

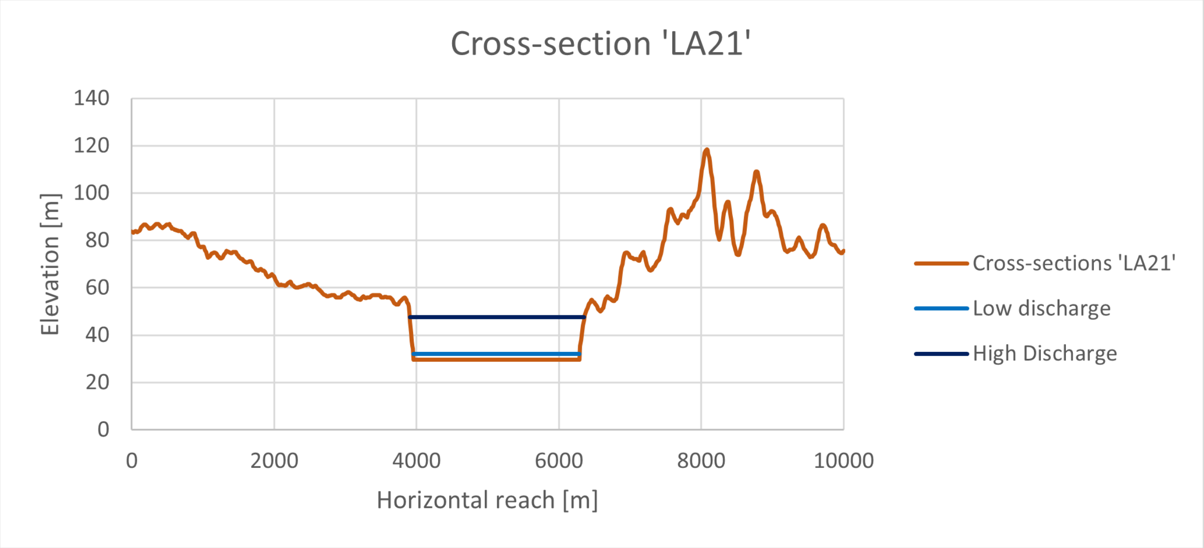


Figure 11: Cross-section ‘LA21’ located at Magway in the Lower Ayeyarwady showing the water level for the low and high river discharge. *The modelled bed level of the channel is shown by the orange line. The light blue line shows the water level at low river discharge, the dark blue line shows the water level at high river discharge. It can be observed that the river flow model is capable of modelling high discharges fairly accurately in addition to the low discharges, further validating the model.*

The sensitivity analysis for the increased river discharge indicates that the model can also be used to model the higher river discharges. Whilst the river discharge was increased to 40,000 m^3/s at the head of the Ayeyarwady Delta between the low and high river flow, the water level in the river rose a maximum of 15.5 meters. This maximum water level increase occurs near Magway in the Lower Ayeyarwady. Figure 11 show the modelled water level for the low and high discharge at Magway (cross-section ‘LA21’). The water level during high discharge approaches the upper limits of the natural channel but does not exceed the natural banks. The average cross-sectional flow velocity of the channel increases to about 1 m/s. The maximum cross-sectional flow velocity exceeds 4 m/s. Though the maximum flow velocity at this high discharge is very high, it occurs locally at an upstream location in the Chindwin river where the slope is relatively steep in comparison with the rest of the model. These upstream flow velocities have a negligible effect on the flow velocities further downstream and on contaminant transport from contamination sources downstream. The results of the analysis for maximum river discharge of the Ayeyarwady river show that the model is also capable of modelling high discharges. An analysis of low and high discharge water levels was conducted during this research for the 13 observation points in the model. A detailed description of the results for these points is presented in Appendix B.

Reference Discharge	2,300 m^3/s		10,000 m^3/s		40,000 m^3/s	
Observation Location	Modelled water level	Water level increase relative to low discharge	Modelled water level	Water level increase relative to low discharge	Modelled water level	Water level increase relative to low discharge
	[m]	[m]	[m]	[m]	[m]	[m]
Myitkyina	130.53	0	132.15	1.62	163.09	5.56
Katha	89.9	0	91.89	1.99	95.99	6.09
Sagaing	62.43	0	65.62	3.19	71.12	8.69
NyaungU	52.06	0	55.21	3.15	61.19	9.13
Chauk	43.62	0	47.14	3.52	54.24	10.62
Magway	32.16	0	37.24	5.08	47.61	15.45
Aunglan	22.97	0	28.15	5.18	37.39	14.42
Pyay	17.74	0	21.31	3.57	28.96	11.22
Hkamti	141.16	0	144.09	2.93	150.15	8.99
Homalin	120.40	0	123.21	2.81	128.38	7.98
Mawlaik	99.54	0	102.8	3.26	109.5	9.96
Kalewa	93.38	0	96.39	3.01	103.59	10.21
Kalewa	67.99	0	70.99	3.00	75.22	7.23

Table 5: Modelled water level and water level increase for 13 monitoring stations in the Ayeyarwady and Chindwin rivers. *Water levels are presented for a river discharge at Pyay of 2300, 10,000, and 40,000* m^3/s*. For every discharge the increase in water level in relation to the low discharge of 2300* m^3/s*.*

Initial & Boundary Conditions

The initial conditions that were defined for the model are a water level per river branch. For the Upper Ayeyarwady and the Chindwin rivers this initial water level was set to 2 meters above bed level. For the lower Ayeyarwady this was set to 5 meters above bed level.

For river discharge, the boundary conditions for the model were determined at the three outer nodes of the model. The boundary node for the Upper Ayeyarwady is located at the confluence of the Mai Kha en Mali Kha. The boundary node for the Chindwin is located at the confluence of the Chindwin and the Tagarkha. The boundary node for the Lower Ayeyarwady is located at the start of the Ayeyarwady delta near Chaung Gyi. The boundary conditions for the upper two boundary nodes in the Upper Ayeyarwady and Chindwin rivers were modelled as constant discharge. This discharge was determined using the catchment area upstream of the boundary node and the expected base-flow. The boundary condition for the Upper Ayeyarwady was set to 277.26 m^3/s and the boundary condition for the Chindwin was set to 153.55 m^3/s. For the Lower Chindwin the boundary condition at the downstream end of the river were modelled as a constant water level. The constant water level was set to the water level measured by SRTM at 0 meters.

Four sets of altered boundary conditions were tested: two sets for the two upper boundary conditions and two sets for the lower boundary condition. For both, the two sets are an increased and decreased boundary condition. For the upper boundary conditions the constant discharge is doubled and halved. For the lower boundary condition, the constant water level is decreased by two meters and increased by 2 meters. It was concluded that the altered boundary conditions for the water level affected the time it takes the model to reach its equilibrium state. The altered boundary conditions for initial discharge only affects the discharge by shifting the discharge relation linearly with the increase or decrease of river discharge.

Surface Roughness

The surface roughness affects the modelled flow and the resulting water levels. Every cross-section in the model was assigned a surface type and corresponding surface roughness. This parameter was modelled using the Gauckler-Manning for values between 0.035 and 0.050 $s/m^{1/3}$. The resulting water levels are shown in table 6. Surface types were derived from the *Geological map of Myanmar (2014)* [36] which is presented in appendix D. It is observed that the model sensitivity to the Manning surface roughness is limited.

Surface Type	Manning Roughness $[s/m^{1/3}]$	Manning Roughness $[s/m^{1/3}]$	Manning Roughness $[s/m^{1/3}]$
Q2	0.035	0.045	0.044
Ub	0.035	0.045	0.035
Km	0.035	0.045	0.035
v2	0.035	0.045	0.035
m1	0.035	0.045	0.035
m2	0.035	0.045	0.035
Ir	0.035	0.045	0.043
Tm	0.035	0.045	0.050
RMSE of water levels relative to the SRTM measurements in [m]	0.253	0.301	0.266

Table 6: Results for the sensitivity analysis for surface roughness. *Three combinations of surface roughness were tested for Manning roughness between 0.035 and 0.05 m/s. For every combination, the RMSE of the modelled water level to the SRTM water level is presented. The surface types are derived from the Geological map of Myanmar (2014) [36] which is presented in appendix D. It can be observed that the differences are small. The expected error for the modelled water level in relation to the measured water level is around 0.3 meters.*

Horizontal Dispersion Coefficient

The horizontal dispersion coefficient is the rate at which substances in the water are mixing. A higher horizontal dispersion coefficient resembles a higher rate of horizontal mixing of contaminants and other substances in the river. Variation in horizontal dispersion coefficient was quantified using 5 values: 0.1, 1, 10, 100, 1000 and 10,000 m^2/s. Model contamination events was set to 100 g/m^3 for a duration of 2 weeks. Conservative tracer 1 (cTR1) is released at the most upstream model location in the Ayeyarwady and conservative tracer 2 (cTR2) is released at the most upstream location in the Chindwin river. For every horizontal dispersion coefficient, the time the contamination exceeds 10^{-5} g/m^3 at the observation location at Pyay is recorded. It is also recorded when the peak is first noticed. The results of the sensitivity analysis for the horizontal dispersion coefficient are shown in table 7.

Horizontal Dispersion Coefficient $[m^2/s]$	Start peak since release of contaminants $[time]$	End peak since release of contaminants $[time]$	Contamination peak $[g/m^3]$
Ayeyarwady (cTR1)			
0.1	14-04-2021 11:00	18-05-2021 07:00	0.0421
1	14-04-2021 11:00	18-05-2021 08:00	0.0421
10	14-04-2021 07:00	18-05-2021 19:00	0.0420
100	13-04-2021 02:00	23-05-2021 09:00	0.0408
1000	07-04-2021 11:00	07-06-2021 12:00	0.0335
10,000	24-03-2021 21:00	02-07-2021 09:00	0.0201
Chindwin (cTR2)			
0.1	17-04-2021 17:00	19-05-2021 13:00	0.0424
1	17-04-2021 16:00	19-05-2021 13:00	0.0424
10	17-04-2021 15:00	19-05-2021 16:00	0.0423
100	16-04-2021 23:00	20-05-2021 19:00	0.0421
1000	12-04-2021 12:00	28-05-2021 17:00	0.0374
10,000	29-03-2021 07:00	29-06-2021 23:00	0.0212

Table 7: Sensitivity of the horizontal dispersion coefficient. *Tracers are released upstream and the discharge peak is recorded at Pyay, the most downstream observation point. Typical horizontal dispersion coefficients for a river are estimated to be between 100 - 1000* m^2/s.

Contaminant concentrations are found at the observation location at Pyay almost 3 weeks earlier for a horizontal dispersion coefficient of 10,000 m^2/s then for a horizontal dispersion coefficient of 1 m^2/s or lower. The contamination peak for higher horizontal dispersion coefficient is observable over a longer period of time whilst showing a smaller peak contamination. For the higher dispersion coefficient of 10,000 m^2/s, the contamination peak is twice as high as for the dispersion coefficients of 1 m^2/s and below. It is also observed that the shape of the peak hardly changes for horizontal dispersion coefficients from 1 m^2/s and smaller. Tracers released upstream in the Ayeyarwady typically show a lower contamination peak than tracers released upstream in the Chindwin river. The duration of the peak from tracers released upstream in the Ayeyarwady is typically longer that than the duration of the contamination peak of tracers released upstream in the Chindwin river. Figure 12 shows the peaks described above for both conservative tracers for a horizontal dispersion coefficient of 10,000 m^2/s and for 0.1 m^2/s.

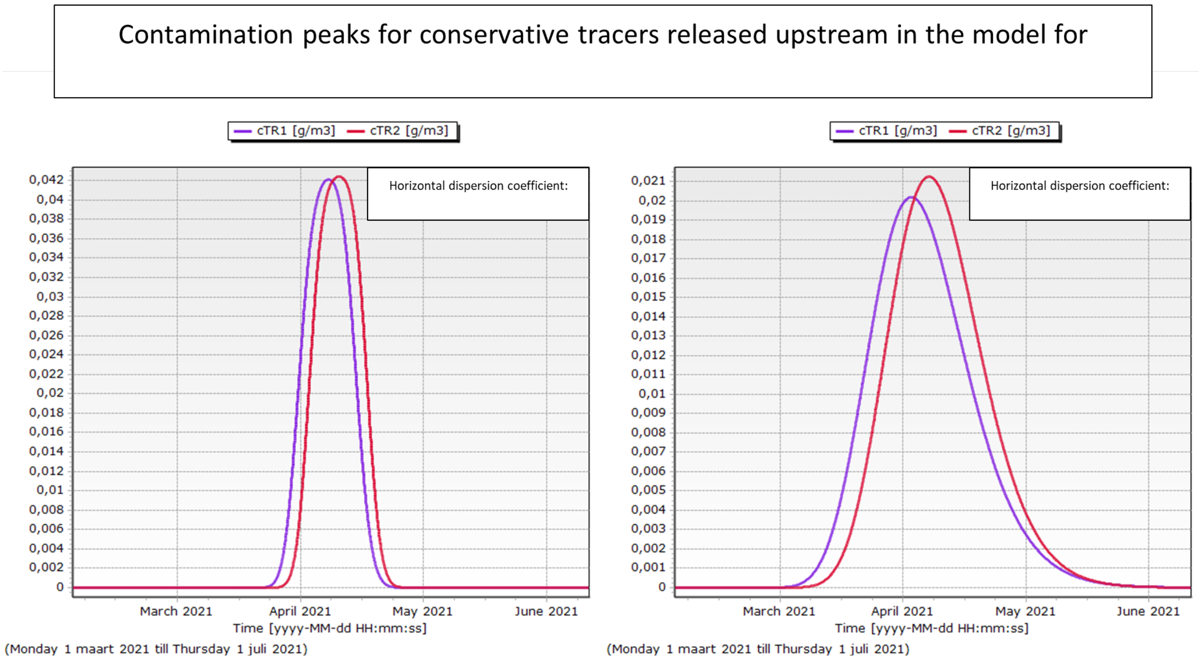


Figure 12: Contamination peaks for conservative tracers released upstream. *Contamination peaks for conservative tracer 1 (cTR1) released upstream in the Ayeyarwady and conservative tracer 2 (cTR2) released upstream in the Chindwin for horizontal dispersion coefficients of 0.1 m2/s (left) and 10,000 m2/s (right). A concentration of 100 g/ m3 was released for both tracers and tests.*

6.2 Conservative Contaminant Transport

This chapter describes the results of the conservative tracer analysis. Conservative tracers are released at several locations in the model. The volume of tracers that is released in the river is not affected by decay or other forms of reactions during the time that it is transported by the river. Because the released tracers are non reactive, this analysis is used to find to what extent contamination can be measured in the river. If the concentrations of conservative tracers that are released upstream in the river decrease rapidly, these tracers may already be difficult to measure here. Any reactive tracer would likely have lower concentrations at the same points in the river than these conservative tracers. High quality and expensive measurement equipment might be needed to measure contamination in these cases. The analysis of the conservative tracers will show the contamination peak at the observation locations along the rivers.

For the conservative tracer transport experiments, the model has a run time of 1 year. During this time, the discharge is set to a constant low river discharge as determined in chapter 5.2.

6.2.1 Contamination originating from the upper reaches of the model

Conservative tracers are released from the most northern reaches of the model. The first tracer, 'Conservative tracer 1', is released in the Upper Ayeyarwady at the confluence of the Mali Kha and N'Mai Kha Rivers. The second tracer, 'Conservative tracer 2', is released in the Chindwin at the confluence of the Chindwin and the Tagarkha River.

Conservative tracers: 100 g/s for 24 hours

The first analysis was performed by modelling the release of 100 g/s of conservative tracers for a period of 24 hours in the most upper reaches of the model. The modelled contamination peaks are shown for the observation point along the Upper and Lower Ayeyarwady. The complete set of resulting contamination peaks are presented in Appendix C. The contamination peaks for both the tracers are observed and shown for the most upstream location and the observation points that are present in the model in Table 8.

