UNDERSTANDING RIVER DYNAMICS OF THE AYEYARWADY RIVER, MYANMAR

How dynamic behaviour contributes to adapting the river morphology for navigational purposes

Master Thesis

Utrecht University, Faculty of Geosciences

MSc student	Jouke van der Velden
Supervisor Utrecht University	Prof. Dr. H. Middelkoop
Supervisor Deltares	Dr. C.J. Sloff

Universiteit Utrecht

Deltares
Enabling Delta Life

Image on front page

SATELLITE IMAGE OF THE AYEYARWADY RIVER DURING FLOOD, DOWNSTREAM THE CONFLUENCE WITH THE CHINDWIN RIVER. 23-10-2001 LANDSAT 7

Preface and acknowledgements

In front of you lies the product of my hard work during the last six months of my MSc study Earth surface and Water at Utrecht University. I was offered the opportunity to work at Deltares and be part of the Ayeyarwady project team. Thank you, Kees Sloff and Erik Mosselman for giving me this chance.

This work combines my specific interests in fluvial systems and unimpaired natural landscapes. The Ayeyarwady River has proven to be an ever changing and unpredictable river. With my work only a small part of its interesting dynamics is uncovered.

As part of my research I got to visit Myanmar and sail the Ayeyarwady River between Mandalay and Nyaung-U. Thank you Kees Sloff, Marten Hillen and Joost Lansen for the warm welcome in Yangon and for helping me familiarize with the work-related travel style. This was a new, exciting experience to me. Thank you Chit Yan Toe for joining me in Mandalay and during the sailing trip on the Ayeyarwady River and for sharing your culture with me.

Hans Middelkoop, thank you for your clear comments and your enthusiasm when discussing my newest ideas. You have travelled to Delft for me several times and have set up Skype meetings at home. Thank you for accepting me as your graduate student, even though you did not understand why I was so persistent. I do.

SUMMARY

The Ayeyarwady River in Myanmar is an important navigational trading route and contributes a large part to the Myanmar economy. Almost all of the rivers drainage basin lies within the country borders. It flows from the Himalayan mountain range in the north to the Andaman Sea in the south. It is a melt water and rain fed river with most of the discharge flowing between May and October. Water levels between winter and summer (monsoon period) vary up to 10 metres. This variation in water levels and the dynamic morphology of the river create navigational problems. Often water depths are not sufficient and the channel thalweg – which is the best navigational route – is continuously changing. Its behaviour is unpredictable and navigational management teams find difficulties anticipating on these changes.

This research is part of the Deltares contribution to the Ayeyarwady Integrated River Basin Management plan (AIRBM), commissioned by a partnership between the Netherlands and Myanmar. The project team is assigned the task to update an existing River management master plan and to propose two river engineering pilots. The Deltares project area is situated between the important harbour of Mandalay and the city Nyaung-U near touristic Bagan. In this area the Chindwin River joins the Ayeyarwady River. This research focuses on the river reach below the confluence point, which is dynamically braiding and shows many variations in its planform. The main objective is to determine how the dynamic behaviour of the river can contribute to adapting the river morphology for navigational purposes.

Satellite images were used to describe and visualise the morphologic changes of the river in the past 15 years. Simulations with Delft3D-FLOW contributed to a better understanding of these processes and to review the effect of upstream changes on downstream sections. A data analysis of the water level and discharge datasets provided information on the hydrology of the river. Sediment size and sediment discharge for the past 35 years were reviewed. Also a field trip in Myanmar contributed to analysing the active shift of the river.

In this report an overview is provided of the morphodynamic changes of the river within the research area. In most of the research area the river has two parallel channels except for the sinuous reach at Nyaung-U. The island in between the two channels is formed by formation of braiding bars and consequent stabilisation by vegetation. At the point where the two channels confluence, the confluence angle and discharge ratio of the two channels determines the main flow direction downstream and with that the downstream river planform. In the research area there are two types of river banks – the resistant river banks and the non-resistant floodplains. The channels along the resistant river banks are confined and stabilized, with higher flow velocities and larger water depths attracting the major part of the discharge. At locations with two channels which are both not confined, bar migration is more active and the channel thalweg is difficult to determine.

For river engineering, structures should be used which are adaptable to the ever-changing river dynamics, preferably even on a 5-year timescale. When adjusting the planform of one section of the river, the morphological effects will be visible for more than 50 kilometres downstream. It is recommended to start the first Deltares project pilot in the upstream parts of the river and review its upstream hydrologic and downstream morphologic effects with model simulations combined with past planform changes. Current research and model simulations are not of sufficient quality to guarantee the effect of river management plans. To improve the quality of these models, hydrologic data with higher accuracy is required.

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1 INTRODUCTION

The Ayeyarwady River in Myanmar forms an important navigational artery for trading and recreational use. In this mostly braiding river water levels can vary with up to 10 meters. The river is very dynamic in its planform changes, which are largely dependent on the discharge regime. Despite harbours up to 1000 km upstream being reachable all year round, navigational issues are common in many river sections, including the section between Nyaung-U and the important harbour of Mandalay. Because the country was ruled by military regime between 1962 and 2011, little to no investments have been done on river improvements. Inhabitants of the region are used to adapt to the morphodynamics of the river. The continuously changing thalweg of this river makes its behaviour unpredictable and it is difficult for navigational management teams to anticipate on these changes.

The navigational problem in the Deltares project area (Mandalay to Nyaung-U) is double layered. The direct physical problems are caused by shallow water and bedrock exposure. Ships often run onto high ground during low water. Freeing the vessel can cost several hours and the economic damage is large. Also ships are structurally damaged during low water due to bedrock exposure. Such damage is very costly and can even be dangerous in case of vessels that carry liquid. Long term operational problems are caused by the dynamic shifting of the river. For river management it is hard or even impossible to keep up with the continuously changing 'optimal navigation route'. This route is equal to the continuously shifting thalweg. Each day manual measurements are carried out to detect changes in thalweg location, but the system is too large to be covered entirely by hand.

In addition to an existing feasibility study on navigational improvements from 1988 (Haskoning, The World Bank, & UNDP, 1988) a consortium of Dutch engineering companies is asked to propose a new/extended river basin management plan (AIRBM) for navigational improvements between Mandalay and Nyaung-U, based on 1-D and 2-D simulations (Ministerie van Economische Zaken & Rijksdienst voor Ondernemend Nederland (RVO), 2014). Deltares is responsible for the models and contributes to proposing two pilots in the project area. This research is part of the AIRBM project contribution executed by Deltares.

1.1 OBJECTIVES

Based on the current limited knowledge of active processes in the Ayeyarwady River and high requirements for the Deltares project, this study focusses on an understanding of the river's dynamic morphological behaviour within the project area. Also it forms a tool for determining the optimal navigational channel, based on limited data. The main objective was to determine how the river's dynamic behaviour can contribute to adapting the river morphology for navigational purposes. To meet his objective several questions were formulated

1. How did the river change its planform in the last 15 years?
2. What patterns can be recognized in spatial bar migration?
3. How does the secondary channel affect the stability of the main channel?
4. What up- and downstream factors influence planform change?
5. How does bar behaviour and planform change influence the navigation route?

