Analysis of sand mining in a mega-delta using satellite image processing

Applied to the Vietnamese Mekong Delta

Majolie Eek

Delft University of Technology

Analysis of sand mining in a mega-delta using satellite image processing

Applied to the Vietnamese Mekong Delta

by

Majolie Eek

to obtain the degree of Master of Science
at the Delft University of Technology,
to be defended publicly on Wednesday December 6, 2023 at 11:00 AM.

Student number:	4644034	
Project duration:	March 20, 2023 – December 6, 2023	
Thesis committee:	Dr. ir. A. Blom,	TU Delft
	Dr. S. Lhermitte,	TU Delft and KU Leuven
	Dr. ir. C.J. Sloff,	Deltares and TU Delft
	Dr. S. Eslami,	Deltares
	Dr. A. Moreno Rodenas,	Deltares

Preface

The completion of this thesis was the last step of a long road to obtain the degree of Master of Science in Hydraulic Engineering at Delft University of Technology. It marks the end of my years as a student. I have grown a lot academically and personally during my student years, years that were filled with countless great experiences in many ways. This thesis is the culmination of years of hard work and combines topics that I am passionate about: hydraulic engineering, the environment, people, and my love for Asia.

I would like to thank my thesis committee for their feedback and support over the past 8 months. Kees, thank you for welcoming me with open arms to Deltares, for your help in finding a thesis topic that I was passionate about, and for the enjoyable conversations. Sepehr, thank you for your feedback and guidance from another continent, for your enthusiasm about this project, and for supporting me so well when I went to Vietnam. Antonio, for me, this thesis was a deep dive into the unknown world of satellite images and machine learning, and I cannot thank you enough for your help and infinite patience in supporting me every step of the way. Astrid, thank you for teaching me to be more critical of my own work and for challenging me to be better. And Stef, thank you for sharing your knowledge of satellite images and machine learning, and for your willingness to think along with the challenges during the project.

I was lucky enough to be able to visit Vietnam as a part of this thesis, which is one of the highlights of this project. It was a valuable experience, in large part because of the people who were willing to meet me and talk about the sensitive topic of sand mining. I would like to thank all of them for sharing their knowledge and personal experiences with me, and for allowing me to find even more motivation to work on this project.

Lastly, I would like to thank my family and friends for their support and encouragement throughout the years. My family has been with me every step of the way and has always been there, no matter what was going on. I feel lucky to have friends whom I can share laughter and tears with, who made studying so much more fun, and who I have shared so many memorable moments with during the past years.

Majolie Eek
Delft, November 2023

Summary

The Vietnamese Mekong Delta (VMD) is under pressure due to climatic and anthropological drivers. Vietnam's food security, the development of the delta and the livelihood of its people are under great threat. The delta faces land subsidence, increased saltwater intrusion, riverbed incision, riverbank and coastal erosion, and a decrease in wildlife. The main cause of the increased salinity, riverbank, riverbed and coastal erosion is a reduced sediment load, sea level rise, and land subsidence. The reduced sediment supply is a consequence of the construction of hydropower dams in the entire Mekong Basin and sand extraction in the delta. It is a challenge to obtain accurate sand extraction rates due to the scale of sand mining activities and the lack of data. This study aims to analyse how sand mining vessels can be detected and classified with remote sensing methods, as well as how detected vessels can be translated into sand extraction rates. Two research questions are answered: *'What factors determine the performance of a vessel classification system?'*, and *'How can the outcome of a vessel detection and classification system be translated to a sand mining estimate?'*.

To gain more insight into sand mining activities, I visited two locations in the VMD in June 2023. These were locations where bank erosion occurred and where sand mining took place. As a part of the visit, interviews were conducted with various stakeholders, which resulted in a better understanding of the sand mining activities and the consequences of sand extraction. The majority of the vessels that extract sand are barges with cranes. The crane extracts the sand from the riverbed and puts it in a different barge for transport.

We addressed the first research question by developing a vessel classification model for vessels in the VMD based on optical satellite imagery. As a first step, optical and SAR data sets are reviewed. The optical data sets considered are Sentinel-2, PlanetScope, and SkySat. The considered SAR data sets are Sentinel-1 and ICEYE. Then, a data set is manually acquired with PlanetScope data with a 3-meter resolution. Vessels in the images are labelled as sand mining vessels or as other vessels. The model is based on a deep-learning algorithm. The input data of the model are images of vessels with a certain label, with which the model is trained and tested. The outcome is a model that predicts the class of an input image. The result of testing the model is an overall model accuracy of 0.85, which means that the model predicts the right label for 85% of the images in the test data set. The main factors that determine the performance of a classification model are the amount of input data, the balance of the classes of the input data, and the spatial resolution of the satellite images.

We answered the second research question by evaluating existing methods to obtain sand extraction rates. Then, we describe a methodology to estimate sand extraction rates for the VMD, based on a vessel detection and classification model. The first step in the described methodology is that vessels in the area of interest should be detected. After the detection of a vessel, the vessel can be classified with a machine-learning model similar to the one developed for this study. The number of sand mining vessels needs to be determined for the entire VMD, for several years. The annual number of detected sand mining vessels can be used to determine sand extraction rates. To do this, a daily production rate needs to be determined for the sand mining vessels. A correction factor should be applied to take into account false positives.

This study is only a step in a much bigger process to be able to determine sand extraction rates for mega-deltas like the VMD. It indicates the most important factors that influence the performance of a vessel classification model, and it describes a method to apply such a model to obtain sand extraction rates.

List of abbreviations

CFAR	Constant False Alarm Rate
ESA	European Space Agency
GEE	Google Earth Engine
HUNRE	Hanoi University of Natural Resources and Environment
Lao PDR	Lao People's Democratic Republic
LMB	Lower Mekong Basin
NIR	Near Infrared
NDWI	Normalised Difference Water Index
SAR	Synthetic Aperture Radar
SIWRP	Southern Institute for Water Resource Planning
SWIR	Short-wave Infrared
VMD	Vietnamese Mekong Delta
WWF	World Wildlife Fund for Nature

Contents

1 Introduction

1.1 The Mekong Delta under pressure

The Mekong River flows from the Tibetan Plateau in China through Myanmar, Thailand, Lao People's Democratic Republic (Lao PDR), Cambodia, and Vietnam. With a length of nearly 4800 km, it is the 12th longest river in the world. In the South of the Lower Mekong Basin (LMB), it forms the Mekong Delta in Cambodia and Vietnam and flows into the South China Sea. The Mekong River and its basin are shown in Figure 1.1. The delta covers an area of 60,000 m^2 and is the third largest delta in the world (Anthony et al., 2015). The Vietnamese Mekong Delta (VMD) has a population of 17 million and produces 50% of Vietnam's food. Anthropological activities such as the construction of dams, sand mining, and groundwater extraction for irrigation are putting the future of the delta and the people living there at risk. These activities result in a reduced sediment load and land subsidence. The delta has an aggradation rate of 0.3-1.8 mm/year, which is exceeded by land subsidence rates of several cm/year and an absolute sea level rise of 2-4 mm/year (Jordan et al., 2019). Recent research shows that the mean elevation of the Mekong Delta is 0.8 m above sea level, which is much lower than the earlier assumed 2.6 m (Minderhoud et al., 2019).

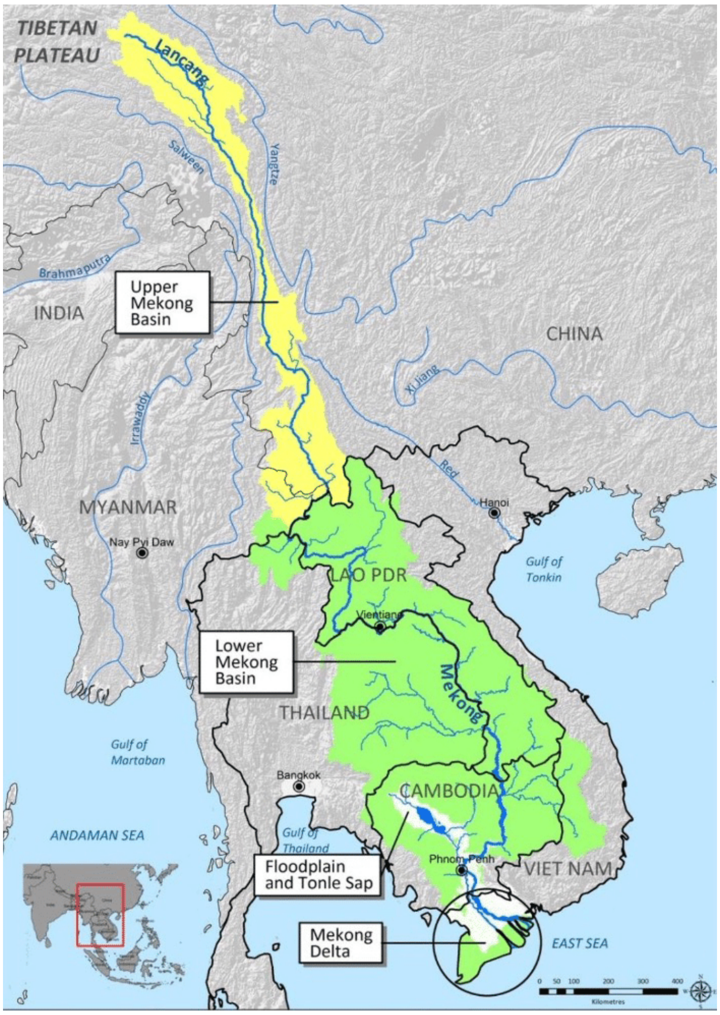

Figure 1.1: The Mekong Basin (Mekong River Commission, 2019)

Sand extraction rates in the Mekong Delta exceed the natural sand supply (Hackney et al., 2021). Sand mining activities cause riverbank instability, bank erosion, a decrease of wildlife in the river, and increased saltwater intrusion in the Mekong Delta (Hackney et al., 2020; Gruel et al., 2022; Koehnken et al., 2020; Eslami et al., 2019).

After water, sand is the most used commodity in the world (Beiser, 2022). It is used in different industrial and manufacturing processes, such as glass, computers, and concrete. The demand for sand will increase as long as large cities are emerging in developing countries. The price of sand keeps increasing, making it an interesting commodity for trade. However, sand mining causes bank erosion, resulting in lost homes, roads, shops, and farm fields. An example of a case of severe erosion in the VMD in May 2023 is shown in Figure 1.2. The lives of people living near the riverbanks in the VMD are at risk, therefore thousands of houses in the Mekong Delta need to be relocated (Coroneo, 2022). During a visit to Vietnam, locals said that when they were young, they could see the bottom of the Mekong River during low tide and even play football on the sandbanks. However, the sandbanks are disappearing and the riverbed cannot be seen anymore. This is not necessarily due to sand mining, but can also be the result of land subsidence and sea level rise.

Figure 1.2: Example of collapsed houses in the An Giang Province in the VMD, May 2023 (Khanh, 2023).

Sand mining also affects the river ecology: the dredging scours the riverbed and increases water turbidity. It harms fish species, plants, and other living organisms in the river (Beiser, 2021). Most countries, including Vietnam, issue sand mining licenses and official regulations are in place. However, there is insufficient enforcement of the regulations, resulting in the illegal extraction of sand. Due to the illegal activities, there is a lack of reliable data, making it hard to determine exact sand extraction rates (Koehnken and Rintoul, 2018).

1.2 Current sand extraction estimates

Several studies have been carried out to estimate the sand budget of (parts of) the Mekong Delta. Different studies, conducted by Bravard et al. (2013), Anthony et al. (2015), Gruel et al. (2022), Hackney et al. (2021) and Deltares (2023), used different methods to estimate the extracted sand volumes. The applied methods can mainly be distinguished by whether the research was conducted in the field or with the use of remote sensing methods.

Barges with cranes are the main vessels that extract sand in the VMD, but other sand mining vessels can be pump dredgers or illegal boats that have a disguise. The barges have cranes with grabbers, that grab sand from the river bed and put it on another barge for transport. Once the barge for transport is full, it transports the sand to another location. Another barge for transport is then moored next to the barge with the crane and filled with sand. Figure 1.3 shows several active barges with cranes.

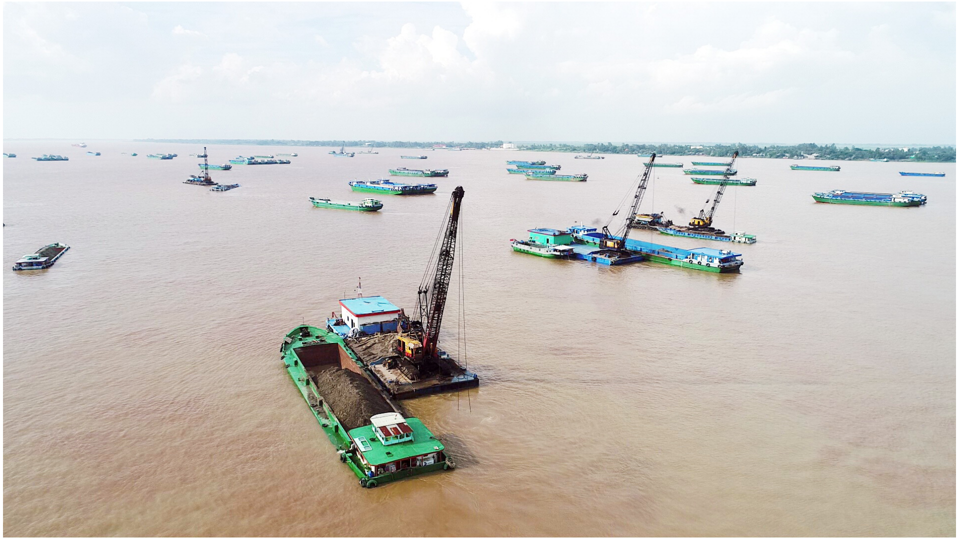

Figure 1.3: Sand mining in the VMD: barges with cranes are grabbing sand from the riverbed and putting it on the barges for transport that are moored next to them.

Bravard et al. (2013) used a rapid assessment method to estimate the extracted sand volumes. They carried out field investigations in the main stem of the river in Lao PDR, Thailand, Cambodia, and Vietnam. Anthony et al. (2015) showed that shoreline erosion happened at over 50% of the 600 km long coast, which according to them is in line with a reduced sediment supply from the Mekong River, large-scale sand mining in the delta, and land subsidence due to groundwater extraction. However, they did not find any evidence of a direct link between a reduced sediment supply and coastal erosion. They also did not quantify the sand extraction rates. The study of Jordan et al. (2019) estimated extraction rates based on an analysis of bathymetric maps and local refilling processes. They conducted the study for only 20 km of the river, which is just a small part of the river and the delta.

Deltares (2023), Gruel et al. (2022), and Hackney et al. (2021) used satellite imagery processing to determine the sand extraction rate in the Mekong Delta. However, the data sets that were used and the methods that were applied differed. An overview of the satellite imagery data sets applied in the studies and the characteristics of the data sets is shown in Table 1.1. The relevant characteristics are:

- Spatial resolution: metres per pixel in an image.
- Temporal resolution: how frequently the satellite revisits and takes images of a specific location.
- Optical or Synthetic Aperture Radar (SAR) images: Optical images contain three spectral bands in the visible spectrum: red, green, and blue. They also contain bands in the electromagnetic spectrum, such as Near Infrared (NIR) and Short-wave Infrared (SWIR). Therefore, the images can be shown in RGB. However, they can only be used during the day and when there are no clouds. SAR images contain one spectral band and electromagnetic waves are emitted at a given frequency, which is related to the band. The signal backscatters from Earth's surface to the antenna of the satellite. The brightness of a pixel in a SAR image is defined by the magnitude of the backscatter, resulting in images with a grayscale. They are independent of time and weather conditions. The differences are described in more detail in section 3.3.

Table 1.1: Overview of satellite imagery data sets (*Modified after Deltares, 2023*)

Data set	Type	Spatial resolution & extent	Temporal resolution & extent	Data availability	Applied in study
Sentinel-1	SAR	10 m (global extent)	12 days (2014 - 2022)	Free access	Gruel, et al. (2022)
Sentinel-2	Optical	10 m (global extent)	5 days (2015 - Now)	Free access	Deltares (2023)
Landsat-8	Optical	30 m (global extent)	16 days (2013 - Now)	Free access	Gruel, et al. (2022)
PlanetScope	Optical	3 m - 5 m (global extent)	Sub-daily (2016 - Now)	On-demand	Hackney, et al., (2021)

Deltares (2023) established the sand budget of the VMD. As a part of the sand budget study, Deltares (2023) estimated the sand extraction rates with the use of satellite imagery processing. They used Sentinel-2 (optical) images with a 10 m resolution to determine the sand extraction volume. The methodology that was used is shown in Figure 1.4.

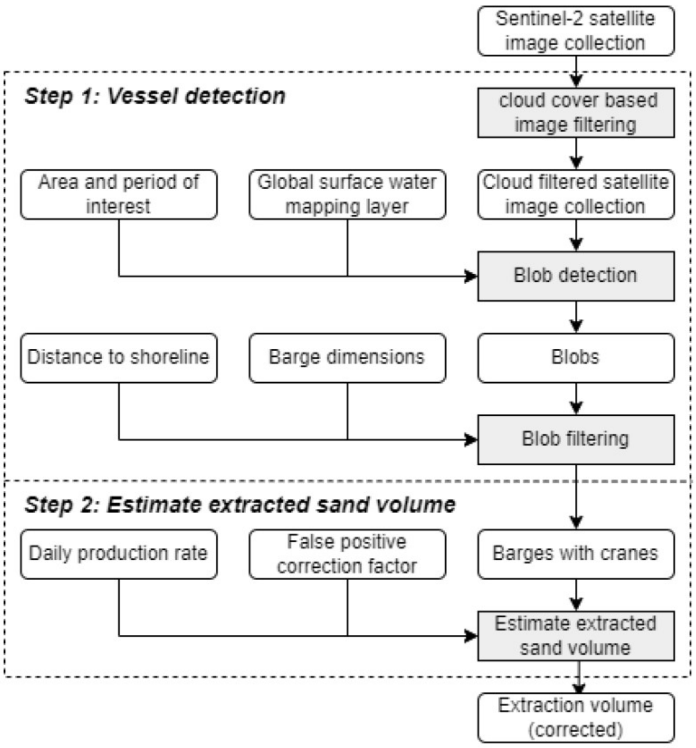

Figure 1.4: Methodology for sand extraction estimates by Deltares (2023).

First, they identified non-water objects on the water's surface, such as vessels, fish farms, or patches of land. These objects are called blobs and they were identified by applying several filters to the satellite images. Blobs closer than 100 m to the riverbanks were discarded, as they were assumed to be moored and thus inactive. Then the blobs were filtered based on their dimensions. The sand extraction rate was estimated based on the number of filtered blobs, which are assumed to be barges with cranes. The extraction rate for a barge with a crane was estimated to range between 300 and 600 m^3/day and was used to determine the sand extraction estimates. This resulted in a yearly extraction rate of 35 - 55 Mm^3 for the VMD.

The filtering of blobs based on geometry is not a reliable way to classify vessels with Sentinel-2 data with a resolution of only 10 m. It is hard to distinguish double-moored vessels and barges with cranes from each other. To take this into account, they added a correction factor based on manually counting double-moored barges and barges with cranes in Google Earth imagery. It was concluded that 65% of the cases were barges with cranes, so the correction factor was set to 0.65.

In the study of Gruel et al. (2022), Sentinel-1 radar imagery (SAR) with a 10 m resolution and Landsat-8 (optical) imagery with a 30 m resolution were used. Gruel et al. (2022) specified three groups of vessels, based on the following dimensions:

- Barges with Crane (BC): L = 37 m; A = 450 m^2;
- Barges for Transport (BT): L = 47 m; A = 558 m^2;
- Blue Boats (BB): L = 47 m; A = 375 m^2

First, they used Landsat 8 imagery to determine the location of the water surface of the channels in the VMD. Non-channel areas, such as canals, paddies, houseboats and ferry paths were removed. All parts of the river within 50 m of the riverbanks were also removed, to take into account non-active vessels that were moored near the riverbank. Then, vessels on the water's surface were detected with Sentinel-1 data. They determined a sand extraction volume based on the correlation between the vessel detection system with Sentinel-1 data and a locally measured bathymetric survey in a particular area. The estimated sand mining budget for the 6-year study is 254 Mm^3, with an average rate of 42 Mm^3/year.

The use of Sentinel-1 data for the classification of vessels based on dimensions brings uncertainty. The use of SAR imagery also means that the images contain less spectral information, such as colour. Another assumption is that the relationship between erosion rates and any type of vessel density is equal for the entire VMD, which is not necessarily the case.

Hackney et al. (2021) used PlanetScope (optical) imagery with a 5 m resolution to estimate sand extraction volumes in part of the Mekong Delta in Cambodia. Monthly composite images with minimal cloud cover were used, to ensure cloud cover effects were minimal, especially during the monsoon periods with high cloud coverage. Sand mining vessels were identified based on colour and dimensions. The total number of visible boats was counted for each monthly time step. The spatial resolution of the satellite imagery is sufficient to identify sand mining vessels. Smaller vessels cannot be identified and larger vessels, such as container vessels, are clearly visible but are easy to distinguish due to their size. Thus Hackney et al. (2021) assumed that most of the waterborne traffic from the monthly composite images is related to sand mining activity. Furthermore, Hackney et al. (2021) also assumed that vessels within 100 m from the riverbanks are moored and not actively mining. To obtain the yearly volume of extracted sand, the number of active vessels observed each month was converted to a volume of sand. These estimates were integrated over the calendar year. The boat dimensions are shown in Figure 1.5.

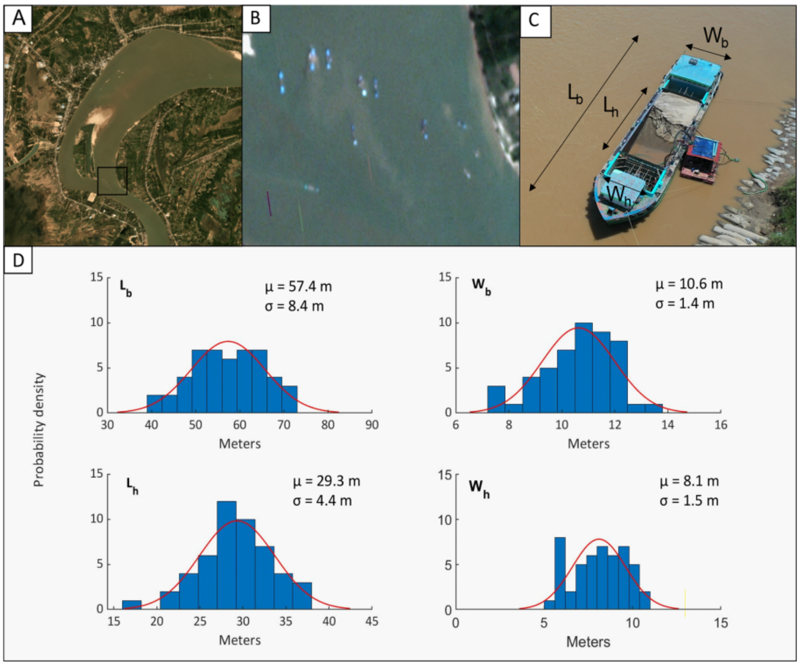

Figure 1.5: A: PlanetScope monthly composite image. B: Zoomed in area of A. C: Dimensions of mining vessels including the boat length (L_B), the boat width (W_b), the hold length (L_h), and the hold width (W_h). D: Estimated dimensions of mining vessels active on the Mekong River (Hackney et al., 2021).

The PlanetScope images that were used for this study are monthly composite images. This means that one image can consist of satellite images taken on different days. As a result, there is a possibility that a vessel is shown in one image more than once. There is also some uncertainty about the movement of the barges, on which the sand mining estimates are based.

1.3 Problem statement

The problem with research based on site visits and field measurements is that the VMD covers a total of 40,000 km^2, with a channel network of around 700 km^2, making it hard to focus on the entire delta for one study. There is a lack of reliable data, which makes it hard to obtain exact sand extraction rates. That is where satellite imagery processing can be useful: it is a relatively easy way to look into changes and activities in the entire delta. However, the current studies have limitations because of cloud cover when using optical data, or because of low resolutions for the available satellite data sets. The satellite data allows the detection of vessels, but the current spatial resolution of the data precludes the identification of active sand mining vessels. Another challenge is to validate the vessel detection and classification models with low-resolution imagery. The general problem, therefore, is that there is a lack of data and there are limitations to the data that is openly available and used in previous studies, resulting in sand mining estimates with large uncertainties.

1.4 Objective and research questions

The objective of this report is to analyse the factors that determine the performance of a vessel classification system, and how a vessel detection and classification model can be used to obtain a sand mining estimate. To do so, the following research questions are answered:

- What factors determine the performance of a vessel classification system?
- How can the outcome of a vessel detection and classification system be translated to a sand mining estimate?