Close to the contamination sources, the maximum peak tracer concentration is approximately 0.35 g/m^3 in the Upper Ayeyarwady and 0.65 g/m^3 in the Chindwin River. The peaks show a decrease in tracer concentrations for locations downstream. After the confluence of the Ayeyarwady and Chindwin Rivers at Nyaung U, the concentrations have decreased to approximately 0.013 g/m^3 for the contamination from the Ayeyarwady River and 0.0085 g/m^3 for the contamination from the Chindwin River. At Pyay, the most downstream observation point in the model, these concentrations have decreased even further to approximately 0.011 and 0.007 g/m^3 for contamination from the Ayeyarwady and Chindwin respectively. Here, the peak concentrations of contamination from the Ayeyarwady has reduced to less than 3% of the concentration near the point of release. The peak concentration of contamination from the Chindwin has reduced to 1% of this maximum peak tracer concentration. The concentration decrease from dilution due to increasing discharge downstream is determined to be 12.2% for water from the Ayeyarwady and 6.8% for water from the Chindwin. It is also observed that the contamination peak originating from the Ayeyarwady River occurs earlier than the contamination peak from the Chindwin river. The remaining peak concentration originating from the Ayeyarwady River is higher than the remaining peak concentration from the Chindwin River. Concentration of contamination originating from the Ayeyarwady shows a lower relative dilution than contamination from the Chindwin. Remarkably it is also observed that

Location	Discharge contribution Ayeyarwady [%]	Remaining peak concentration of Conservative Tracer 1 [%]	Discharge contribution Chindwin [%]	Remaining peak concentration of Conservative Tracer 2 [%]
Upstream	100	100	100	100
Hkamti	0	0	60.7	26.9
Homalin	0	0	44.4	11.7
Mawlaik	0	0	33.2	6.8
Kalewa	0	0	31.9	6.6
Monywa	0	0	23.1	4.1
Myitkyina	91.4	80.4	0	0
Katha	39.3	7.1	0	0
Sagaing	24.1	3.5	0	0
Nyaung U	13.9	3.7	7.7	1.3
Chauk	13.5	3.5	7.5	1.2
Magway	12.9	3.3	7.2	1.2
Aunglan	12.6	3.1	7.0	1.1
Pyay	12.2	3.0	6.8	1.0

Table 8: Contamination peaks originating from the most upstream points in the model for 100g/s for 1 day. *For the duration on 24 hours, conservative tracers 1 and 2 were released at 100 g/s at the most upstream model locations in respectively the Upper Ayeyarwady and the Chindwin Rivers.*

the concentration of cTR1 is higher at the observation point at NyaungU than it is at Sagaing. Possibly contamination remains at the downstream location of NyaungU longer than it does at Sagaing due to the rivers behaviour downstream of the confluence.

Conservative tracers: 100 g/s for 14 days

The second analysis was performed by modelling the release of 100g/s of conservative tracers for a period of 14 days in the most upper reaches of the Ayeyarwady, at the confluence of the Mali Kha and N'Mai Kha Rivers. The modelled concentrations of the contamination peaks are shown for the observation points along the Upper and Lower Ayeyarwady. The complete set of resulting contamination peaks are presented graphically in Appendix C. The contamination peaks for both the tracers are observed and shown for the most upstream location and the observation points that are present in the model in Table 9.

Location	Discharge contribution Ayeyarwady [%]	Remaining peak concentration of Conservative Tracer 1 [%]	Discharge contribution Chindwin [%]	Remaining peak concentration of Conservative Tracer 2 [%]
Upstream	100	100	100	100
Hkamti	0	0	60.7	60.7
Homalin	0	0	44.4	43.8
Mawlaik	0	0	33.2	33.2
Kalewa	0	0	31.9	31.9
Monywa	0	0	23.1	22.6
Myitkyina	91.4	91.5	0	0
Katha	39.3	39.4	0	0
Sagaing	24.1	23.8	0	0
Nyaung U	13.9	27.2	7.7	7.7
Chauk	13.5	26.3	7.5	7.4
Magway	12.9	25.2	7.2	7.1
Aunglan	12.6	24.1	7.0	6.9
Pyay	12.2	23.6	6.8	6.8

Table 9: Contamination peaks originating from the most upstream points in the model for 100g/s for 14 day. *For the duration on 14 days, conservative tracers 1 and 2 were released at 100 g/s at the most upstream model locations in respectively the Upper Ayeyarwady and the Chindwin Rivers.*

Close to the contamination sources, the peak tracers concentration is approximately 0.35 g/m^3 in the Upper Ayeyarwady and 0.65 g/m^3 in the Chindwin River. The peaks show a decrease in peak tracer concentrations for locations lower downstream. After the confluence of the Ayeyarwady and Chindwin Rivers at Nyaung U, the concentrations have decreased to approximately 0.098 g/m^3 for the contamination from the Ayeyarwady River and 0.05 g/m^3 for the contamination from the Chindwin River. At Pyay, the most downstream observation point in the model, these concentrations have decreased even further to approximately 0.085 and 0.044 g/m^3 for contamination from the Ayeyarwady and Chindwin respectively. Here, the peak concentrations of contamination from the Ayeyarwady has reduced to 23.6% of the concentration near the point of release. The peak concentration of contamination from the Chindwin has reduced to 6.8%. The peak concentrations of cTR1 have decreased relatively less than cTR2. It is also observed that the contamination peak originating from the Ayeyarwady River occurs earlier than the contamination peak origination in the Chindwin river. The peak concentration originating from the Ayeyarwady River is higher than the peak contamination origination in the Chindwin River. Concentration of contamination originating from the Ayeyarwady shows an even lower relative dilution than contamination from the Chindwin for a longer contamination period. Remarkably, it is again observed that the concentration of cTR1 is higher at the observation point at NyaungU than it is at Sagaing. Possibly contamination remains at the downstream location of NyaungU longer than it does at Sagaing due to the rivers behaviour downstream of the confluence. Also, the contamination from the Chindwin has diluted at approximately the same rate as the rate that additional water has entered the river system.

6.2.2 Contamination originating from the confluence of the Ayeyarwady and Chindwin Rivers

To gain insight in the effect and contributions of the Ayeyarwady and Chindwin rivers, conservative tracers were released just upstream of the confluence of both rivers.

In both rivers, 100g/s of conservative tracers were released for a duration of 1 day. For the Upper Ayeyarwady the load consists of 'Conservative tracer 1' and was released between the last cross-section of the Upper Ayeyarwady ('UA81') and the confluence. For the Chindwin River, the load consists of 'Conservative tracer 2' and was released between the last cross-section of the Chindwin River ('CH108') and the confluence. Both loads were released at approximately 5 km upstream of the confluence. The peak concentrations are shown in Table 10 as modelled at the five observation points along the Lower Ayeyarwady River: NyaungU, Chauk, Magway, Aunglan and Pyay. The contamination peaks are shown graphically in Appendix C

When the contamination was released, the concentrations of cTR1 and cTR2 were respectively 0.078 and 0.141 g/m^3. When the peaks reach Nyaung U these concentrations have reduced to 0.06 and 0.035 g/m^3. At the most downstream observation location, Pyay, the concentrations have diluted further to 0.026 and 0.014 g/m^3. Table 10 shows that the contamination originating from the Chindwin river dilutes at a higher rate than the contamination from the Ayeyarwady. The contribution in terms of discharge for the Lower Ayeyarwady is also higher than the Chindwin.

Location	Discharge contribution Ayeyarwady [%]	Remaining peak concentration of Conservative Tracer 1 [%]	Discharge contribution Chindwin [%]	Remaining peak concentration of Conservative Tracer 2 [%]
Confluence	100	100	100	100
Nyaung U	64.2	76.9	35.5	24.8
Chauk	62.6	56.4	34.6	17.7
Magway	59.8	42.3	33.1	12.8
Aunglan	58.0	37.2	32.1	10.6
Pyay	56.6	33.3	31.3	9.6

Table 10: Contamination peaks originating from just upstream of the confluence for 100g/s for 1 day. *For the duration on 1 days, conservative tracers 1 and 2 were released at 100 g/s just upstream of the confluence in respectively the Upper Ayeyarwady and the Chindwin Rivers. The peak concentrations of contamination from the Chindwin dilute more rapidly than the contamination from the Ayeyarwady.*

6.3 Implementation of Contamination Scenarios

In the second research component (chapter 4), several contamination scenarios were identified. The results of the implementation of the scenarios for the Waste Water Treatment Plant (chapter 6.3.1 and the Tailings Dam Failure (chapter 6.3.2 are presented in this chapter.

6.3.1 Waste Water Treatment Failure

The first scenario is the failure of the No. 8 Mandalay Waste Water Treatment Plant. As described in chapter 4.2, one of the WWTPs present in Mandalay is the No.8 water treatment plant with a treatment capacity of 45.000 m^3/day. In this scenario, the treatment plant stops working and discharges directly into the river for a period of 1 hour, 1 day and 1 week. Though in reality additional water would flow into the Ayeyarwady together with the contamination, this amount is negligible (around 0.05%). In this analysis the additional water is not taken into account. Also, the water would contain a wide variety of contamination substances. Due to the probability of power outages in Myanmar,there is a non-zero chance of similar contamination events occurring in the future. The release of the tracers at the location of the waste water treatment plant in Mandalay gives insight in the distribution of contaminants for similar events.

Tracer	Initial Concentration $[g/m^3]$	Discharge $[m^3/day]$	Total Contamination $[g/s]$	Decay Rate $[1/d]$
cTR1	1	45,000	0.52	0
dTR1	1	45,000	0.52	0.01
dTR3	1	45,000	0.52	0.05

Table 11: Scenario parameters for the WWTP failure of 2 weeks. *For the duration of 14 days, one of the WWTPs in Mandalay stops and discharges untreated water into the Ayeyarwady River. The initial concentrations that are modelled are shown in the table.*

Three tracers were used to model the contaminants in the untreated water. A conservative tracer with an initial concentration of 1 g/s and two reactive tracers that decay at the rate of 0.01 and 0.05 $1/d$. Table 11 shows the assumed initial concentration of the water, the reactive tracer's decay rates and the resulting amount of tracers that is released to model the untreated discharge. The results are shown in a separate table, table 12.

Location	Failure duration: 1 hour	Failure duration: 1 day	Failure duration: 1 week
cTR1	Height of contamination peak [%]	Height of contamination peak [%]	Height of contamination peak [%]
WWTP	100	100	100
Sagaing	3.9	74.2	95.3
Nyaung U	0.8	17.9	55.1
Chauk	0.7	15.9	53.4
Magway	0.6	13.6	52.5
Aunglan	0.5	12.3	48.3
Pyay U	0.5	11.4	47.0
dTR1 0.01 [1/day]	Height of contamination peak [%]	Height of contamination peak [%]	Height of contamination peak [%]
WWTP	100	100	100
Sagaing	3.9	73.1	94.3
Nyaung U	0.7	16.4	50.8
Chauk	0.6	14.3	48.3
Magway	0.5	11.8	44.1
Aunglan	0.4	10.2	41.1
Pyay U	0.4	9.4	39.0
dTR3 0.05 [1/day]	Height of contamination peak [%]	Height of contamination peak [%]	Height of contamination peak [%]
WWTP	100	100	100
Sagaing	3.7	69.9	91.1
Nyaung U	0.5	12.2	37.1
Chauk	0.4	9.7	32.2
Magway	0.3	6.9	25.4
Aunglan	0.2	5.4	21.2
Pyay U	0.2	4.6	18.4

Table 12: Percentage of the concentration peak remaining in relation to the initial peak concentration for the Mandalay WWTP failure. *The Mandalay WWTP failure is modelled for the duration of 1 hour, 1 day and 1 week. Due to the failure the WWTP discharges untreated water into the Ayeyarwady River. For every failure duration the contamination is modelled using a conservative tracer and two reactive tracers with a decay rate of 0.01 [1/day] for dTR1 and 0.05 [1/day] for dTR3.*

When the contamination is released, the concentration of cTR1 is 0.52 g/m^3. For a WWTP failure of 1 week, the remaining concentration cTR1 at the most downstream observation location, Pyay, is 47% (2.22 mg/m^3). For the shorter failure durations of 1 day and 1 hour, these concentration is significantly smaller. For a duration of 1 day, the remaining peak concentration is 11.4% (0.45 mg/m^3) and for 1 hour it is 0.5% (0.0022 mg/m^3).

For the decaying tracers, these concentrations are smaller. For a WWTP failure of 1 week, the remaining concentration dTR1 at Pyay is 39% (1.84 mg/m^3). For a duration of 1 day, the remaining peak concentration is 9.4% (0.5 mg/m^3) and for 1 hour it is 0.4% (0.0019 mg/m^3). For a WWTP failure of 1 week, the remaining concentration dTR3 at Pyay is 18.4% (0.087 mg/m^3). For a duration of 1 day, the remaining peak concentration is 4.6% (0.022 mg/m^3) and for 1 hour it is 0.2% (0.0009 mg/m^3).

6.3.2 Tailings Dam Failure

As described in chapter 4.3, another scenario that is modelled in this research is the failure of a tailings dam in the Chindwin River. Approximately 1,000,000 m^3 of tailings are released during a period of two hours, resulting in a contamination load of approximately 500g/s. The contamination is modelled using three tracers: a Conservative tracer (cTR1) and two reactive tracers. The first reactive tracer (dTR1) has a decay rate of 0.01 [1/day] and the second reactive tracer (dTR3) has a decay rate of 0.05 [1/day]. Each of the tracers is released with an initial concentration of 500g/s. The initial concentrations of the contamination originating from the tailings dam failure is shown in table 13. The resulting contamination peaks are shown in 14

Tracer	Discharge $[m^3/day]$	Total Contamination $[g/s]$	Decay Rate $[1/d]$
cTR1	1,000,000	500	0
dTR1	1,000,000	500	0.01
dTR3	1,000,000	500	0.05

Table 13: Scenario parameters for the tailing dam failure of 2 hours. *For the duration of 2 hours, a tailings dam failure occurs at one of the mining operations along the Chindwin River. 1,000,000 m^3 of tailings are discharged into the Chindwin River. The initial concentrations that are used to model the tailings dam failure are shown in the table.*

Tracer	cTR1	dTR1	dTR3
Location	Height of contamination peak [%]	Height of contamination peak [%]	Height of contamination peak [%]
Tailings Dam	100	100	100
Mawlaik	85.3	77.9	52.9
Kalewa	76.5	67.6	42.6
Monywa	44.1	37.4	17.9
Nyaung U	13.5	10.7	4.2
Chauk	12.6	9.7	3.5
Magway	11.3	8.5	2.6
Aunglan	10.6	7.6	2.1
Pyay U	10.0	7.2	1.9

Table 14: Percentage of the concentration peak remaining in relation to the initial peak concentration for the Chindwin tailings dam failure. *The Chindwin Tailings dam failure is modelled for the duration of 2 hours. Due to the failure the tailings dam discharges large quantities of contamination into the Ayeyarwady River. The contamination is modelled using a conservative tracer and two reactive tracers with a decay rate of 0.01 [1/day] for dTR1 and 0.05 [1/day] for dTR3.*

When the contamination is released, the concentration of cTR1 is 0.034 g/m^3. For a tailings dam failure of 2 hours, the remaining concentration cTR1 at the most downstream observation location, Pyay, is 10% or 0.0034 g/m^3. A significant dilution is observable between Monywa and NyaungU. For the decaying tracers, these concentrations are smaller. For a tailings dam failure of 2 hours, the remaining concentration dTR1 at Pyay is 7.2% (0.0025 g/m^3). The remaining concentration dTR3 at Pyay is 1.9% (0.6 mg/m^3).

7 Discussion

The results presented in this report should be interpreted with caution. The study has a number of limitation that have resulted in simplifications of some parts of the research.

The first results presented in this research is the analysis of the water quality monitoring systems that are present in the Ayeyarwady Basin and three other river systems in the Southeast Asia region: the Mekong, Chao Phraya and Hong (Red) River Basins. The river systems were assessed using reports that are drafted by the responsible organisations like progress reports and supported by research papers and other reports. Actual measurement data from the monitoring systems was not always available. Because of this, it was not verified whether and how measurements are performed in reality. In most cases, the organisations responsible for the water quality measurements publish (processed) results of the water quality in the river system, often in relation to previous years.