1.2 GENERAL APPROACH

The Deltares project area covers the river section between Mandalay (upstream) and Nyaung-U (downstream). The area of interest for this research lies within the Deltares project area, and focusses on the part downstream of the confluence with the Chindwin River. A detailed description of the boundary conditions in the Ayeyarwady catchment and of the project requirements for Deltares is provided.

Water level, sediment and discharge variations are reviewed for the research area. Satellite images were used for analysis of the Ayeyarwady River's past flow paths and changes in morphology. Model simulations provide more insight in general morphodynamic processes and are used for supporting and discussing previous observations. All observations and measurements are finally correlated to give insight in the effect of upstream changes on downstream river planform and vice versa.

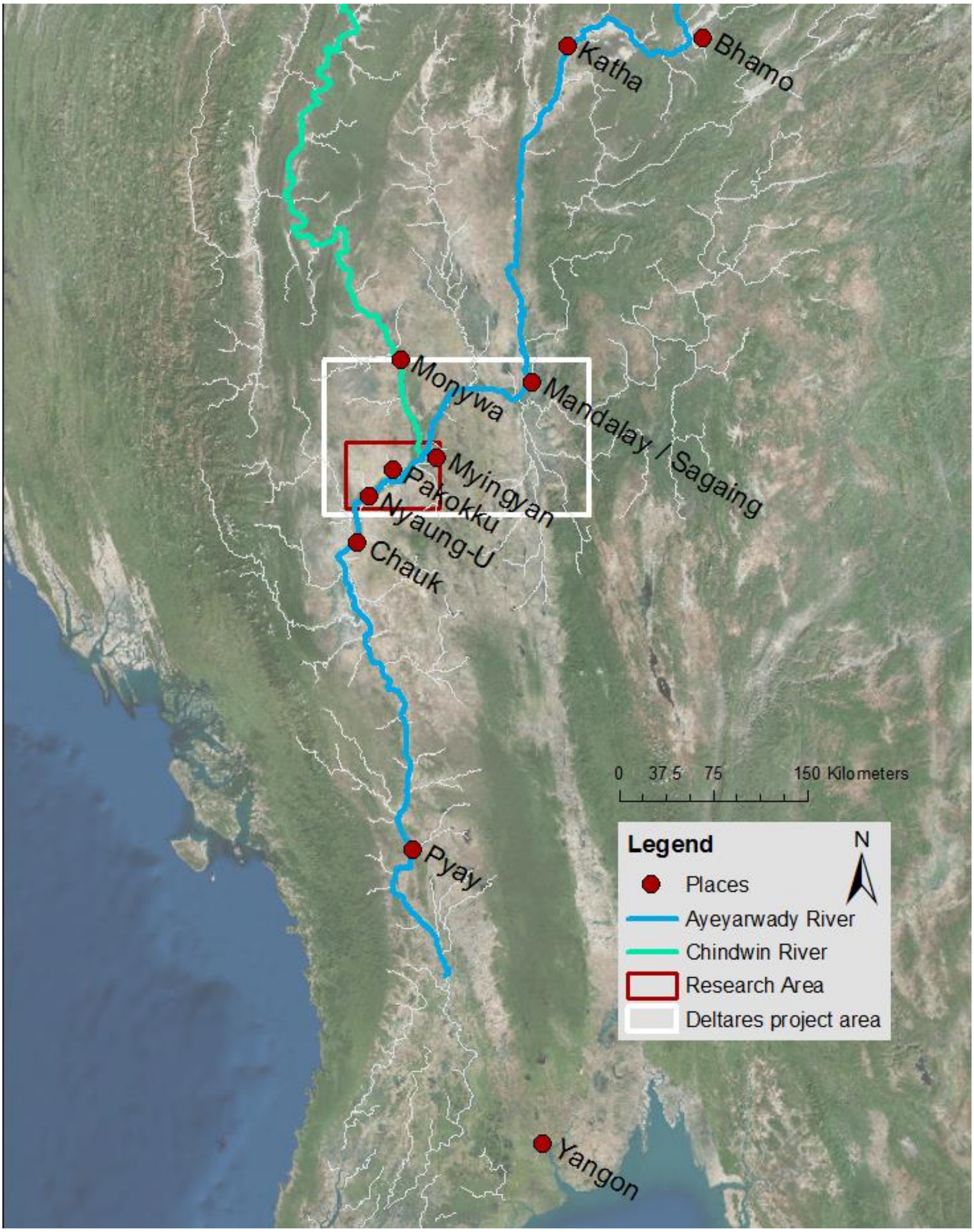

FIGURE 1.1 OVERVIEW OF THE AYEYARWADY DRAINAGE BASIN IN MYANMAR, WITH LOCATIONS OF RELEVANT CITIES AND GAUGING STATIONS. THE WHITE BOX PRESENTS THE LOCATION OF THE DELTARES PROJECT AREA, OF WHICH THE DOWNSTREAM PART IS THE AREA OF INTEREST FOR THIS RESEARCH.

2 AYEYARWADY CATCHMENT

The Ayeyarwady River is situated in Myanmar, 98% of its drainage basin lies within the country borders. For researching a part of the Ayeyarwady River, it is relevant to know more about its boundary conditions. Key characteristics are discharge regime, climate, tectonics and continental setting, forming the boundary conditions for further research on smaller scales.

2.1 TECTONICS AND GEOLOGY

Myanmar is located in a geologically active region, east of the Himalayan orogeny zone. The western side of Myanmar is bordered by the Naga Hills, Chin Hills and Arakan mountains. The ranges are part of the geological complex or “knot” marking the northeast limit of the encroaching Indian-Australian plate (Hadden, 2008). The mountain ranges lie perpendicular to the orientation of the Himalayan Mountains and they separate the coastline from the central basin where the Ayeyarwady is situated (see Chin Hills and Arakan Yoma in light pink in the west in Figure 2.1). It has an average elevation of approximately 1800 meters above sea level. This mountain range is composed of limestone, shale and conglomerate. The Chindwin and Manipur rivers drain this area and carry the erosional products of these rock types. The Shan Plateau in the east of Myanmar is a relatively flat mountainous area with elevations between 500 and 2000 metres (green and pink in the east in Figure 2.1). In this area a combination of limestone and dolomite, and sandstone, shales and conglomerates can be found. The Shan Plateau is known for its abundant amount of rubies and sapphires. Along the borders of the plateau and in the northern regions of Myanmar gneiss, schists and granitic rocks are found. The central basin is covered with “soft rocks” consisting of Pleistocene and Holocene alluvial and gravel soils (Myanmar Geosciences Society, 1977), with sandstone, shale, limestone and some conglomerates (Hadden, 2008). The river channel belt is covered with at least 6m of soil (U.S. Geological Survey (USGS), 2007). A small north-south orientated mountain range is the Bago mountain range (Pegu Yoma). This belt divides the Ayeyarwady valley and the valley of the Sittang River.