1.5 Approach

To answer both research questions, the following steps are taken:

1. **Literature review**
   The first aim of the literature review is to understand the general characteristics of the VMD and its processes. Furthermore, it aims to better understand different satellite data sets and their advantages and disadvantages. It provides an overview of the methods used in previous studies on vessel detection and classification models. It is important to understand the limitations of the studies and to know where these studies can be improved.
2. **Visit to the VMD**
   Several places in Vietnam are visited for this study. The purpose of the visit is to gain a better understanding of the sand mining activities in the VMD and to familiarise myself with the social and environmental context in which sand mining occurs. The VMD is visited to analyse sand mining sites. Several stakeholders are interviewed to obtain more data and insight on sand mining activities in the VMD.
3. **Create an input data set of satellite images**
   A satellite image data set is chosen for the development of the model. The choice depends on the characteristics and availability of the satellite data set. Images are collected and vessels in the images are selected and labelled.
4. **Train a model to identify vessels in waterways**
   The satellite images in the input data set are used to develop a model to classify vessels in the VMD. The data set is split into images for training, validation and testing. The model is developed with the use of machine learning and is based on PlanetScope (optical) satellite images.
5. **Testing of the model**
   The model is tested with the images in the testing data set and the accuracy and precision of the model are determined. The aim is to realise a high-accuracy model. The model is adjusted based on the outcome of the testing, to optimise the performance of the model. This is an iterative process.
6. **Assess the vessel detection model**
   The limitations of the model are recognised and it is discussed how these limitations affect the performance of the model. Trends in the predictions of the model are analysed and elaborated on.
7. **Describe a methodology to obtain sand mining estimates based on the model**
   A methodology is described on how to obtain sand mining estimates based on a vessel detection and classification model. The methodology is based on an existing study and the vessel classification model that is developed for this study. Future steps to improve the model and to upscale it for the entire VMD are discussed.

1.6 Structure of the report

The report outline is as follows:

- A short system description of the Mekong Basin and the VMD is given in Chapter 2, based on the literature review, and insights from the field observations and interviews in Vietnam. Two anthropological activities that are affecting the VMD are described: sand mining and the construction of hydropower dams.
- Chapter 3 aims to answer the first research question. It describes the steps to develop a vessel classification model based on satellite image processing. At the end of the chapter, the performance and outcome of the model are discussed.
- A methodology to determine sand extraction estimates, based on the developed vessel classification model, is described in Chapter 4. This chapter answers the second research question.
- In Chapter 5 the discussion of the study can be found, followed by the conclusion and recommendations in Chapter 6.

2 System description: The Vietnamese Mekong Delta

This chapter provides a system description of the Vietnamese Mekong Delta (VMD). Furthermore, it describes the effects of hydropower dams and sand mining. The final section covers erosion in the VMD.

2.1 General characteristics

The Mekong River originates from the Tibetan Plateau in China and flows through Myanmar, Thailand, Lao PDR, and Cambodia before it reaches Vietnam. In Cambodia, the Mekong River bifurcates into multiple channels. The main river branches in Vietnam are the Bassac River and the Tien (Mekong) River. The delta covers an area of over 60,000 km^2 and has a 600 km-long coastline. The VMD is illustrated in Figure 2.1, indicating the locations of the Bassac and Tien Rivers.

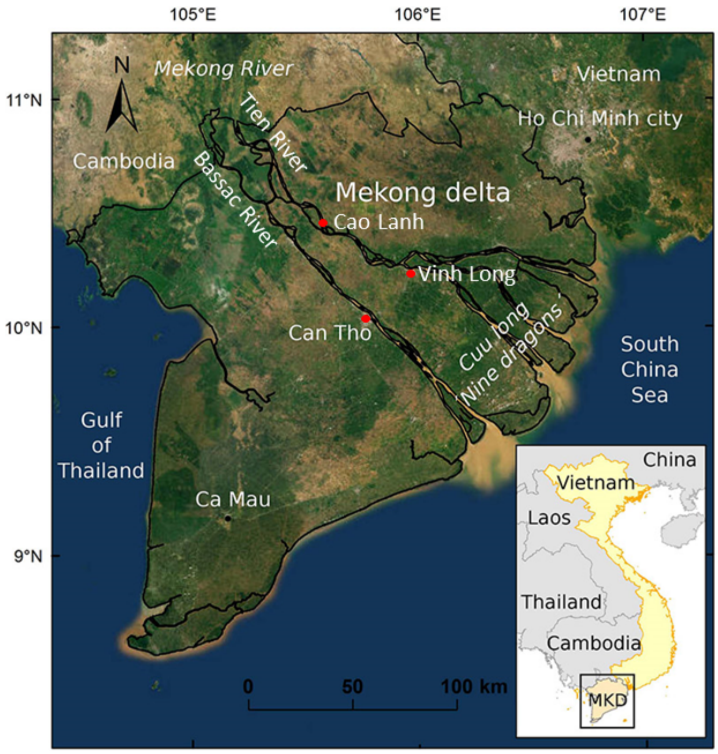

Figure 2.1: A map of the VMD (modified after Minderhoud et al. (2020))

The Mekong Delta was formed over the past 6000-7000 years, after the high sea level during the late Holocene. The delta prograded over 200 km from the Cambodian border to the current Vietnamese coastline. Before 3000 years ago, the progradation of the delta was tide-influenced. Once the delta was exposed more to ocean waves, the delta developed in a wave-influence environment (Ta et al., 2002, Nguyen et al., 2000). In the present day, the delta is wave-induced and tide-dominated.

The delta is influenced by the Southeast Asian monsoon, which is from May to October. The mean annual flow at Kratie, Cambodia, is 12,756 m^3/s. During the dry season, the average flow is under 4,000 m^3/s; during the flood season, it is over 27,000 m^3/s (Mekong River Commission, 2019).

2.2 Sediment characteristics

According to Kondolf (1997) the perfect river system can be divided into three zones: sediment production (or erosion), sediment transport and sediment deposition. The second zone can be viewed as a conveyor belt. Kondolf (1997) states the following about a change of sediment load in a river: *'If the continuity of sediment transport is interrupted by dams or removal of sediment from the channel by gravel mining, the flow may become sediment-starved (hungry water) and prone to erode the channel bed and banks.'*.

There are four main types of sediment load that can be distinguished, namely bedload and suspended load. Wash load is part of the suspended load. All three are defined as follows:

- **Bedload**: coarser sediments like sand and gravel. Bedload is transported by rolling and sliding over the riverbed. In general, the transport rate of bedload in the Mekong Delta is relatively low compared to the total sediment load.
- **Bed material load**: consists of the bed load and the part of the suspended load that falls back on the bed. It is the transported load of all the material that interacts with the riverbed.
- **Suspended load**: finer sediments like silt. Suspended load is transported in suspension, there is barely any interaction with the riverbed. Suspended load moves faster than the bedload since it is transported in the water. The suspended load requires moving water to keep the particles above the bed. It may fall to the bed during low flows.
- **Wash load**: the finest of the suspended sediment. Wash load is part of the suspended load, but it does not settle at the bottom of a waterway during low flow. Wash load is in permanent suspension.

The average suspended sediment load at Kratie from 2009-2013 was 72.5 Mton/year. The estimated bedload transport rate during this time was 1.2-2.1 Mt/year. The bedload was dominated by coarse to fine sand (Koehnken, 2014). A reduced sediment load in the VMD has two main causes: sediment trapping by dams in the Mekong River as well as the extraction of sand from the river. This was confirmed from interviews taken with people from several organisations in Vietnam (see Appendix B). The effect of both activities is described in Section 2.3 and Section 2.4.

In the Lower Mekong Basin (LMB), there has been a rapid development of hydropower dams. Many dams have been built and more dams are currently being constructed or planned for future construction. All dams are shown in Figure 2.2. Hydropower dams provide 10% of the electricity in the LMB. The total reservoir storage in the entire Mekong Basin increased from 5,910 Mm^3/s in 2000 to 56,301 Mm^3/s in 2020, which is over 14% of the mean annual runoff of the river (Mekong River Commission, 2019). In 2019, there was a total of 89 hydropower dams constructed in the LMB with a total capacity of over 12,000 MW. The estimated installed hydropower capacity is more than 30,000 MW in 2040.

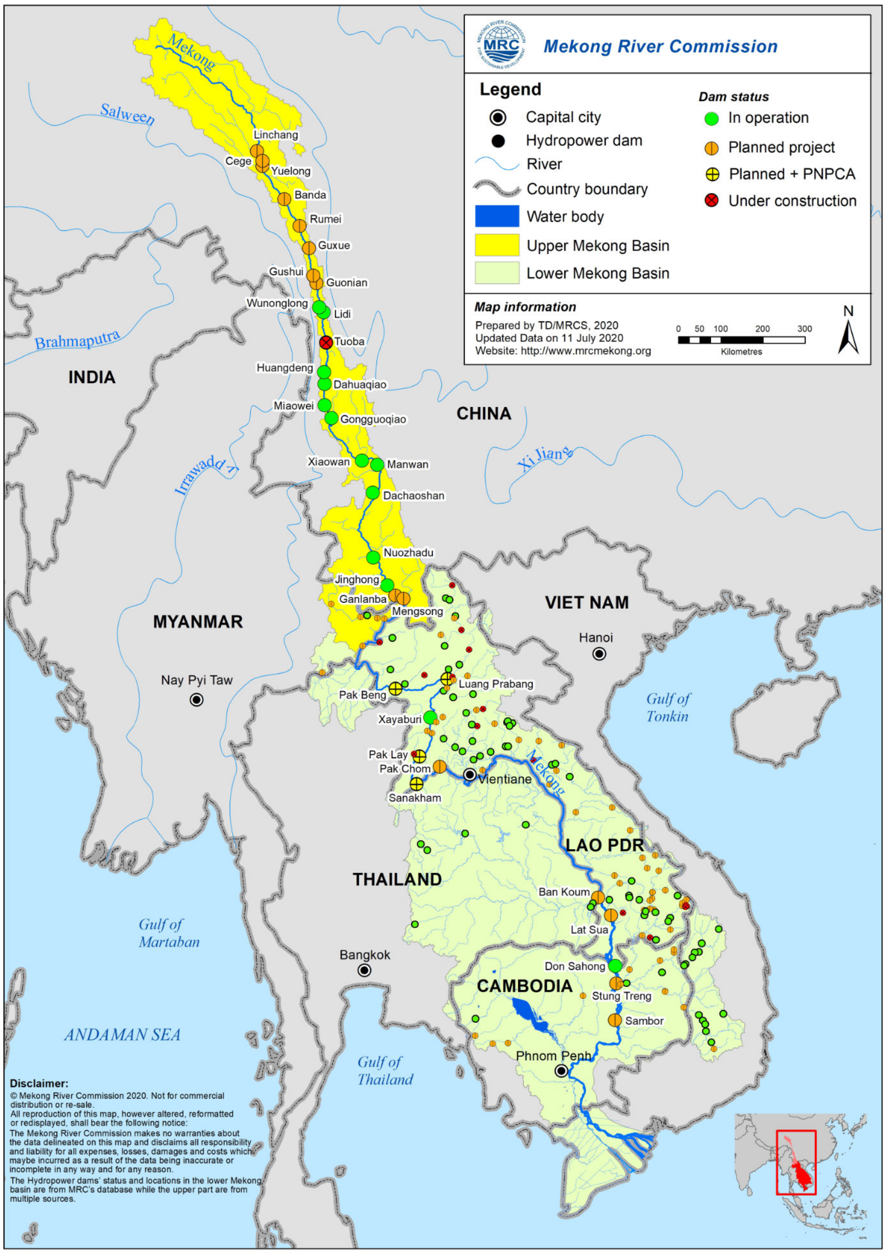

Figure 2.2: All the operational and planned dams in the entire Mekong Basin (Mekong River Commission, 2023).

2.3 Hydropower dams

All dams trap sediment to a certain extent and most dams change the seasonal distribution of flows and the flood peaks. Dams trap all the bedload and most of the suspended load. The conveyor belt is interrupted by dams and sediment is deposited in the reservoirs upstream of the dam. The water that is released has the energy to move sediment. However, the water does not have any sediment to transport and no sediment is entering the conveyor belt anymore. This results in 'sand hunger', the sediment that is transported by flow is not replaced with sediment from upstream, which causes erosion. The short- and long-term effects of a dam in a river are shown in Figure 2.3. An erosion wave starts directly downstream of the dam: the bed starts eroding and the erosion gradually travels downstream. The erosion wave starts to travel downstream once there is no sand left to take from a location. The speed of this wave is very slow if the riverbed consists of sand or sand and gravel, as the motion of sediment is mostly due to bedload. The propagation of the erosion is slow because the bedload travels slowly. The erosion wave therefore only travels with a maximum speed of a few kilometres per year (Sloff and Mosselman, 2021).

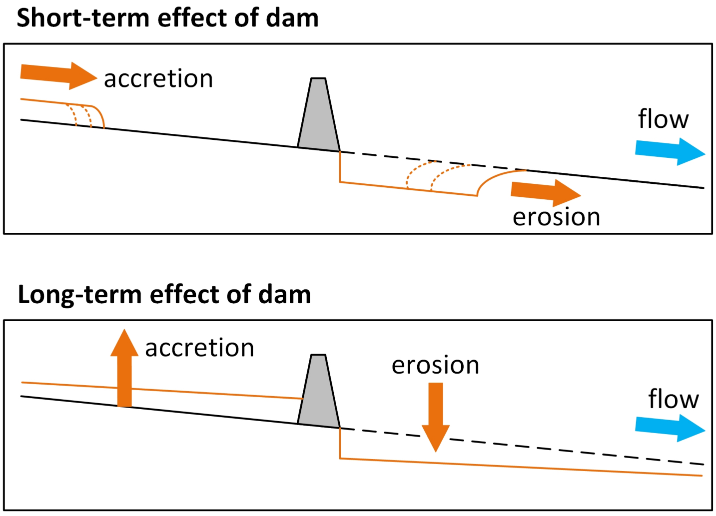

Figure 2.3: Effects of a dam on a sand or gravel-sand riverbed (modified after Sloff and Mosselman (2021)).

It is expected that the hydropower dams will increase the dry season flow at Kratie, Cambodia by 19% on average and by 40% in March. The discharges in the wet season will decrease by an average of 4% (Mekong River Commission, 2011). This is a secondary impact due to flow alterations. The reduction of peak flows may cause a net reduction of the transport capacity of the flow on average. The conveyor belt slows down and on average less sand will be moved through the river, even if the erosion wave is still far upstream. However, future numbers are uncertain and depend on decisions made by upstream countries. The change in discharge affects the sediment transport downstream of the dam.

The Tonle Sap Lake is located downstream of Kratie and partially absorbs the flood peaks from upstream. It is connected to the main stem of the Mekong River through the Tonle Sap River at Phnom Penh. The lake is shown in Figure 2.4. During flood season, the level of the Mekong River is higher than that of the lake, resulting in a flow from the Mekong River to the lake. During the dry season, the water level of the Tonle Sap Lake is higher than that of the Mekong River, resulting in a gradual flow of water to the Mekong River. The Tonle Sap Lake absorbs the flood flows during the wet season. By storing water, the lake attenuates the flood levels downstream of the lake. The permanent lake area is 2,400 km^2, with a water level of 1.44 m during the driest months. During flood season, the area of the lake increases with an average maximum of 10,800 km^2, to 13,200 km^2 with a water level of 9.09 m (Kummu and Sarkkula, 2008). Over 50% of the water that flows into the lake originates from the Mekong River (Kummu et al., 2013). Around 88% of this water returns to the Mekong River during the dry season (Kummu and Sarkkula, 2008). The lake reduces the effects that the upstream dams have on the discharge of the Mekong River. Due to the Tonle Sap Lake that absorbs the flood flow as well as the slow propagation of an erosion wave downstream of a dam, there is no change in the sediment supply of coarser sediments like sand to the VMD due to hydropower dams yet. However, it does have an effect on the suspended load, which travels faster than the bedload.

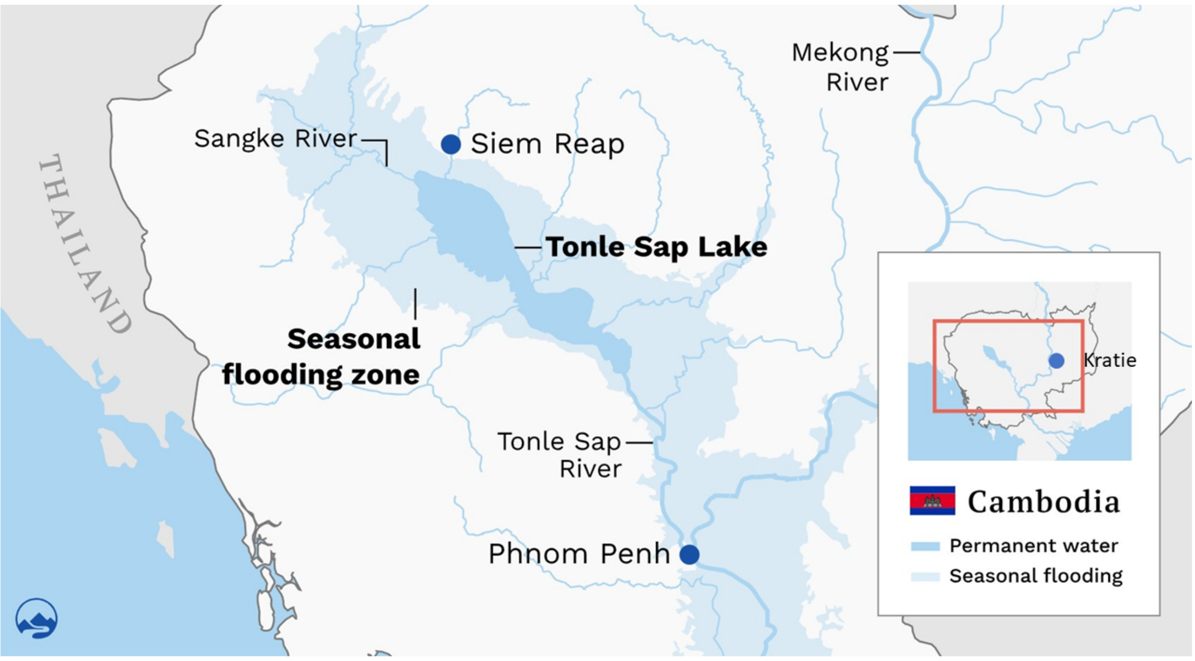

Figure 2.4: Part of Vietnam, showing the Tonle Sap Lake and Tonle Sap River. The darker blue is the permanent lake area. The light blue is the flood plain (modified after Roney (2020)).

2.4 Sand mining

Can Tho is the largest city in the VMD. For this study, I met with Dr. Thanh from Can Tho University and Ms. Phuong from WWF-Vietnam to interview them about sand mining in the VMD. According to Dr. Than from Can Tho University, sand mining started around 40 years ago. However, the sand mining vessels back then were much smaller than the current sand mining vessels. Sand mining also happens near Can Tho, especially the area around Con Son is subject to sand mining. Con Son is an island located in the river a few kilometres upstream of Can Tho. I visited the riverbanks around the island to analyse the sand mining. There were barges with sand in the area and an active barge with a crane close to the riverbank. In the distance, there were more sand mining vessels. The full cycle of the crane on the nearby barge was timed, including the grabbing of the sand and putting it on the vessel next to the barge. Pictures taken near Can Tho can be seen in Figures 2.5, 2.6, 2.7 and 2.8.

Figure 2.5: Sand mining in the distance near Can Tho.

Figure 2.6: Crane extracting sand near Can Tho.

Figure 2.7: Barge filled with sand near Con Son island.

Figure 2.8: A lorry transporting sand near Can Tho.

Sand mining results in channel instability, caused by the change in the pre-existing channel geometry or the effects of incision and the undercutting of the riverbanks (Padmalal and Maya, 2014). Sand extraction sites in the VMD can extend over several kilometres. Some sand mining pits in the Mekong Delta reach a depth of 17 m compared to the surrounding bathymetry (Jordan et al., 2019). The flow velocity at the location of an erosion pit decreases due to the greater depth compared to the surrounding area. When the flow velocity decreases, the sediment transport capacity of the water also decreases. This results in a deposition of sediment in the sand mining pit. After the water passes the erosion pit, the velocity increases again, increasing sediment transport capacity. However, the sediment is deposited in the pit and thus sand hunger occurs downstream of the pit, causing erosion of the river bed. The one-dimensional effects of long-term sand mining are shown in Figure 2.9. The short-term effect shows the initial response of the river to long-term sand mining at one location. Due to the local deepening of the bed, backwater curves occur upstream and downstream of the sand mining pit, which affects the river morphology upstream as well as downstream of the sand mining site. An erosion wave develops downstream, which deepens the bed. In the long term, the river finds a new equilibrium. The channel adjusts its slope so it can transport the supplied sediment downstream. If there is less sediment to transport, the flow velocity decreases and eventually the slope of the riverbed decreases. The long-term effect is shown in the bottom image of Figure 2.9.

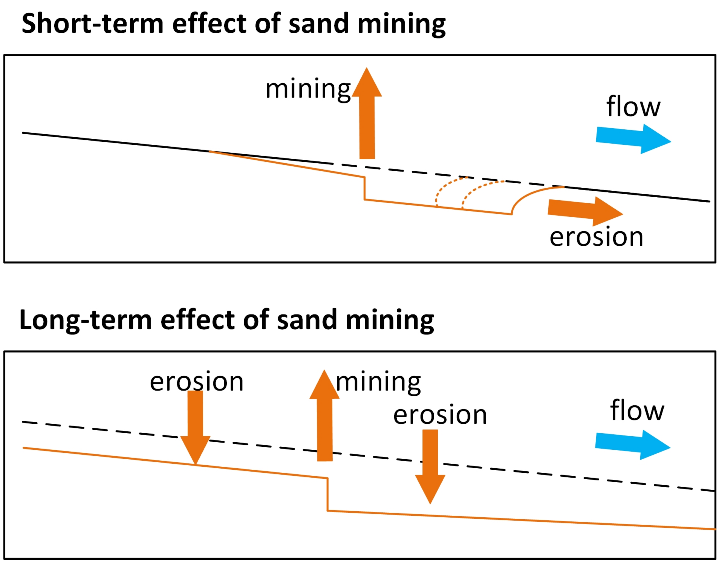

Figure 2.9: The short- and long-term effects of long-term sand mining (modified after Sloff and Mosselman (2021)).

Jordan et al. (2019) conducted surveys of the bathymetry on a 20 km stretch of the Tien River in the VMD in both the dry season and the wet season. The changes in bed elevation between the seasons showed that a new equilibrium could be reached after only a few months, based on observations of bed elevation changes between the dry and wet seasons. They showed that the cumulative sedimentation in the pits was up to 14 metres and that the river bed around the pit eroded. They set up a hydro-morphodynamic numerical model to calculate the duration of the refilling process. A complete refill is likely to take one year for most mining sites, if the site is undisturbed. However, there is long-term sand mining in the VMD. Jordan et al. (2019) conclude that the pit is not only refilled by bedload, but also partially by the trapping of suspended load and the influx of bed material around the pit.

There are many reports about the effects of sand mining on the morphology of rivers across the world. Rovira et al. (2005) showed that extensive sand mining in the lower Tordera River in Spain caused an incision of up to 2 metres over the whole reach. The extraction rate was 14 times higher than the replenishment rate. They estimated that it would take 420 years for the river to recover.

In the Manimala River in India, there was heavy sand mining. This led to river bed incision and bank erosion. In the Bharathapuzha River in India, a bridge collapsed due to channel incision caused by sand mining (Padmalal and Maya, 2014). This shows the consequences that sand mining can have on the environment around a river.

2.5 Bank and bed erosion

From several interviews I conducted for this study with different stakeholders in Vietnam, it could be concluded that the interviewees find that the main problems caused by sand mining are bank erosion, river bed incision, and coastal erosion due to the lack of sand that reaches the coast. It affects local people since their livelihoods depend on the delta and their houses are located on the riverbanks. Vinh Long is known to be an active sand mining area and there have been severe cases of erosion in the area. The owner of the homestay in Vinh Long, who has lived there his entire life, opened up about erosion and sand mining in the area. In December 2022, there was a case of severe erosion near his house. A total of 13 houses disappeared in the river. Before this happened, sand mining vessels were active in front of his house, located on the riverbank. After the event, the sand mining vessels moved to another location in the river. He showed the erosion site, which is shown in Figure 2.10 and Figure 2.11.

Figure 2.10: Remains of a house after severe erosion Vinh Long

Figure 2.11: Bank erosion in Vinh Long province

3 Vessel classification model for sand mining

This chapter describes how a vessel classification model for the Vietnamese Mekong Delta (VMD) based on satellite images is developed. First, a literature review is done for the detection and classification of vessels with optical and SAR satellite images, and it provides a summary of the vessel detection model that was developed for the sand budget study. Then, the characteristics of sand mining vessels for the area of interest are described and visualised. This is followed by a description of a vessel detection system. Lastly, the procedure of the development the vessel classification model for this study is described. The performance and the outcome of the model are discussed at the end of the chapter.

3.1 Introduction to previous research of vessel detection with satellite images

Kanjir et al. (2018) reviewed 119 papers on vessel detection and classification with optical satellite images for a period from 1978 to March 2017. The study showed that the most common factors influencing the accuracy of vessel detection are: weather conditions affecting the water surface characteristics, cloud cover and haze, solar angle, and imaging sensor characteristics. SAR images are better for vessel detection than optical satellite images. One of the main reasons for this is that SAR is independent of daylight and cloud cover. Also, vessels made of metal and with sharp edges appear as bright dots, which makes it easy to detect them (Mattyus, 2013). However, SAR images also have several disadvantages. A high level of intrinsic noise results in a higher number of false positives. The classification and identification of vessels is very difficult, due to less spectral information. Optical images contain more spectral information, making it easier to identify vessels.