The second results presented in this research are the future predictions for Myanmar and potential contamination scenarios. These scenarios are based on three of the largest threats to the water quality in the Ayeyarwady Basin: urbanization, industrialization and increased agricultural activity. Especially the future predictions for Myanmar should be interpreted with caution. The predictions are based on reports and data from before the corona pandamic and the military coup that has occurred in Myanmar. A coup d'état by the Myanmar military took place in the morning of February 1^{st} 2021. Since then, the future of Myanmar is increasingly uncertain. The country has shifted to a controversial military leadership which was internationally criticized and nationally contested by large scale protests. Due to the uncertainty that is the result of the coup, (international) businesses, institutions and investors have expressed their concerns and ongoing projects have been halted. Due to the current state and the expected developments of the country in the future, it is crucial to realize that the projections are now subject to a larger degree of uncertainty. It is expected that the economy of Myanmar will experience significant effects of the events. For the prediction on population this does not necessarily need to be the case. Increasing population and urbanisation are a global phenomena that are expected to continue, especially in the global South [33][26].

The third results present the model of the Ayeyarwady Basin that was produced for this research. The model was made in the modelling suits SOBEK 3.7.13.40404. This model was designed to model contamination events and the resulting breakthrough curves at the different observation points. Some simplifications were implemented in the model because of the large spatial scale of the model and the limited availability of data on the river. First a flow model was made. In this model, the inflow of water from precipitation and groundwater are modelled using available quantitative discharge data that is simplified to an expected flow at the cross-sections present in the model. The same holds for the depth of the assumed rectangular channel. As data was limited, the channel depth was interpolated between the available measurements. A third simplification in the flow model was the implementation of a limited amount of 259 cross-sections that were implemented in the model at an interval of 9 kilometers. Though the river flow model is simplified in regards to reality, increasing the level of detail would add unnecessary complexity to the model. Moreover, an increased level of detail is not supported by the available data and would result in false precision and precision bias.

A water quality module was added to the river flow model to enable the modelling of tracers and thus the breakthrough curves at the observation locations. The model was not designed to model the complex 2D behaviour of particles in the river system in detail. To still be able to model these tracers, a horizontal dispersion coefficient was used. This parameter models the dispersion of tracers throughout the river system. This parameter does not allow for transient storage to be specifically modelled. Because there is no transient storage, none of the contamination particles that are released in the model will be (temporarily) stored and delayed in location where this would be expected in reality. Storage could occur in "hyporheic zones or in-channel dead zones created by boulders, constrictions, and vegetation in the main channel" [70]. This means that the modelled tails of the breakthrough curves are shorter than in reality. This research shows the extent to which contamination can be measured and what measurement quality and frequency is needed to do so. Transient storage could slightly lower the peak of the breakthrough curve and due to the longer tail elongate the time that it can be measured. Not including transient storage could therefor result in a slightly higher modelled contamination peak than in reality reducing the required measurement accuracy but oppositely show a shorter contamination peak, increasing the required measurement frequency. Modelling transient storage in large rivers using 1-D models is a complex modelling step that 'fail to describe the multimodal nature of breakthrough curves" [1].

Finally, the model was used to find to what extent contamination event in the Ayeyarwady Basin can be measured. Several scenarios were implemented into the model in which conservative tracers are released in the river at different locations. In EU, US and WHO guidelines, acceptable levels of contaminants in drinking water can range from about 50 mg/l (e.g. nitrates) to 0.1 $\mu m/l$ (e.g. pesticides) [19][63][68]. Though guidelines for drinking water are more strict than guidelines for surface water, they present a lower limit to the measurement accuracy needed. Unfortunately, "no water quality acts or guidelines are available to determine the water quality" in Myanmar [21].

For the first experiment 100 g/s of contamination was released in the most upper reaches of the Upper Ayeyarwady and Chindwin for a duration of 1 day. The concentration of the contamination at release was 0.36 and 0.65 g/m^3 for the Ayeyarwady and the Chindwin respectively. At Pyay, the concentrations of contamination had reduced to less than 3% originating from the Ayeyarwady and less than 1% originating from the Chindwin River. Of the initial contamination of 100 g/s released in the river, concentrations of 0.011 and 0.007 g/m^3 are still detectable at the observation location at Pyay. In comparison, for a contamination of 100 g/s for a duration of 14 days, the remaining detectable concentrations for contamination from the Upper Ayeyarwady and Chindwin are still 23.5% (0.085 g/m^3) and 6.8% (0.044 g/m^3) respectively. Subsequently, for a duration of 14 days, 100 g/s of contamination was released just upstream of the confluence of the Ayeyarwady and Chindwin Rivers. At the point of release the concentrations of the contamination was 0.078 and 0.141 g/m^3 respectively. At the observation location at Pyay, these concentrations have decreased to 33.3 % (0.026 g/m^3) for contamination from the Upper Ayeyarwady and 9.6% (0.014 g/m^3) for contamination originating in the Chindwin River. In both situations the contamination can be measured during the peak.

After the generic scenarios, the failure of a waste water treatment plant in Mandalay scenario was modelled. During periods of 1 hour, 1 day and 1 week, the WWTP discharges untreated water into the Ayeyarwady River. Approximately 0.52 g/s of contamination is released resulting in an initial concentration of 0.472 mg/m^3. At the observation location at Sagaing, upstream of the confluence, the concentrations have decreased to 3.9% (0.019 mg/m^3), 74.2% (0.350 mg/m^3) and 95.3% (0.450 mg/m^3) for respectively 1 hour, 1 day and 1 week. At Pyay these have decreased further to 0.5% (0.002 mg/m^3), 11.4% (0.054 mg/m^3) and 47.0% (0.222 mg/m^3). A significant influence of the duration that a contaminant is released is observed on the concentration that is detectable downstream. It also shows that a significant drop in peak concentrations is caused by the confluence. This effect is larger for contaminants originating from the Chindwin than those origination in the Upper Ayeyarwady because the Upper Ayeyarwady has a higher discharge than the Chindwin. For the short failure duration, the concentrations at Pyay near the detection limit.

Another scenario models the failure of a tailings dam along the Chindwin River. During a period of 2 hours a large amount of tailings is released. About 345 g/s of contamination is released resulting in an initial concentration of 0.472 mg/m^3. At the observation location at Sagaing, upstream of the confluence, the concentrations have decreased to 3.9% (0.019 mg/m^3), 74.2% (0.350 mg/m^3) and 95.3% (0.450 mg/m^3) for respectively 1 hour, 1 day and 1 week. At Pyay these have decreased further to 0.5% (0.002 mg/m^3), 11.4% (0.054 mg/m^3) and 47.0% (0.222 mg/m^3).

Based on the results from this research, we find that in the scenarios used for this research, measurability at the most downstream monitoring locations near the limits of detection, but are still measurable. Monitoring here would require high-end and expensive equipment. The observation points used in this research are based on the pre-monitoring system of DWIR [51] located near towns, bridges and locations where water quality measurements are already taken. These observation locations are approximately evenly distributed in the Lower Ayeyarwady and Chindwin. However, the distribution of the observation locations in the Upper Ayeyarwady leaves significant gaps. Though it is the longest part of the river, only three monitoring locations are present in this part of the river. Besides the extra monitoring locations it is also important to get a good understanding of the contamination that originates from the the Upper Ayeyarwady and the Chindwin. This can be achieved by situating a monitoring location just upstream of the confluence of the Ayeyarwady and Chindwin rivers before the contamination is significantly diluted at the confluence.

Based on this research the following recommendations are done for future research:

- Expand scope of the model:
  - Include or look into additional tributaries in detail. Certain tributaries could possibly have significant contamination sources and transport.
  - Include or look into the Ayeyarwady delta. The tidal influences and reduced slope in the delta could affect contamination transport.
  - Expand frequency of cross-sections to more accurately model river flow and contaminant transport.
- Verify the model input:
  - Measure river depth at additional locations in the river for different river discharges and improve bathymetry.
  - Measure river discharge at additional locations in the rivers
- Model river behaviour for seasonal variation to increase knowledge on the differences in contaminant transport.
- Model substances in more detail. This research used tracers to model contamination transport. Different kind of particles could be transported in slightly different ways. Modelling important water quality parameters in more detail would increase knowledge on contamination distribution.
- Model particle behaviour in more detail (particle lagging, particles reacting etc.). In some scenarios reactive (decaying) tracers were used to approach particle behaviour. Adding more complex behaviour would increase knowledge on contamination distribution.

8 Conclusions

The purpose of this report is to present the research into what extent contamination events in the Ayeyarwady River system can be measured downstream and to find the requirements for a water quality monitoring system in the Ayeyarwady basin. The research was divided in four research components: comparing water quality monitoring systems for four different river systems in Southeast Asia, identification of contamination scenarios for the Ayeyarwady and Chindwin rivers, building a model of the Ayeyarwady and Chindwin rivers system and an analysis of the monitoring system performance.

First, an analysis of the Ayeyarwady, Mekong and Chao Phraya and Hong (Red) River basins resulted in an overview of the way that water quality parameters are monitored. Typically, water quality is measured (bi-)monthly in the river systems. Water quality is monitored by an organized monitoring network where a single entity is responsible for taking the measurements. In Myanmar these responsibilities are fractured and most measurements are collected project-based. Accessibility and sharing of measurement data is often poor and limited due to interdepartmental competition and bureaucracy.

Secondly, three main potential sources of contamination in the Ayeyarwady basin were identified and quantified: waste water treatment plant failure, tailings dam failure and agriculturalization. The first two of these contamination sources were used as contamination scenarios in the last part of the research where monitoring system performance was tested.

Thirdly, a model was built of the Ayeyarwady river and its main tributary, the Chindwin. The model is capable of modelling contamination using conservative and reactive tracers.

Finally, to find to what extent contamination events can be measured downstream, several contamination scenarios were run using the river system model .The first scenarios were generic contamination scenarios where contamination loads were released in the most upstream parts of the model and just upstream of the confluence.
For the first scenario, contamination was released in the most upstream parts of the Ayeyarwady and Chindwin rivers for a duration of 14 days. It was found that the remaining concentrations of contamination modelled at Pyay (near the start of the Ayeyarwady Delta) were 23.6% and 6.8% for contamination originating from respectively the Ayeyarwady and Chindwin rivers. At the confluence of the Ayeyarwady and the Chindwin, contamination that originates upstream is diluted significantly.

For the second scenario, contamination released just upstream of the confluence of the Ayeyarwady and Chindwin rivers for a duration of 1 day, the remaining concentrations were respectively 33.3% and 9.6%.

Then, the contamination scenarios that were identified in the second part of this research were implemented into the river model.
For the WWTP failure in Mandalay, a discharge of 45.000 m^3/day of contaminated water was modelled for a duration of 1 week, 1 day and 1 hour and for a conservative and two reactive tracers. For the conservative tracer the remaining concentrations at Pyay were 47.0%, 11.4% and 0.5% for 1 week, 1 day and 1 hour respectively.
For the two reactive tracers, a decay rate of 0.01 and 0.05 [1/day] was used. Because of the decay and the length of the rivers, the remaining concentrations significantly decrease. For the reactive tracer with a decay rate of 0.01 [1/day] the remaining concentrations decrease to 39.0%, 9.4% and 0.4%. For the reactive tracer with a decay rate of 0.05 [1/day] the remaining concentrations decrease to 18.4%, 4.6% and 0.2%.
For the tailing dam failure in the Chindwin river, a discharge of 1.000.000 m^3 of contaminated water was modelled for a duration of 2 hours and for a conservative and two reactive tracers. The remaining concentrations at Pyay were 10.0%, 7.2% and 1.9% for respectively the conservative and decaying tracers with a decay rate of 0.01 and 0.05 [1/day].

To be able to monitor water quality in the Ayeyarwady basin the following is recommended:

- Measurement responsibility should be clearly defined and distributed. Measurement data should at least be made available to other Myanmar government departments to increase effective use of data.
- The importance of water quality monitoring is highest during low river discharge. During high river discharge, the remaining concentrations can be over 17 times smaller than during low discharge.
- Based on international water quality guidelines, the water quality monitoring stations should have an accuracy around 0.1 $\mu g/l$ for different water quality parameters. Exact measurement accuracy still needs to be determined for specific parameters.
- The measurement frequency should be at least weekly to be able to monitor contamination events with a short duration.
- At least two high-quality monitoring stations should be located just upstream of the confluence of the Ayeyarwady and Chindwin rivers. One in the Ayeyarwady and one in the Chindwin river. These locations would be able to detect contamination events upstream before contamination is diluted significantly at the confluence.

References

[1] Anderson, E. J. and Phanikumar, M. S. (2007). Surface storage dynamics in large rivers: Comparing three-dimensional particle transport, one-dimensional fractional derivative, and multirate transient storage models. *Water Resources Research*, 47(9). https://doi.org/10.1029/2010WR010228.

[2] Arzrumtsyan, A. (2011). World rivers. http://worldmap.harvard.edu/data/geonode:world_rivers_dSe. [GIS shapefile] Accessed: December 10, 2020.

[3] Asian Development Bank (ADB) (2020). Economic indicators for Myanmar. https://www.adb.org/countries/myanmar/economy. Accessed: January 07, 2021.

[4] Azam, S. and Li, Q. (2010). Tailings dam failures: A review of the last one hundred years. *Geotech. News*, 28:50–54.

[5] Bhardwaj, S., Owen, L., and Leinbach, T. (2011). Irrawaddy river. https://www.britannica.com/place/Irrawaddy-River.

[6] Bowles, J. (2013). Irrawaddy river research. https://www.researchgate.net/publication/258045519_Irrawaddy_River_Research.

[7] Breuer, L., Hiery, N., Kraft, P., Bach, M., Aubert, A., and Frede, H. (2015). Hydrocrowd: a citizen science snapshot to assess the spatial control of nitrogen solutes in surface waters. *Scientific Reports*, 5(16503). https://doi.org/10.1038/srep16503.

[8] Buyaert, W., Zulkafli, Z., Grainger, S., Acosta, L., Alemie, T., Bastiaensen, J., De Bièvre, B., Bhusal, J., Clark, J., Dewulf, A., Foggin, M., Hannah, D., Hergarten, C., Isaeva, A., Karpouzoglou, T., Pandeya, B., Paudel, D., Sharma, K., Steenhuis, T., Tilahun, S., Van Hecken, G., and Zhumanova, M. (2014). Citizen science in hydrology and water resources: opportunities for knowledge generation, ecosystem service management, and sustainable development. *Frontiers in Earth Science*, 2(26). https://doi.org/10.3389/feart.2014.00026.

[9] CABI (2020). Project to help achieve sustainable agriculture in Myanmar already bearing 'fruitful' results. https://www.cabi.org/news-article/project-to-help-achieve-sustainable-agriculture-in-myanmar-already-bearing-fruitful-results/. Accessed: January 13, 2021.

[10] Centre for Environmental Monitoring (CEM) (2018). Situation of environmental monitoring system in Vietnam. http://cem.gov.vn/mang-luoi-quan-trac-moi-truong/thuc-trang-he-thong-quan-trac-moi-truong-o-viet-nam-1. Accessed: January 06, 2021.

[11] Damania, R., Desbureaux, S., Rodella, A., Russ, J., and Zaveri, E. (2019). *Quality Unknown: The Invisible Water Crisis.* The World Bank. https://doi.org/10.1596/978-1-4648-1459-4.

[12] Deltares (2019). *SOBEK: Hydrodynamics, Rainfall Runoff and Real Time Control User Manual.*

[13] Deltares (2020). Sobek suite. https://www.deltares.nl/en/software/sobek/. Accessed: November 10, 2020.

[14] Department of Geological Survey and Mineral Exploration (2012). Data base building in ministry of mines, Myanmar. https://themimu.info/sites/themimu.info/files/documents/Presentation_Mining_in_Myanmar_Governement_of_Myanmar_Mar2012.pdf. Accessed: 04 February, 2021.

[15] Department of Population (2015). The 2014 Myanmar population and housing census. https://unstats.un.org/unsd/demographic/sources/census/wphc/Myanmar/MMR-2015-05.pdf. Accessed: January 07, 2021.

[16] Embassy of the kingdom of the Netherlands in Myanmar (2016). Water in Myanmar. https://www.nederlandwereldwijd.nl/binaries/nederlandwereldwijd/documenten/publicaties/2016/03/21/factsheet-water-iwrm-nl-myanmar/factsheet-water-iwrm-nl-myanmar-15-03-2016-final.pdf. Accessed: December 03, 2020.