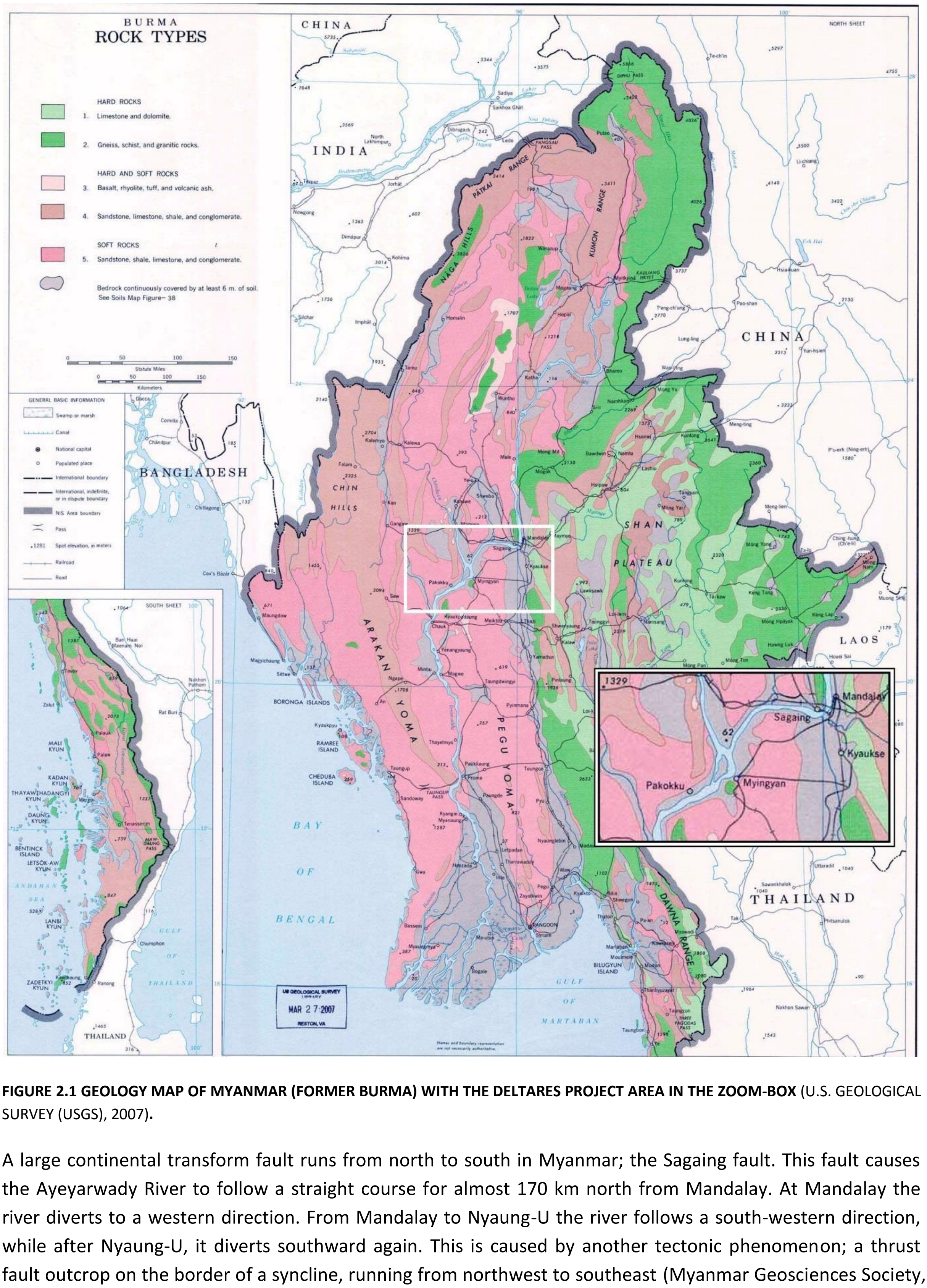

FIGURE 2.1 GEOLOGY MAP OF MYANMAR (FORMER BURMA) WITH THE DELTARES PROJECT AREA IN THE ZOOM-BOX (U.S. GEOLOGICAL SURVEY (USGS), 2007)**.**

A large continental transform fault runs from north to south in Myanmar; the Sagaing fault. This fault causes the Ayeyarwady River to follow a straight course for almost 170 km north from Mandalay. At Mandalay the river diverts to a western direction. From Mandalay to Nyaung-U the river follows a south-western direction, while after Nyaung-U, it diverts southward again. This is caused by another tectonic phenomenon; a thrust fault outcrop on the border of a syncline, running from northwest to southeast (Myanmar Geosciences Society, 2014).

2.2 CLIMATE

About two-third of Myanmar is located between the tropic of Cancer and the Equator, resulting in a tropical climate. Most of Myanmar's climate is determined by the monsoon periods. The southwest monsoon exists from May to October, bringing in almost all of the yearly rainfall. The central part of the country, where the research area is situated, lies in the rain shadow of the Arakan Mountains, making it the driest region of Myanmar with an average annual rainfall of 760 mm. The dry and cool northeast monsoon exists from October to February, bringing the temperature in Mandalay down from 30°C to 20°C (Hadden, 2008) (see also Figure 2.2). The northern mountains receive snowfall for two months a year. This region is also a supplier of discharge to the Ayeyarwady River.