35% of the authors of the 119 papers reviewed by Kanjir et al. (2018) used images from Google Earth as the input data for vessel detection. These images are composite, cloudless mosaics that Google buys from Maxar, Airbus, CNES, and Quickbird. The images have a high spatial resolution, ranging from 0.3 to 0.5 m, and show texture and geometry. However, the images are pre-processed and have poor spectral information. There is also a high amount of radiometric distortions. The images are composite images and not instantaneous images, and therefore can result in inaccurate results for sand mining estimates, which are based on the detection of sand mining vessels on a daily basis.

The workflow that most of the authors used for the vessel detection is shown in Figure 3.1.

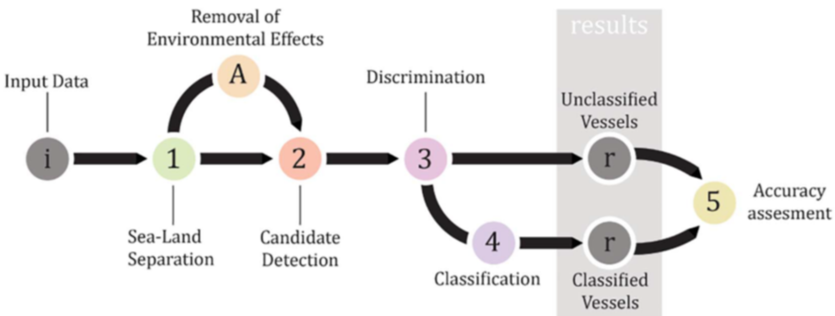

Figure 3.1: Workflow vessel detection (Kanjir et al., 2018)

The first step is to separate the land from the water surface. It is optional to remove environmental effects, such as waves, clouds, and the reflection of sunlight on the water. The next step is the detection of candidate vessels. The main aim of this step is to detect objects that could potentially be a vessel. Most authors used methods based on shape and texture, threshold and salient-based methods. Deep-learning methods are used the least, which was expected because they were only introduced to remote sensing recently. Once potential vessels are detected, vessels need to be distinguished from non-vessels. This is called discrimination. Most authors used geometrical features of detected vessels for this step, like the size, area and length-to-width ratio of the vessels. Some authors only used spectral features or a combination of spectral and geometric features. After the discrimination of vessels, the vessels can be classified based on their characteristics. The classification depends on what is desired and can be based on spatial or spectral characteristics. Various machine-learning methods were used for the classification of the vessels.

It is important to evaluate the detection models, to know the model's accuracy. Only 55% of all the authors of the reviewed literature evaluated their methods. Most of these authors manually identified vessel targets as reference data, usually because of the lack of available data in the region.

The review of Kanjir et al. (2018) also concluded that the classification of vessels smaller than 10 m in length is almost impossible. Furthermore, Deltares (2023), Gruel et al. (2022) and Hackney et al. (2021) estimated the sand extraction rate in different parts of the Mekong Delta with the use of satellite data sets. This is described in Section 1.2.

Deltares (2023) developed a vessel detection model to detect barges with cranes in the VMD. They used Sentinel-2 data for the model, which is optical satellite data with a spatial resolution of 10 m. The following steps were taken to create the model:

1. The area of interest is specified, it covers the main river branches in the VMD.
2. The water surface within the area of interest is determined with the JRC Global Surface Water Mapping Layers.
3. The Normalised Difference Water Index (NDWI) is calculated for the water surface within the area of interest, based on the green band and NIR band of the satellite image. An example of this is shown in image A Figure 3.2. The dark spots indicate non-water objects on the water surface.
4. The Otsu threshold method, an image thresholding algorithm, is used to separate the water surface from non-water elements in the river. A mask layer is made to visualise the Otsu threshold method that is used. Based on the threshold, parts of the image are either black or white. This is shown in image B in Figure 3.2. This results in unfiltered blobs, which can be vessels, patches of land, or other false positives.
5. The blobs are filtered based on dimensions and position. From high-resolution satellite data, the geometry and dimensions of (active) barges with cranes are determined. The barges with cranes are usually located next to other vessels. The dimensions range from 50-80 m in length and 20-40 m in width and the footprint area is around 1000-1600 m^2. Filtered blobs are within the determined dimensions and are located further than 100 m from the riverbank. It is assumed that vessels that are within 100 m of the riverbank are inactive.

Deltares (2023) visualised the results of the unfiltered and filtered blobs in Google Earth Engine (GEE), which can be seen in image C in Figure 3.2. The black blobs are unfiltered and the yellow blobs indicate filtered blobs, which are assumed to be barges with cranes.

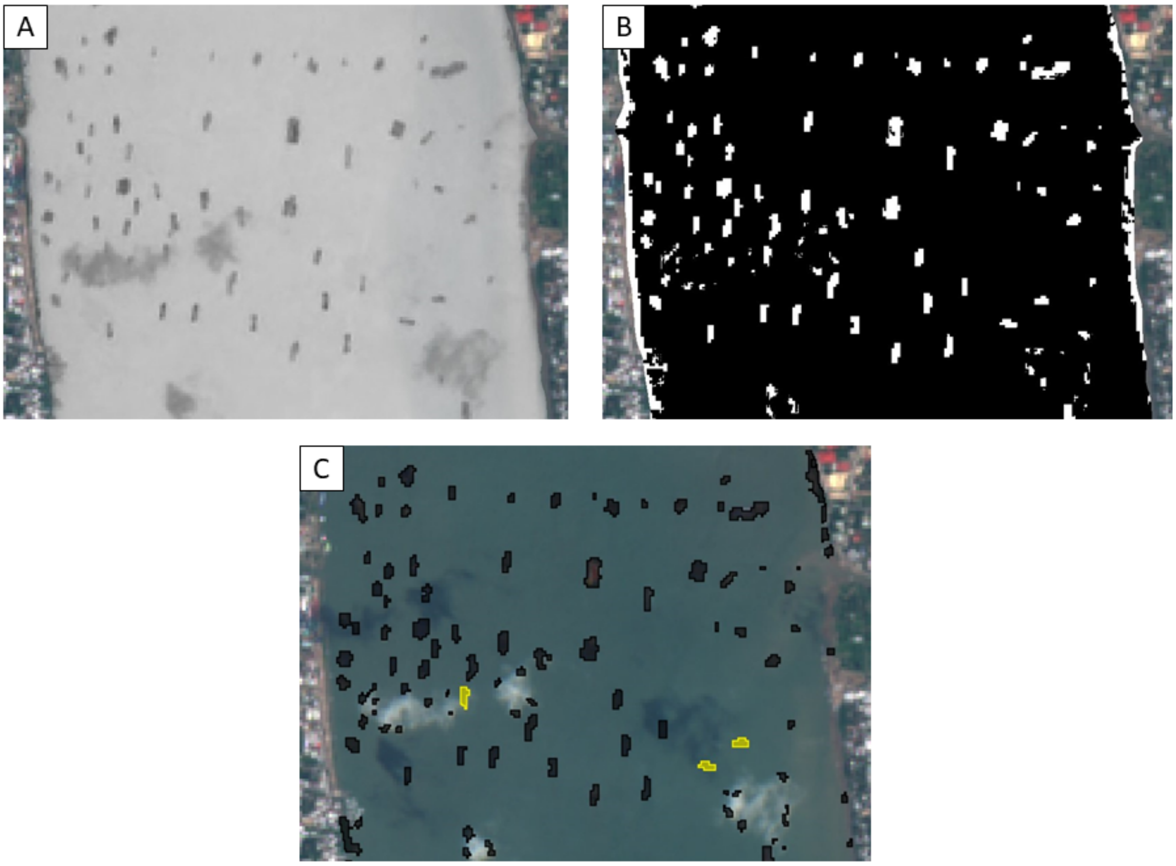

Figure 3.2: The steps that Deltares (2023) took for the development of the vessel detection model developed for the sand budget study. A) The NDWI mask for a Sentinel-2 image; B) The mask based on the Otsu threshold method for a Sentinel-2 image; C) Unfiltered blobs (black) and filtered blobs (yellow).

Besides optical satellite images, there is SAR imagery. SAR satellites actively emit radio waves with a given frequency, which are reflected on the surface of an object or the Earth, back to the satellite. SAR works during the day and night and is not subject to cloud coverage. Therefore, SAR is widely used for the detection of vessels at sea. A vessel appears as a bright spot on an image, especially with metal surfaces since they are good radar reflectors. The water surface appears dark in the image, making it easy to distinguish large vessels from the water surface. However, SAR images are subject to background noise, resulting in a higher number of false positives compared to vessel detection with optical data. Vessels have similar appearances in the images, making it difficult to distinguish vessels from each other (Yang et al., 2023).

The Constant False Alarm Rate (CFAR) algorithm is the most used algorithm to detect vessels with SAR images (Ouchi, 2016). It is a threshold-based algorithm. The signal is compared to a certain threshold based on the background statistics. In CFAR, the intensity of every pixel in the image is scanned and compared to the threshold value. If the intensity of the pixel is higher than that of the threshold, it can be an object on the water's surface. The resulting probability of a false alarm is kept constant for different conditions and environments. The average cloud coverage for the Mekong Delta during the rainy season is 85%-95%, making vessel detection with the use of optical satellite data a challenge (Leinenkugel et al., 2013).

3.2 Characteristics sand mining vessels

The characteristics of sand mining vessels in the VMD need to be known to be able to detect them. The two main types of vessels involved in sand mining activities that can be distinguished are:

- Barges with cranes: Barges with cranes extract sand from the river.
- Blue boats for transport: Blue boats are widely used throughout the entire Mekong Delta to transport all types of goods, sand is one of them.

Since blue boats transport different goods in the Mekong Delta, it is hard to say whether it is sand or something else that is transported when they are detected. Also, there is a lot of uncertainty about the movements of the blue boats. It is unknown what distance they cover to transport sand and whether they transport sand only once a day or more often. This information is necessary to estimate the sand extraction rates based on vessels that transport sand. In Vietnam, we observed that barges with cranes stay around the same location for a day. From observations in the PlanetScope data set, it also follows that barges with cranes usually stay in the same spot for longer than just one day. Since the barges with cranes do not move while extracting sand, there is more certainty when estimating the sand extraction rates from detected barges with cranes. Therefore, we built a vessel classification model to detect barges with cranes.

In order to classify vessels in the VMD and to distinguish barges with cranes from other vessels, we obtained multiple examples of sand mining vessels from high-resolution imagery from Google Earth. It is observed that active barges with cranes are grouped with boats for transport. A few examples of sand mining vessels that were spotted are shown in Figure 3.3.

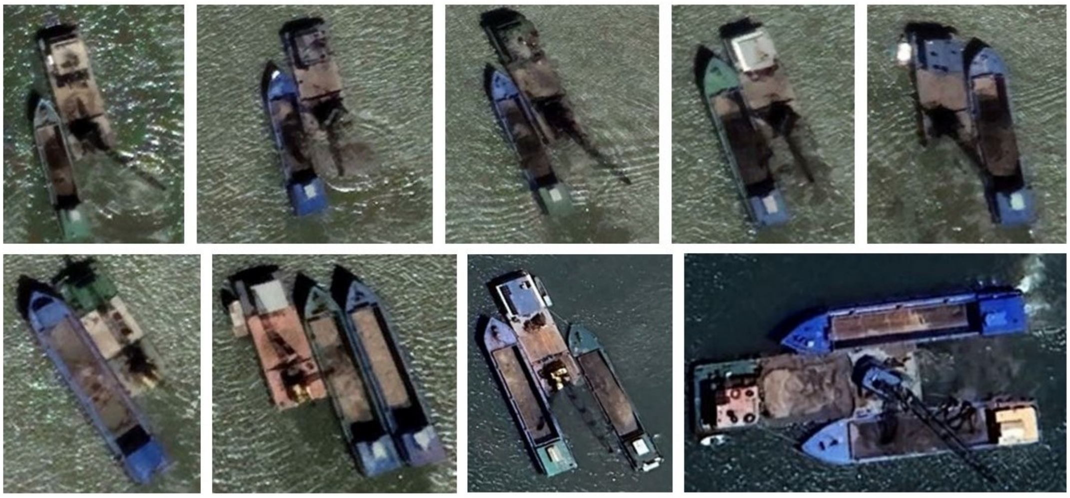

Figure 3.3: Examples of barges with cranes obtained from Google Earth (Maxar, 2023).

3.3 Satellite data sets

There is a large number of satellites and thus satellite data sets, some are freely accessible. The data sets have different characteristics. For this study, the most important characteristics of a data set are spatial and temporal resolution, the type of data (SAR or optical), and the availability of the data. The data sets that we considered for this study are listed in Table 3.1. The differences in spatial resolution are visualised in Figures 3.5 and 3.6.

Table 3.1: Characteristics of satellite data sets considered for this study

Data set	Type	Spatial resolution	Temporal resolution	Number of bands	Data availability
Sentinel-1	SAR	10 m	12 days (2014-now)	1: C-band	Free access
Sentinel-2	Optical	10 m	5 days (2015-now)	13	Free access
PlanetScope	Optical	3-5m	daily (2016-now)	8	On-demand
ICEYE	SAR	0.5m	daily (2018-now)	1: X-band	On-demand
SkySat	Optical	1m	sub-daily (2013-now)	5	On-demand

Spatial resolution of satellite images

A high-resolution Maxar image with a spatial resolution of 1 m/px is downloaded. Two types of double-moored vessels are identified from the image: a barge with a crane moored with a normal barge, and double-moored barges. This is shown in Figure 3.4.

Figure 3.4: A high-resolution image with a resolution of 1 m/px (modified after Maxar (2023))

As a part of this study, we downsampled Figure 3.4 by bilinear interpolation. This method uses the weighted average of neighbouring pixels to calculate a value for the new pixel. It reduces the resolution of the images. The double-moored vessels that are shown in Figure 3.4 are cropped from the downsampled images. This results in Figure 3.5 and Figure 3.6. When the spatial resolution gets lower, it is harder to distinguish vessels from each other. For a resolution of 1 m/px, the two vessel types are distinguishable and the crane on the barge can still be seen. For a resolution of 3 m/px, the crane can still partially be seen, but not as clear. The vessels and the geometry can still be seen and distinguished from each other. When the resolution gets lower, it is not possible to distinguish the vessel types from each other. The crane is not visible anymore and the geometry of the vessel types starts to look similar.

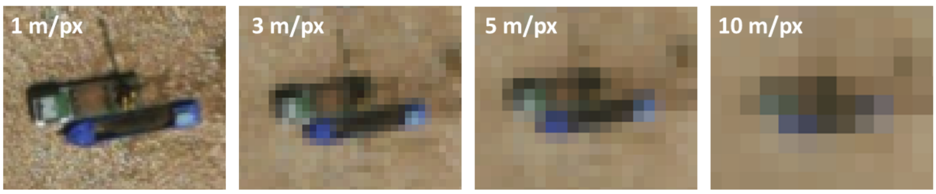

Figure 3.5: Example of a barge with craned moored with a barge when the resolution changes

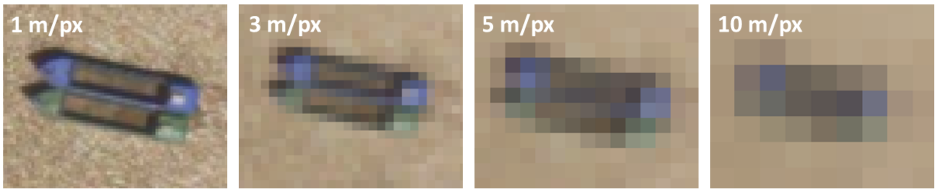

Figure 3.6: Example double-moored barges when the resolution changes

Cloud coverage

Optical satellites depend on solar radiation that is reflected off Earth's surface. Therefore, optical satellite images can only be used during the day and when there are no clouds. The optical images cannot be used for the detection and classification of vessels in the VMD when the sky is overcast. The average cloud coverage for the Mekong Delta during the monsoon season from May to October is 85%-95%, which makes vessel detection with the use of optical satellite data a challenge (Leinenkugel et al., 2013).

Optical satellite data sets

In the following paragraphs, we discuss some optical satellite data sets and show examples of images. Optical satellites are passive: the sensors detect and collect solar radiation reflected from Earth's surface into space in the visible or near-visible part of the electromagnetic spectrum. Therefore, optical satellites depend on daylight and clouds. There are multiple spectral bands that can be captured with optical satellite sensors. The most common bands are red, green, blue, and NIR.

Sentinel-2

Sentinel-2 is a freely available satellite data set with a spatial resolution of 10 m. Deltares (2023) used this data set in the vessel detection system that was developed for the sand budget study. The main applications of the data are agriculture, land ecosystems monitoring, forest management, inland and coastal water quality monitoring, disaster mapping, and civil security (Copernicus, 2023b; European Commission, 2023). Sentinel-2 data has 13 spectral bands. Four of the bands have a resolution of 10 m: the red, green, blue, and NIR band.

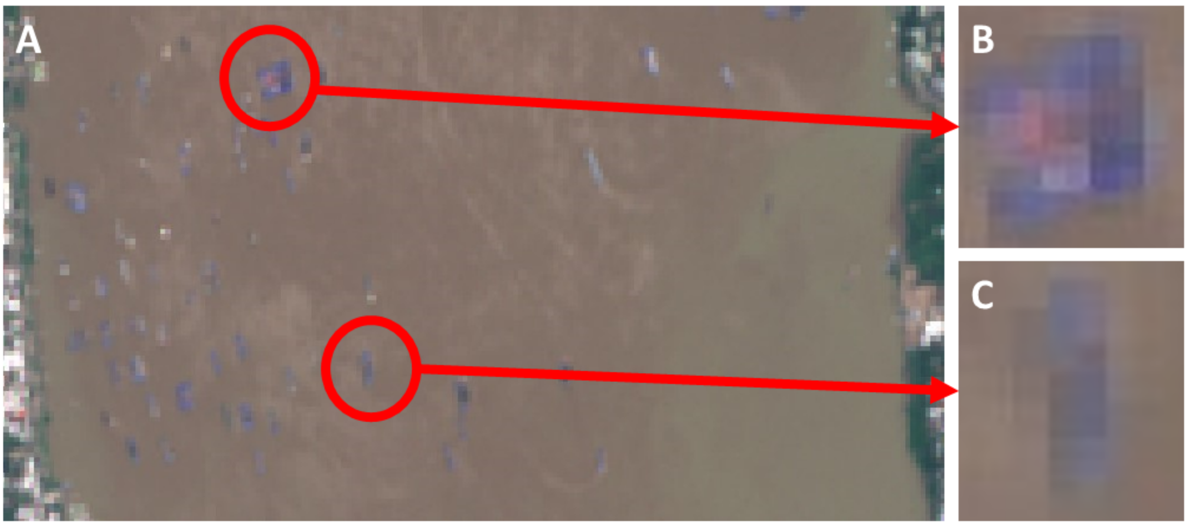

Figure 3.7: A: A Sentinel-2 image with a 10 m resolution at the Vietnamese-Cambodian border; B, C: Examples of vessels shown in the Sentinel-2 image.

PlanetScope

PlanetScope is an optical satellite data set that is available on demand. For research purposes, one can get limited access to the PlanetScope data sets. The available images are monthly composite images that consist of the best daily images over a month, and daily images. The monthly composite images have minimal cloud cover, so there is no need to filter the images. However, the images are a composition of images taken on different days. This means that the same vessel can be in the composite image more than once or some vessels do not appear at all. Therefore, the use of daily images is preferred. For the daily images, cloud coverage needs to be taken into account and the images need to be filtered. The spatial resolution of the images is 3 m and the data has eight bands: red, green, blue, NIR, coastal blue, green I, yellow, and red edge. Applications of PlanetScope data include monitoring transport and urban infrastructure, detailed vegetation mapping, surface deformation (earthquake displacements), monitoring rapid changes in vegetation and land use, as well as emergency and security applications.

Figure 3.8: A: A PlanetScope image with a 3 m resolution at the Vietnamese-Cambodian border; B, C: Examples of vessels shown in the PlanetScope image.

SkySat

SkySat is an optical satellite data set and another product of Planet, but it has a higher spatial resolution of 1 m. The data is only available by purchase. An example of a SkySat image is shown in Figure 3.9. There are SkySat scenes, which are real-time images, and there are images that are composed of around 60 SkySat Scenes. The applications of SkySat data are similar to those of PlanetScope data. The data has five spectral bands: blue, green, red, NIR, and panchromatic (black and white).

Figure 3.9: SkySat image of vessels moored to a jetty.

SAR data sets

Synthetic Aperture Radar (SAR) satellites are active satellites that emit electromagnetic waves with a certain frequency and polarisation. The emitted waves are reflected on Earth's surface and back to the satellite. The sensors are independent of daylight and clouds, and they collect data with a given frequency band. The most common bands are the C-band, the X-band, and the L-band. Characteristics and applications for these bands can be found in Table 3.2. The data only has one spectral band and after processing the images are shown in grayscale.

Table 3.2: Characteristics of the three most widely used bands in SAR sensors (modified after Detektia (2023)).

Band	Frequency	Wave-length	Characteristics	Applications
X	8-12 GHz	3.8-2.4 cm	High spatial resolution, low penetration, not useful in vegetated areas. It is more affected by atmospheric conditions.	Urban and infrastructure monitoring, ice and snow, weather
C	4-8 GHz	7.5-3.8 cm	Medium spatial resolution, medium penetration. It provides more stable images for different weather conditions.	Urban and infrastructure monitoring, ice, maritime navigations, glaciers
L	1-2 GHz	30-15 cm	Medium spatial resolution, high penetration	Soil moisture, biomass and vegetation mapping, geophysical monitoring

Sentinel-1

Sentinel-1 is a freely available satellite data set, with a spatial resolution of 10 metres. An example of a Sentinel-1 image is shown in Figure 3.10. Sentinel-1 is designed for imaging all global land masses, coastal zones, and shipping routes. Sentinel-1 has a single C-band SAR instrument. Vessels in this band are expected to appear as bright spots on a dark background. Some applications of Sentinel-1 data are monitoring sea ice and icebergs, river and lake ice monitoring, oil spills and ships, marine winds and waves, land-use change, agriculture, deforestation, and support to emergency management such as floods and earthquakes (Copernicus, 2023a;, European Commission, 2023).

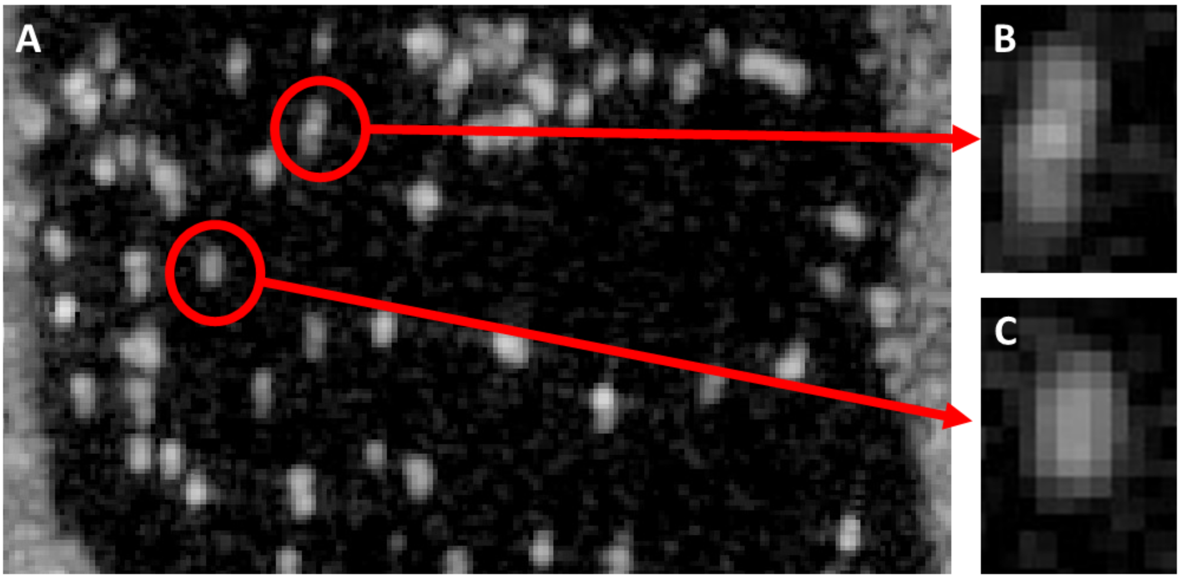

Figure 3.10: A: A Sentinel-1 image with a 10 m resolution at the Vietnamese-Cambodian border; B, C: Examples of vessels shown in the Sentinel-1 image.

ICEYE

ICEYE[1] is a private company that operates a high-resolution SAR constellation. The constellation contains 27 X-band SAR satellites. The data is only available by purchase. There are three ICEYE products: Spot, Spot Extended Area (SLEA) and Strip. The characteristics of each product are as follows:

- Spot: width x height = 5 km x 5 km, spatial resolution = 0.5 m;
- SLEA: width x height = 15 km x 15 km, spatial resolution = 1 m;
- Strip: width x height = 30 km x 50 km, spatial resolution = 3 m.

This research received the support of ESA and Third Party Missions through a special grant for research, with the application ID PP0091449, to access high-resolution X-band SAR data. There was no historical imagery available that would be representative of sand mining activities. Therefore, we and ICEYE planned a mission to acquire relevant imagery of a specified location. We chose the area of interest to be a location of the Mekong River just upstream of Cao Lanh, since this area is known to be heavily mined (see Appendix B.2 and Figure 2.1). The area of interest is shown in Appendix C. ICEYE conducted the tasking on three different days for the three products as indicated below:

- Spot: 28 September 2023, 20:19 local time;
- SLEA: 23 September 2023, 19:56 local time;
- Strip: 25 September 2023, 20:17 local time.