[17] Food and Agriculture Organization of the United Nations (FAO) (2016). Vietnam: environment and health. http://www.fao.org/nr/water/aquastat/countries_regions/Profile_segments/VNM-EnvHea_fra.stm. Accessed: January 06, 2021.

[18] Fukase, E. and Martin, W. (2020). Economic growth, convergence, and world food demand and supply. *World Development*, 132(104954). https://doi.org/10.1016/j.worlddev.2020.104954.

[19] Het Europees Parlement En De Raad Van De Europese Unie (2020). Richtlijn (EU) 2020/2184 van het Europees Parlement en De Raad van 16 december 2020 betreffende de kwaliteit van voor menselijke consumptie bestemd water (herschikking). https://eur-lex.europa.eu/legal-content/NL/TXT/PDF/?uri=CELEX:32020L2184&from=EN. Accessed: 15 June 2021.

[20] Hu, L., Wu, H., Zhang, L., Zhang, P., and Wen, Q. (2017). Geotechnical properties of mine tailings. *Journal of Materials in Civil Engineering*, 29(2). http://dx.doi.org/10.1061/(ASCE)MT.1943-5533.0001736.

[21] Integrated Ayeyarwady Delta Strategy (IADS) (2018). Ayeyarwady delta atlas. Unpublished.

[22] International Monetary Fund (IMF) (2020). Myanmar. https://www.imf.org/en/Countries/MMR. Accessed: January 07, 2021.

[23] Irwin, A. (1995). *Citizen Science: A Study of People, Expertise and Sustainable Development*. Routledge.

[24] Khon, R. (2011). Water quality management at river basin in Myanmar. https://web.archive.org/web/20160816103822/http://www.wepa-db.net/pdf/1203forum/10.pdf.

[25] KNOEMA (2021). Myanmar - fertilizer consumption per unit of arable land. https://knoema.com/atlas/Myanmar/Fertilizer-consumption#:~:text=Myanmar%20%2D%20Fertilizer%20consumption%20per%20unit%20of%20arable%20land&text=Myanmar%20fertilizer%20consumption%20was%20at,is%20a%20change%20of%2024.96%25. Accessed: 05 February, 2021.

[26] Kookana, R. S., Drechsel, P., Jamwal, P., and Vanderzalm, J. (2020). Urbanisation and emerging economies: Issues and potential solutions for water and food security. *Science Of The Total Environment*, 732. https://doi.org/10.1016/j.scitotenv.2020.139057.

[27] Kravtsova, V., Mikhailov, V., and Kidyaeva, V. (2009). Hydrological regime, morphological features and natural territorial complexes of the Irrawaddy River Delta (Myanmar). *Water Resources*, 36-3(243-260). https://doi.org/10.1134/S0097807809030014.

[28] Kumar, a., Chen, Y., Kirby, J., Williams, M., Kookana, R., and O'Neill, C. (2017). Soba 1.3: Water pollution survey. https://airbm.org/downloads/SOBA/SOBA%201.3_water_pollution_2017_F.pdf. Accessed: January 20, 2021.

[29] Kyaw, S. (2019). Myanmars lifeblood in peril. https://www.mmtimes.com/news/myanmars-lifeblood-peril.html. Accessed: 29 April, 2021.

[30] LaJeunesse Connette, K., J., Connete, G., Bernd, A., Phyo, P., Htet Aung, K., Lin Tun, Y., Min Thein, Z., Horning, N., Leimgruber, P., and Songer, M. (2016). Assessment of mining extent and expansion in Myanmar based on freely-available satellite imagery. *Remote Sensing*, 8(912). https://doi.org/10.3390/rs8110912.

[31] Lazar, D., Alexandru, M., and Purcel, A. (2019). Pollution and economic growth: Evidence from central and eastern European countries. *Energy Economics*, 81(1121-1131). https://doi.org/10.1016/j.eneco.2019.05.011.

[32] Lebreton, L., van der Zwet, J., Damsteeg, J., Slat, B., Andrady, A., and Reisser, J. (2017). River plastic emissions to the world's oceans. *Nature Communications*, 8(15611). https://doi.org/10.1038/ncomms15611.

[33] Leeson, G. W. (2018). The growth, ageing and urbanisation of our world. *Journal of Population Ageing*, 11(107-115). https://doi.org/10.1134/S0097807809030014.

[34] Leibengut, C., Malowszewskim, P., and Kulls, C. (2009). *Tracers in Hydrology.* Wiley.

[35] Milliman, J. and Giosan, L. (2019). River inputs. *Encyclopedia of Ocean Sciences (Third Edition)*, 6(100-107). https://doi.org/10.1016/B978-0-12-409548-9.10814-0.

[36] Myanmar Geosciences Society (2014). Geological map of Myanmar (2014). [Geological Map].

[37] Myat., S. S. and Joshi, P. (2017). No. 8 water treatment plant, Mandalay, Myanmar. http://www.jwrc-net.or.jp/aswin/en/newtap/report/NewTap_043.pdf.

[38] National Oceanic And Atmospheric Administration (NOAA) (2020). Etopo1 global relief model. https://www.ngdc.noaa.gov/mgg/global/. Accessed: December 10, 2020.

[39] Newland Bowker, N. and Chambers, D., M. (2015). The risk, public liability, & economics of tailings storage facility failures. https://www.earthworks.org/cms/assets/uploads/2018/12/44-Bowker-Chambers.-2015.-Risk-Public-Liability-Economics-of-Tailings-Storage-Facility-Failures.pdf. Accessed: 04 February, 2021.

[40] Piman, T., Krittasudthacheew, C., Gunawardanaa, S., and Shresthaa, S. (2020). Monitoring and modelling mining impacts on water quality in Chindwin River Basin, Myanmar. https://meetingorganizer.copernicus.org/EGU2020/EGU2020-15824.html. https://doi.org/10.5194/egusphere-egu2020-15824.

[41] Ra, K. (2011). Water quality management at river basin in Myanmar. http://www.wepa-db.net/pdf/1203forum/10.pdf. Accessed: November 16, 2020.

[42] Research Program on Water, L. and Exosystems (2017). Mk24: Rivers for life and livelihoods: classification of river health in the Ayeyarwady River Basin. https://wle.cgiar.org/project/mk24-rivers-life-and-livelihoods-classification-river-health-ayeyarwady-river-basin. Accessed: November 16, 2020.

[43] Riesch, H. and Potter, C. (2013). Citizen science as seen by scientists: Methodological, epistemological and ethical dimensions. *Public Understanding of Science*, 23(1). https://doi.org/10.1177/0963662513497324.

[44] Robb, L., J. and Searle, P. (2014). The metallogenic provinces of Myanmar. *Applied Earth Science*, 123(25-38). https://doi.org/10.1179/1743275814Y.0000000049.

[45] Robinson, R., Bird, M., Oo., N. W., Hoey, T., Aye., M. M., Higgitt, D.and X, L., Swe., A., Tun., T., and Win., S. L. (2007). The Irrawaddy River sediment flux to the Indian Ocean: The original nineteenth-century data revisited. *The Jorunal of Geology*, 115(629-640). https://doi.org/10.1086/521607.

[46] RVO (2014). Myanmar IWRM stratigic study. https://europa.eu/capacity4dev/file/22304/download?token=0H4XJrGQ. Accessed: December 03, 2020.

[47] Singkran, N., Anantawong, P., Intharawichian, N., and Kunta, K. (2019). The Chao Phraya River Basin: water quality and anthropogenic influences. *Water Supply*, 19(1287-1294). https://doi.org/10.2166/ws.2018.167.

[48] Taft, L. and Evers, M. (2016). A review of current and possible future human–water dynamics in Myanmar's river basins. *Hydrology and Earth System Sciences*, 20(4913-4928). https://doi.org/10.5194/hess-20-4913-2016.

[49] Thandar Ko, N., Suter, P., Conallin, J., Rutten, M., and Bogaard, T. (2020). The urgent need for river health biomonitoring tools for large tropical rivers in developing countries: Preliminary development of a river health monitoring tool for Myanmar rivers. *Water*, 12(1408). https://doi.org/10.3390/w12051408.

[50] Thatoe Nwe Win, T., Bogaard, T., and van de Giesen, N. (2015). Water quality assessment of Ayeyarwady River in Myanmar. http://resolver.tudelft.nl/uuid:aa7ab12c-db3f-4340-bc38-b4fb1c08d52e. Accessed: December 15, 2020.

[51] Thatoe Nwe Win, T., Bogaard, T., and van de Giesen, N. (2019). A low-cost water quality monitoring system for the Ayeyarwady River in Myanmar using a participatory approach. *Water*, 11(1984). https://doi.org/10.3390/w11101984.

[52] The Mekong River Commission Secretariat (2017). 2017 lower Mekong regional water quality monitoring report. https://mrcmekong.org/assets/Publications/technical/Annual-Water-Quality-Report-2014-final-lowres.pdf.

[53] The World Bank (2019). Vietnam: Toward a safe, clean, and resilient water system. https://openknowledge.worldbank.org/handle/10986/31770.

[54] The World Bank (2020a). Global economic prospects. https://www.worldbank.org/en/publication/global-economic-prospects#data. Accessed: January 07, 2021.

[55] The World Bank (2020b). Myanmar: Project to boost agricultural productivity, support farmers in wake of covid-19. https://www.worldbank.org/en/news/press-release/2020/06/26/myanmar-project-to-boost-agricultural-productivity-support-farmers-in-wake-of-covid-19-coronavirus. Accessed: January 13, 2021.

[56] The World Bank (2020c). National food and agriculture system project. https://projects.worldbank.org/en/projects-operations/project-detail/P164448. Accessed: January 13, 2021.

[57] The World Bank (2020d). Population growth (annual %) - Myanmar. https://data.worldbank.org/indicator/SP.POP.GROW?locations=MM. Accessed: January 07, 2021.

[58] The World Bank (2020e). Population, total - Myanmar. https://data.worldbank.org/indicator/SP.POP.TOTL?locations=MM. Accessed: January 07, 2021.

[59] The World Bank (2021). Fertilizer consumption (kilograms per hectare of arable land). https://data.worldbank.org/indicator/AG.CON.FERT.ZS?end=2016&start=2002&view=chart. Accessed: 05 February, 2021.

[60] United Nations Environment Programme (UNEP) (2020). An introduction to SDG indicator 6.3.2: Proportion of bodies of water with good ambient water quality. https://communities.unep.org/display/sdg632/Documents+and+Materials?preview=/32407814/38306458/SDG_632_Introduction%20to%20the%20Methodology_EN%20(3).pdf#DocumentsandMaterials-Intro. Accessed: December 03, 2020.

[61] United Nations Population Fund (UNFPA) (2020). Myanmar overview. https://www.unfpa.org/data/world-population/MM. Accessed: January 07, 2021.

[62] United Nations (UN) (2019). World population prospects 2019. https://population.un.org/wpp/Publications/Files/WPP2019_DataBooklet.pdf. Accessed: January 07, 2021.

[63] United States Environmental Protection Agency (EPA) (2009). National primary drinking water regulations. https://www.epa.gov/sites/production/files/2016-06/documents/npwdr_complete_table.pdf. Accessed: 15 June, 2021.

[64] Water Environment Partnership in Asia (WEPA) (2020). Water quality monitoring systems. http://www.wepa-db.net/policies/enforcement/monitoring/vietnam.htm. Accessed: January 06, 2021.

[65] Win, S. and Myo Myint, M. (1998). Mineral potential of Myanmar. *Resource Geology*, 48. https://doi.org/10.1111/j.1751-3928.1998.tb00018.x.

[66] WISE (2021). Chronology of major tailings dam failures. http://www.wise-uranium.org/mdaf.html. Accessed: 04 February, 2021.

[67] Woodroffe, C. and Saito, Y. (2011). River-dominated coasts. *Treatise on Estuarine and Coastal Science*, 3(117-135). https://doi.org/10.1016/B978-0-12-374711-2.00306-5.

[68] World Health Organisation (WHO) (2017). Guidelines for drinking-water quality: Fourth edition incorporating the first addendum. https://www.who.int/publications/i/item/9789241549950.

[69] World Wide Fund (W.W.F) (2018). The Ayeyarwady River and the economy of Myanmar. https://d2ouvy59p0dg6k.cloudfront.net/downloads/ayeyarwady_risks_and_opportunties_report_v1_en_web.pdf.

[70] Zarnetske, J., Gooseff, M., Brosten, T. R., Bradford, J. H., McNamara, J. P., and Bowden, W. B. (2007). Transient storage as a function of geomorphology, discharge, and permafrost active layer conditions in arctic tundra streams. *Water Resources Research*, 43. https://doi.org/10.1029/2005WR004816.

[71] Zheng, H., Huai, W., and Huang, L. (2015). Relationship between pollution and economic growth in China: Empirical evidence from 111 cities. *Journal of Urban and Environmental Engineering*, 9(22-31). https://doi.org/10.4090/juee.2015.v9n1.022031.

A Appendix A: Annual Measurements in the River Systems

This appendix presents the annual measurements that are performed by the responsible entities in the Ayeyarwady, Mekong, Chao Phraya, and Hong river basins. If available, the recommended analytical methods used to measure the water quality parameters are also presented in the table.
The annual measurements are presented for every river basin individually.

- Table 15: Ayeyarwady Basin
- Table 16: Mekong Basin
- Table 17: Chao Phraya Basin
- Table 18: Hong Basin

Table 15: Overview of annual measurements by DWIR. *Basic water quality parameters are measured annually by DWIR. Myanmar lacks a water quality measuring system that monitors the development of water quality in the Ayeyarwady Basin.*

Locations	Parameters	Measuring Unit
Kyankhin	Dissolved oxygen (DO)	mg/L
Myanaung	Nitrate	mg/L
Hinthada	Nitrite	mg/L
Zalun	pH	mg/L
Aphauk	Turbidity	NTU
Zakargyi	Iron	mg/L
Danubyu	Chloride	mg/L
Nyaungdon	Chlorine	mg/L
Maubin	Alkalinity	mg/L
Twante	Hardness	mg/L
	Ammonia	mg/L
	Phosphate	mg/L
	Fluoride	mg/L

Table 16: Overview of measured parameters in the Mekong river. *Measured parameters and recommended analytical methods as described in the Annual Mekong Water Quality Report* [52].

Analytical Parameter	Measuring Unit	Recommended Analytical Methods
Temperature	C^o	2550-Temp/SM
pH	mg/L	4500-H+/SM
Electrical conductivity	mS/m	2510-EC/SM
Alkalinity/ Acidity	mg/L	2320-A/SM
Dissolved Oxygen (DO)	mg/L	4500-O/SM
Biological Oxygen Demand (BOD)	mg/L	5210-BOD5/SM
Chemical Oxygen Demand (COD)	mg/L	Permanganate Oxidation
Total phosphorous (T-P)	mg/L	4500-P/SM
Total Nitrogen (T-N)	mg/L	4500-N/SM
Ammonium (NH4-N)	mg/L	4500-NH4/SM
Total Nitrite and Nitrate (NO(2-3)-N)	mg/L	4500-NO2-3/SM
Faecal Coliform	mg/L	9221-Faecal Coliform group/SM
Total Suspended Solid	mg/L	2540-D-TSS-SM
Calcium (Ca)	mg/L	3500-Ca-B/SM
Magnesium (Mg)	mg/L	3500-Mg-B/SM
Sodium (Na)	mg/L	3500-Na-B/SM
Potassium (K)	mg/L	3500-K-B/SM
Sulphate (SO4)	mg/L	4500- SO4 –E/SM
Chloride (Cl)	mg/L	4500-Cl/SM

Table 17: Overview of measured parameters by the PCD in the Chao Phraya river [47].

Analytical Parameter	Measuring Unit
Temperature	C
pH	mg/L
Salinity	mg/L
Electrical Conductivity (EC)	mS/m
Dissolved Oxygen (DO)	mg/L
Biochemical Oxigen Demand (BOD)	mg/L
Nitrage-nitrogen (NO3-N)	mg/L
Total Phosphorus (TP)	mg/L
Lead (Pb)	mg/L
Mercury (Hg)	mg/L
Faecal Coliform Bacteria (FCB)	mg/L

Table 18: Overview of measured parameters in Vietnam's National Monitoring Network [64].