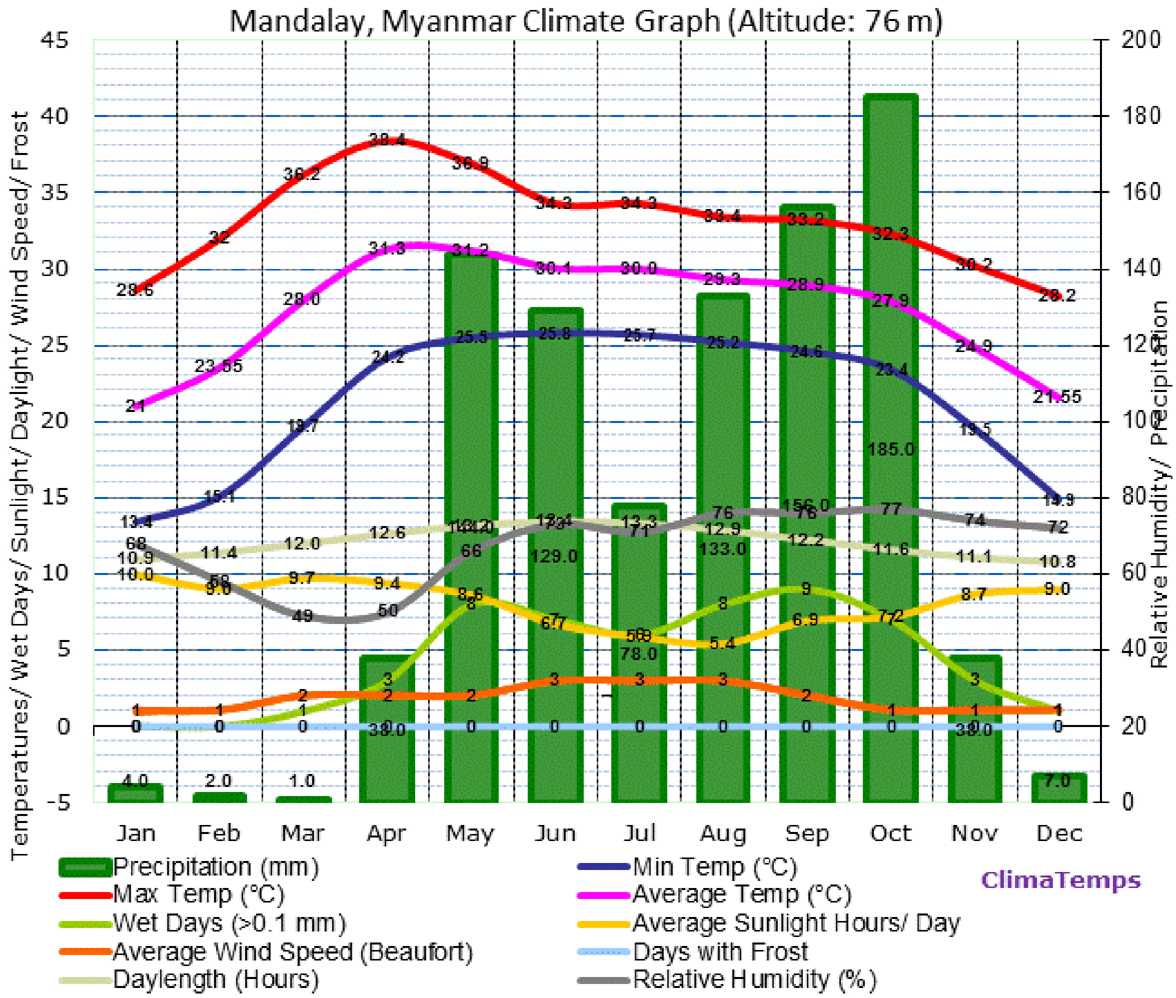

FIGURE 2.2 CLIMATOGRAM FOR MANDALAY, MYANMAR (CLIMATEMPS, 2015)

Myanmar is also subject to tropical cyclones. Cyclone Nargis hit Myanmar in May 2008 as a category 4 cyclone. Large parts of the Ayeyarwady delta were flooded and delta infrastructure was destroyed. Other significant storms in the past 10 years were Cyclone Giri (2009) and Cyclone Mala (2006) (AccuWeather, 2015).

2.2.1 VEGETATION

The vegetation of the floodplains and surrounding hilly landscapes consists of low bushes and trees resistant to drought. There are deciduous trees and thick green shrubs. The emerging mid- and side channel bars in the river are quickly cultivated by locals. They grow rice, peas and beans. Tributaries and flash floods of the rivers are used for irrigation (Aquastat, 2011).

FIGURE 2.3 PAGODAS AND VEGETATION IN OLD BAGAN, MYANMAR (VAN DER VELDEN, 2015)

2.2.2 DISCHARGE REGIME

As with the rainfall, most of the discharge flows between May and October (Aquastat, 2011). The glacial melt water of the Himalayan Mountains also contributes to the total discharge, but the Ayeyarwady is a mostly rain fed river. At Mandalay, annual variations between low-water level and flood level of 10 metres have been recorded. The lowest water level occurs in February, and the highest in August (Encyclopaedia Britannica, 2015). The combined discharge of the Ayeyarwady and Chindwin Rivers at Chauk is 30000 m^3/s at its maximum and 1500 m^3/s minimum.

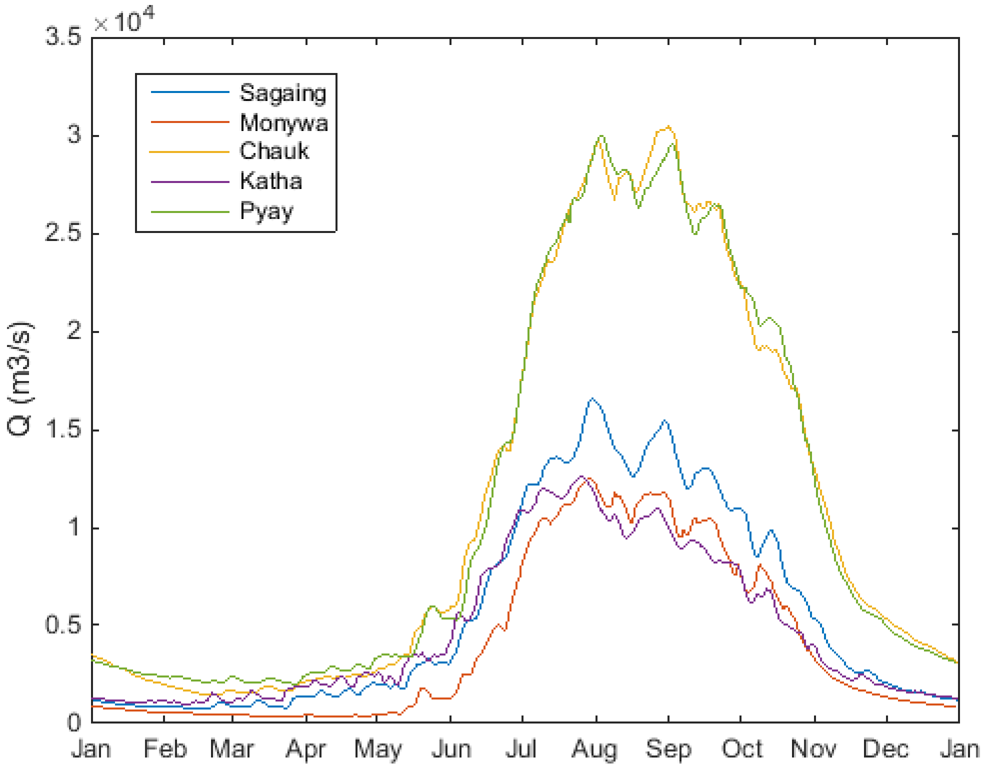

FIGURE 2.4 DAILY DISCHARGE AT 5 MEASURING STATIONS ALONG THE AYEYARWADY RIVER AND CHINDWIN RIVER (MONYWA). DISCHARGE IS AVERAGED OVER THE PERIOD 2005-2014. SEE FIGURE 1.1 FOR LOCATIONS.