The location of the images is at Cao Lanh, as indicated in Appendix C. The full images can be found in Appendix C, the historical imagery is not publically available and we are the first ones to analyse the relevant features of the ICEYE images for the detection of sand mining vessels. Both the spot image and the SLEA image were cropped to analyse the vessels shown in each image. The cropped spot image, with a spatial resolution of 0.5 m, is shown in Figure 3.11. A number is assigned to each vessel, which corresponds with the vessels shown in Figure 3.11. The resolution is high enough to be able to see the shapes of the cranes on the barges. This is indicated by the yellow dashed line for vessels 1 and 9.

[1]The source of the ICEYE data for this study is European Space Agency (ESA). The data was accessed with a special grant for research. ID of application: PP0091449.

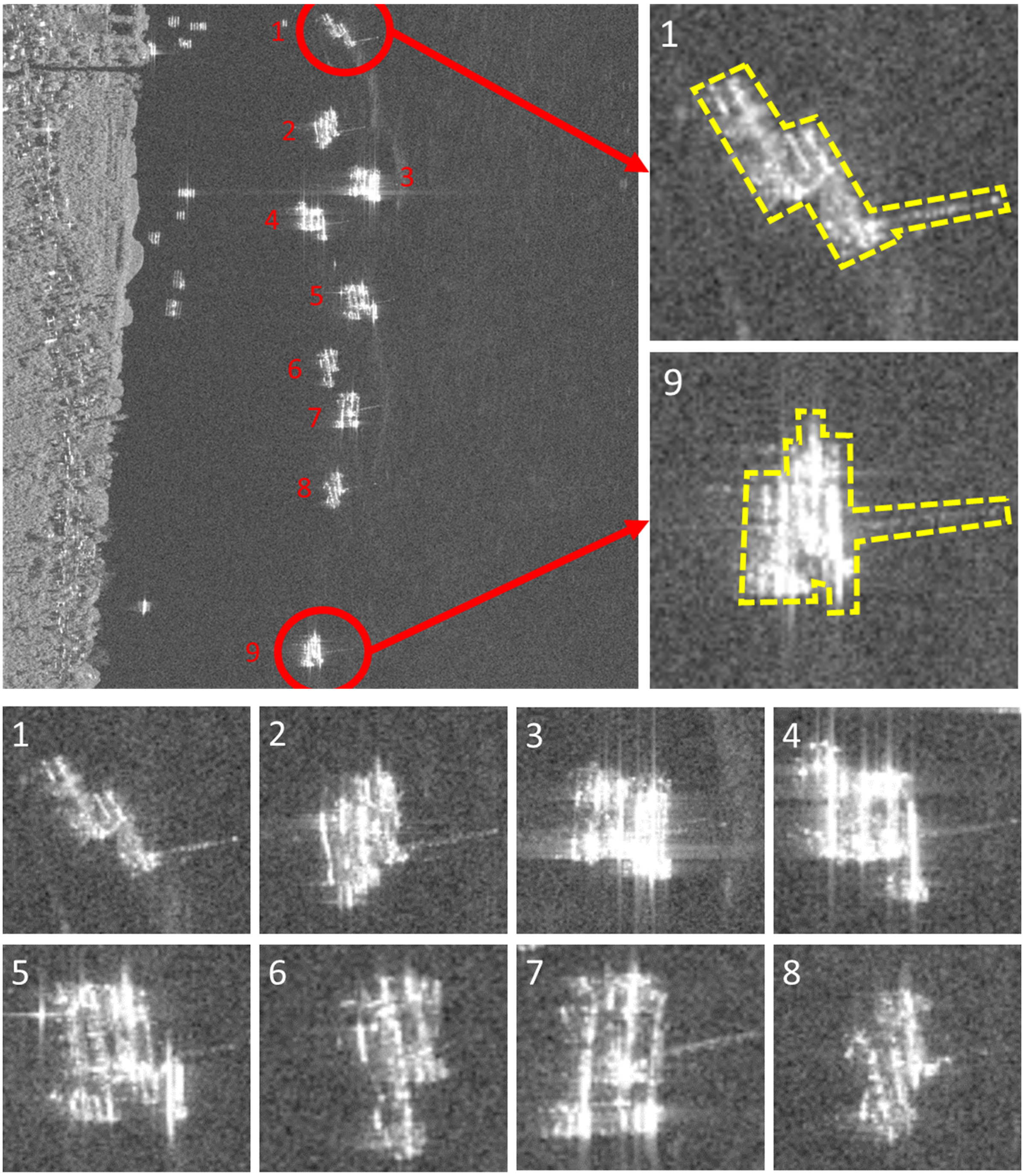

Figure 3.11: ICEYE spot image from the tasking, showing the geometry (yellow dashed line) of two vessels.

The cropped SLEA image, with the numbered vessels, can be found in Figure 3.12. The resolution of the SLEA image is 1 m. For some vessels, the cranes can also be seen in the image. Two examples are indicated with the yellow dashed line, which are vessels 4 and 9.

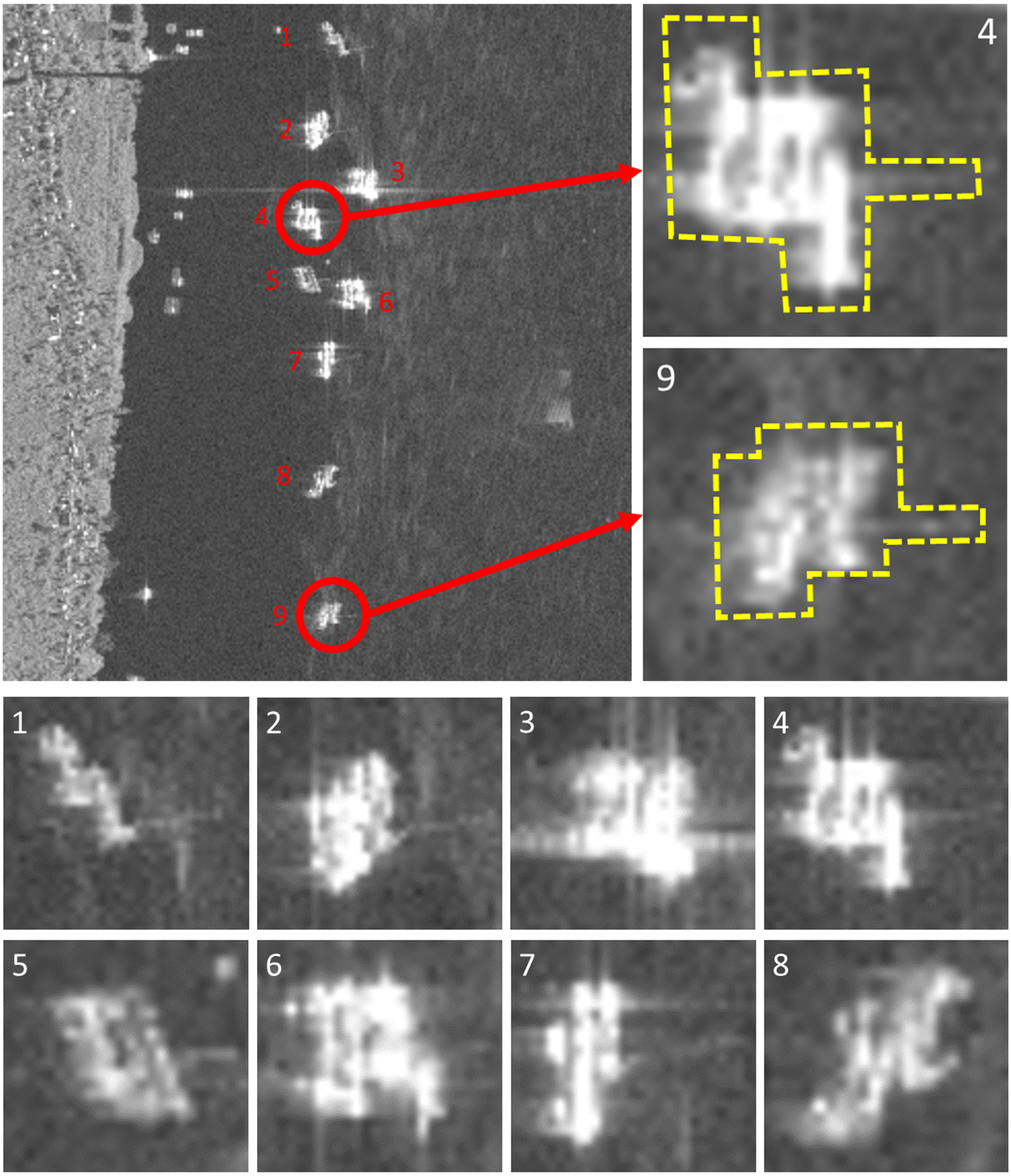

Figure 3.12: ICEYE SLEA image from the tasking, showing the geometry (yellow dashed line) of two vessels.

Another part of the ICEYE SLEA image is shown in Figure 3.13. This location is right beneath the location of Figure 3.12. It clearly shows several groups of vessels, which can be distinguished as normal vessels that are moored together. Two examples of this are shown in the figure, the outline of the vessels is indicated by the yellow lines.

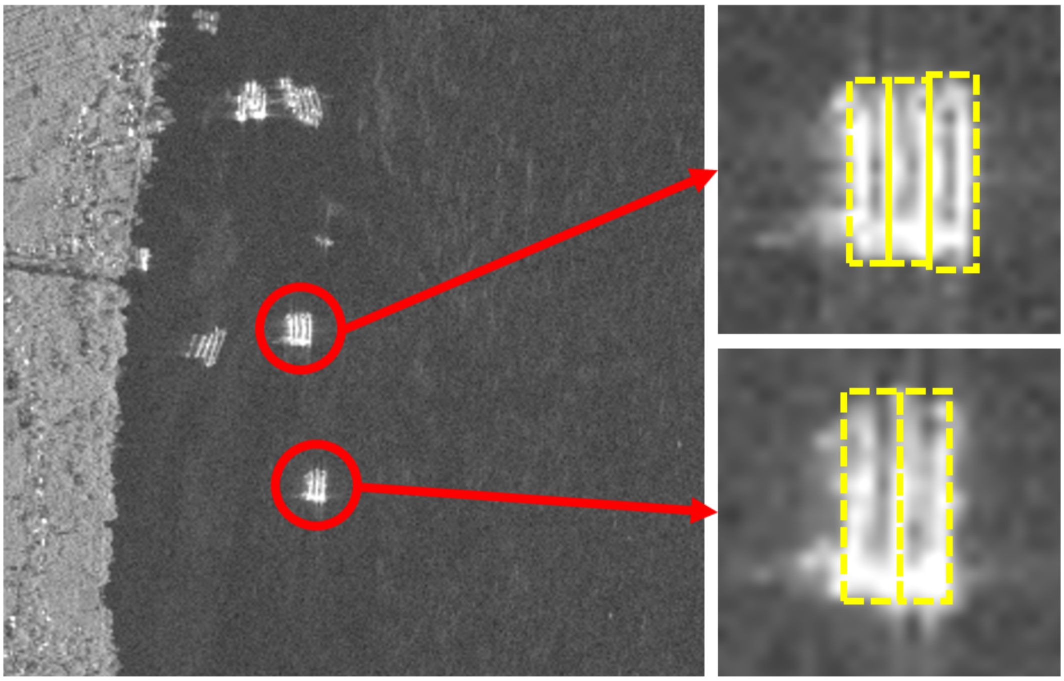

Figure 3.13: A crop of the ICEYE SLEA image, showing the geometry (yellow dashed line) of moored vessels.

Three types of vessels or vessel groups that are visible in every ICEYE product are compared in Figure 3.14. The figure shows that the spatial resolution of 0.5 metres of the spot and of 1 metre of the SLEA are both sufficient to distinguish vessel types. However, the spatial resolution of 3 metres for the strip is too low to be able to differentiate between single vessels and vessel groups. The three barges that are shown on the last row of the figure, appear as one bright spot on the strip image. It is not possible to tell whether it is a group of barges or a barge with a crane with a barge for transport moored next to it.

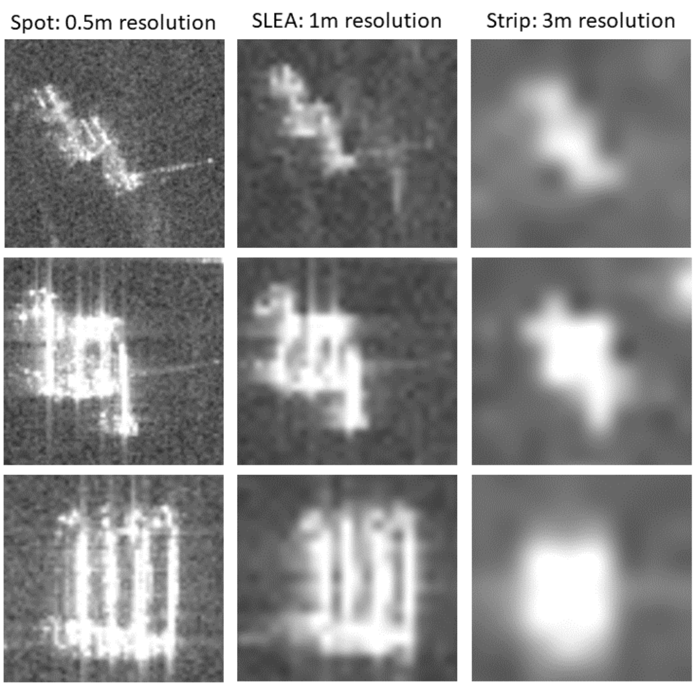

Figure 3.14: Comparison of several vessels for the three ICEYE products: spot, SLEA, and strip.

The ICEYE images that we obtained for this study through ESA are one of a kind. We used the images to explore the features of the satellite images. The relevant features of barges with cranes are visible in the images up to a resolution of 1 metre, which means that barges with cranes can be distinguished from other vessels in the VMD for this resolution. At this moment, there is no historical data available for ICEYE images of the VMD. This means that right now it is not feasible to develop a vessel detection and classification model with this data. It does show potential for future research with high-resolution SAR images to detect vessels. The images seem to be sufficient for vessel classification. Due to the very limited data that is available right now, ICEYE images are not used for the rest of this study.

3.4 Vessel detection and classification with PlanetScope satellite imagery

The satellite image data set that we chose for the development of the model in the continuation of this study is PlanetScope. This choice is made based on the spatial resolution of 3 m, a high temporal resolution, and the availability of the data. Daily imagery can be accessed and downloaded for research purposes, with a maximum of 5000 km^2 a month. Compared to the Sentinel-2 data that Deltares (2023) used, both the spatial and temporal resolution are higher. Based on the analysis of the spatial resolution of satellite data sets and the analysis of PlanetScope data, we assume that the spatial resolution of 3 m is high enough to be able to distinguish barges with cranes from other vessels in the VMD. Therefore, PlanetScope images are used for the remainder of this study.

The methodology that we used for this study is shown in Figure 3.15. First, PlanetScope images are acquired and a cloud filter is applied. The images have four spectral bands: red, green, blue, and NIR. Then, an NDWI mask is applied to the the images. Water has a high absorption of wavelengths in the range from visible to NIR, compared to non-water objects, which makes it an effective method to distinguish the two. The NDWI mask is calculated by:

$$\text{NDWI} = \frac{X_{green} - X_{NIR}}{X_{green} + X_{NIR}}$$

Then, the Otsu threshold method is applied to the NDWI image. The method determines a threshold value and in this example, all the pixels that are above the threshold value are set to black and all the pixels beneath the threshold are set to white. Based on this threshold method, non-water objects can be detected on the water's surface. Bounding boxes are then placed around the detected vessels, and the vessels are classified in the last step with a convolutional neural network (CNN) classification model.

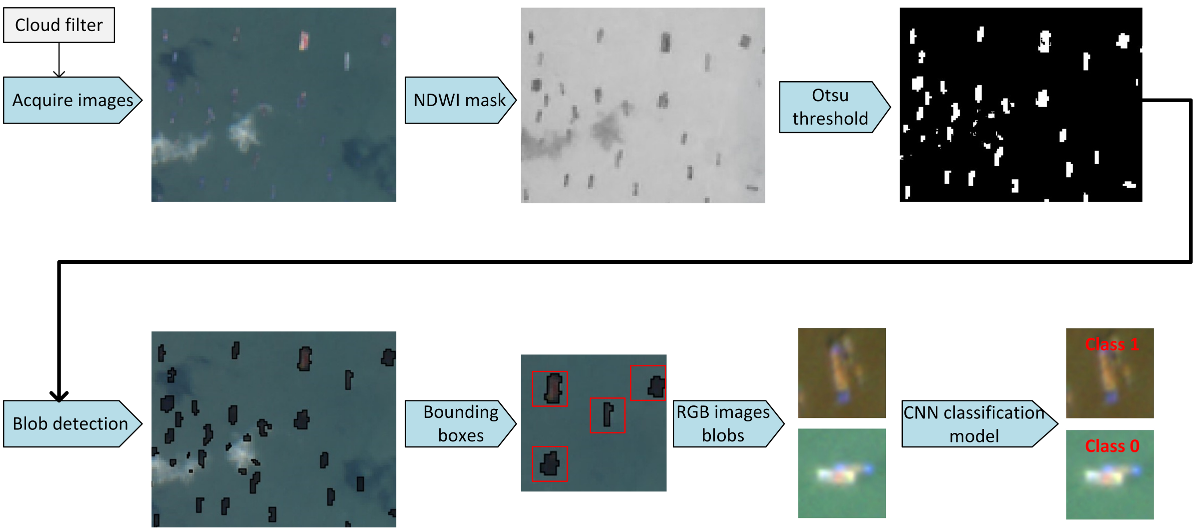

Figure 3.15: Methodology for the vessel detection and classification in this study.

Vessel detection

Satellite data sets are widely used for the detection of vessels, as shown in Section 3.1. Deltares (2023) used a threshold method to detect vessels on the water's surface, which was applied to the NDWI mask of a satellite image. The PlanetScope images also contain the four spectral bands that Deltares (2023) used for the vessel detection model with Sentinel-2 data. Therefore, it is possible to take the same steps for vessel detection based on PlanetScope data. Figure 3.16 shows an example of an NDWI image for PlanetScope data, which are converted from a PlanetScope image for this study. The figure shows that the Otsu threshold method can also be applied to Planetcope images. The water surface is indicated as black and objects on the water's surface are white.

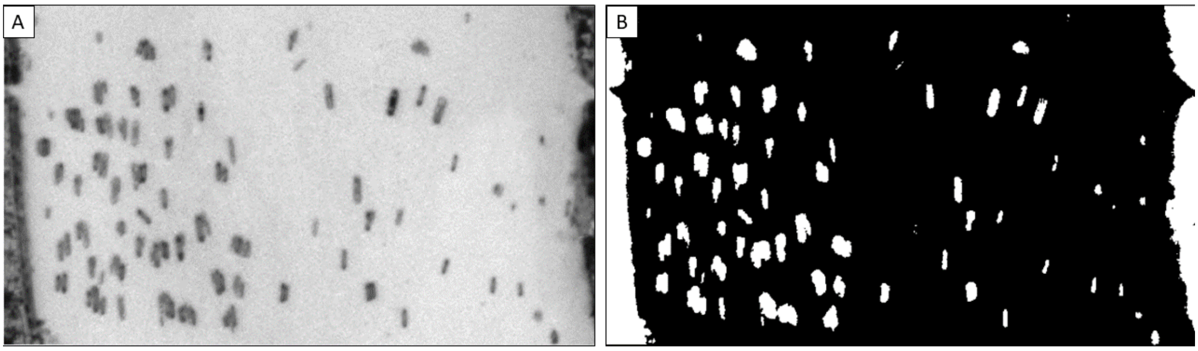

Figure 3.16: A) Example of an NDWI image of PlanetScope data obtained for this study; B) Example of the Otsu threshold method applied to an NDWI image of PlanetScope data. The white parts are non-water objects such as vessels and land. The image was obtained for this study.

The threshold method that was used for the sand budget study works very well for the detection of vessels. When the vessels are detected with this method, bounding boxes can be placed around the vessels. The coordinates of the location and the geometrical aspects of the vessel can be determined. The vessels can be classified based on the bounding boxes around them after they are detected. Vessel classification of the vessels is discussed in Section 3.4.

Vessel classification based on deep learning

Vessel detection is followed by vessel classification. Deltares (2023) did this the vessels based on their geometry. However, the spatial resolution of the Sentinel-2 imagery that was used for the classification is only 10 metres. Different vessel types cannot be distinguished, which is shown in Section 3.3. Therefore, we choose to use PlanetScope images with a higher resolution for this study. Then, we develop a classification system with a deep-learning algorithm. The system classifies vessels based on the features of the vessels in input images, including shape, colour and texture properties. The model is developed with a deep-learning algorithm, which is different from geometry-based classification applied by Deltares (2023). The model is developed to be able to identify barges with cranes.

Creating a data set

We create a manually labelled data set to be able to train the model in a later stage. The steps to create the data set are:

1. Download satellite images of the main branches in the VMD. The images need to be clear (no clouds) and vessels need to be visible in the images.
2. Annotate the images. Every vessel in each image is segmented and labelled.

First, we took snapshots of small sections of the Bassac River and the Co Tien River branches of the Mekong River in the PlanetScope explorer. Vessels need to be visible in the images to be able to annotate for the next step. The vessels can be any vessel because the data set needs to contain sand mining vessels as well as other vessels. The model is trained with all the vessel types, so it can detect and identify different vessel types. The images are taken on different dates ranging from 2020 to 2023. The data that is downloaded has four bands: red, green, blue, and NIR.

The downloaded GeoTiff files are loaded in QGIS to check whether the images are sufficient. The files are converted to PNG files to be able to annotate the vessels. Then, we manually segmented and labelled each vessel in each image to create the training and testing data set. This is done with Labelme. However, the uncertainty of the labelling due to potential human error is not determined for this study. The labels that are chosen for the vessels are:

- Barges with cranes
- Blue boats for transport
- Boats for transport
- Other (fishing boats, ferries, tourist boats)

The way of selecting the vessels depends on the object detection algorithm that is used. Two types of algorithms can be used to detect the vessels. The first is object detection: the model detects an object and puts a bounding box around it. To create the data set for this type of algorithm, the vessels need to be selected in bounding boxes, which are rectangular. The bounding box contains the object, but also the background. The second method is object segmentation, which recognises every pixel of the object, and provides more information than bounding boxes. To create a data set for object segmentation, the vessels need to be selected with a polygon around the edges. It is more time-consuming to select vessels by polygons instead of bounding boxes. However, the selected objects only contain the actual object and no background. This might lead to more accurate results because the shape of the vessels is important when labelling them. It is also possible to convert polygons to bounding boxes in a data set, but not the other way around. Therefore, object segmentation is chosen to make the data set. An example of a Labelme annotation is shown in Figure 3.17.

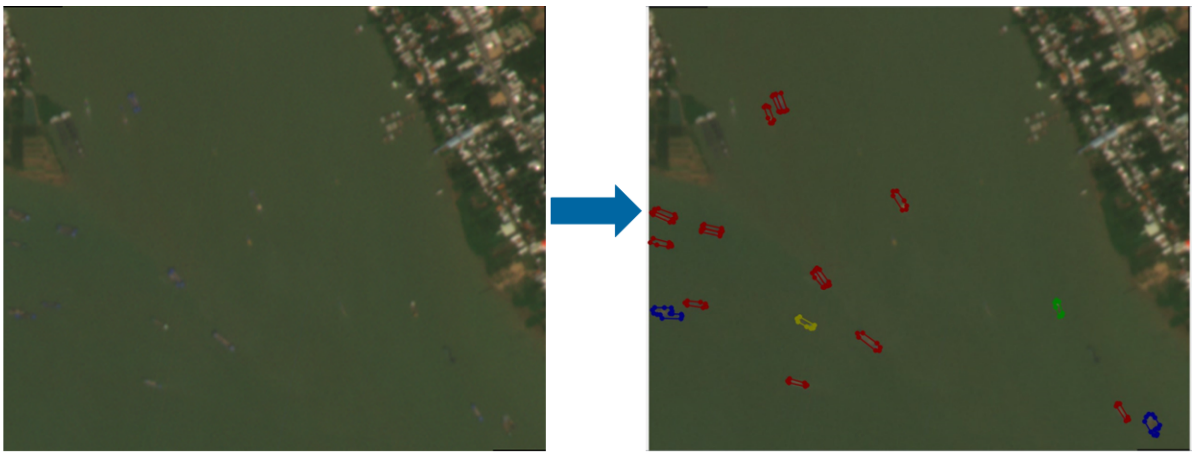

Figure 3.17: An example of Labelme with segmentation. The left image shows a PlanetScope image. The image on the right shows polygons around vessels that are shown in the image.

It must be noted that all the vessels are labelled manually. Therefore, there is a possibility that some vessels are labelled incorrectly due to human error or a low resolution of the images.