Analytical Parameter	Measuring Unit
Temperature	C
pH	mg/L
Turbidity	NTU
Biochemical Oxigen Demand (BOD)	mg/L
Ammonia-Nitrogen (Nh4-N)	mg/L
Ferrous Quantity	mg/L
Calcium (Ca)	mg/L
Magnesium (Mg)	mg/L
Sodium (Na)	mg/L
Potassium (K)	mg/L
Sulphate (SO4)	mg/L
Chloride (Cl)	mg/L
Bicarbonite (HCO3)	mg/L
Silicon Dioxide (SiO2)	mg/L

B Appendix B: Water Levels During High And Low River Discharge

This appendix presents the output of the water quality model in terms of water level for the Ayeyarwady and Chindwin Rivers for high and low river discharge. The river's cross-section as well both of the water levels for the rivers are shown. Additionally, aerial imagery of the situation of the river at every observation point is shown. For every observation point the resulting water levels are presented consecutively.

High and low river discharge as modelled at the observation point along the three river branches: Chindwin, Upper Ayeyarwady, and Lower Ayeyarwady.

- Figure 13: Chindwin (Hkamti, Homalin, Mawlaik)
- Figure 14: Chindwin (Kalewa, Monywa)
- Figure 15: Upper Ayeyarwady (Myitkyina, Katha, Sagaing)
- Figure 16: Lower Ayeyarwady (NyaungU, Chauk, Magway)
- Figure 17: Lower Ayeyarwady (Aunglan, Pyay)

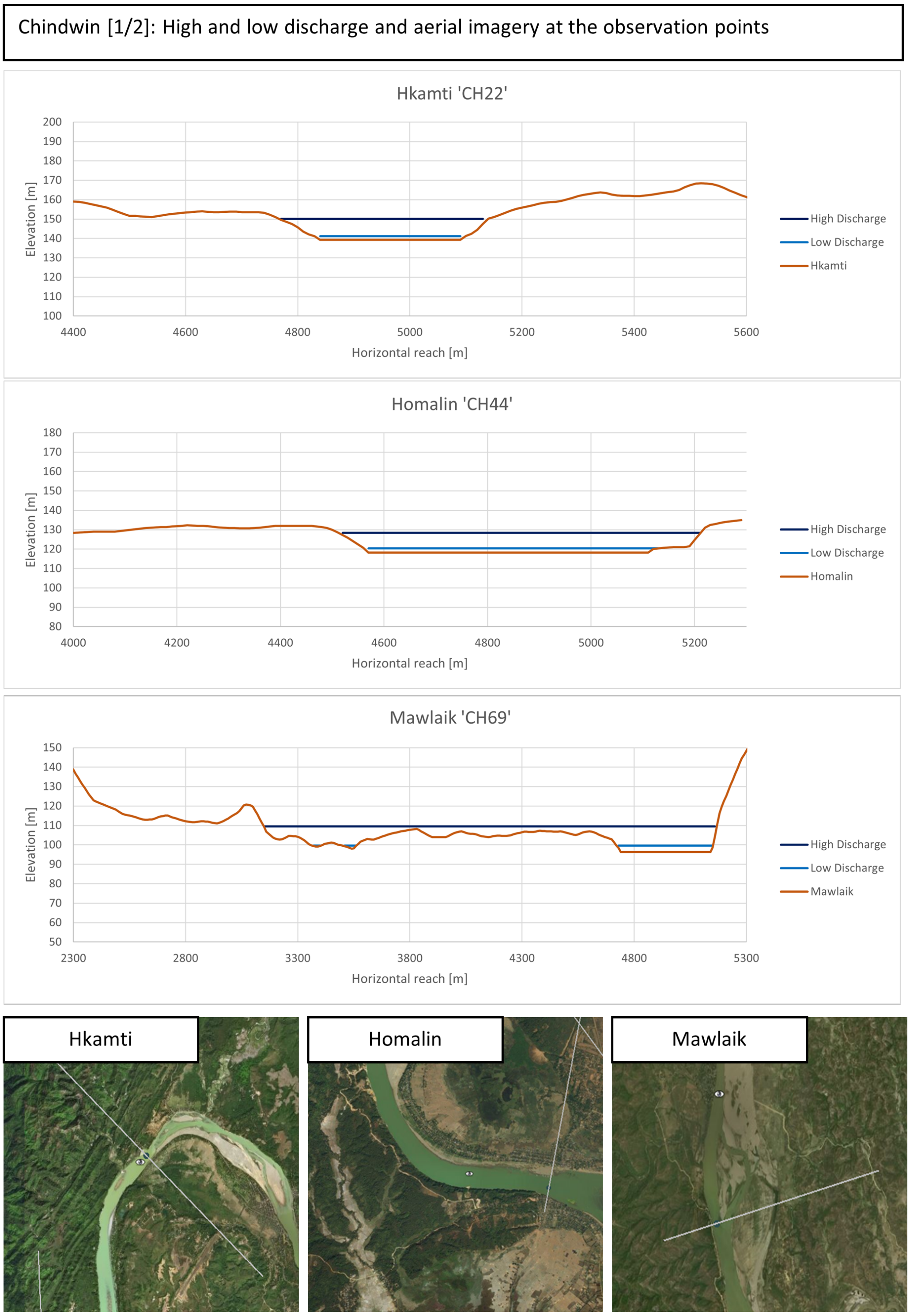


Figure 13: Modelled water levels in the Chindwin river for high and low discharge (1/2) *The water levels show that the model is capable to model high and low discharge. The water levels for the assumed high discharge approach the natural bankfull water level, further strengthening the confidence in the model's accuracy.*

Figure 14: Modelled water levels in the Chindwin river for high and low discharge (2/2) *The water levels show that the model is capable to model high and low discharge. The water levels for the assumed high discharge approach the natural bankfull water level, further strengthening the confidence in the model's accuracy.*

Figure 15: Modelled water levels in the Upper Ayeyarwady for high and low discharge *The water levels show that the model is capable to model high and low discharge. The water levels for the assumed high discharge approach the natural bankfull water level, further strengthening the confidence in the model's accuracy.*

Lower Ayeyarwady [1/2]: High and low discharge and aerial imagery at the observation points

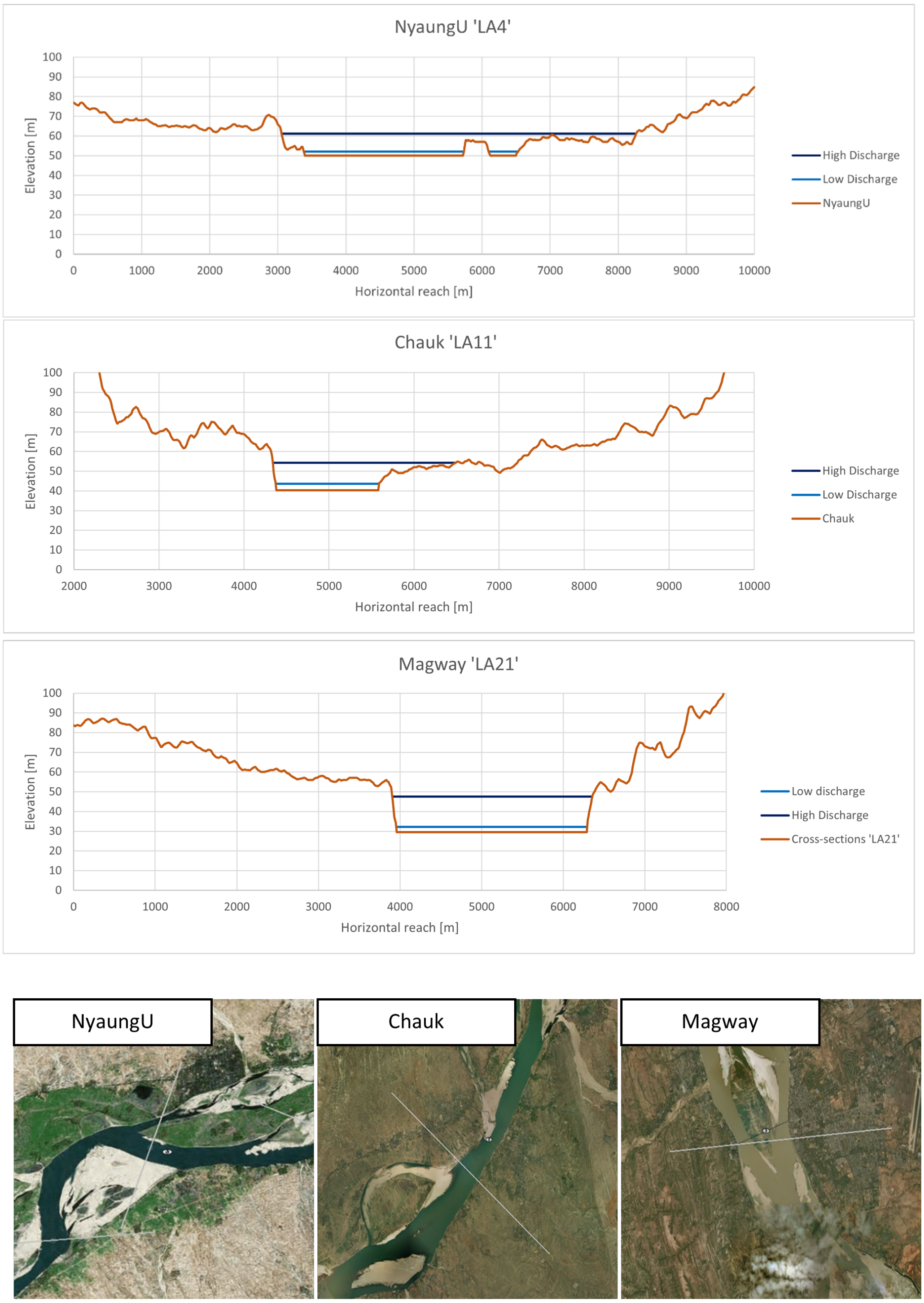


Figure 16: Modelled water levels in the Lower Ayeyarwady for high and low discharge (1/2) *The water levels show that the model is capable to model high and low discharge. The water levels for the assumed high discharge approach the natural bankfull water level, further strengthening the confidence in the model's accuracy.*

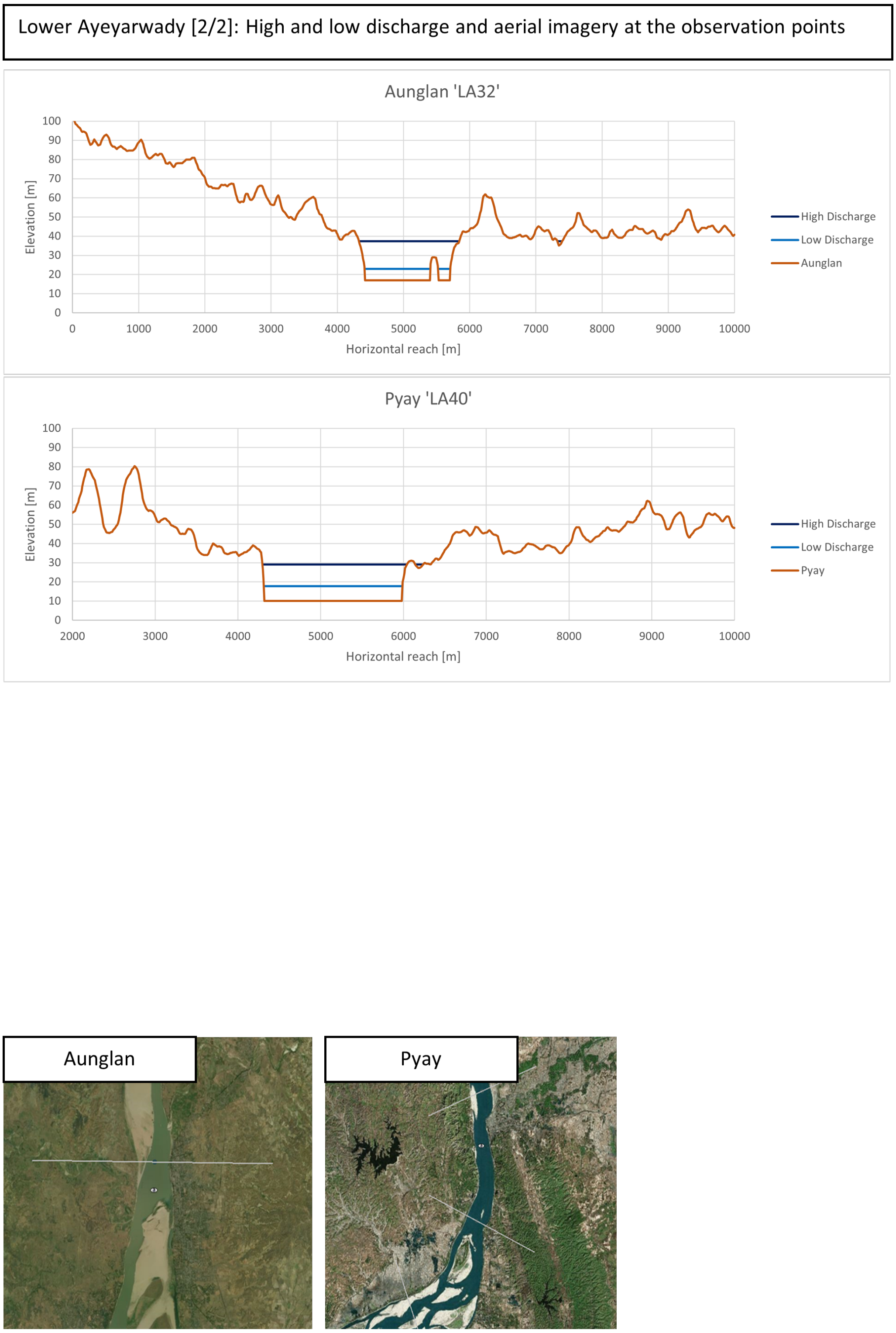


Figure 17: Modelled water levels in the Lower Ayeyarwady for high and low discharge (1/2) *The water levels show that the model is capable to model high and low discharge. The water levels for the assumed high discharge approach the natural bankfull water level, further strengthening the confidence in the model's accuracy.*

C Appendix C: Contamination Peaks

This appendix presents the output of the water quality model for the Ayeyarwady and Chindwin Rivers. The contamination curves resulting from the release of tracers in the river are shown. A number of tests have been performed during this research that are presented consecutively:

- Upstream tracer release of 100 [g/s] for a duration of 1 day. cTR1 was released upstream in the Upper Ayeyarwady and cTR2 was released upstream in the Chindwin River.
  - Figure 18: Upper Ayeyarwady
  - Figure 19: Chindwin
  - Figure 20: Lower Ayeyarwady
- Upstream tracer release of 100 [g/s] for a duration of 14 days. cTR1 was released upstream in the Upper Ayeyarwady and cTR2 was released upstream in the Chindwin River.
  - Figure 21: Upper Ayeyarwady
  - Figure 22: Chindwin
  - Figure 23: Lower Ayeyarwady
- Tracer release just upstream of the confluence of the Ayeyarwady and Chindwin. 100 [g/s] was released for a duration of 1 day. cTR1 was released just upstream of the confluence in the Upper Ayeyarwady and cTR2 was released just upstream of the confluence in the Chindwin River.
  - Figure 24: Lower Ayeyarwady
- Mandalay waste water treatment plant failure. 0.52 [g/s] of a conservative tracer and two reactive tracers are released in the north west of the city of Mandalay. cTR1 is the conservative tracer, dTR1 and dTR3 are reactive tracers with a decay rate of respectively 0.01 and 0.05 [1/day].
  - Figure 25: WWTP failure for a duration of 1 hour
  - Figure 26: WWTP failure for a duration of 1 day
  - Figure 27: WWTP failure for a duration of 1 week

- Chindwin tailings dam failure for a period of 2 hours. A conservative tracer and two reactive tracers are released in the north west of the city of Mandalay. cTR1 is the conservative tracer, dTR1 and dTR3 are reactive tracers with a decay rate of respectively 0.01 and 0.05 [1/day].
    - Figure 28: Chindwin
    - Figure 29: Lower Ayeyarwady