2.3 RIVER SYSTEM

The Ayeyarwady River springs in the Himalayan Mountains and drains 2170 km downstream to the south in the Andaman Sea, adjacent to the Bay of Bengal. It is one of the largest rivers in south-east Asia. The Chindwin stretches 1207 km and joins the Ayeyarwady at Myingyan. The drainage area of the combined Ayeyarwady and Chindwin covers about 413,710 km^2 of which the Ayeyarwady represents about 71% (Directorate of Water Resources and Improvement of River Systems (DWIR), 2014b; FAO, 2014). Almost the entire drainage catchment is located within Myanmar. Less than 10% of the area lies within China (Ayeyarwady) and India (Chindwin). The drainage area can be divided into three sub-catchments: Upper Ayeyarwady, Chindwin and Lower Ayeyarwady. The river drains in the 35,000 km^2 large Ayeyarwady Delta region.

The north-south orientation of both the Shan plateau in the east and the Assam-Arakan fold belt in the west forces the river in a stretched drainage pattern with many small side channels draining to the main channel directly. Many intermittent streams are only discharging water during the monsoon season (Commandeur, 2014). The continental setting of the Ayeyarwady River is along a strike of folded mountains, with a major depositional basin in between the two strikes (based on Potter (1978) and Mertes and Magadzire (2007)), (Figure 2.5). The drainage pattern of the Ayeyarwady River is largely controlled by the underlying geology and can be classified as contorted (Howard, 1967). This pattern shows some tight hairpin turns and angular drainage directions. On a smaller scale drainage networks can be classified differently. Manipur River, part of the Chindwin system, follows the north south orientation of the Chin Hills with a trellis pattern. The lower part of the Ayeyarwady is considered to be dendritic. The drainage patterns in the northern parts of both the Chindwin and Ayeyarwady Rivers are rectangular. The eastern tributaries of the Ayeyarwady River show a contorted pattern.

The river (within the project area) is classified as braiding, although its planform varies a lot. At the city of Mandalay the Ayeyarwady River enters a narrow passage, crossing the Sagaing fault, after which the river has a sinuous pattern, with bars migrating through the channel. A few kilometres downstream (still upstream of Myingyan) the river enters a more resistant geologic substrate and becomes almost straight. Near Myingyan the Chindwin River joins the Ayeyarwady River, associated with large bifurcations and confluences. Past this joint the river shows a braiding pattern, with stable vegetated islands and unstable sandy bars. Near Nyaung-U the river encounters the resistant and elevated thrust fault in the west, making the river to “bend” southwards. The research area is located at the confluence point of the Upper Ayeyarwady and Chindwin, entering the lower sub-basin. This is the sediment transfer zone of the river (Schumm, 1977). The downstream gradient of this central belt is estimated as 10^{-4} m/m by Commandeur (2014).

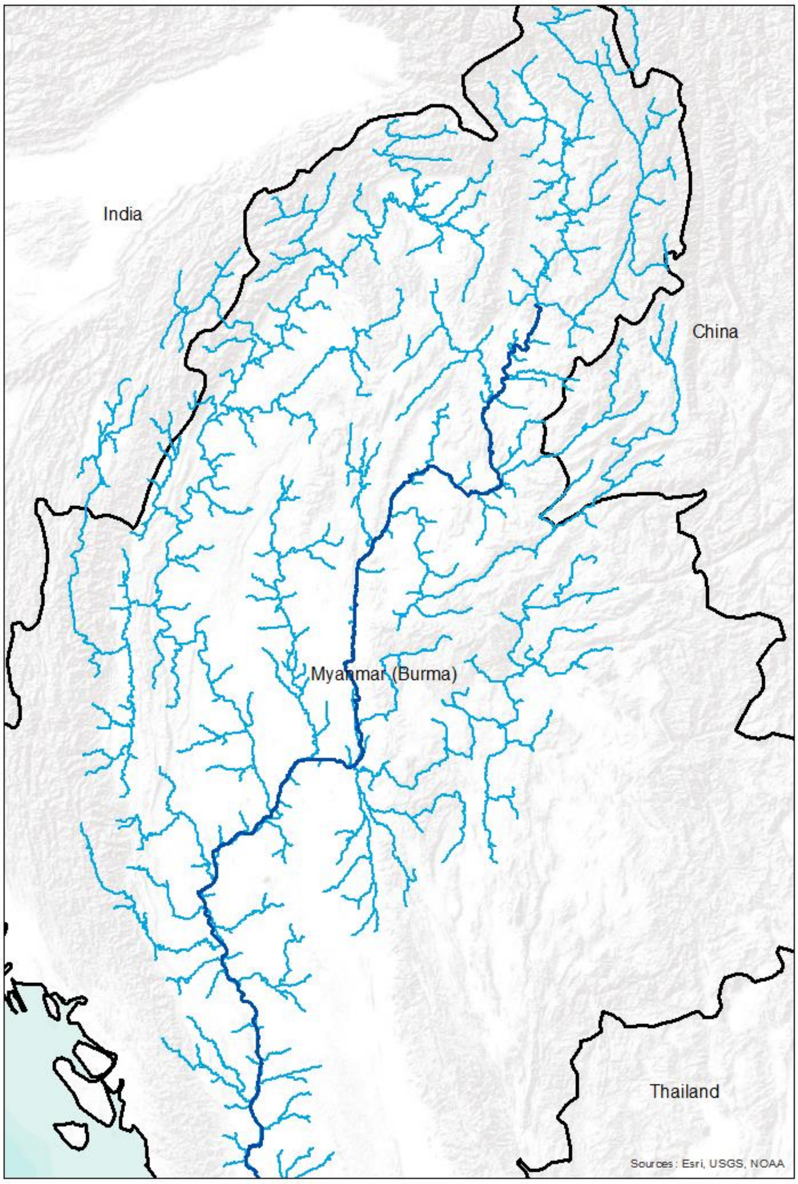

FIGURE 2.5 DRAINAGE NETWORKS OF THE AYEYARWADY RIVER AND CHINDWIN TRIBUTARY

2.4 WATERWAY TRANSPORT

During the past three decades the national water way transport has increased to large quantities. In 1986 Haskoning proposed a Master plan for Navigation improvements of the Ayeyarwady River and lower Chindwin River (Haskoning et al., 1988). All river improvements have been implemented; albeit to a certain extent because of financial reasons. The ever-changing nature of the river brought up the urgency to adapt the master plan to the new circumstances.

TABLE 2.1 IMPROVEMENT OF INLAND WATERWAY TRANSPORT BETWEEN 1988-1989 AND 2010-2011. (ROYAL HASKONINGDHV, 2015A)

Item (in millions)	1988-1989	2010-2011
Passengers	14.55	27.57
Passenger miles	344.60	902.21
Cargo ton	1.84	4.89
Cargo ton miles	267.36	753.69

3 DELTARES PROJECT AREA

The Deltares project area is located in the region between Mandalay and Nyaung-U, in the central basin of Myanmar (see the white box in Figure 1.1). Mandalay is the second-largest city of Myanmar, and is large in navigation, trading and tourism economy. Nyaung-U is a small township near the touristic Bagan.