Model training

We developed the vessel classification model with a deep-learning algorithm. The model is built with EfficientNetv2 using the library TensorFlow (Abadi et al., 2016). EfficientNetV2 is a convolutional neural network (CNN) architecture, which returns an image classification model. The model is described in detail by Tan and Le (2021). The architecture of the algorithm that was used to train the model for this study is shown in Figure 3.18. The input consists of RGB images with a certain height and width. EfficientNetV2 uses a pre-trained encoder model (using the ImageNet-21k data set) from the TensorFlow library. The output is a flattened layer, which is a vector with 1280 parameters. A dropout layer is added with a dropout rate of 0.3 to avoid overfitting the model. During the training of the model, 30% of the 1280 numbers in the vector are set to zero, so the model is trained to recognise more patterns. If there is no dropout layer, there is a risk that for every training step, the model finds the same features for a class which does not necessarily apply to all the images. After the dropout layer, we apply a dense layer, which fully connects to the previous layer. This layer is used to classify the image based on the output from the other layers in the network.

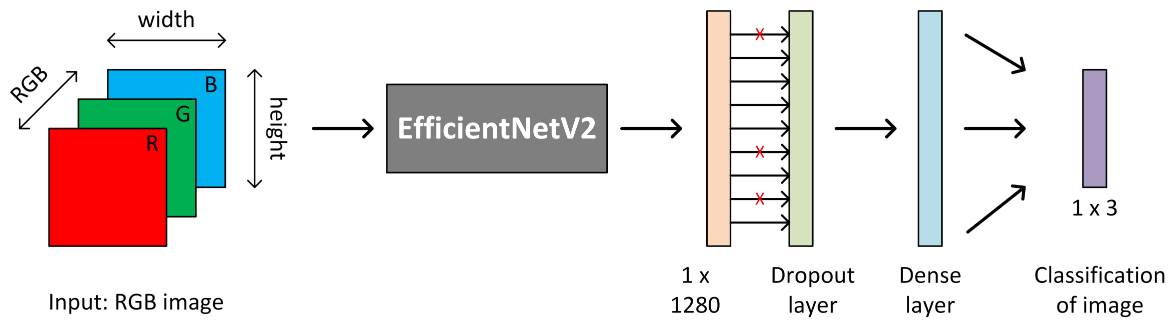

Figure 3.18: Architecture of the vessel classification model for this study.

The EfficientNetV2 encoder is shown in Figure 3.19. The pre-trained encoder model has previously been trained on large data sets to classify certain objects. We optimise this pre-trained model with a Stochastic Gradient Descent (SGD) optimiser so it is trained to classify vessels in the VMD. The model is trained for 50 epochs. During the training, weights are applied to the input data and iteratively adjusted for each step. The optimiser updates the weights throughout the training to improve the ability of the model to predict the class of images accurately.

```
_________________________________________________________________
 Layer (type)                Output Shape              Param #
=================================================================
 keras_layer (KerasLayer)    (None, 1280)              207615832

 dropout (Dropout)           (None, 1280)              0

 dense (Dense)               (None, 3)                 3843

=================================================================
Total params: 207619675 (792.01 MB)
Trainable params: 3843 (15.01 KB)
Non-trainable params: 207615832 (791.99 MB)
_________________________________________________________________
```

Figure 3.19: Summary of the EfficientNetv2 model that was used for this study

To train the model, we altered the obtained data set. Only two classes of vessels are used as input for the model. The first class is 'barge with crane' and the second class is 'others'. The latter contains all annotations of the other classes: 'blue boats for transport', 'boats for transport', and 'other'. The purpose of the model is to detect barges with cranes. For now, it is irrelevant what types of vessels the other vessels are. Reducing the number of vessel classes from four to two makes it easier to build and train a model. Additionally, we added a third class: *background*. The background class contains pictures of water and clouds from the satellite images. The input of the model is a data set with images of the same size that contain the annotated vessels or only a part of the background. Therefore, all polygons are converted to images of a size of 40x40 pixels. To do so, the first step is to determine the centre of a polygon. Then, the images are cropped around the centre of each polygon. The spatial resolution of the images is 3m/px, which means that the images show an area of 120x120 m^2 to make sure every vessel is fully shown in each image.

The number of images per class for the created data set is as follows:

- Barge with crane (class 0): 103, which is 4% of all images
- Others (class 1): 1,085, which is 43% of all images
- Background (class 2): 1,332, which is 53% of all images

The data set is unbalanced since class 0 does not contain many images and is underrepresented. Therefore, we augmented 80% of the images of class 0 by horizontal and vertical flipping, and by a 90-degree rotation. The other 20% of the images are stored in a separate testing data set that is used in a later step. This is done to make sure that the testing images are not similar to the images of the input data set. The testing data set is now independent of the training and validation data set, which gives more reliable results.

The total number of images of class 0 for the input data set, including augmented images, is 332. For both class 1 and class 2, we randomly select 352 images, which is the total number of training, validation, and testing images for class 0. Of these 352 images, 20 are randomly selected and stored in the testing data set. The total number of images per class is now the same for the training, validation, and testing data sets.

Then, we split the input data set into a training and a validation set. 80% of the images are used for training the model and the remaining 20% are used for the validation data set. The model is trained for 50 epochs. The testing and validation accuracy of each training step can be found in Appendix D.

Model testing

Once we trained the model or 50 epochs, the model was tested with the testing data set. The testing data set consists of 60 images; 20 images of each class. The testing data set is independent of the training data set. The result of testing the model is an overall accuracy of 0.82. The confusion matrix of the model is shown in Table 3.3 as *'case 1'*. The vertical axis of the matrix indicates the label that was given to an image, indicated in Table 3.3 as 'actual class'. The horizontal axis indicates the class that was predicted by the model for the image. The diagonal shows the number of images that were predicted correctly for each class. The matrix shows that the model predicted 15 out of 20 barges with cranes in the testing data set correctly.

The accuracy of the data set is high, but the number of testing images is low. Therefore, we expand the testing data set by downloading more satellite images and labelling more barges with cranes (class 0). The total amount of testing images for class 0 is 51. For class 1 and class 2, 51 random images are selected for the new testing data set. The confusion matrix of the testing results for this expanded data set is shown in Table 3.3 as *'case 2'*. The overall testing accuracy is 0.85, which is only a bit higher than before. 41 out of 51 images of class 0 were predicted correctly by the model.

Table 3.3: Confusion matrix for 51 testing images per class. The vertical axis indicates the label of an image. The horizontal axis indicates the class that was predicted by the model. The bold numbers on the diagonal are images that were correctly predicted by the model.

		Case 1			Case 2		
		Predicted class			Predicted class		
		0	1	2	0	1	2
Actual class	0: barge with crane	**15**	5	0	**41**	10	0
	1: other	3	**16**	1	8	**39**	4
	2: background	1	1	**18**	1	0	**50**

With the confusion matrix, we calculate the precision and recall of the model for each class. The precision (or positive predictive value) is the fraction of the number of images correctly identified as a class compared to all the images that are identified as that class. Recall (or sensitivity) is the fraction of images correctly identified as a class compared to all cases that belong to that class. The precision and recall are calculated as:

$$\text{precision} = \frac{\text{no. of correctly predicted image of class X}}{\text{total no. of images predicted as class X}}$$

$$\text{recall} = \frac{\text{no. of correctly predicted image of class X}}{\text{total no. of images labelled as class X}}$$

The results for precision and recall of each class are shown in Table 3.4.

Table 3.4: Precision and recall for each class, with 51 testing images per class.

Class	Precision	Recall
0: barge with crane	0.82	0.80
1: other	0.80	0.76
2: background	0.93	0.98

The result of the model is visualised in Figure 3.20. The figure shows 20 examples of images from the test data set, with the actual label and the predicted label.

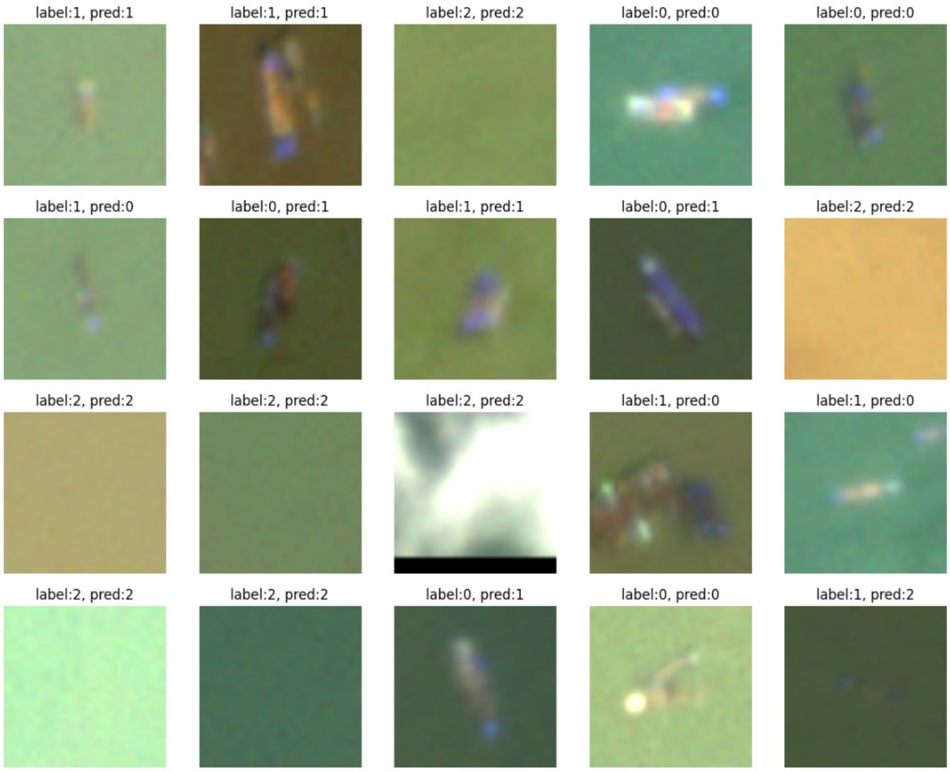

Figure 3.20: Visual results of model that show the actual label ('label') and predicted label ('pred'). 0 is a barge with crane, 1 is other and 2 is background.

Model performance

To assess the model's performance, we analyse images with certain predictions to find similarities and trends in the predictions. The three cases that we consider are:

- Images with the label 'barge with crane' (0) that are predicted incorrectly as another class;
- Images that were incorrectly predicted as 'barge with crane' (0);
- Images that were correctly predicted as 'barge with crane' (0).

Pictures that were incorrectly predicted by the model are shown in Figures 3.21, 3.22 and 3.23. Figure 3.24 shows examples of barges with cranes that were predicted correctly. Figure 3.21 shows that other vessels (class 1) are incorrectly predicted as barges with cranes (class 0). There are two possible reasons for this that can be identified from the examples in the figure. The first is that groups of vessels are identified as barges with cranes. The second reason is that the colours differ from the blue that is often seen in the other vessels.

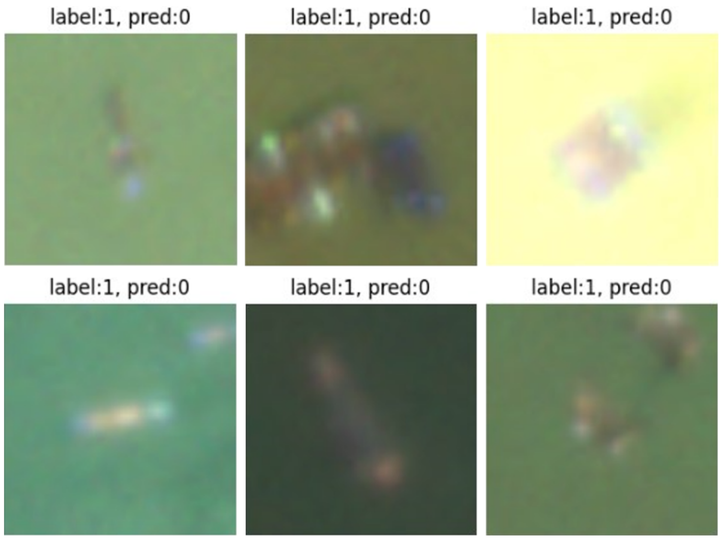

Figure 3.21: Images of class 1 (other) are incorrectly predicted as class 0 (barge with crane). Every image shows the actual label ('label') and predicted label ('pred').

In Figure 3.22, vessels that we labelled as barges with cranes (class 0) are incorrectly predicted as other vessels (class 1). There are several potential causes for this. The first is that the vessels seem to be mainly blue, which is in many cases true for the other vessels. The second cause is that the vessels look long and narrow, even though there are two vessels in the images. The vessels seem to merge together, which could make it hard for the model to distinguish the two vessels. The vessels seem like one single barge, instead of two vessels moored next to each other. The last is that the bottom right image is unclear. This image is labelled as a barge with a crane, because of the shape. However, there is some uncertainty in the label of the image.

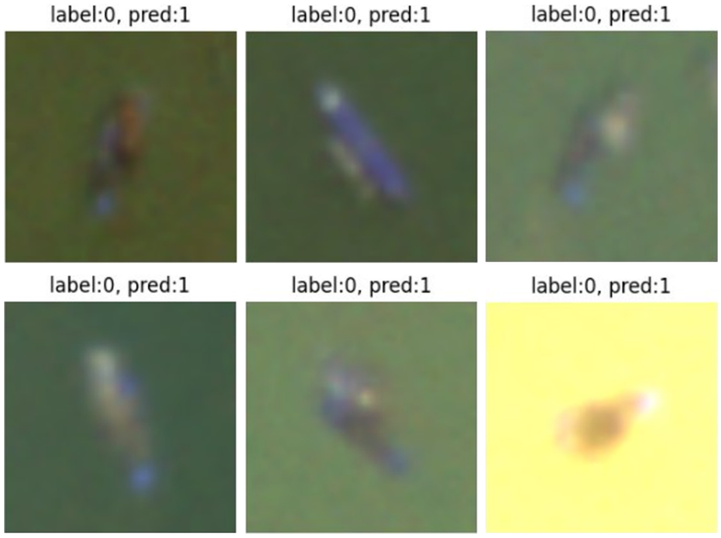

Figure 3.22: Images of class 0 (barge with crane) are incorrectly predicted as class 1 (other). Every image shows the actual label ('label') and predicted label ('pred').

In Figure 3.23 other incorrectly predicted images are shown. It shows some images of class 1 (other), which are predicted as class 2 (background). The vessels are barely visible, which is probably the reason that the prediction of the images is incorrect. The image at the bottom left shows a background, but the prediction is class 0 (barge with crane). However, there is no vessel visible in the image. It is unknown why the model predicted this image as class 0.

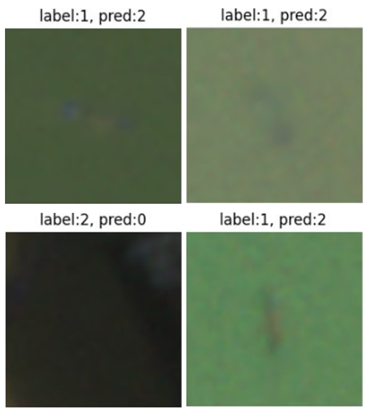

Figure 3.23: Incorrect predictions of model, every image shows the actual label ('label') and predicted label ('pred'). 0 is a barge with crane, 1 is other and 2 is background.

Figure 3.24 shows images with the label 'barge with crane' that are correctly predicted by the model. The main similarity in all the images is that the vessels are grouped and have other shapes. This is in line with the vessel characteristics described in Section 3.2.

Figure 3.24: Correctly predicted images of class 0: barge with crane.

It was challenging to label some of the vessels in the images. This happened when the outline of the vessels was not clear. The images are snapshots covering the width of the river and as a result, the vessels appear small in the images. We therefore download an image that is more zoomed in, to see if it is easier to annotate the vessels when they appear larger in the original downloaded picture. The cropped part of the larger picture in Figure 3.25 is darker than the picture that was downloaded while zoomed in, shown in Figure 3.26. This could make it easier to annotate the images. However, the spatial resolution does not seem to be different.

Figure 3.25: PlanetScope image that was zoomed in on and cropped after downloadign

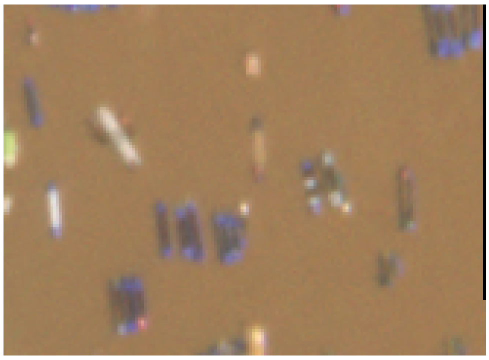

Figure 3.26: PlanetScope image was zoomed in on before downloading

The overall accuracy of the model of 0.85 is high, especially when considering the low number of input images in the model. The model performs well for the independent testing data set that was used to determine its performance. The performance of the model depends on several factors, namely the availability of the satellite data set, the spatial resolution of the satellite images, and the segmentation and labelling of the vessels.

Model outcome

The outcome of the model is a classification system for vessels in the VMD. Even though there is limited data available, especially images of barges with cranes, the model shows great potential. The accuracy of the model with the augmented data is 0.85. From the figures of the testing results, we recognised a few trends for incorrect predictions of a class by the model. These are:

- The model predicts class 0 (barge with crane) when vessels are grouped together in a different geometry than barges that are moored exactly next to each other.
- The model predicts class 0 (barge with crane) when vessels have a variety of colours.
- The model predicts class 1 (other) when a vessel seems to be one long vessel.
- The model predicts class 1 (other) when the colour of the vessel is mainly blue.
- The model predicts class 2 (background) when the vessel is barely visible.

During the development of the model, some points of discussion appeared. First, in most cases, blue barges and other barges were easy to label. However, in some cases, it was hard to distinguish barges with cranes from other groups of vessels. There were two main reasons for this: the spatial resolution of the images was not high enough, or there was some kind of distortion in the images that caused other colours or flares. The consequence of this is that there is a possibility that some vessels have the wrong label. The model is then trained with a few wrong labels, resulting in a model with a lower reliability. Human error should be taken into account. Satellite images with a higher spatial resolution would make the labelling of vessels more accurate. The labelling was done very carefully and the images were assessed after the labelling. Therefore, the chance that an image is labelled incorrectly is small. The visualisation of the testing results shows that the labelling is done mostly correctly and that the model works well.

The labelling was done by one individual, and thus the labels of the vessel are dependent on one person's perspective. Even though the labelling is based on observations of high-resolution satellite imagery, such as Google Earth, it might be biased. One type of vessel shape that is not a barge with a crane, can mistakenly be labelled as one multiple times. This can also happen for another vessel that is a barge with a crane. The model is trained with the given labels, and can therefore be trained wrongly and be biased. This results in a less reliable outcome of the model. This could be changed by letting several people label the images, individually or together. This would result in a more reliable data set and model because the labels are based on the views of several people. However, the characteristics of sand mining vessels in the VMD were analysed before the images were labelled, and the labelling is based on this analysis. The effects on the reliability of the approach are currently unknown. They can only be determined when other people have applied the same approach to make a data set, and have taken the next steps of training and testing the model.

The number of images for class 1 and class 2 are over 1000 and it is easy to increase this number. The occurrence of other vessels (class 1) is abundant in many places as well as many images. The same holds for class 2. However, the number of labels for class 0 (barge with crane) is only 134 and is thus too low to make a reliable model. If the model is trained with all the images, class 0 is underrepresented and the model would not perform well for this class. To get a more realistic performance of the model, the model should be balanced. Decreasing the number of labels of class 1 and class 2 to 134 results in a balanced model. However, the model would not be trained well for all three classes in this case. For the final model, we augmented the images in class 0 in three different ways. By augmentation, the number of images for class 0 in the training data set is increased to 332, which should result in a more reliable model performance.

Augmentation results in four images of the same barge with a crane for one original label. The four images are similar. We tested the performance of the model with a testing data set, which consists of randomly selected images from every class. This testing data set needs to be independent of the augmented images. If the images in the testing data set are partially augmented, the images might be very similar to those in the training data set. The model would work well for this testing data set, but it could be overfitted. Therefore, the images in the final testing data set are new images that are not augmented and therefore independent from the training images. At first, there were only 20 images of each class in the testing data set. For the final testing, we increased this number to 51 to make sure that the model was tested more properly. This gives more reliable results.

All in all, the model that was developed for this study is a step in a good direction. It shows that it is possible to classify vessels in the VMD based on machine learning and with the use of optical satellite data with a 3-metre resolution. The results of the model are promising, and it is recommended to expand the model by training and testing it with more data. In addition, the analysis of the ICEYE images in Section 3.3 shows that the relevant features of barges with cranes are distinguishable up to a 1-metre spatial resolution. There is no historical data, but this shows great potential for a model based on high-resolution SAR images if a sufficient amount of them can be made available.

4 Estimation of sand mining

The first section of this chapter describes the stakeholders that we met in Vietnam. Then, the methodology to obtain sand extraction estimates from the vessel detection model for the sand budget study from Deltares (2023) is described. Small adjustments are made with newly obtained information. Finally, the second research question is answered by describing a method to obtain sand extraction estimates based on the vessel detection model described in Chapter 3.

4.1 Stakeholder perspectives

The stakeholders that are involved in the project, or affected by sand mining activities, whom we met during the visit, are:

- **WWF: Mr. Anh Ha Huy and Ms. Phuong**
  The World Wildlife Fund for Nature (WWF) set up the 'Resilient Asian Deltas Initiative'. *The vision of the initiative is that the long-term resilience of Asia's Delta system is secured through unprecedented political and financial investment in 'building with nature', which will protect and restore the natural river and coastal processes that replenish deltas and will keep them - and the societies, economies and nature that depend on them - above the rising seas.* (WWF, 2023)
- **SIWRP: Nam Nguyen Trung**
  The Southern Institute for Water Resource Planning (SIWRP) is a Vietnamese government agency under the Ministry of Agriculture and Rural Development that advises on all water-related issues, such as irrigation, erosion, and the construction of hydraulic structures.
- **Can Tho University: Dr. Vo Quoc Thanh**
  Can Tho is the largest city in the Vietnamese Mekong Delta VMD. It has a population of 1 million with 54,000 students attending the university. As the university is located in the VMD, this is a study area for the students and professors at the university.
- **Thuy Loi University: Truong Hong Son**
  Thuy Loi University is located in Hanoi. It has a faculty of Civil Engineering and a water resources engineering department. A meeting was scheduled with an employee and researcher, who works for the hydraulic engineering department of the university. He researches the erosion in the Mekong River and works together with both the WWF-Vietnam and the government.
- **Hanoi University of Natural Resources and Environment (HUNRE): Dr. Thuc Anh**
  A meeting was scheduled with a professor, who has done a lot of research on sand mining in the Red River in Northern Vietnam. Her knowledge and insights on sand mining are also useful for the VMD.
- **Vietnamese-German University: Doan van Binh**
  The Vietnamese-German University is located near Ho Chi Minh City and is a collaboration between Vietnam and several German universities. An online meeting was planned with an employee and researcher, who is doing research on long-term bank erosion in the whole Mekong River. He has also researched bed-level incision.
- **Local people**
  Local people are the people who live in the Mekong Delta. Their houses are located near the riverbanks and their livelihoods depend on the delta. They suffer the consequences of sand mining and other human activities in the delta. It is important to hear their side of the story, because they know the delta best and for them, the stakes are the highest. If the water ecology decreases, their livelihoods will suffer. Their houses are at risk too, as they are located near the riverbanks.

The full interviews can be found in Appendix B.

Ongoing solutions for the impact of sand mining activities

During the interviews, we asked the interviewees about implemented solutions and possible future solutions to mitigate the effect of human activities in the VMD.

Several solutions have been implemented. The Vietnamese government is trying to move people in the delta away from the riverbanks, to reduce the risk of a loss of property or lives due to bank erosion. However, people want to stay where they are since their lives are based on the river: they use the river to move around and their livelihoods depend on the river. It is better to prevent bank erosion. Additionally, the government built many hard structures to protect the riverbanks. This is only a short-term solution and it is expensive. The Vietnamese government also gives out a limited number of sand mining licenses, to limit the amount of sand extraction in the delta. Vessels with a license are only allowed to extract a certain amount of sand, but this cannot be checked. They often can extract more sand than they are allowed to. Also, during the night there is a lot of illegal sand mining activity. Police do monitor this, but there is often not enough of a police presence to check for illegal activity in the whole delta. Every province has their own rules and their authorities. Vessels move from one province to another, to make sure they are not caught. Some borders of provinces are located in the centre of the river, parallel to the riverbanks. A vessel can extract sand at one side of the river, in one of the provinces. If police from another province are patrolling the other side of the river, they will not do anything since it is not the province they work for.

Every interviewee mentioned that one future solution could be to find an alternative source of sand or an alternative building material for concrete. It is also important that countries in the Mekong Basin work together and share data. Sand mining is a problem in Cambodia and Lao PDR too, which also affects Vietnam. On a smaller scale, the provinces in Vietnam also need to work together and implement the same rules and regulations. The delta works as one big system, not as several individual systems.

In addition to implementing these solutions, it is important to know the sand volume that is entering the VMD, how much sand is leaving the delta and how much sand is being extracted from the delta. Therefore, Deltares (2023) established a sand budget of the VMD together with WWF-Vietnam, which can be a basis for sustainable management of sand mining and mitigation of the effects of climate change and anthropological activities in the Mekong Basin. The methodology to determine sand extraction rates is discussed in the following sections.

4.2 Sand extraction estimates for sand budget study

For the sand budget study of the VMD, Deltares (2023) estimated the extracted sand volume based on the number of detected vessels obtained with the model described in section 3.4. To do so, the following assumptions were made:

- The number of active barges with cranes for a specific day is assumed to be constant until the next satellite image is available.
- The production rate for a barge with a crane ranges between 300-600 m^3/day.
- Correction factor of 0.65.
- Size of a bucket: 1-1.5 m^3
- Extraction speed (seconds/bucket of sand): 90-60 seconds.
- Hours of extracting sand per day: 9-10 hours.