Figure 18: Tracer distribution in the Upper Ayeyarwady (Upstream - 1 Day). *100 [g/s] of CTR1 and CTR2 was released for a period of 1 day upstream in respectively the Upper Ayeyarwady and the Chindwin.*

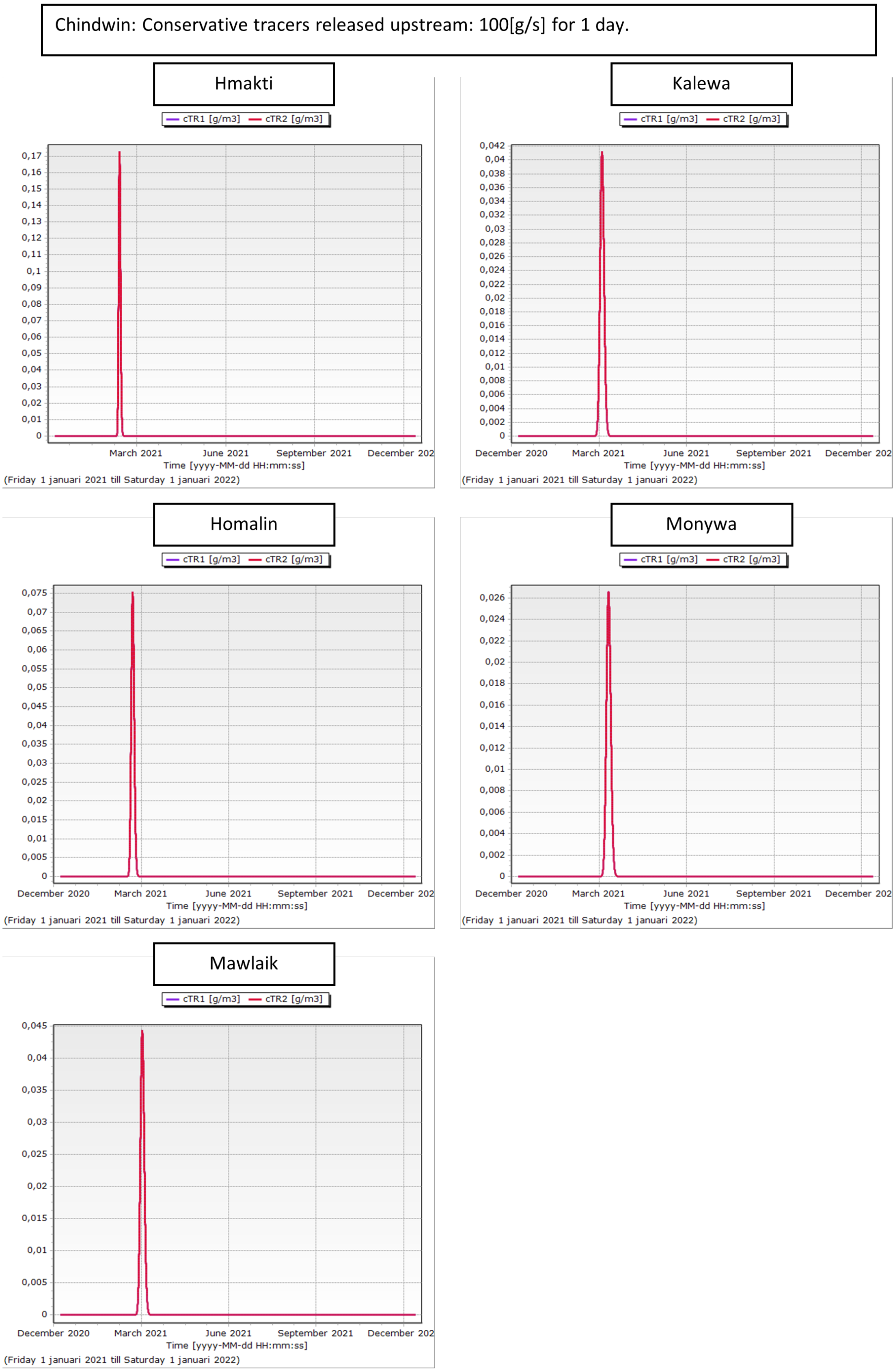


Figure 19: Tracer distribution in the Chindwin (Upstream - 1 Day). *100 [g/s] of CTR1 and CTR2 was released for a period of 1 day upstream in respectively the Upper Ayeyarwady and the Chindwin.*

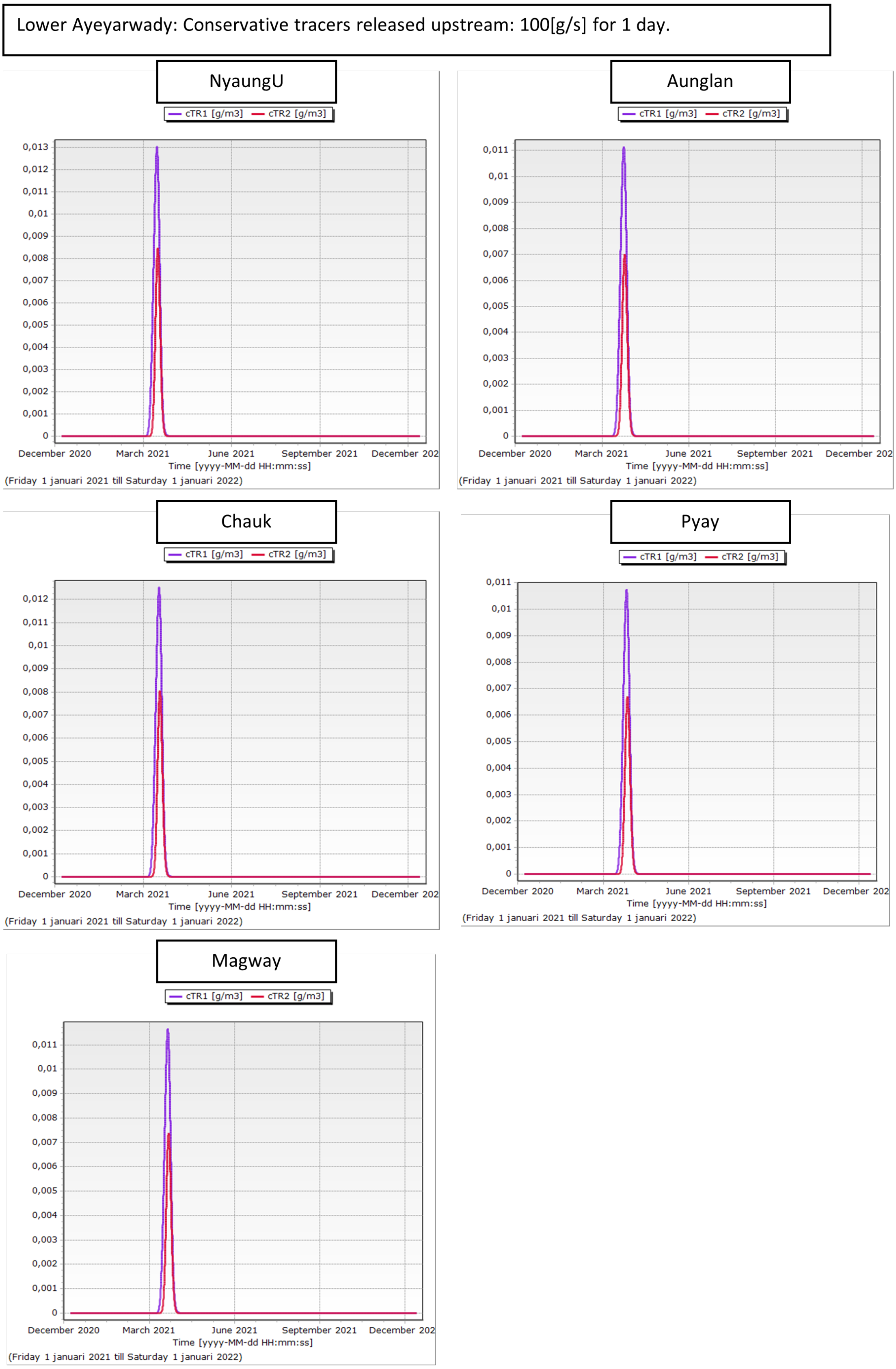


Figure 20: Tracer distribution in the Lower Ayeyarwady (Upstream - 1 Day). *100 [g/s] of CTR1 and CTR2 was released for a period of 1 day upstream in respectively the Upper Ayeyarwady and the Chindwin.*

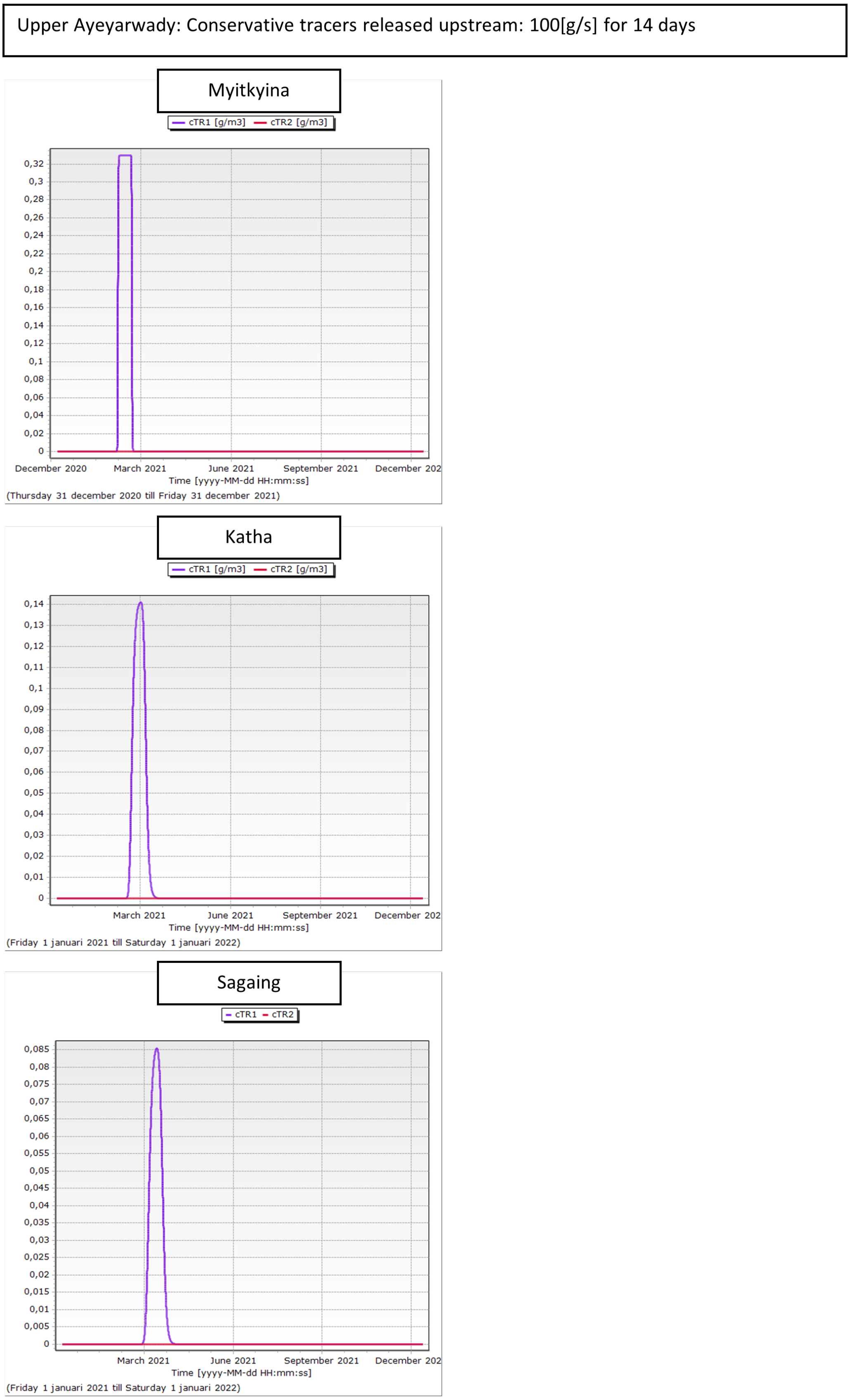


Figure 21: Tracer distribution in the Upper Ayeyarwady (Upstream - 14 Days). *100 [g/s] of CTR1 and CTR2 was released for a period of 14 days upstream in respectively the Upper Ayeyarwady and the Chindwin.*

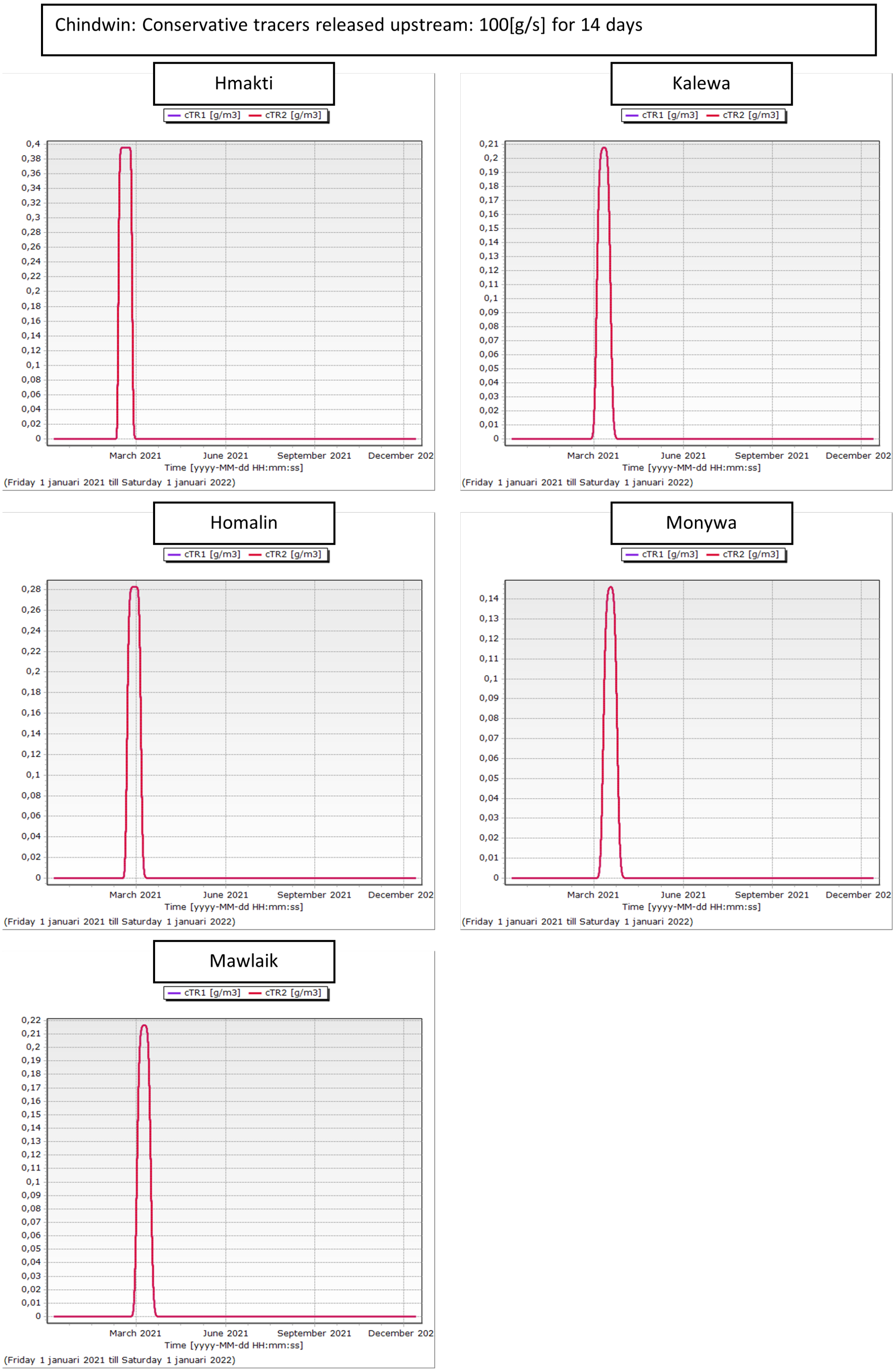


Figure 22: Tracer distribution in the Chindwin (Upstream - 14 Days). *100 [g/s] of CTR1 and CTR2 was released for a period of 14 days upstream in respectively the Upper Ayeyarwady and the Chindwin.*