The section between Mandalay and Nyaung-U covers roughly 177 kilometres of bends, braids and bars. The river width varies from 1.5 km in the dry season to 5 km in the monsoon season (measured just below Pakokku). Within the project area the largest river widths can be measured at the confluence point, where the two rivers mix and many small side channels and wide floodplains have formed. The narrowest part of the river is found upstream this confluence point, where the Ayeyarwady River lays constraint within elevated plains which are not flooded during high water. The river varies from one to two channels. Upstream the confluence it predominantly is one channel, below the confluence two channels are active. Also in the whole project area some small side channels have formed.

This region is selected by collaboration between the government of Myanmar and the Netherlands for the executing of an Integrated River Basin Management project. Deltares is selected as one of the companies working on this project. More about the project description, -requirements and -plan is explained in this chapter. Also an overview is given of existing river training works.

3.1 PROJECT DESCRIPTION

RVO Netherlands has established a partnership between the Netherlands and Myanmar on three themes: integrated water management, reinforcing cooperation between the Netherlands and Myanmar, and supporting Myanmar's national water management. This partnership is part of the Global Water Program of the Dutch government and is supported by the World Bank. The Ayeyarwady Integrated River Basin Management (AIRBM) project includes:

- Phase 1: Updating the Masterplan for Navigation improvements (Haskoning et al., 1988)
- Phase 2: Preparing two river regulating pilots between Mandalay and Nyaung-U.

It is recommended to improve navigation by increasing water depth. The required depth is maximum ship draught + 30%. An increase in least available depth (LAD) can be obtained by recurrent dredging – annually after high water, or channel narrowing regulation structures. The navigation channels do not only have to be deepened, but also stabilized, so that channel migration is limited. An improvement of the navigation channel is estimated to increase shipping economy by 30%. River improvements have to be executed gradually, in order to prohibit the river from becoming unstable.

The AIRBM project will be carried out in corporation with the Directorate of Water Resources and Improvement of River Systems (DWIR) of the Ministry of Transport in Myanmar. (Ministerie van Economische Zaken & Rijksdienst voor Ondernemend Nederland (RVO), 2014) In 2014 Deltares applied to provide its services for Phase 2: Preparing two river regulating pilots. Deltares is assigned to do the 1D morphologic modelling of the project area between Mandalay and Nyaung-U, and the detailed 2D/3D modelling of the two pilots. The 1D model product specifies the boundary conditions for the 2D/3D modelling. Tasks include:

- Supervising data collection and analysis
- Updating the existing WFLOW hydraulic model with new measurement data
- Creating a 1D SOBEK-RE model (morphology) together with the consultant
- Supporting consultant in morphologic studies with Delft3D

Deltares notes that data availability is low. This, together with the complexity of the Ayeyarwady River, makes it a difficult task to construct and validate the models. Both Deltares and Royal HaskoningDHV project leaders have travelled to Myanmar for project management purposes and to take measurements of sediment, topography, water depth, GPS coordinates etc. (Deltares, 2014c). The Deltares project goal is to determine the best approach for 'natural river training'. This consists of adjustments of the navigation channel, stimulating the river to further develop in a natural manner and maintain the wanted situation. The project leader at Deltares is Dr C.J. Sloff.

3.2 NAVIGATION REQUIREMENTS

'Because of the large seasonal variations in discharges on the river systems, water depths available for navigation at critical sections on this 1000 km long trade route range from less than 1 m in the dry season (December-May) to well over 6 m in the monsoon season (July-October).' (Haskoning et al., 1988) Cities upstream Bhamo are only accessible for seven months a year, during high water.

Ten days a year navigation depth is not sufficient (Ministerie van Economische Zaken & Rijksdienst voor Ondernemend Nederland (RVO), 2014). Though, also in average conditions vessels run into low ground. This is caused by the rapid changes in channel/bar location, which the navigation management team cannot keep up with. Landmarks, buoys and posts have to be replaced in order to indicate the navigation channel. Channel shifts and bar migration take place at a fast rate and are difficult to predict. Also change rates are not uniform: increased dynamics after high water create most problems.

A possible solution for the braiding sections of the river is to dredge in one channel, and fill the other channel with the dredged material. In theory this would lead to increased erosion in the dredged channel and silting up of the filled channel. Though, choosing the right channel to dredge is key. Both upstream angle and sediment-flow ratio influence the development of the channels. Also effects on up- and downstream sections are important to be aware of. Furthermore, channels which are migrating, but are very predictable in their behaviour do not necessarily need adjustments. If a meander bend migrates at a stable rate, one can predict the location for the upcoming years. It should be monitored so that up- and downstream conditions should remain stable as well.

TABLE 3.1 DRAFT RESTRICTIONS IN THE AYEYARWADY RIVER BETWEEN NOVEMBER AN MAY OF EACH YEAR (ROYAL HASKONINGDHV, 2015A)

Waterway	Draft restrictions (m) Nov till May
Myitkyeenar – Sinbo	0.8
Bhamo - Katha	1.1
Katha - Mandalay	1.2
Mandalay – Pyay	1.5
Pyay - Hinthada	1.7

3.3 ARTIFICIAL AND NATURAL TRAINING WORKS

Along the Ayeyarwady River only few river training works are found. Examples are: dikes with dike protection, pumping stations, flood defence walls and groynes. Groynes are commonly constructed of piled boulders, natural materials or sometimes concrete (Figure 3.1). Within the 177 kilometre river stretch within the project area, only 8 kilometres of dikes were constructed along the city of Mandalay. Within the Deltares project area three bridges can be found. Near Mandalay two bridges were built: The Ayeyarwady-Yadanarbon Bridge and the Inwa Bridge, of which the latter is situated 700 meters downstream of the former. In Pakokku the longest bridge of Myanmar was finished in 2011. It stretches 3.5 kilometres. (MNA, 2012)

FIGURE 3.1 ARTIFICIAL TRAINING WORKS ALONG THE AYEYARWADY RIVER BETWEEN MANDALAY AND NYAUNG-U. A: GROYNE, B: DIKE PROTECTION, C: PUMPING STATION, D: FLOOD WALL (COMMANDEUR, 2013)

4 METHODS

In this chapter more information is given on data availability and data processing. Following, the structure of this research is explained and the research methods are described.

4.1 DATA AVAILABILITY

To execute this research large datasets were required. Here an overview is provided of all types of relevant data and their sources (Table 4.1). Myanmar institutes have provided various sources of information. Though measurements were only taken over a short time period or accuracy is questionable. Navigational maps have been created by DWIR using a combination of satellite images, visual inspections and manual measurements. They are all handwritten in Burmese language. This also holds for the bathymetry maps, which were created by a combination of GPS and echo sounder tools. DMH provided information on daily water level, discharge and sediment discharge.