Correction factor: The dimensions of active barges with cranes are similar to the dimensions of two barges moored together. The limited resolution of Sentinel-2 imagery makes it difficult to distinguish active sand mining vessels from two moored vessels, as shown in Section 3.3. This results in false positives in the model. Therefore, Deltares (2023) estimated a correction factor by manual classification for the two cases based on high-resolution composite imagery. Of the manually classified cases, 65% were labelled as active barges with cranes and the other 35% were labelled as double-moored vessels. The correction factor was therefore chosen to be 0.65.

Sand extraction volume: Deltares (2023) estimated the annual extracted sand volumes for 2017 to 2022. They based the extraction rates on the assumed production rates of the barges with cranes (300 to 600 m^3/day), the number of filtered blobs and the correction factor. The results are shown in Figure 4.1.

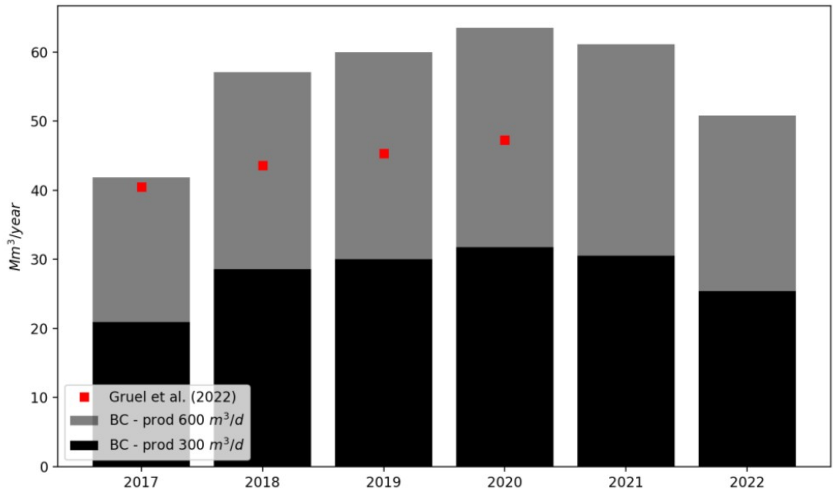

Figure 4.1: Annual extracted sand volume estimated by Deltares (2023) compared to Gruel et al. (2022) (Deltares, 2023).

4.3 Adjusted production rates of sand extraction

This section aims to adjust the production rates of sand extraction based on the rates in Section 4.2 to improve the accuracy. New information was obtained for the bucket size of the cranes and some assumptions have changed. The new assumptions are:

- Size of a bucket: 2.5-3 m^3
- Production rate based on Figure 4.2: 430 - 510 m^3/hour for a bucket size of 10 m^3

Production rate: We determined a new production rate based on the graph shown in Figure 4.2. The hoisting time is half the cycle time. The red line indicates a hoisting time of 30 seconds and the blue line represents a hoisting time of 45 seconds. The production rate for a bucket size of 10 m^3 can be read from the graph. The determined production rates are shown in Table 4.1.

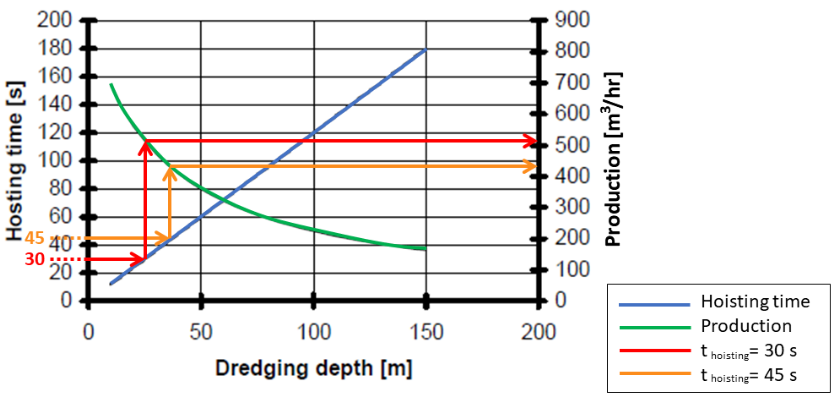

Figure 4.2: Production rate based on hoisting time (modified after Central Dredging Association, 2023).

Table 4.1: Production rate for a bucket size of 10 m^3, based on Figure 4.2

Hoisting time [s]	Production rate [m^3/hour]
30	510
45	430

To obtain the production rate for the bucket sizes of 2.5-3 m^3, we divided the production rates shown in Table 4.1 by 10 and multiplied them by 2.5 and 3 respectively. All the minimum and maximum values for each parameter are shown in Table 4.2 for a hoisting time of 30 seconds and for a hoisting time of 45 seconds. With these parameters, the production rates in m^3 are calculated per hour, per day, and per year for one barge with a crane.

Table 4.2: Minimum and maximum production rate for a hoisting time of 30 seconds and 45 seconds

	Hoisting time = 30 s		Hoisting time = 45 s	
	Mininum	Maximum	Mininum	Maximum
Bucket volume [m^3]	2.5	3	2.5	3
Working hours per day	9	10	9	10
No. of mining days/month	24	30	24	30
No. of mining days/year	288	365	288	365
Production rate [m^3/hour]	127.5	153	107.5	129
Production rate [m^3/day]	1147.5	1530	967.5	1290
Yearly extracted volume [m^3/year]	330,480	558,450	278,640	470,850

4.4 Sand extraction estimates based on a deep learning model

To obtain sand mining estimates for the entire VMD, the model needs to be upscaled. The model is a vessel classification model. It is not able to detect vessels, but it can classify vessels once they are detected. The vessel detection model that Deltares (2023) developed for the sand budget study works well to detect blobs on the water's surface. This method of detecting vessels can be applied to other satellite data such as PlanetScope, to first detect objects on the water's surface. The detected blobs can then be classified with a classification model as described in Chapter 3.

The model that we developed only distinguishes barges with cranes from other vessels. However, there are more vessel types that extract sand in the VMD, such as pump dredgers and smaller illegal vessels. The sand mining estimates will be underestimated if they are based solely on the barges with cranes. Therefore, a vessel detection and classification model should consider all other vessel types that extract sand.

More high-resolution satellite data is required to upscale the model to obtain estimates for the whole VMD. The satellite data needs to cover all river branches in the VMD. To gain better insight into the sand budget of the VMD and to get more accurate estimates, data is required for a larger time frame and as frequently as possible. PlanetScope data is available from June 2016 and there are daily images. Therefore, in the future, it would be possible to obtain sand mining estimates for 2017-now and for the last six months of 2016. Even though the images are available near-daily, there will not be a useful image for every day due to cloud coverage. For both SkySat and ICEYE images, there is no historical satellite data available for the VMD. Therefore, it is not possible to obtain sand mining estimates for the past with these data sets. However, the spatial resolution of both data sets is sufficient for accurate classification of vessels in the VMD, as shown in Chapter 3. To use the data sets for future sand mining estimates, daily taskings need to be conducted.

There are no daily images available for optical satellite data, mainly due to the high cloud cover in the VMD. Therefore, the number of vessels is assumed to be constant until the next available image. This brings along a higher uncertainty in the sand mining estimates since vessels move around to other locations. To be able to take into account both nighttime sand mining activity and also get rid of the effect of clouds, SAR images can be used. There are two data sets that were considered in Section 3.3. The first was Sentinel-1 with a spatial resolution of 10 m and a temporal resolution of 12 days. The spatial resolution is not high enough to distinguish vessels and due to the low temporal resolution, the number of vessels should also be assumed to stay constant for 12 days. However, the data is freely available. The other SAR data set that is considered is ICEYE which has a resolution of <1 m and daily images. In Section 3.3, it was shown that the spatial resolution is sufficient to detect vessels and distinguish them by geometry and size. The data is only available on-demand and there is no historical data available for the VMD. It is not possible to estimate sand extraction rates for the past. However, it shows a large potential for applying the model with high accuracy in the future.

We also need to validate the model and determine a correction factor for the detected and classified vessels. This correction factor takes into account false positives and false negatives. The most reliable way to validate the model is to compare the results of the model to field observations. Pictures should be taken at several sand mining locations and for several days. This could be done from a boat on the river, from the riverbanks, or with a drone. The images should be taken at moments of the overpass of the satellites that the model is based on. The model should be run for the dates that the pictures are taken. The results of the model can then be compared to the field observations. The correction factor can be based on the ratio of the number of observed sand mining vessels and the number of detected sand mining vessels.

For the sand budget study, Deltares (2023) divided the area of interest in the VMD into 182 tiles of 256 x 256 pixels. The area of interest consists of all the river branches in the VMD. With a 10 m spatial resolution, this results in tiles of 2,560 x 2,560 m^2, or 2.56 x 2.56 km^2. The total area of all the tiles is 1,193 km^2. In the best-case scenario, there is a daily usable image for every tile. In this case, the area of the available satellite images is 435,356 km^2 each year.

A research plan needs to be purchased to obtain a larger amount of PlanetScope data. With the research plan, all the PlanetScope and RapidEye archives can be accessed. The PlanetScope archive dates back to 2016 with near-daily images. A total of 30 million km^2 of images can be downloaded with the plan and a maximum of 25 people can use it. The total amount of satellite images that are needed to obtain sand mining estimates for 2016-2023 is 3.5 million km^2, if there are daily images available. However, this is not the case due to the high cloud cover percentage in the VMD. Either way, the plan provides a sufficient amount of data. The plan costs $13,500.

We calculated the amount of data that is needed for ICEYE and PlanetScope images for one day and one year based on the TIF files from both data sets. The size of the different ICEYE products spot (0.5 m resolution) and SLEA (1 m resolution) is both 9040 kb/km^2, so the total amount of data is also the same for the two products. The total amount of ICEYE data of one product for one day is 10.78 GB and for a year is $3.94 * 10^3$ GB, assuming that there are images available for every day. The ICEYE images are not subject to cloud cover or nighttime, so there will be more images available than for PlanetScope data. For Planetscope, the size of the data is smaller with an average of 521 kb/km^2. The average size is 0.62 GB for one day and $0.23 * 10^3$ GB for a year, if there are images available for every day of the year.

In conclusion, the similar method that Deltares (2023) used to obtain sand mining estimates can also be applied to a vessel detection and classification model based on machine learning. Some changes need to be made. First of all, the new production rate that was determined in this study should be applied. Furthermore, sand mining estimates should be based on all vessels that extract sand, and not only on barges with cranes. This should be implemented in the machine learning model that was used. Lastly, a new correction factor should be applied, that is based on field observations, and an analysis of vessels in satellite images. For example, someone can take pictures of vessels in the delta at the time of a satellite overpass and compare them. Another method is to install a camera in the VMD at a location that is subject to sand mining. The footage of the camera can then be compared to satellite images and the results of the vessel detection and classification model. A general method to obtain sand mining estimates, based on the method of Deltares (2023) is:

1. Quantify the number of vessels that extract sand from the delta. Take into account all vessels, such as barges with cranes and dredgers,

2. Determine the daily production rate of the sand mining vessels,
3. Determine a correction factor, to take into account false positives. The correction factor can be based on a combination of field observations, and an analysis of vessels in satellite images. A visualisation of the detected and classified images can be analysed to also consider when determining a correction factor. The advantage of satellite data with a resolution of 3 metres or higher, is that in most cases it is possible to manually confirm the prediction of the model.
4. Estimate the sand extraction rate by multiplying the number of sand mining vessels with their production rates and the correction factor.

5 Discussion

This chapter discusses the assumptions that were made during the study and their effects on the research. First, the vessel classification model will be discussed, followed by a discussion of the sand extraction estimates. The study is put in a wider context and compared to previous research. At the end of the chapter, the implications of this study are stated.

Vessel classification model

The first part of this thesis aims to analyse what factors influence the performance of a vessel detection and classification system. Therefore, a classification system was built with a deep-learning model. The model was trained with a data set that was manually obtained by collecting satellite images of different vessel types in the Vietnamese Mekong Delta (VMD). The satellite data set chosen for this model is PlanetScope, which is an optical data set and has a spatial resolution of 3 metres. After downloading satellite images, the outlines of the vessels seen in the images were selected by a polygon and labelled as 'barge with crane' or 'other'. A third label was added for the model; 'background', which contained images of the water surface and the clouds in the satellite images. Both data availability and the labelling of vessels came with assumptions and challenges.

Studies conducted by Gruel et al. (2022), Hackney et al. (2021), and Deltares (2023) also used satellite data to detect and classify sand mining vessels in the VMD. The model in this study only classifies vessels and does not detect them. The vessel detection based on a threshold method developed by Deltares (2023) worked well, but the vessel classification based on 10-metre resolution satellite data in previous studies was not reliable. Therefore, we chose to focus on vessel classification once the vessels have been detected. Hackney et al. (2021) also used PlanetScope data for their study. However, they used monthly composite images, which are different to the near-daily images that were used for this study. The monthly composite images are mosaics that consist of several images of different days in a month that are put together to create a cloudless image and there is only one image a month. The near-daily images that were used for this study are instantaneous images that represent a certain moment on a certain day. Due to the high cloud cover in the VMD, not all images are usable for the detection of vessels. There are images available for at least a few days a month, so there is still a larger amount of usable instantaneous images available than the monthly composite images.

Gruel et al. (2022) used Sentinel-1 satellite data and Deltares (2023) used Sentinel-2 data, which are both open source and thus freely available. The images for both data sets have a 10-metre spatial resolution, which is lower than the 3-metre resolution of PlanetScope data. In some cases in this study, it was hard to distinguish barges with cranes from other groups of vessels in the PlanetScope images. There were two main reasons for this: the spatial resolution of the images was not high enough, or there was some kind of distortion in the images that caused other colours or flares. We discarded some images that experienced the latter, to minimise mistakes in labelling the vessels. There is still a possibility that some vessels are labelled incorrectly due to the resolution, so human error should be taken into account. However, the labelling was done very carefully and the images were assessed after the labelling. Therefore, the chance that an image is labelled incorrectly is small. The visualisation of the testing results shows that the labelling is done mostly correctly and that the model works well. It does show that a 3-metre resolution is on the edge of the minimum resolution that satellite images should have, and therefore a 10-metre resolution does not seem sufficient to classify sand mining vessels in the VMD. For this study, the 3-metre resolution was sufficient in most cases and therefore the results of the model are barely affected by this. The Sentinel-2 data is an optical satellite data set, and Deltares (2023) used four spectral bands: red, green, blue, and near-infrared (NIR). PlanetScope images contain the same spectral bands. Sentinel-1 is a SAR data set, which is not subject to clouds or daylight. Gruel et al. (2022) could use Sentinel-1 images for any moment of the day and for every weather condition, which is an advantage when considering the high cloud cover in the VMD, especially during the rainy season. However, SAR images only have one spectral band and contain less spectral information than optical images.

We developed the vessel classification model based on a deep-learning algorithm. A similar method has not been used before for the detection or classification of sand mining vessels in the VMD. A machine-learning model needs to be trained with a large data set. There was no data set yet, so we manually created a data set for this study. The input data set needs to be large, so the model can be trained well with a large number of images for each class. However, there was a limited amount of data available for downloading since PlanetScope is only available on-demand. For this thesis, the free 'Education and Research program' was used. This program has a maximum of 5000 km^2 a month. If one wants more data, it needs to be purchased. This is in contrast with the Sentinel data sets that Deltares (2023) and Gruel et al. (2022) used for their studies. However, as stated before, this data has a much lower spatial resolution for which it is impossible to distinguish vessel types from each other. It is therefore not possible to manually label the vessels to create a training and testing data set for a machine-learning model.

We increased the size of the data set by augmenting images with barges with cranes (class 0). The augmentation was done in three ways by horizontal and vertical flipping of the images, and by rotating the images by 90 degrees. By augmenting the images, for every original image of 'barge with crane', there are three augmented images that are similar to the original image. This can result in overfitting of the model. Therefore, the testing data set consisted of 51 images that were independent of the augmented images. The testing is more reliable with an independent testing data set, and the overall accuracy of the model was 0.85. Despite the small amount of data, the model shows good results with the available data that was used. This shows great potential for a model that is trained with more data and it shows that this method is well-chosen for the objective of this study.

The advantage of a machine-learning based classification model is that more features of the detected vessels are taken into account compared to the studies of Deltares (2023) and Gruel et al. (2022). Where the vessel classification in the other studies is only based on the geometric features of the vessels, the model in this study takes into account shape, size, and colour. This is an improvement compared to the other studies, since an analysis of the sand mining vessels in Section 3.2 showed that barges with cranes with barges for transport moored next to them have a distinguishable shape compared to other vessels.

Sand mining estimates

The second part of this thesis describes how a vessel detection and classification model can be used to obtain sand mining extraction rates. The model that we developed for this study only distinguishes barges with cranes from other vessels. Therefore, if the sand mining estimates are determined based on this model, they are only based on the sand extraction by barges with cranes. This is similar to the method that Deltares (2023) used, they detected barges with cranes to obtain sand mining estimates for the sand budget study of the VMD that they conducted. In contradiction to detecting sand mining vessels that extract sand, Hackney et al. (2021) only considered blue boats that transport sand. The movement of the blue boats is unknown, so in their study, it is assumed that the vessels are filled with sand once a day. However, it is not known whether this is the case. A methodology that is based on the detection of barges with cranes considers the direct source of the sand extraction in the delta. However, they are not the only vessels that extract sand from the delta. There are also pump dredgers, which are not considered in this study. As a result, sand extraction rates that are solely based on barges with cranes will be underestimated. It is hard to detect and classify dredgers with satellite data since they look similar to normal vessels from a top view, unlike barges with cranes. Therefore, they were not in the scope of this study, which also holds for the other studies that were conducted. This study does show that vessels in the VMD can be classified with the use of machine learning, which is promising for the classification of more vessel types in the future.

In addition, there is also illegal sand mining activity in the VMD. In theory, both legal and illegal activities are captured by this approach, in contradiction to sand mining estimates that are solely based on sand mining licenses like Eslami et al. (2019) did. The barges with cranes have licenses but the sand volume they extract cannot be monitored, but the detection of barges with cranes with satellite images can change this. Barges with cranes partake in illegal sand mining, since they may extract a larger volume of sand from the riverbed than they are allowed to according to their licenses. However, not all illegal activity has been covered in this study for several reasons. First, most of the illegal activity takes place during the night. The classification model in this study is based on optical satellite data, which means there are no images available during the night. Secondly, the illegal vessels are smaller boats and can often be disguised, e.g. as a fishing boat. It was out of the scope of this study to analyse the illegal boats and consider them for the vessel classification model.

The advantage of using satellite data to obtain sand mining estimates compared to field investigations is that it can be done remotely on a large scale, it is transboundary, and it is less time-consuming. Conducting surveys in a mega-delta like the VMD takes time and it is preferable to take several surveys throughout the year to compare sand mining activities during different seasons. The use of satellite data can create an overview of what is happening in the entire delta in a relatively short amount of time. However, field investigations are necessary to validate a model, so the delta should still be visited. We visited the delta to some extent, but it was not possible to validate the model based on field observations. The model is validated with a testing data set. We did manage to analyse sand mining vessels and speak to several people throughout Vietnam about sand mining, hydropower dams, and erosion in the VMD. However, it was not in the scope of this study to validate the model with an extensive field investigation.

The PlanetScope data that we used for this study is optical. There are no daily images available, mainly due to the high cloud cover in the VMD. Therefore, the number of vessels is assumed to be constant until the next available images, similar to the studies of Hackney et al. (2021) and Deltares (2023). This brings along a higher uncertainty in the sand mining estimates since vessels move around to other locations. To be able to take into account both nighttime sand mining activity and also eliminate the effect of clouds, SAR images can be used. An analysis of the freely available Sentinel-1 satellite data that Gruel et al. (2022) used, showed that the 10-metre spatial resolution is too low to distinguish vessel types. The temporal resolution of this data set is only 12 days, which means that for this data set the vessels should be assumed to stay constant for 12 days. The on-demand ICEYE data set has a resolution of <1 metre and daily images. In Section 3.3, we showed that the spatial resolution is sufficient to detect vessels and distinguish them by geometry and size. The data is only available on-demand and there is no historical data available for the VMD. It is not possible to estimate sand extraction rates for the past. However, it shows a large potential for applying the model with high accuracy in the future.

Implications for stakeholders

This study has shown that it is possible to detect and classify sand mining vessels in the VMD based on satellite images. The model that was developed for this study, can be applied to get a general overview of sand mining at certain locations and time spans. The examined approach is an inspiration and a step in a long process for national and international scientists and technicians to develop a full-scale sand extraction estimation toolbox. This toolbox is essential to support local stakeholders to better manage the declining sand resources in the VMD at different scales (provincial or delta-wide). The outcome of the model is still too rough to apply on a provincial level. Management of sand mining in the VMD could be based on the outcome of a vessel detection model, for example by analysing the locations of detected sand mining vessels. The model is not meant to monitor all individual vessels but to support planning, strategy, and policies considering sand mining. It should be stated that erosion will travel upstream and downstream of sand mining locations, which means that long-term sand mining will affect an entire reach of a river and not just the locations of the sand extraction.

Another implication of a model based on satellite images is that the model is transboundary. The area of vessel detection is not limited to just the VMD. There are other places in Vietnam where sand mining occurs, such as the Red River in the north of the country. Sand mining also occurs in other countries in the Lower Mekong Basin, which also affects the sand supply to the VMD. Given that sand mining vessels at other locations have similar characteristics on satellite images, the model can be applied to those locations too once it is fully developed.

6 Conclusion and recommendations

A method to determine sand extraction rates with higher accuracy than existing methods based on satellite data was developed for this study. The method consists of a vessel classification system made with a machine-learning algorithm based on satellite images. Based on assumptions, a methodology is described to translate the results of the model to sand mining extraction rates. This chapter contains the conclusion and recommendations of this study. First, the two research questions will be answered in the conclusion. Then, recommendations for future research are given.

6.1 Conclusion

We developed a vessel classification model to detect sand mining vessels in the Vietnamese Mekong Delta (VMD) based on satellite data. The model has been analysed with a testing data set and has not been applied to the entire VMD, and the number of sand mining vessels was not quantified. The aim of this study was to analyse the performance and accuracy of such a model. The number of sand mining vessels that could be detected with such a model can be translated into sand extraction rates with the following steps:

1. Quantify the number of sand mining vessels: barges with cranes and dredgers,
2. Determine the daily production rate of the sand mining vessels,
3. Determine a correction factor, to take into account false positives. The correction factor can be based on field observations.
4. Estimate the sand extraction rate by multiplying the number of sand mining vessels with their production rates and the correction factor.

In this study, sand extraction rates have not been quantified and compared to each other. The aim was to describe a methodology that can be applied to quantify sand extraction rates in the future.

The first research question to be answered is: *What factors determine the performance of a vessel classification system?*

There are several factors that were identified during this research to have an effect on the performance of the vessel classification model. All the factors lead back to the satellite data set, but are based on different characteristics of the data set.

Firstly, the spatial resolution of the satellite images is important for the performance of the model. The spatial resolution should be sufficient to distinguish vessel types from each other when labelling the vessels in the images. The PlanetScope data used for the development of the model in this study had a spatial resolution of 3 m. This was sufficient most of the time to distinguish barges with cranes from other vessels. However, sometimes it was impossible to distinguish the two from each other. This can cause mistakes in labelling the vessels, which decreases the reliability and performance of the model. Therefore, a spatial resolution of at least 3 m is needed for the development of a vessel classification model based on machine learning.

The second factor is the availability of the data. A large data set is necessary to train a machine learning model that is reliable and has a high performance. The PlanetScope data set that was used was only available to a certain extent and there was not enough data to train the model. A high temporal resolution has a positive effect on the performance since there are more images available throughout time.

Lastly, the input data of the model is what mainly determines the performance of the model. The input data is based on the acquired data set and depends on several factors: the amount of data for each class, the labelling of the data, and augmenting the data. The input data set should be balanced, so it does not train the model very well for only a part of the classes. All classes would be equally trained, to have a reliable model. The labelling of the data should be done very carefully, based on a prior analysis of the objects that have to be labelled. It should be taken into account that there may be an element of bias from the person or people selecting and labelling the data. When there is a small amount of data, it can be useful to augment this data to increase the number of images in a data set. However, too much augmenting of the data results in an overfitted model, which will perform low when tested with new data.

The second research question is: *How can the outcome of a vessel detection and classification system be translated to a sand mining estimate?*

First, the characteristics of vessels in the area of interest need to be determined. The characteristics should be linked to the activity of the vessel. The vessels that are involved in sand mining activities should be analysed. In the Vietnamese Mekong Delta, there are two activities related to sand mining: the extraction of sand, and the transportation of sand. The sand extraction is done by barges with cranes, dredgers, or illegal sand mining vessels. The vessels that are extracting the sand can be translated to sand extraction estimates. To do so, a vessel detection and classification model can be developed. The classification of the detected vessels is based on their characteristics. For this study, only barges with cranes are considered for sand extraction. It should be noted that it is assumed that most sand is being extracted by barges with cranes. However, it is not known to what extent barges with cranes contribute to the extraction of sand from the riverbed compared to other sand mining vessels.