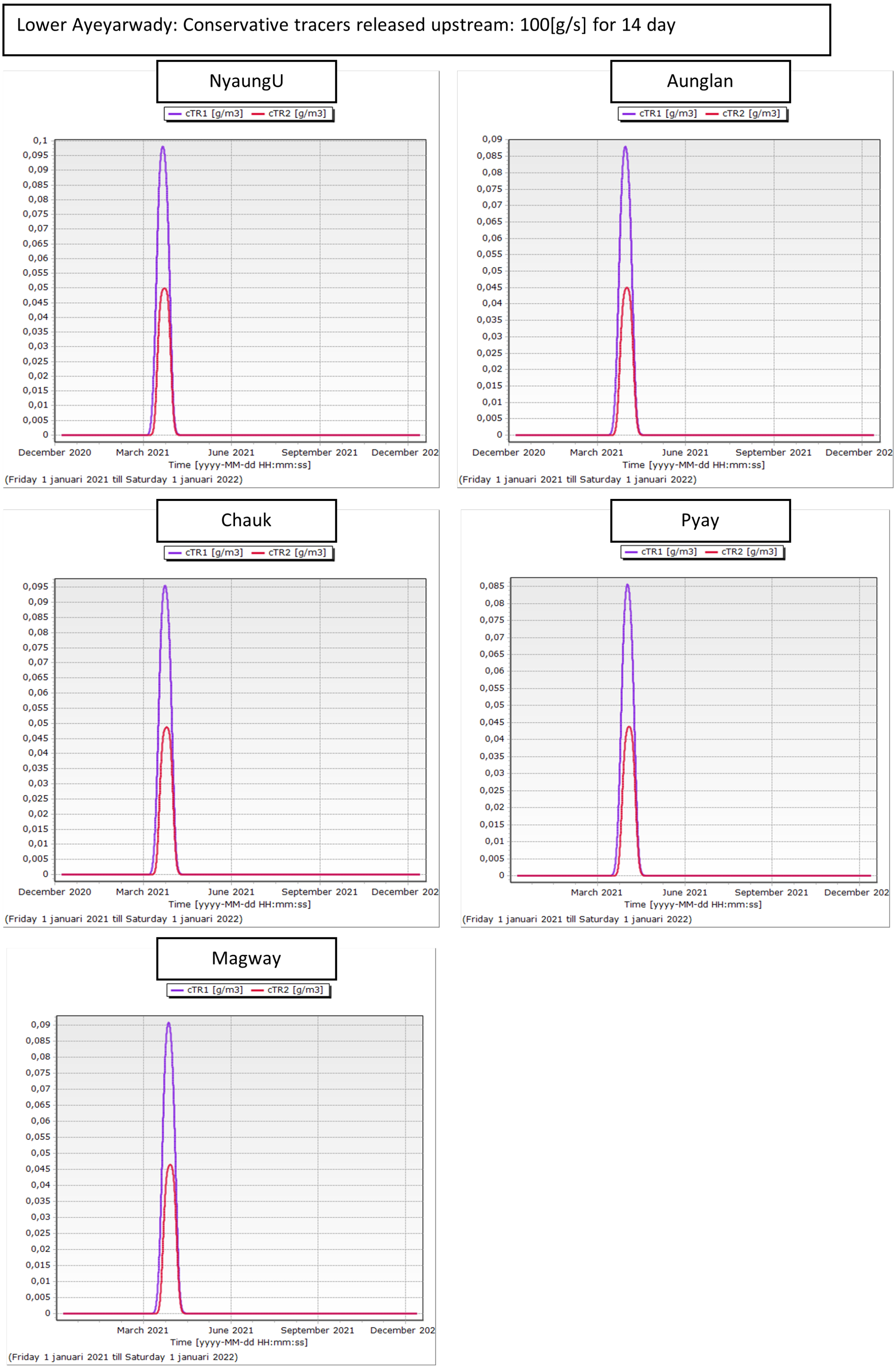


Figure 23: Tracer distribution in the Lower Ayeyarwady (Upstream - 14 Days). *100 [g/s] of CTR1 and CTR2 was released for a period of 14 days upstream in respectively the Upper Ayeyarwady and the Chindwin.*

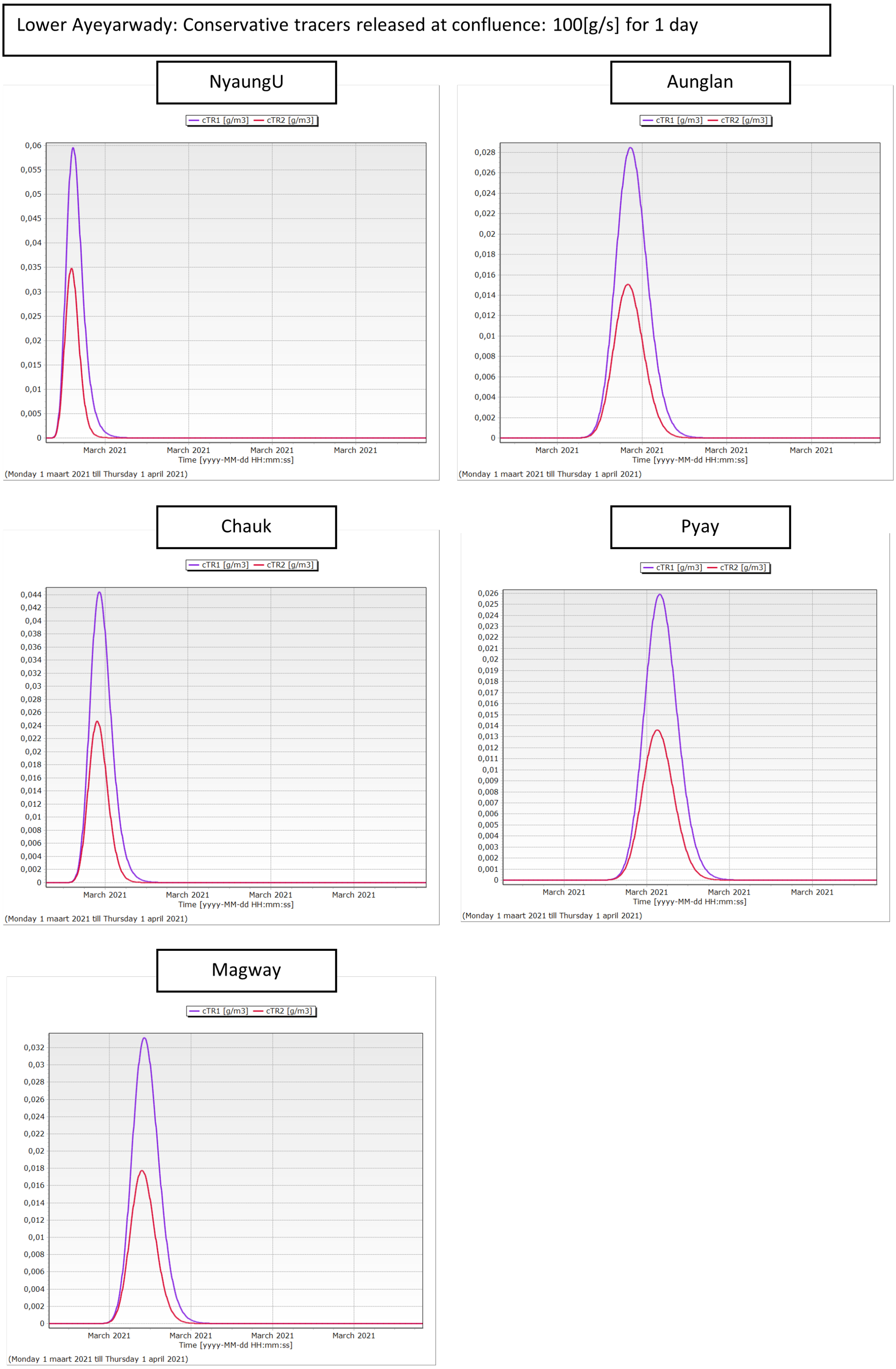


Figure 24: Tracer distribution in the Lower Ayeyarwady (Confluence - 1 Day). *100 [g/s] of CTR1 and CTR2 was released for a period of 24 hours just upstream of the confluence in respectively the Upper Ayeyarwady and the Chindwin.*

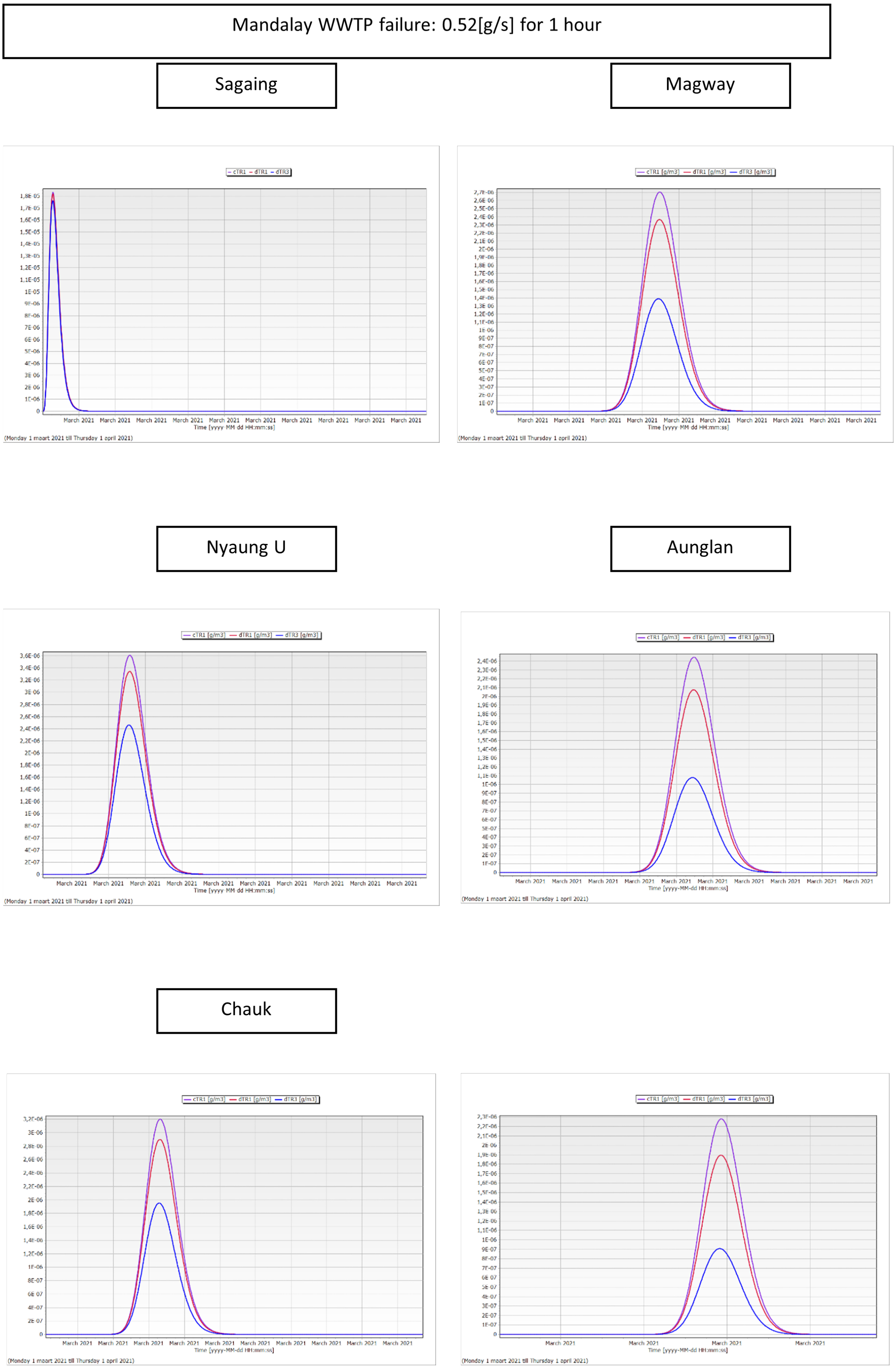


Figure 25: Tracer distribution of a WWTP failure of 1 hour. *0.52 [g/s] of CTR1, dTR1, and dTR2 was released for a period of 1 hour at the WWTP in Mandalay.*

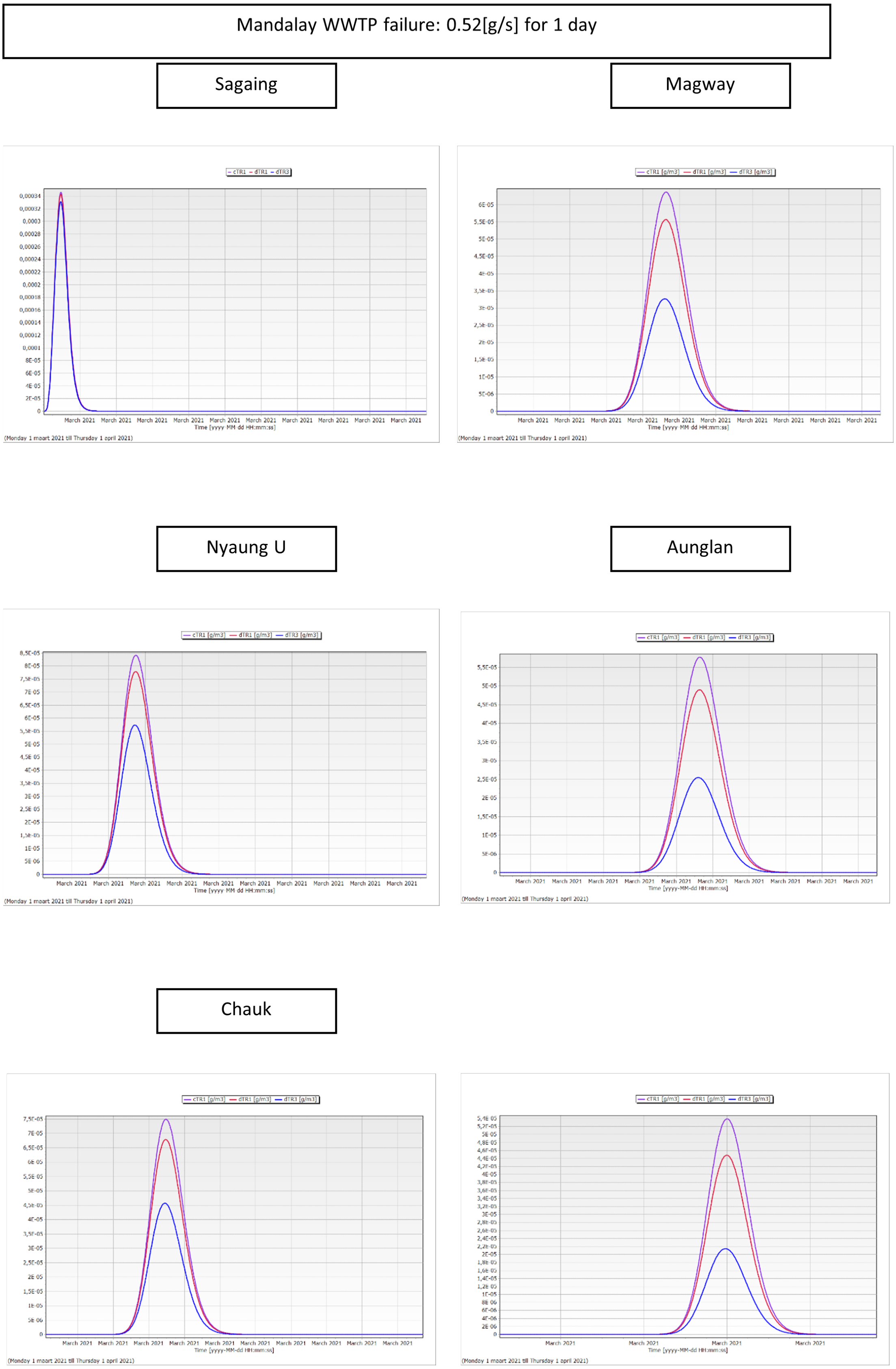
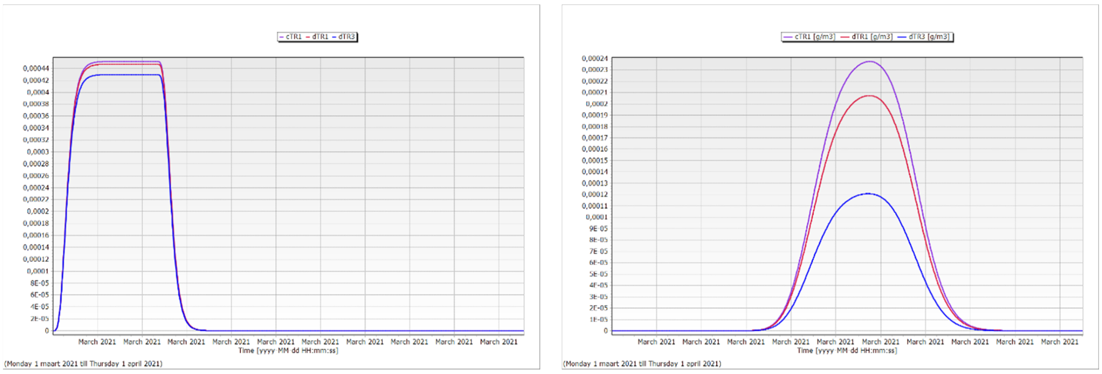