TABLE 4.1 BASIC INFORMATION ON THE USED TYPES OF INFORMATION AND THEIR SOURCES

Type	Description	Date created	References
Logbook + sediment samples	Navigation route between Mandalay and Bagan	25-26 Nov 2014	(Deltares, 2014a)
Sediment sample analysis	Obtained with grabber from riverbed, between Mandalay and Bagan	25-26 Nov 2014	(Myayarpin Engineering Co. & Deltares, 2014)
Data Review	Review on DWIR data, part of the feasibility study	28 Jan 2015	(Royal HaskoningDHV, 2015a)
Least Available depth charts	Between Mandalay and NyaungDon	5-11 March 2014	(Directorate of Water Resources and Improvement of River Systems (DWIR), 2014a)
Improvement works review	Old navigation maps from 1983 compared with current situation, including review of engineering works	28 Jan 15	(Royal HaskoningDHV, 2015b)
River surveys	Planform and river depths between Myitsone (upstream) and Bhamo (downstream), in Burmese language	2009 - 2014	(Directorate of Water Resources and Improvement of River Systems (DWIR), n.d.-b)
SRTM Myanmar	Elevation (90x90m)	Feb 2000	(U.S. Geological Survey (USGS), 2000)
Geology maps	Old and new geology maps	1977, 2007, 2014	(Myanmar Geosciences Society, 1977, 2014; U.S. Geological Survey (USGS), 2007)
Navigational maps	In Burmese language	*Unknown*	(Directorate of Water Resources and Improvement of River Systems (DWIR), n.d.-a)
Previous Haskoning studies	Irrawaddy and lower Chindwin river study & Myanmar Comprehensive transport study	1988, 1993	(Haskoning et al., 1988)

Photos	Structures, cities, environment, ships, natural river etc.	Nov 2013	(Commandeur, 2013)
Report	1-D Morphological model of the Ayeyarwady	26 Jan 14	(Commandeur, 2014)
Hydrologic datasets	Water level, discharge, sediment	1980-2014	(Department of Meteorology and Hydrology (DMH), 2014)
Satellite imagery	Landsat 4-5, 7 and 8 (see Appendix 3)	1989-2015	(U.S. Geological Survey (USGS), 2014b)

4.1.1 SEDIMENT SAMPLES

On the 29th and 30th of November 2014, 23 sediment samples were taken along the Ayeyarwady River between Mandalay and Nyaung-U by a Deltares executive. The sediment samples were taken from the river bed with a grabber device. The Burmese Myayarpin engineering company carried out the sediment analysis, consisting of a sieve analysis and a particle analysis for each sample (Myayarpin Engineering Co. & Deltares, 2014). See Figure 4.1 for the sampling locations.

FIGURE 4.1 SEDIMENT SAMPLING LOCATIONS WITHIN DELTARES PROJECT AREA. OBTAINED THE 29TH AND 30TH OF NOVEMBER 2014 BY DR C.J. SLOFF (DELTARES, 2014A)

4.1.2 Discharge data

The Directorate of Water Resources and Improvement of River (DWIR) and the Department of Meteorology and Hydrology (DMH) provided data on discharge, water level and sediment discharge. It includes daily water level measurements in the period between 1980 and 2014. Daily averages were provided for up to 10 measurements a day.

DMH works from ten stations: Monywa, Zalun, Pyay, Aunglan, Magway, Chauk, Nyaung-U, Sagaing, Katha and Myitkyin. Each measuring station has its own reference point, but is not given in absolute height above sea level. The water level data from the different stations could therefore not be mutually compared. Also deriving water depth from water levels would not be accurate, since erosion and sedimentation occurs on a daily basis. Still the discharge and water level data have been interesting for visualizing annual trends and for computing multi-year averages.

Discharge was determined by DMH based on a defined rating curve for each measuring station. Flow velocity were measured with a current meter (type and interval unknown) and combined with water depth to obtain discharge. There was no information available on the timing and exact location of the sampling from which this relation was established. Also sediment discharge was calculated from a rating curve. The formula of the rating curve is unknown, but the 'false' rating curve in Figure 4.2 provides a visualization of the relation between discharge and water levels.

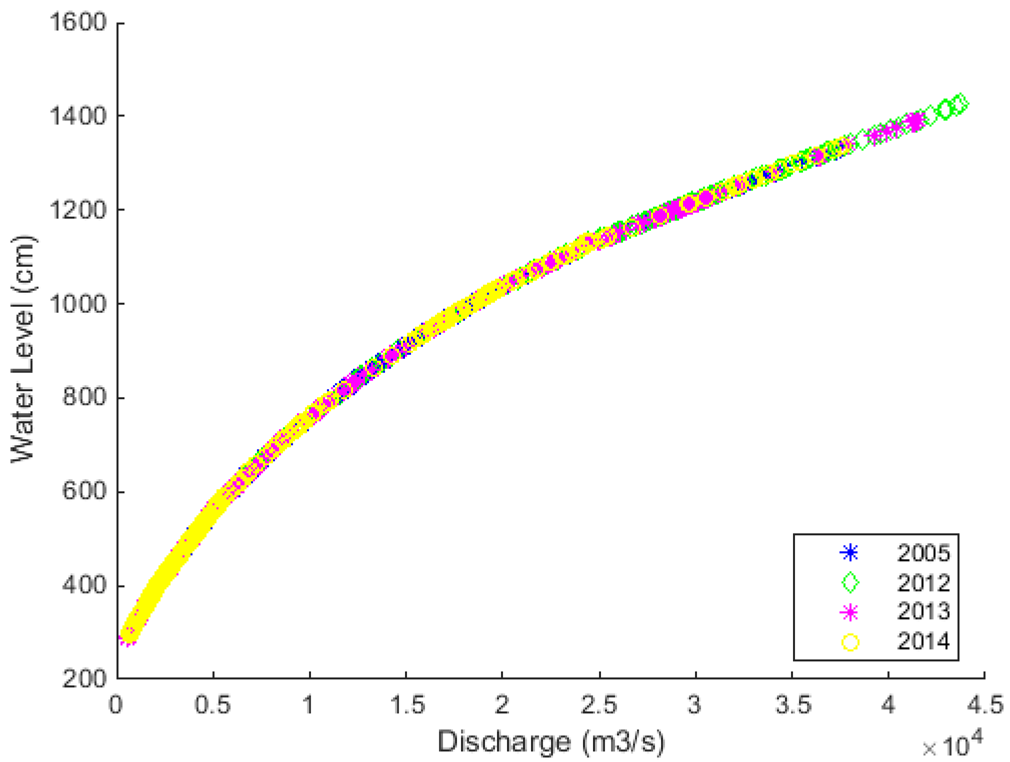

FIGURE 4.2 RATING CURVE FOR DERIVING DISCHARGE FROM WATER LEVEL DATA IN CHAUK. BASED ON DATASETS FROM (DEPARTMENT OF METEOROLOGY AND HYDROLOGY (DMH), 2014)**.**

For simulation and analysis purposes three measuring stations were used. The Sagaing station provided discharge and water level data for the Ayeyarwady upstream the confluence. The Monywa station provided information for the Chindwin River. Chauk represented the downstream combined discharges of the Chindwin and Ayeyarwady Rivers after the confluence (for locations see Figure 1.1).