The time scale for which the sand extraction estimates can be determined depends on the availability of satellite data. A satellite data set with a high temporal resolution is preferred, to be able to detect and classify vessels for more days. This will lead to more accurate sand mining estimates. Another aspect is how far the satellite data set goes back in time. The PlanetScope data set that was used to develop the model for this study, started in 2016. Therefore, no sand extraction rates can be determined before the start of the collection of PlanetScope images.

First, satellite images for several years and for the entire VMD should be obtained. The vessel detection and classification model should be applied to every image that is available. Optical images are subject to cloud cover, so not every image can be used. In this case, the number of detected sand mining vessels is assumed to stay constant until the next image is available. The yearly number of sand mining vessels should be obtained for the entire VMD. Once the vessels are detected and classified for each year with available satellite data, the sand extraction rates can be estimated.

6.2 Recommendations

The results of this study are promising, but this thesis is only a step in a much bigger process to be able to determine sand extraction rates for the VMD. This creates several possibilities for future research.

To start with, the testing and training data set for the model should be expanded. By obtaining more PlanetScope data and increasing the amount of images of barges with cranes, the model can be trained with more data. The results can be analysed, to see how the performance of the model changes and to see whether the accuracy of the model increases. It is recommended to have several people label the images, to eliminate the possible biases. It is also recommended to apply a correction for the labelling of the images. One option to do this is with an evaluation of the labelled images, which is done by carefully examining the images and their labels. If an image is labelled incorrect, the given label should be updated if possible. If it is not possible to tell if the label is correct, the image should be discarded.

The next step is to upscale the model so it can be applied to the entire VMD. The model is made for the classification of vessels, but first, the vessels need to be detected. The vessel detention system that was developed based on the Otsu threshold method for the sand budget study, worked very well for detecting the vessels. This method shows great potential for the detection of vessels with high-resolution satellite images. First, a threshold method can be applied to detect vessels in PlanetScope satellite images. Then, the detected vessels can be classified based on the machine-learning vessel classification model.

In order to upscale the model to the entire VMD and to obtain results for several years, a large amount of satellite data is needed. The satellite data should be collected over several years and over the entire area of interest. An option is to buy PlanetScope satellite data, that can be used to obtain sand extraction rates from 2016.

The model should be validated in order to assess its performance. One way to validate the model is to compare the results from the model to field observations. This can be done by visiting the VMD and observing vessels at the time a satellite overpass takes place. The field observations can be compared to the satellite images. This could also be done by installing a camera at a location in the VMD, that takes photos and/or videos of the river. This allows for remote use of the field data, as well as allowing observations over a longer period. The results of comparing field observations to the outcome of the model, should also be used to determine a correction factor for the model.

In this study, the vessel classification system only focused on barges with cranes for the extraction of sand. However, there are other vessels that should be taken into account as well. It is important to be able to detect and classify other vessels that are extracting sand from the VMD. These are mainly dredgers and illegal sand mining vessels. The characteristics of both vessel types should be analysed, which can be done by field observations. Important characteristics are size (width, length), geometry, and colour.

To develop the model for this thesis, PlanetScope data was used. However, there are many other satellite data sets with other characteristics. Two options should be explored in the future: a model with a high-resolution SAR data set, and a model with a high-resolution optical data set. The ICEYE images that were obtained with a tasking in the VMD show great potential for a vessel detection and classification system. The features of barges with cranes are distinguishable for a spatial resolution of 1 m. To realise a model based on these images, much more ICEYE data needs to be available to create a model. There is no historical data, but it is highly recommended to obtain new ICEYE images to develop a model based on the newly obtained images. The main advantage of SAR images is that they can be used at any moment of the day and independent of weather conditions. Since most illegal sand mining activity takes place during the night, this creates a possibility to also detect illegal sand mining vessels. By using high-resolution optical data, the labelling of vessels is easier and the model will be more reliable.

References

Abadi, M., Barham, P., Chen, J., Chen, Z., Davis, A., Dean, J. M., Devin, M., Ghemawat, S., Irving, G., Isard, M., Kudlur, M., Levenberg, J., Monga, R., Moore, S., Murray, D. G., Steiner, B., Tucker, P. A., Vasudevan, V., Warden, P., . . . Zheng, X. (2016). TensorFlow: a system for large-scale machine learning. *Operating Systems Design and Implementation*, 265–283. https://doi.org/10.5555/3026877.3026899

Anthony, E. J., Brunier, G., Besset, M., Goichot, M., Dussouillez, P., & Nguyen, V. T. (2015). Linking rapid erosion of the Mekong River delta to human activities. *Scientific Reports*, *5*. https://doi.org/10.1038/srep14745

Beiser, V. (2021). A Closer Look Into a River That Feeds 60 Million People. https://www.nationalgeographic.com/science/article/vietnam-mekong-illegal-sand-mining

Beiser, V. (2022). Why the world is running out of sand. https://www.bbc.com/future/article/20191108-why-the-world-is-running-out-of-sand

Bravard, J.-P., Goichot, M., & Gaillot, S. (2013). Geography of Sand and Gravel Mining in the Lower Mekong River. *EchoGéo*, (26). https://doi.org/10.4000/echogeo.13659

Central Dredging Association. (2023). *Grab or clamshell dredger*.

Copernicus. (2023a). Thematic Areas and Services - Sentinel 1 - Sentinel Online. https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-1/thematic-areas

Copernicus. (2023b). Thematic Areas and Services - Sentinel 2 - Sentinel Online. https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-2/thematic-areas-and-services

Coroneo, J. (2022). In Vietnam's Mekong Delta, sand mining means lost homes and fortunes. https://www.thethirdpole.net/en/livelihoods/in-vietnam-mekong-delta-sand-mining-means-lost-homes-and-fortunes/

Deltares. (2023). *Sand budget of the Mekong Delta* (tech. rep. No. 11206927).

Detektia. (2023). SAR Synthetic-Aperture Radar. https://detektia.com/en/sar-synthetic-aperture-radar/

Eslami, S., Hoekstra, P., Trung, N. N., Kantoush, S. A., Van Binh, D., Dung, D., DO, Quang, T. T., & Van Der Vegt, M. (2019). Tidal amplification and salt intrusion in the Mekong Delta driven by anthropogenic sediment starvation. *Scientific Reports*, *9*(1). https://doi.org/10.1038/s41598-019-55018-9

European Commission, 1.-2. (2023). Copernicus Emergency Management Service - Mapping. https://emergency.copernicus.eu/mapping/#zoom=2&lat=25.89862&lon=33.82273&layers=0BT00

Gruel, C.-R., Park, E. J., Switzer, A. D., Kumar, S., Ho, H. T., Kantoush, S. A., Van Binh, D., & Feng, L. (2022). New systematically measured sand mining budget for the Mekong Delta reveals rising trends and significant volume underestimations. *International journal of applied earth observation and geoinformation*, *108*, 102736. https://doi.org/10.1016/j.jag.2022.102736

Hackney, C., Darby, S. E., Parsons, D. R., Leyland, J., Best, J. L., Aalto, R., Nicholas, A., & Houseago, R. C. (2020). River bank instability from unsustainable sand mining in the lower Mekong River. *Nature sustainability*, *3*(3), 217–225. https://doi.org/10.1038/s41893-019-0455-3

Hackney, C., Vasilopoulos, G., Heng, S., Darbari, V., Walker, S., & Parsons, D. R. (2021). Sand mining far outpaces natural supply in a large alluvial river. *Earth surface dynamics*, *9*(5), 1323–1334. https://doi.org/10.5194/esurf-9-1323-2021

Jordan, C., Tiede, J., Lojek, O., Visscher, J., Apel, H., Nguyen, H. Q., Quang, C. N. X., & Schlurmann, T. (2019). Sand mining in the Mekong Delta revisited - current scales of local sediment deficits. *Scientific Reports*, *9*. https://doi.org/10.1038/s41598-019-53804-z

Kanjir, U., Greidanus, H., & Oštir, K. (2018). Vessel detection and classification from spaceborne optical images: A literature survey. *Remote Sensing of Environment*, *207*, 1–26. https://doi.org/10.1016/j.rse.2017.12.033

Khanh, H. (2023). Erosion eats up Mekong Delta houses. https://e.vnexpress.net/news/news/environment/erosion-eats-up-mekong-delta-houses-4609601.html

Koehnken, L. (2014). *Discharge Sediment Monitoring Project (DSMP) 2009 - 2013 Summary & analysis of Results. Final report* (tech. rep.). Mekong River Commission. https://portal.mrcmekong.org/assets/v1/documents/Report-workshop/Technical-Report_DSMP/DSMP-Report-2009_13-Final-Report-July-2014.pdf

Koehnken, L., & Rintoul, M. (2018). *Impacts of sand mining on ecosystem structure, process & biodiversity in rivers* (tech. rep. ISBN: 978-2-940529-88-9). WWF.

Koehnken, L., Rintoul, M. S., Goichot, M., Tickner, D., Loftus, A.-C., & Acreman, M. (2020). Impacts of riverine sand mining on freshwater ecosystems: A review of the scientific evidence and guidance for future research. *River Research and Applications*, *36*(3), 362–370. https://doi.org/10.1002/rra.3586

Kondolf, G. (1997). PROFILE: Hungry Water: Effects of dams and gravel mining on river channels. *Environmental Management*, *21*(4), 533–551. https://doi.org/10.1007/s002679900048

Kuenzer, C., Guo, H., Huth, J., Leinenkugel, P., Li, X., & Dech, S. (2013). Flood mapping and flood dynamics of the Mekong Delta: ENVISAT-ASAR-WSM based time Series analyses. *Remote Sensing*, *5*(2), 687–715. https://doi.org/10.3390/rs5020687

Kummu, M., & Sarkkula, J. (2008). Impact of the Mekong River flow alteration on the Tonle SAP flood pulse. *AMBIO: A Journal of the Human Environment*, *37*(3), 185–192. https://doi.org/10.1579/0044-7447(2008)37

Kummu, M., Tes, S., Yin, S., Adamson, P., Józsa, J., Koponen, J., Richey, J. E., & Sarkkula, J. (2013). Water balance analysis for the Tonle Sap Lake-floodplain system. *Hydrological Processes*, *28*(4), 1722–1733. https://doi.org/10.1002/hyp.9718

Leinenkugel, P., Kuenzer, C., & Dech, S. (2013). Comparison and enhancement of MODIS cloud mask products for Southeast Asia. *International Journal of Remote Sensing*, *34*(8), 2730–2748. https://doi.org/10.1080/01431161.2012.750037

Mattyus, G. (2013). NEAR REAL-TIME AUTOMATIC MARINE VESSEL DETECTION ON OPTICAL SATELLITE IMAGES. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *XL-1/W1*, 233–237. https://doi.org/10.5194/isprsarchives-xl-1-w1-233-2013

Mekong River Commission. (2011). *Assessment of Basin-wide Development Scenarios* (tech. rep.).

Mekong River Commission. (2019). *State of the Basin Report 2018* (tech. rep.).

Mekong River Commission. (2023). Hydropower. https://www.mrcmekong.org/our-work/topics/hydropower/

Minderhoud, P. S. J., Coumou, L., Erkens, G., Middelkoop, H., & Stouthamer, E. (2019). Mekong delta much lower than previously assumed in sea-level rise impact assessments. *Nature Communications*, *10*(1). https://doi.org/10.1038/s41467-019-11602-1

Minderhoud, P. S. J., Middelkoop, H., Erkens, G., & Stouthamer, E. (2020). Groundwater extraction may drown mega-delta: projections of extraction-induced subsidence and elevation of the Mekong delta for the 21st century. *Environmental research communications*, *2*(1), 011005. https://doi.org/10.1088/2515-7620/ab5e21

Nguyen, V. L., Ta, T. K. O., & Tateishi, M. (2000). Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam. *Journal of Asian Earth Sciences*, *18*(4), 427–439. https://doi.org/10.1016/s1367-9120(99)00076-0

Ouchi, K. (2016). Current status on vessel detection and classification by synthetic aperture radar for maritime security and safety.

Padmalal, D., & Maya, K. (2014). *Impacts of river sand mining*. https://doi.org/10.1007/978-94-017-9144-1\{_}4

Roney, T. (2020). Mekong dams destroy Tonle Sap Lake. https://www.thethirdpole.net/en/regional-cooperation/mekong-dams-destroy-tonle-sap-lake/

Rovira, A., Batalla, R. J., & Sala, M. (2005). Response of a river sediment budget after historical gravel mining (the lower Tordera, NE Spain). *River Research and Applications*, *21*(7), 829–847. https://doi.org/10.1002/rra.885

Sloff, C., & Mosselman. (2021). *Managing river erosion in the Vietnamese Mekong Delta* (tech. rep.).

Ta, T. K. O., Nguyen, V. L., Tateishi, M., Kobayashi, I., Tanabe, S., & Saito, Y. (2002). Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. *Quaternary Science Reviews*, *21*(16-17), 1807–1819. https://doi.org/10.1016/s0277-3791(02)00007-0

Tan, M., & Le, Q. V. (2021). EfficientNetV2: Smaller models and faster training. *arXiv (Cornell University)*. https://doi.org/10.48550/arxiv.2104.00298

WWF. (2023). Resilient Asian Deltas. https://wwf.panda.org/discover/our_focus/freshwater_practice/freshwater_inititiaves/resilient_asian_deltas_initiative/

Yang, X., Zhang, Q., Dong, Q., Han, Z., Luo, X., & Wei, D. (2023). Ship instance segmentation based on rotated bounding boxes for SAR images. *Remote Sensing*, *15*(5), 1324. https://doi.org/10.3390/rs15051324

A Field research Vietnam

As a part of this project, Vietnam was visited to collect data on sand mining activities in the Vietnamese Mekong Delta by interviewing people and going on site visits. Two locations in the delta were visited: Vinh Long and Can Tho, shown in Figure 2.1. Vinh Long is located at the Tien branch of the Vietnamese Mekong Delta VMD. Can Tho is located South of Vinh Long, along the Bassac River branch.

The objectives of the visit to Vietnam were:

- To gain more insight into sand mining activities in the Mekong Delta,
- To analyse areas of the Mekong Delta and sand mining sites,
- To obtain data on sand mining activities and sand mining vessels, as well as certain consequences of sand mining, such as bank erosion. Data can be photos of vessels, sand mining sites, locations of bank erosion, other information on regulations, or the number of vessels at sand mining locations.
- To analyse locations where bank erosion occurs and take photos.
- To get a better understanding of the consequences of sand mining.
- To familiarise with the social and environmental context in which sand mining occurs.

The following activities were carried out during the visit to Vietnam:

- Interviews with different stakeholders,
- Go to sites where river bank erosion occurred,
- Visit and analyse sand mining sites,
- Take notes on and pictures of sand mining vessels.

The stakeholders that are involved in the project, or affected by sand mining activities, who were met during the visit, are:

- **WWF: Mr. Anh Ha Huy and Ms. Phuong**
  The WWF set up the 'Resilient Asian Deltas Initiative'. *The vision of the initiative is that the long-term resilience of Asia's Delta system is secured through unprecedented political and financial investment in 'building with nature', which will protect and restore the natural river and coastal processes that replenish Deltas and will keep them - and the societies, economies and nature that depend on them - above the rising seas.* (WWF, 2023)
- **SIWRP: Nam Nguyen Trung**
  The SIWRP is a Vietnamese government agency under the Ministry of Agriculture and Rural Development that advises on all water-related issues, such as irrigation, erosion, and the construction of hydraulic structures.
- **Can Tho University: Dr. Vo Quoc Thanh**
  Can Tho is the largest city in the VMD. It has a population of 1 million with 54,000 students attending the university. As the university is located in the VMD, this is a study area for the students and professors at the university.
- **Thuy Loi University: Truong Hong Son**
  Thuy Loi University is located in Hanoi. It has a faculty of Civil Engineering and a water resources engineering department. A meeting was scheduled with an employee and researcher, who works for the hydraulic engineering department of the university. He researches the erosion in the Mekong River and works together with both the WWF-Vietnam and the government.

- **Hanoi University of Natural Resources and Environment (HUNRE): Dr. Thuc Anh**
  A meeting was scheduled with a professor, who has done a lot of research on sand mining in the Red River in Northern Vietnam. Her knowledge and insights on sand mining are also useful for the VMD.
- **Vietnamese-German University: Doan van Binh**
  The Vietnamese-German University is located near Ho Chi Minh City and is a collaboration between Vietnam and several German universities. An online meeting was planned with an employee and researcher, who is doing research on long-term bank erosion in the whole Mekong River. He has also researched bed-level incision.
- **Local people**
  Local people are the people who live in the Mekong Delta. Their houses are located near the river banks and their livelihoods depend on the delta. They suffer the consequences of sand mining and other human activities in the delta. It is important to hear their side of the story, because they know the delta best and for them, the stakes are the highest. If the water ecology decreases, their livelihoods will suffer. Their houses are at risk too, as they are located near the river banks.

B Interviews Vietnam

This appendix contains the full interviews that were carried out in Vietnam. The stakeholders that were interviewed are:

- WWF (Can Tho and HCMC)
- Can Tho University
- Southern Institute of Water Resources Planning (SIWRP)
- Hanoi University of Natural Resources and Environment (Hanoi University of Natural Resources and Environment (HUNRE))
- Vietnamese University
- Thuyloi University (Hanoi)

B.1 Interview SIWRP

Date: 13-06-2023, 10:00
Location: Ho Chi Minh City, Vietnam
Interviewee: Nam Nguyen Trung

- **What is your role at SIWRP?**
  Nam works with irrigation and planning in the Vietnamese Mekong Delta VMD. SIWRP supports the government with water management and the planning of hydraulic-related planning in the VMD. He got a Master's degree in water management in Ho Chi Minh City. He says that his focus is agriculture, but sand mining is linked to this too. Therefore, his work is not directly related to sand mining.
- **What previous research did you do on the Mekong Delta and sand mining?**
  None, as this is not his focus in his job.
- **When did sand mining in the Mekong Delta start?**
  He does not know.
- **What are the main problems with and/or consequences of sand mining?**
  The main consequence of sand mining is bank erosion. However, this is also a natural process that always occurs in rivers and deltas, so it is hard to say to what extent it is linked to sand mining.
- **When did these problems start?**
  He does not know.
- **Is there something like sustainable sand mining?**
  Maybe, if you try to determine how much sand is being extracted and how much sand there still is, you can use this information to make it more sustainable. However, sand is valuable and people need to make a living. They extract sand to be able to afford their lives and support their families. So it is hard to decrease the amount of sand mining, or even stop it completely.
- **How does sand mining influence local people who live in the Mekong Delta?**
  Houses disappear due to bank erosion.
- **What solutions have been implemented to prevent the problems or to decrease the impact of sand mining?**
  The government and local authorities want to move people away from the riverbanks, to decrease the risk of their houses collapsing into the river. However, the people want to stay where they are, close to the river. Their lives are based on the river and it is easier for them to live on the river banks: they use the river to move around and their livelihoods depend on the river.

- **To what extent has this worked?**
  This has not really worked, because people do not want to move.
- **What do you think can be possible solutions in the future?**
  - There is not just one solution, but a combination of solutions. There are hard structures to protect the river banks. He was a big fan of these because they are effective. He even mentioned protecting the entire delta with dykes and other structures, like the Netherlands has done in the past.
  - Accept that the banks are eroding, but try to manage it. Erosion is a natural process that always happens in rivers. There is no stopping it at this point, so it is best to accept and manage it. A tool to predict bank erosion could also be very helpful.
  - Authorities need to work together and make the same set of rules that apply to the entire delta. At the moment, the authorities of different provinces do not work together. They have their own rules and regulations for sand mining, but the Mekong Delta works as one big system: not as small systems divided at random locations because of the borders of provinces.
  - Mekong River Commission: they encourage the countries in the Mekong Basin to share data and work together, but in reality, this barely has any effect. Countries still mostly work for themselves and do not work together.
  - Get sand from other sources. The Vietnamese government is looking into the possibility of extracting sand from coastal areas. I asked if that would not just move the problem instead of solving it. He said it might just move the problem, but that they are looking at locations to extract sand where the impact will be minimal.
  - To find an alternative for sand/concrete: Vietnam wants to develop the country a lot economically, for which they are building new motorways, other roads and buildings. Therefore, the demand for sand is high, which is used to make concrete to realise these plans. Part of the solution is to decrease the demand for sand, which right now is only possible by finding an alternative building material.
- **What are the challenges the Mekong Delta faces (in general)?**
  Hydropower dams in the upstream part of the Mekong basin. This is a big problem because it traps the sand, which is also a big cause of erosion. This is managed by other countries, so this is something they have to accept.
- **Do vessels have AIS detection and is it possible to identify vessels with this?**
  Legal vessels have GPS, so they can be tracked. However, most illegal sand mining activities happen during the night. The illegal vessels do not have any GPS, so they cannot be tracked. The police do try to stop it, they will take away the vessels from illegal sand miners. The illegal part also makes this a very sensitive topic for many parties. Nam could talk about this because he is from Ho Chi Minh City, where he lives. He says it is harder to talk about this for people who live in the Mekong Delta.

B.2 Interview Vietnamese-German University (VGU)

Date: 15-06-2023, 14:00
Location: online
Interviewee: Doan van Binh

There is much more bank erosion now than there was in the past. Binh is doing research on long-term bank erosion in the whole Mekong Delta. He uses satellite images and machine learning to try to predict future erosion. There is a website where past erosion, predicted erosion, and other information about the riverbanks in the Mekong Delta can be found. This website is based on surveys and information from local authorities.

Binh said it can add a lot of value to my project if I can also detect the smaller (illegal) sand mining vessels. This will result in much more accurate predictions of sand extraction rates.

Binh grew up near Vinh Long, at the Tien River. He said that erosion has been playing a big role in this area. As a kid, in the early morning (during low tide) Binh would go to the sandbank in the river and play football. Now, there is no bank to be seen anymore. A lot of erosion has occurred in the past 20 years.

He did research on riverbed incision in the last year. The conclusion of his research was that the main cause of the incision is the construction of hydropower dams upstream in the river, and the second cause was sand mining.

Most of the sand mining is happening in the Tien River because about 80% of the sediment from upstream flows in this branch of the river. The remaining sediment flows into the Bassac River, the other branch of the Mekong River.

Binh recommended going to Cao Lanh, a location upstream from Vinh Long where a lot of sand mining is going on. However, to get a good look at it, it is best to go by boat. He said to be careful and not to talk to any locals about it.

B.3 Interview Can Tho University and WWF Can Tho

Date: 16-06-2023, 14:00
Location: Can Tho University, Vietnam
Interviewee: Ms. Phuong (WWF) and Dr. Vo Quoc Thanh (Can Tho University)

- **What is your role at your organisation?**
  - Ms. Phuong: looks into nature-based solutions inland, so not near or in the waterways of the Mekong Delta. Her main focus is agriculture in the Mekong Delta.
  - Dr. Thanh: did his PhD in Delft, about sand transport in the Mekong River. He now works at Can Tho University.
- **When did sand mining in the Mekong Delta start?**
  It started about 40 years ago. However, the vessels were still small and it was not on such a large scale. Back in the day, the boats maybe had a capacity of 20 tonnes, whereas now they have a capacity of 300 tonnes.
- **What are the main problems with and/or consequences of sand mining?**
  There is a lot of bank erosion, but it is hard to directly link it to sand mining. They are looking into it, but it is a complicated topic. It (bank erosion) also happens at locations where no sand mining takes place. Of course, erosion can be caused by sand mining, but it is hard to link it.
- **What solutions have been implemented to prevent the problems or to decrease the impact of sand mining?**
  Hard structures, such as concrete walls, are built. This solution works on a small scale, but it will not solve the problem which is large scale. There are sand mining licenses. Vessels have to tell the authorities where they are extracting sand and how much sand they extracted. However, this is hard to check. They can extract more sand than they say. The authorities cannot check how much sand they actually take.
- **To what extent has this worked?**
  It does not work.
- **What do you think can be possible solutions in the future?**
  The main problem is that there is a high demand for sand in Vietnam. If you stop sand mining, the demand for sand is still high because it is needed for the construction of buildings and roads. The main solution would be to find an alternative source for sand or to find another material than concrete to build with. However, this is very hard. There are policies and you cannot just take any material and use it for construction.
- **Do the authorities check for legal activity?**
  Yes, but it is hard to do this. The boats are smaller and they do it mainly during the night. There are police to check on it, but not enough to track all the illegal activity. The illegal boats know where the police will check and will go somewhere else. The Mekong Delta is too large to constantly check the entire delta for illegal sand mining vessels.

- **What are the challenges the Mekong Delta faces (in general)?**
  Another challenge in the Mekong Delta is land subsidence, due to irrigation and consolidation of the soil.
- **Is the lack of sand in the delta also caused by the construction of hydropower dams?**
  The construction of dams upstream is not a big problem: there are many other sources of sand in the south of Lao PDR and Cambodia, that are located downstream of the dams. However, there is a dam construction planned at Kratie (Cambodia). They are worried that this will reduce the sediment supply and will cause problems for the Mekong Delta. But for now, the Mekong Delta is not affected by the construction of the current dams.
- **Where can I go to see sand mining activities?**
  Just upstream from Can Tho (about 10 km), there is a sand mining location at Con Son Island. It is a touristy island and easy to take a ferry from Can Tho to the island and walk around to observe the sand mining. This is the 'last' sand mining location in the Mekong: downstream from this location, there is no sand mining anymore. The sand there is too fine and it is mainly mud. Dr. Thanh said that it can be helpful to time one circle of a barge with a crane, from grabbing the sand to putting it on the vessel. This can improve the current sand mining estimations.
- **Comments about my research**
  While validating your model, keep in mind that there are no sand mining activities downstream of Can Tho. The model should not detect any sand mining vessels here, as this will be incorrect and result in inaccurate results. Also, it is better to focus on the barges with cranes, instead of the blue boats/ barges for transport. Blue boats are used to transport many different things in the Mekong Delta, not just sand. Even though they usually have a cover over them when they transport something else than sand, it still results in a big uncertainty in the estimations.
- **Questions to me about sand mining in the Netherlands**
  They asked me what building materials we use in the Netherlands, which are mainly concrete. They also mentioned that we do not have any sand mining in the rivers in the Netherlands (for 50 years), but we still take away sand from the coastal areas. So the Netherlands is doing the same to a certain extent.