Figure 26: Tracer distribution of a WWTP failure of 1 day. *0.52 [g/s] of CTR1, dTR1, and dTR2 was released for a period of 1 hour at the WWTP in Mandalay.*

Mandalay WWTP failure: 0.52[g/s] for 1 week

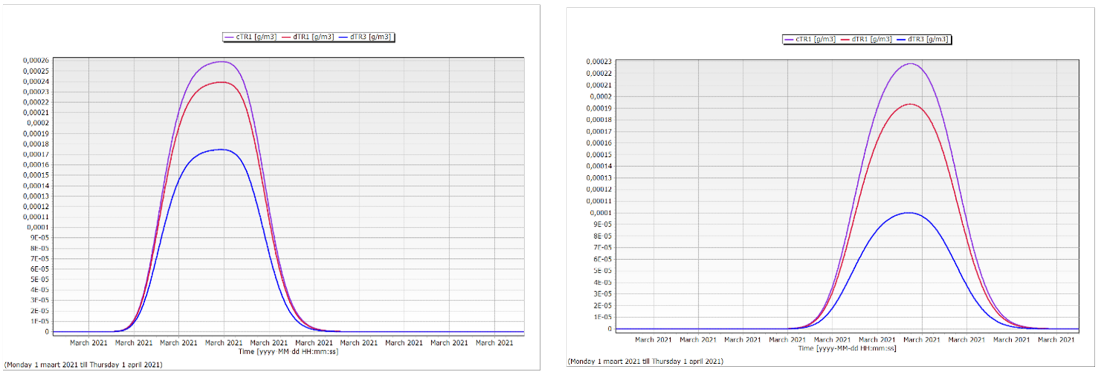
Sagaing

Magway



Nyaung U

Aunglan



Chauk

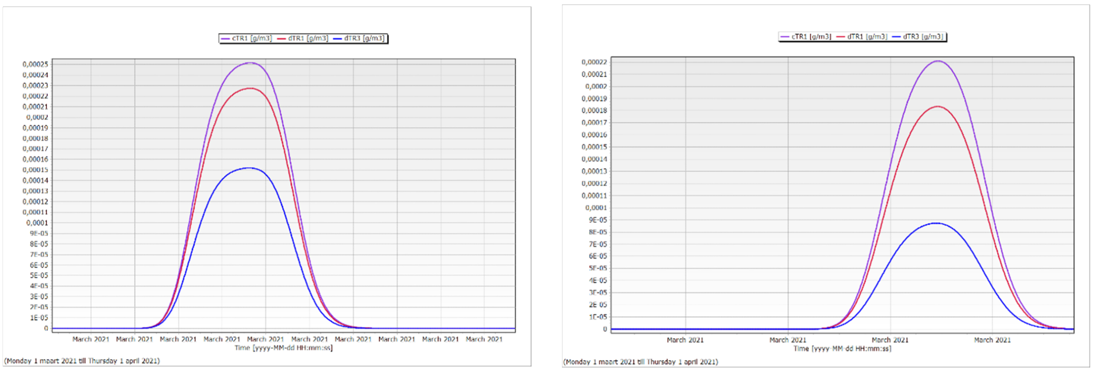
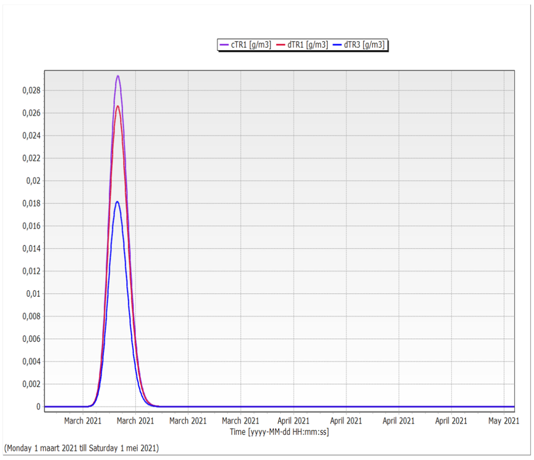


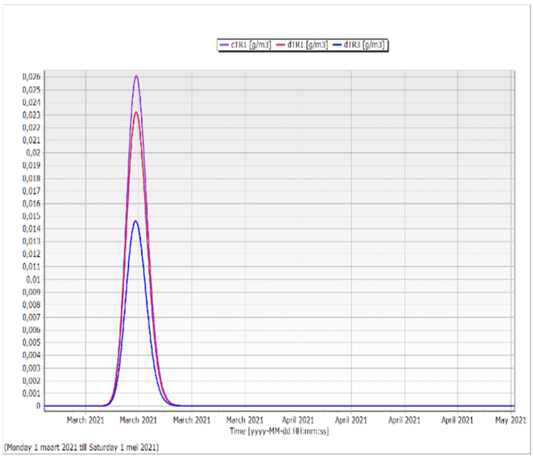
Figure 27: Tracer distribution of a WWTP failure of 1 week. *0.52 [g/s] of CTR1, dTR1, and dTR2 was released for a period of 1 hour at the WWTP in Mandalay.*

(Chindwin): Tailings Dam Failure: 500 [g/s] for 2 hours

Mawlaik



Kalewa



Monywa

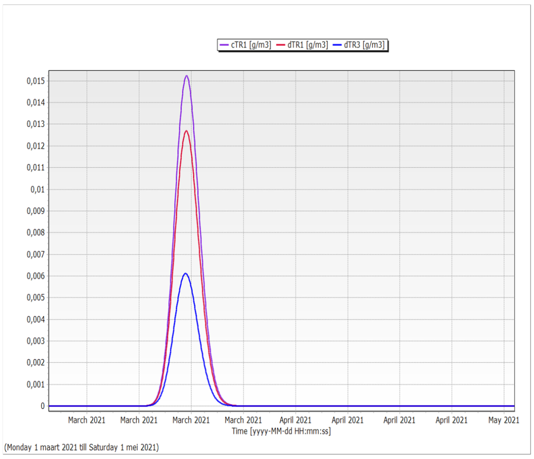
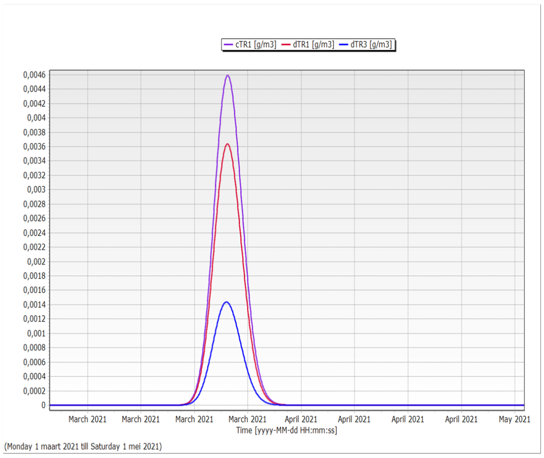


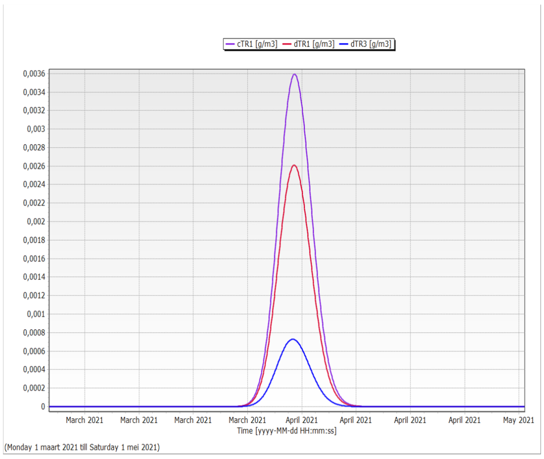
Figure 28: Tracer distribution in the Chindwin for the tailings dam failure of 2 hours. *CTR1, dTR1, and dTR2 were released for a period of 2 hours at the confluence of the Chindwin and Uyu Rivers near Homalin.*

(Lower Ayeyarwady): Tailings Dam Failure: 500 [g/s] for 2 hours

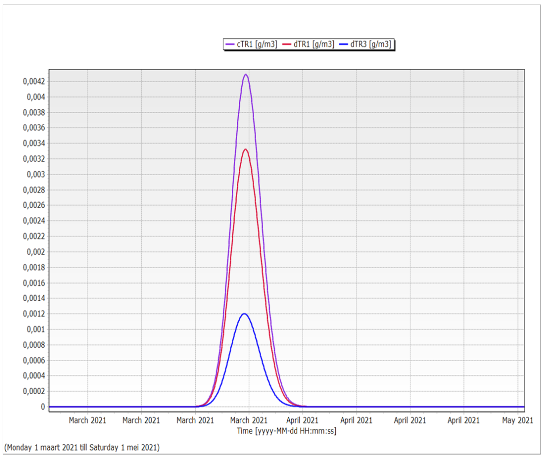
NyaungU



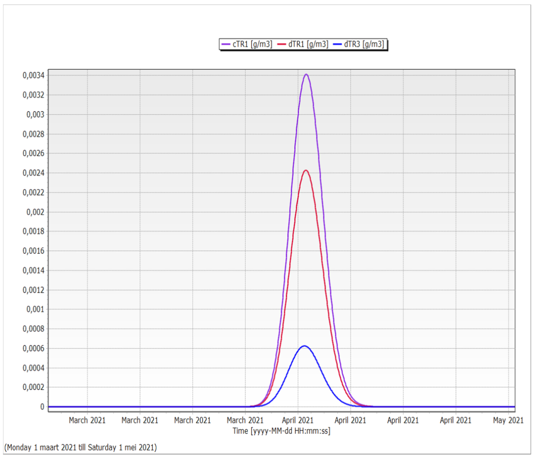
Aunglan



Chauk



Pyay



Magway

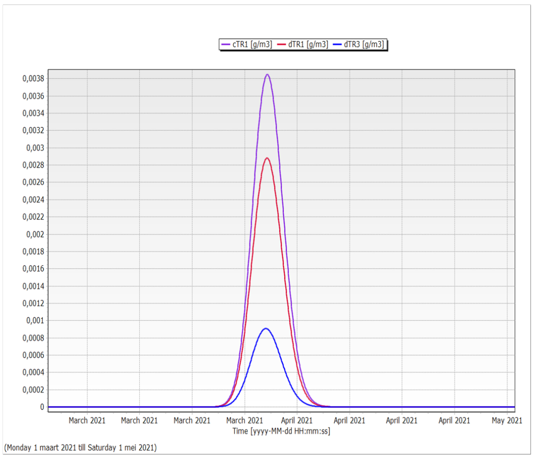


Figure 29: Tracer distribution in the Lower Ayeyarwady for the tailings dam failure of 2 hours. *CTR1, dTR1, and dTR2 were released for a period of 2 hours at the confluence of the Chindwin and Uyu Rivers near Homalin.*

D Appendix D: Geological map of Myanmar

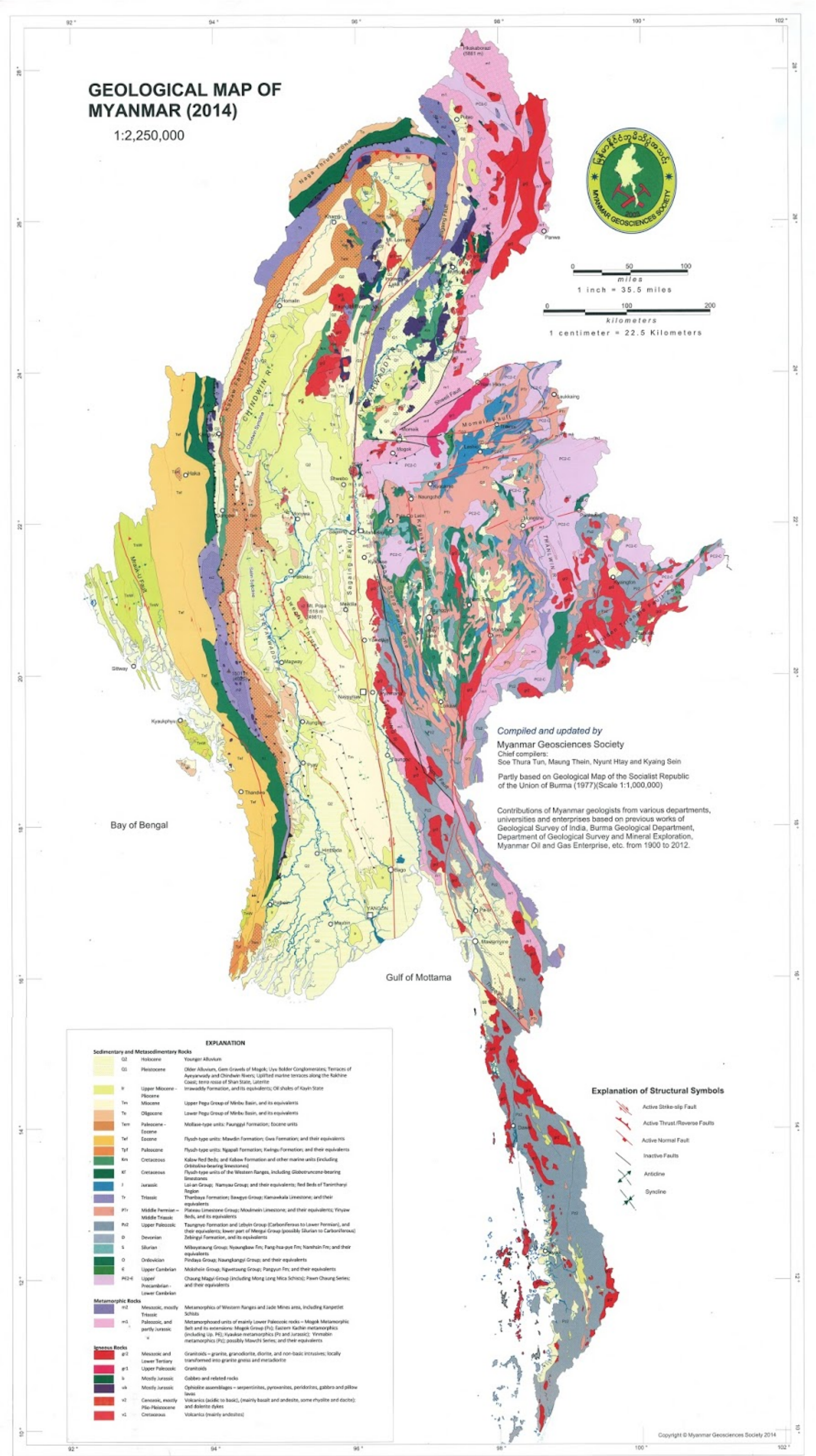


Figure 30: Geological map of Myanmar (2014) [36].