B.4 Interview HUNRE

When: 20-06-2023, 10:00
Location: Hanoi, Vietnam
Interviewee: Dr. Thuc Anh

- **What is your role at HUNRE?**
  Dr. Thuc Anh actually does not work for HUNRE anymore but still supervises several PhD students there. She also works together with the government on different topics, such as sand mining, but also agriculture in Vietnam.
- **What previous research did you do on the Mekong Delta and sand mining?**
  Dr. Thuc Anh does not have a lot of knowledge of the Mekong Delta, but she did a lot of research on sand mining in the Red River in the North of Vietnam. She showed me reports on her sand mining research and showed me the slides of a presentation she gave. It was very informative and focused on sand mining in general. Her research and the methods she used for the Red River are now also used for the Mekong Delta. She mentioned that there is a lack of data on sand mining in the Mekong Delta.
- **What are the main problems with and/or consequences of sand mining?**
  It causes erosion of the riverbanks, as it causes instability of the banks. Sand mining is still going on in the Red River as well, and the problems in the Red River are similar to those experienced in the Mekong Delta.
- **Is there something like sustainable sand mining?**
  She focuses on the sustainable development of sand mining. Around $\frac{2}{3}$ of the worldwide sand extraction takes place in Asia and the Pacific. There are rules and laws for sand mining, but there is a lot of illegal activity. It is a big challenge to manage sand mining activities. According to

Dr. Thuc Anh, the main issues are that there is a limited supply of sand, a growing demand, environmental issues, and the management is hard. The solutions are to avoid the unnecessary use of natural sand, to use alternative materials to replace sand in construction, and to reduce the impact of sand mining by applying current standards and best practice regulation guidelines.

- **How does sand mining influence local people who live in the Mekong Delta?**
  Sand mining has a lot of effects on the livelihoods of the people living near a river and on the ecology of the river.
- **What are the challenges?**
  The challenge is to decrease the demand for sand. The predictions show that the demand for sand will keep increasing in the future. Most concrete is produced in China, India and other countries in Asia.

B.5 Interview Thuyloi University

Date: 21-06-2023, 10:00
Location: Hanoi, Vietnam
Interviewee: Truong Hong Son

- **What is your role at Thuyloi University?**
  Son does research on the Mekong Delta and erosion. He also works together with WWF Vietnam and the Ministry of Agriculture of Vietnam. Son gives support to the Mekong Delta and sand mining. However, sand mining is a sensitive topic and he has to be careful about what he says to me.
- **What previous research did you do on the Mekong Delta and sand mining?**
  Son did his PhD in Delft, where heresearched the flow around mangroves. Now he is writing a paper on erosion and vegetation in the Mekong Delta.
- **What are the main problems with and/or consequences of sand mining?**
  The main problem is erosion: this is the erosion of riverbanks, but also coastal erosion.
- **What solutions have been implemented to prevent the problems or to decrease the impact of sand mining?**
  The government and people in the Mekong Delta tend to think of short-term solutions. They want to fix the problem as fast as they can, but this will only make things worse in the future. There are a lot of hard structures right now, to protect the riverbanks from erosion, but this will not help in the long term. The same solutions are implemented on the coast. At the coast, they built a lot of dykes to protect the land from the water, like what happened in the past in the Netherlands.
- **To what extent has this worked?**
  For now, it works and prevents bank erosion.
- **What do you think can be possible solutions in the future?**
  The best solution is to do a lot of research on the Mekong Delta, to identify the real problems that the delta is facing. Once these problems have been identified, solutions for these problems can be looked into and applied. These need to be long-term solutions.
- **Are hydropower dams also a cause of erosion**
  The dams are not having a large effect on the erosion in the delta. The current erosion is mainly caused by two things:
  - Natural erosion
  - Accelerated erosion due to human activities, such as sand mining, structures in the delta and water extraction
- **Comments about my research**
  It will be helpful to think about the scale I want to build the model for and to quantify this scale, and also how to build the model. He also said the best way to validate the model, is to set up a camera somewhere overlooking the river in Can Tho (on a high building). This will be better than pictures, but it might be hard to do this.

B.6 Interview WWF Ho Chi Minh City

When: 26-06-2023, 11:00
Location: Ho Chi Minh City, Vietnam
Interviewee: Anh Ha Huy

- **What does WWF Vietnam do?**
WWF works together with the government and several other organisations. At the moment, they are developing a sand budget for the Mekong delta. The sand budget is a balance of how much sand comes into the delta, goes out of the delta and the extracted volume of sand. However, there are limited resources, and there is legal and illegal sand mining. They are working with satellite data, but the data has a low resolution, which causes a big uncertainty. They have estimated the sand extraction for 2017-2021, but also want to do this for 2022. Sand mining over the years has become more intensive. WWF is a charity and needs support from stakeholders to fill the gap.
- **What are the main problems with and/or consequences of sand mining?**
One of the problems is that there is legal and illegal sand mining. Legal sand mining is easy to monitor. However, 'legal' means that the sand miners have a license. There is still a problem because the government cannot check how much sand the people with licenses really extract. Illegal sand mining is the main problem, especially during the night. It is not possible to monitor with the open-source satellite data that WWF is using. There is only one political party in Vietnam, so you have to be careful. Sand mining is a sensitive topic in Vietnam and it can be dangerous for a charity like WWF to intervene. Sand mining has very high benefits, as sand has a high value. Sand will become rare, which will make it more expensive in the future.
- **Is there something like sustainable sand mining?**
No, there is no such thing. There is a fear of sand mining in the delta. WWF skipped the study on sustainable sand mining, to focus on other solutions.
- **What solutions have been implemented to prevent the problems or to decrease the impact of sand mining?**
There are sand mining licenses and they try to stop illegal sand mining. In 2017, the export of sand was banned. They are also building hard structures and revetments in the delta, to protect the river banks from eroding. However, this is very expensive and it is not feasible to do this for the whole delta. It costs around $60 million/kilometre, and there are 600 kilometres to cover. It will not solve the problem either.
- **To what extent has this worked?**
There is still a lot of illegal sand mining and even legal sand mining cannot be monitored well. The legal sand mining takes place from 7:00 until 17:00, so during the day. Illegal sand mining happens during the night, and they use a pump to do this. The illegal vessels mainly extract sand near the riverbanks, which is not allowed for legal vessels either. However, it is easier for them to extract it near the riverbanks. The government often patrols at night to see the illegal activity. However, there are not enough people: it is a long river. Every province has their own rules and the illegal vessels move from province to province. In the past, there was more illegal sand mining. Now, the sand is used for big projects like motorways, so the government is trying to control sand mining more. The legal vessels are also a bit illegal because they extract more sand than they are allowed and go outside of their given area to extract sand. The rules are implemented by the provinces, but they have limited resources to reinforce the rules.
- **What do you think can be possible solutions in the future?**
Anh says that the extracted sand volume could be determined with the use of bathymetries or high-quality satellite images. For now, WWF focuses on alternative sources, which are limited to the Mekong Delta. There is no rock and it is a very flat and low area: in some places, the delta is only located a few centimetres above sea level. It could be an option to get sand from outside the Mekong Delta. The first step of the process is the sand budget that they are working on. There is no sand 'created' in the VMD, all the sand flows into Vietnam from Cambodia. Sand mining is also a problem in the other countries upstream of Vietnam, where the sand comes from. They are trying to work together with Cambodia and Laos, but it is hard because there are different politics and systems. That makes it complicated. However, only looking into the VMD will not solve the

problem. If the sand is trapped in upper countries, it will accelerate the sinking and shrinking of the delta, which makes working together very important. WWF has a list of 18 alternative resources. A few alternatives are crushed rock, recycled concrete, agricultural waste, rubber waste, and glass waste. When asked about the plans of the government to extract sand from the sea, Anh answered this was not on the list as this is not sustainable. He said it can even be more dangerous than river sand mining. The problem is moved from the delta to the sea. In 2019, 68% of the shoreline of the Mekong Delta was eroding. This is caused by the lack of sand that reaches the shoreline. The shoreline consists of mud, which makes it easy to erode.

- **How can these alternatives be introduced?**
  If sand mining is banned, it will only increase illegal sand mining. Right now, there are limited alternatives in the Mekong Delta, so it is not possible yet to ban river sand mining. It will take time and it depends on the government and the sector. It will not be easy. The process of research on alternative sources is a complicated and long process. Sand is easy: just extract it and sell it. Alternatives are more expensive and there is a longer supply chain.
- **What are the challenges the Mekong Delta faces (in general)?**
  The delta is shrinking (erosion) and sinking (land subsidence). The main causes are sand mining and hydropower dams.
- **Do you think it is a good approach to focus on the barges with cranes, to estimate the extracted sand volume?**
  Yes, it is good to look at the barges with cranes. However, in some provinces, they use different techniques, so no cranes. At some locations, the sand is mixed with clay/silt, so they will use a pump to extract the sand from the riverbed. There are no cranes on the Tien River. Only focusing on barges with cranes will give an underestimation of the sand extraction rates.
- **Anh said the following about the demand for sand**
  A lot of motorways are built at the same time in Vietnam, so the demand for sand was very high. The government should have prioritised some motorways first, instead of building them all at the same time. That would have distributed the demand for sand over a longer time. They need to plan things like this better. After Covid, the Vietnamese economy is facing problems. To boost the economy, public investments are a solution. The economy is improving now, but there will still be problems in the long term.

B.7 Talk with owner homestay

Date: 14-06-2023
Location: An Binh Island, Vinh Long, Vietnam
Note: this was a casual talk, not an interview

In Vinh Long, I stayed in a homestay that was located on the riverbank. In this area, erosion has played a big role and in December 2022, some terrible erosion happened. I carefully asked the owner of the homestay about the erosion and he started talking.

He told me that there was a very bad case of erosion in December last year (2022). He first saw a video on Facebook and could not believe that this was so close to his home. 13 houses disappeared into the river, but luckily no one died. He started talking about sand mining: in front of his house, a lot of sand mining was happening. However, after the severe erosion, the sand mining vessels moved elsewhere. In the past, he could see the river bed during low tide, but a few years ago he could not see it anymore.

C ICEYE tasking

This appendix shows the full ICEYE images taken during the tasking.

C.1 Area of interest

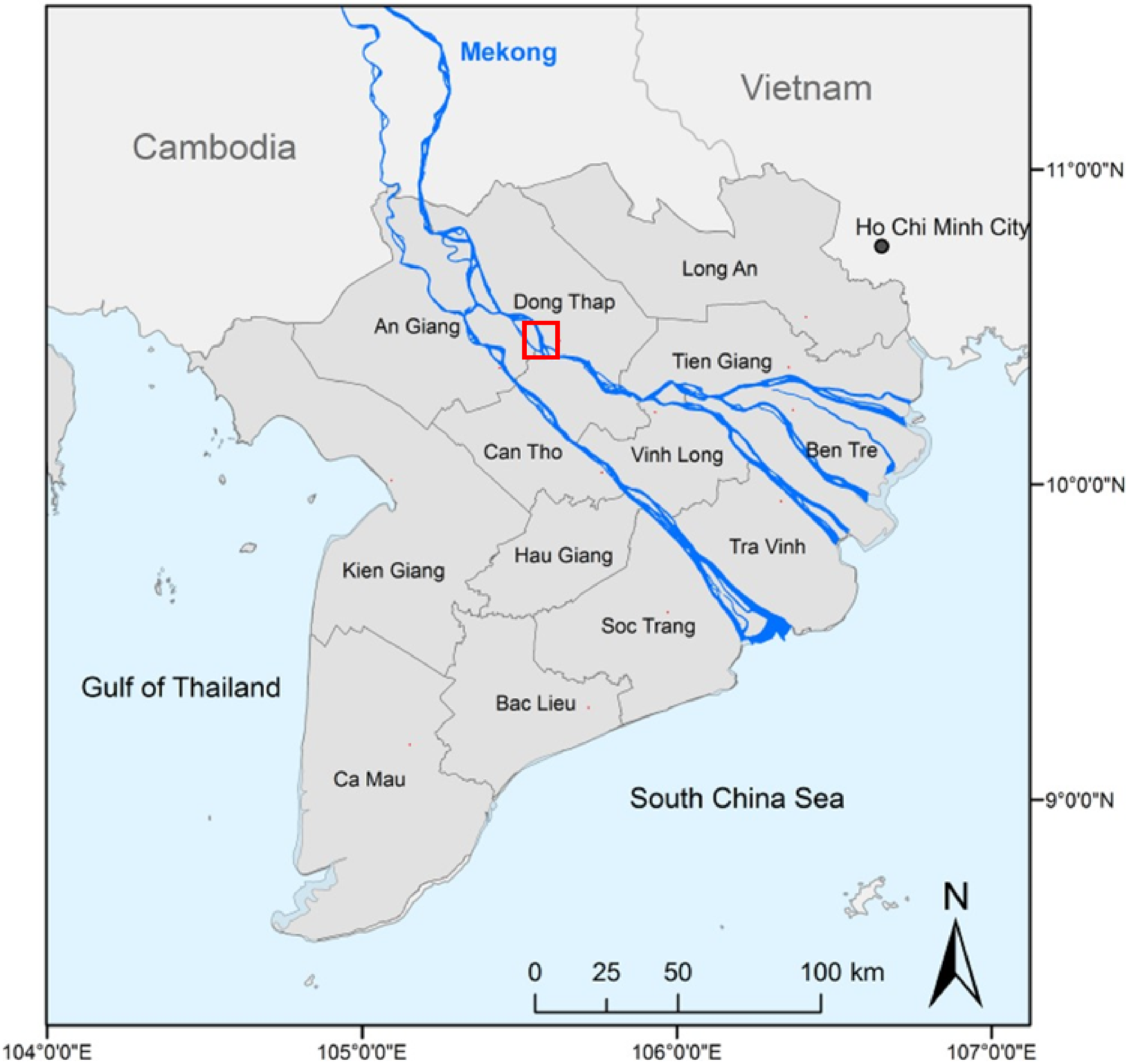

Figure C.1: Area of interest ICEYE tasking just upstream of Cao Lanh, indicated with the red square, which is known to be a heavily mined area (modified after Kuenzer et al. (2013)).

C.2 Spot image: 0.5-metre resolution

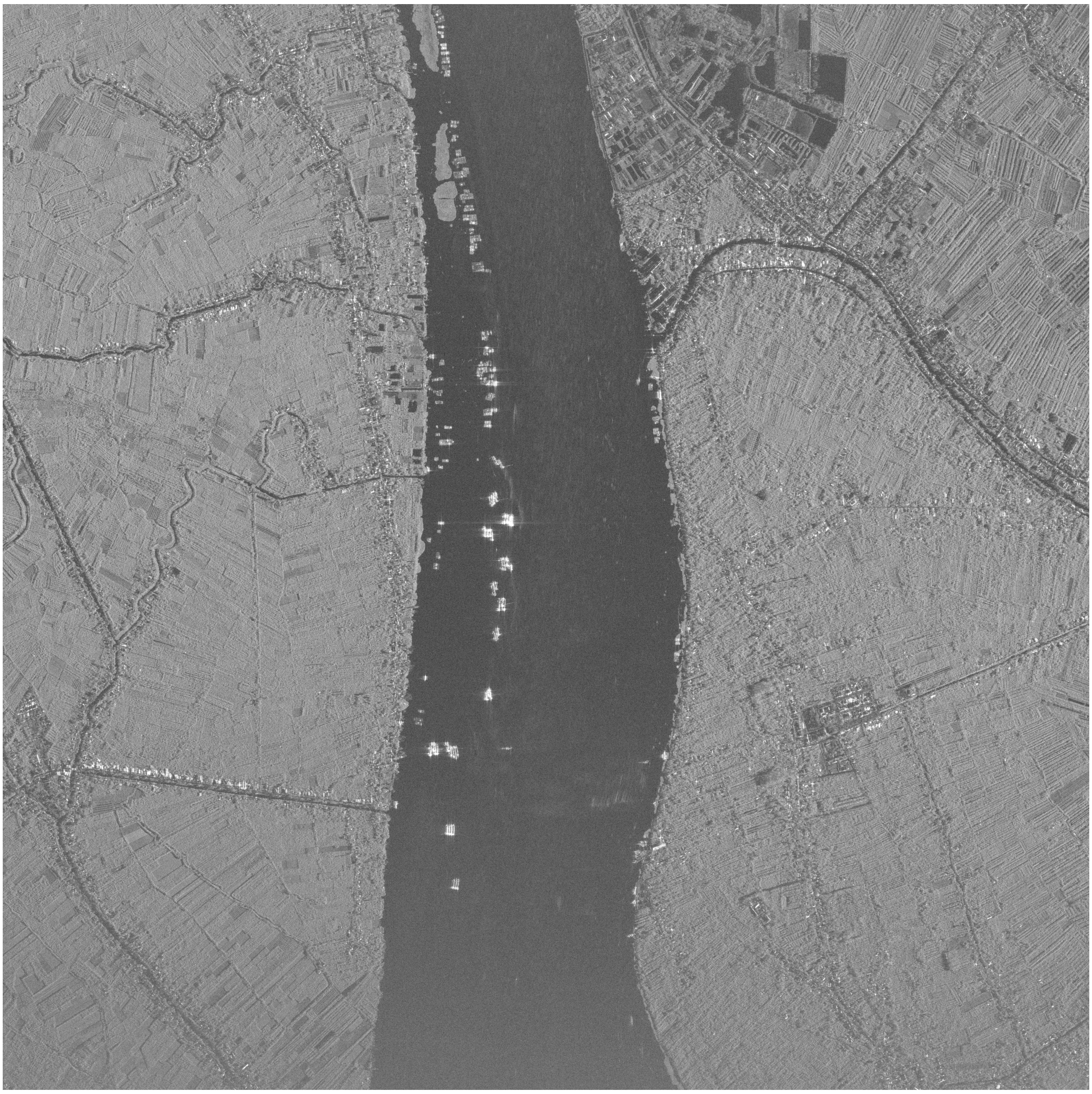

Figure C.2: ICEYE spot image of the specified area of interest in the Vietnamese Mekong Delta with a resolution of 0.5 m

Figure C.3: ICEYE spot image of the specified area of interest in the Vietnamese Mekong Delta with a resolution of 0.5 m

C.3 SLEA image: 1-metre resolution

Figure C.4: ICEYE SLEA image of the specified area of interest in the Vietnamese Mekong Delta with a resolution of 1 m

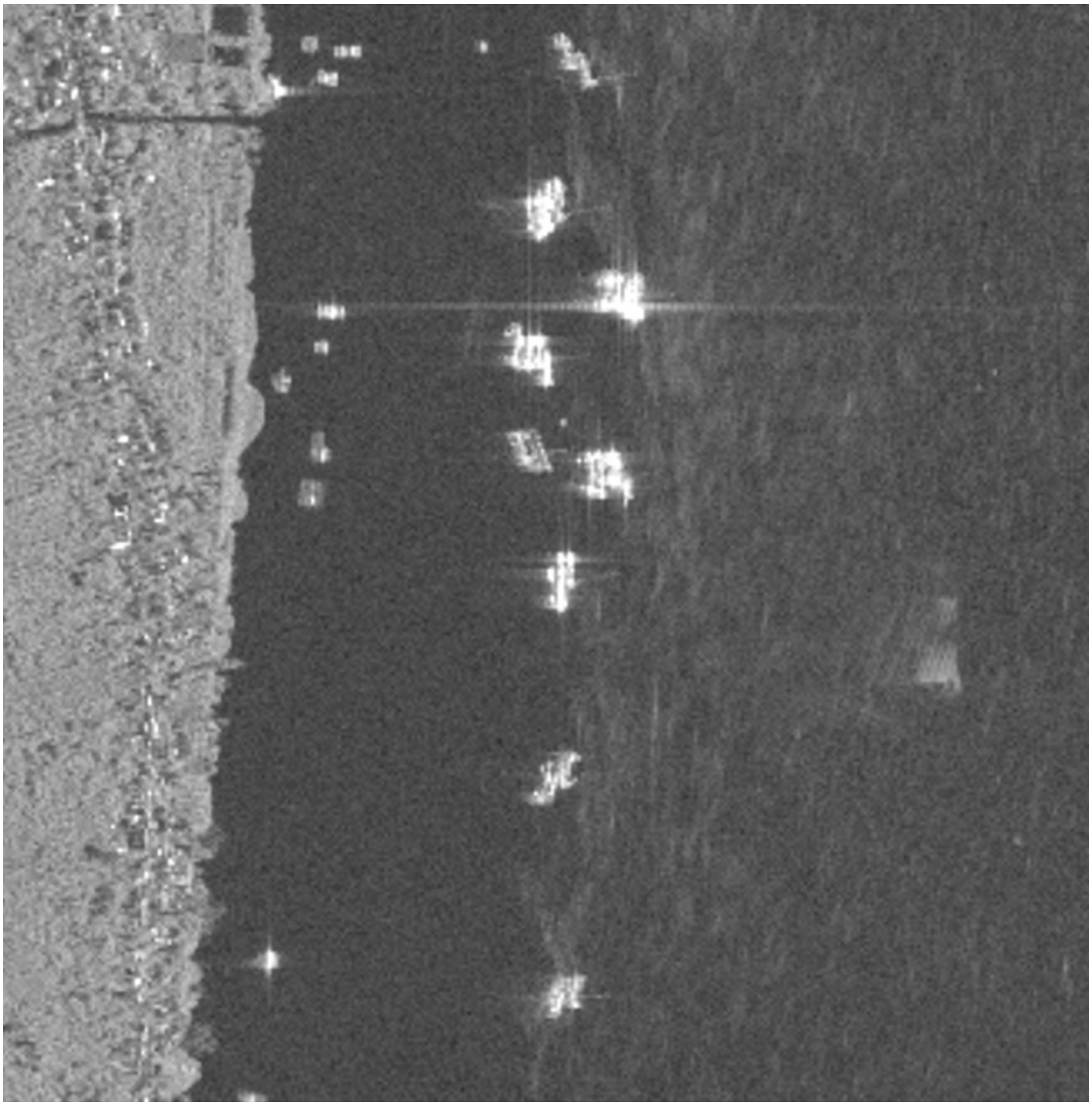

Figure C.5: Crop of the ICEYE SLEA image of the specified area of interest in the Vietnamese Mekong Delta with a resolution of 1 m showing barges with cranes

C.4 Strip image: 3-metre resolution

Figure C.6: ICEYE strip of the specified area of interest in the Vietnamese Mekong Delta with a resolution of 3 m

D Training and validation accuracy vessel classification model

The training (blue line) and validation (orange line) accuracy are plotted here for every training step.

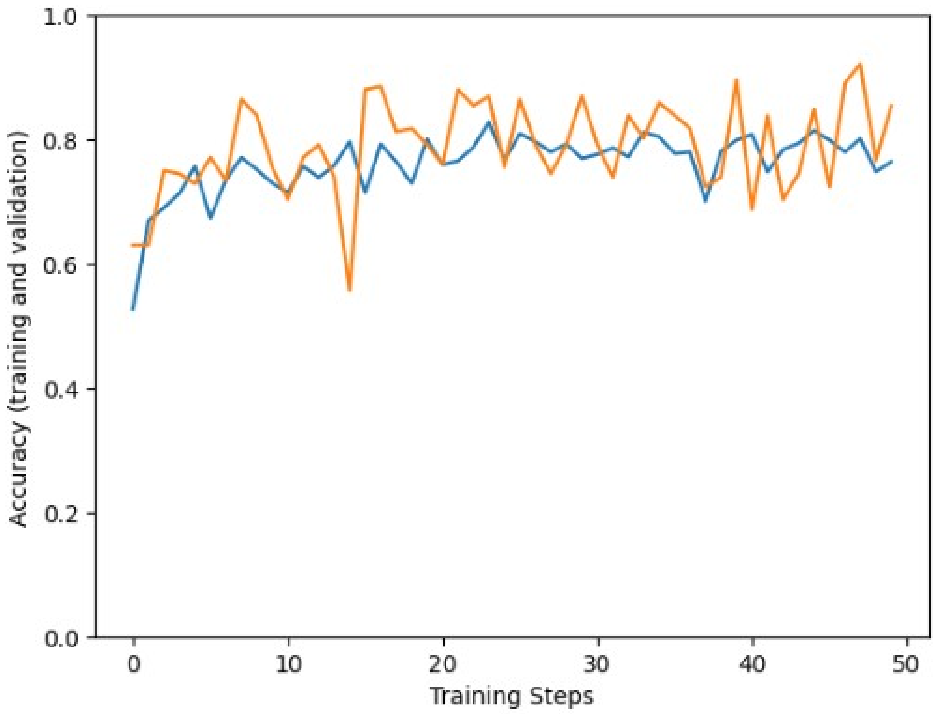

Figure D.1: Training and validation accuracy for each training step of the model