4.1.3 Satellite imagery

The most important source of information is a large number of satellite images coming from NASA Landsat satellites. The LandsatLook viewer provides visual and download access to the USGS "Natural Colour" image product archive (U.S. Geological Survey (USGS), 2014b).

Satellite specifications

The four providing Landsat satellites have different properties (U.S. Geological Survey (USGS), 2014a and USGS webpages). The Landsat Multispectral Scanner (MSS) images consist of four spectral bands with a 60 meter spatial resolution. The Landsat Thematic Mapper (TM) images, have a spatial resolution of 30 meters and consist of seven spectral bands. Landsat ETM+ stands for Enhanced Thematic Mapper plus, which has a resolution of 30 meters, but has increased radiometric sensitivity and dynamic range. It also contains an additional spectral band (Band 8), measuring within the panchromatic spectrum. The most recently launched satellite is the Landsat 8 Operational Land Imager (OLI). Its images consist of 9 spectral bands with a spatial resolution of 30 meters. Also a Thermal Infrared Sensor (TIRS) is built-in, with two thermal infrared bands. In May 2003 the Scan Line Corrector of the Landsat 7 ETM+ failed. This SLC compensates for the forward motion of the satellite, correcting the zigzag pattern of the scan-line. During failure between 2003 and 2012 satellite images contain black stripes in the edge of the images scenes, indicating duplication or data loss.

Because of the large area of interest, the images were downloaded in two parts. Mandalay, the section between Mandalay and the confluence point of the Chindwin and Ayeyarwady River is covered by Landsat tile 133, 45 (path, row). Nyaung-U, the section between the confluence point and the city Nyaung-U is covered by Landsat tile 134, 45 (Figure 4.3). The images were downloaded in Tagged Image File Format (geoTIFF) containing georeferencing information, making them compatible within ArcGIS (Appendix 2: Software).

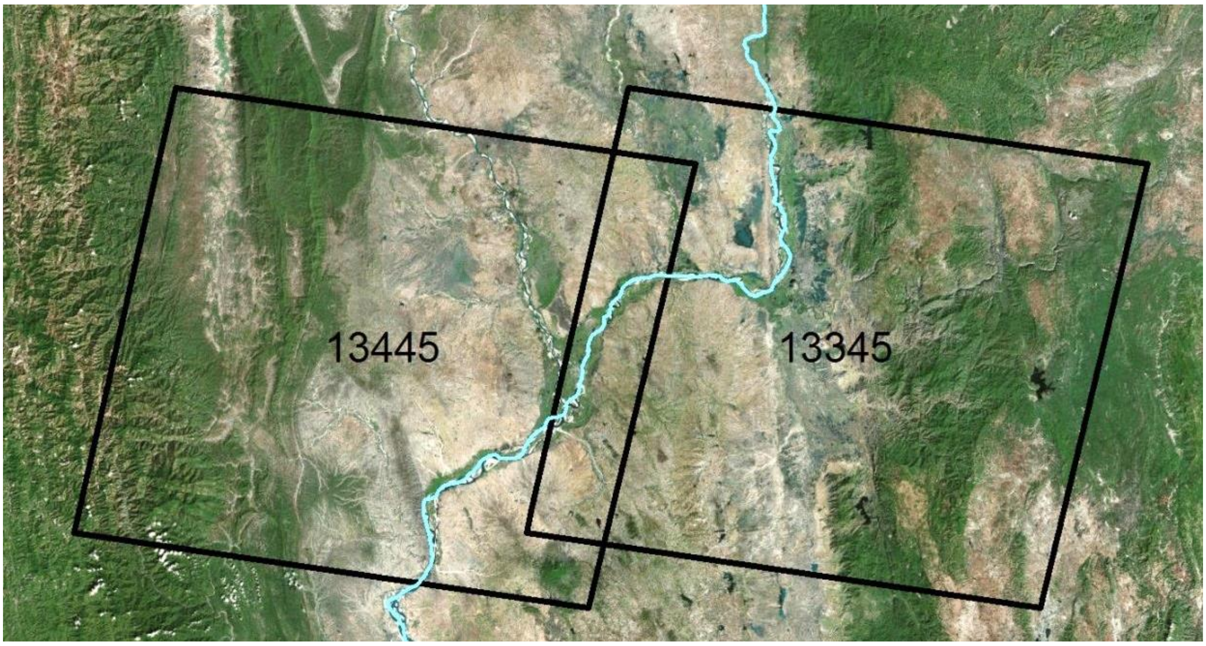

FIGURE 4.3 EXTEND OF THE USED LANDSAT IMAGERY OVER THE PROJECT AREA. PATH 133 AND 134, ROW 45

Processing

Within ArcGIS, the available satellite images were processed to be used for river morphology change analysis. The river, river bars and islands and other object were recognized and classified, in order to visualize shifts and quantify surfaces. Manually doing this task would be time consuming and accuracy can be inconsistent. Therefore it was done in a semi-automatic manner. Object based image analysis (OBIA) was carried out with the Image Classification toolbar within ArcGIS (ArcGIS version 10.2.1).

In each satellite image, four classes were predefined by manual delineation: water, exposed sediment bars/islands, vegetated areas and bare ground or exposed rock. With a spectral graph analysis the classes homogeneity were reviewed. With the 4 classes a signature file is created, which is the input for following Maximum Likelihood classification (ESRI, 2013). The input files for the classification were the image and the signature file. Other settings were a reject fraction of 0.0 and the a priori probability weighting Equal.

The output was a raster file containing all cells classified as one of the four possible classes. Generally, the classification of water and bare ground has the highest confidence level. This is caused by the homogenous visual spectrum of cells in those classes. In the next step, the random noise and small isolated regions were cleaned-up with post-classification processing. The spatial analyst generalization tool Majority cleans up noise, by reclassifying all cells based on the majority of their contiguous neighbouring cells. Boundary Clean smooths the boundary between zones by expanding and shrinking it. Finally, the raster files were converted into polygon shapefiles. The simplifying option was applied, resulting in enhanced smoothing. The shapefiles were used to visualize and analyse river morphology changes.

4.2 RESEARCH STRUCTURE

The structure of this research is based on gradually decreasing spatial and time scale: from drainage basin, to project area, to research area, to river section. Each next step is based on conclusions from the previous step.

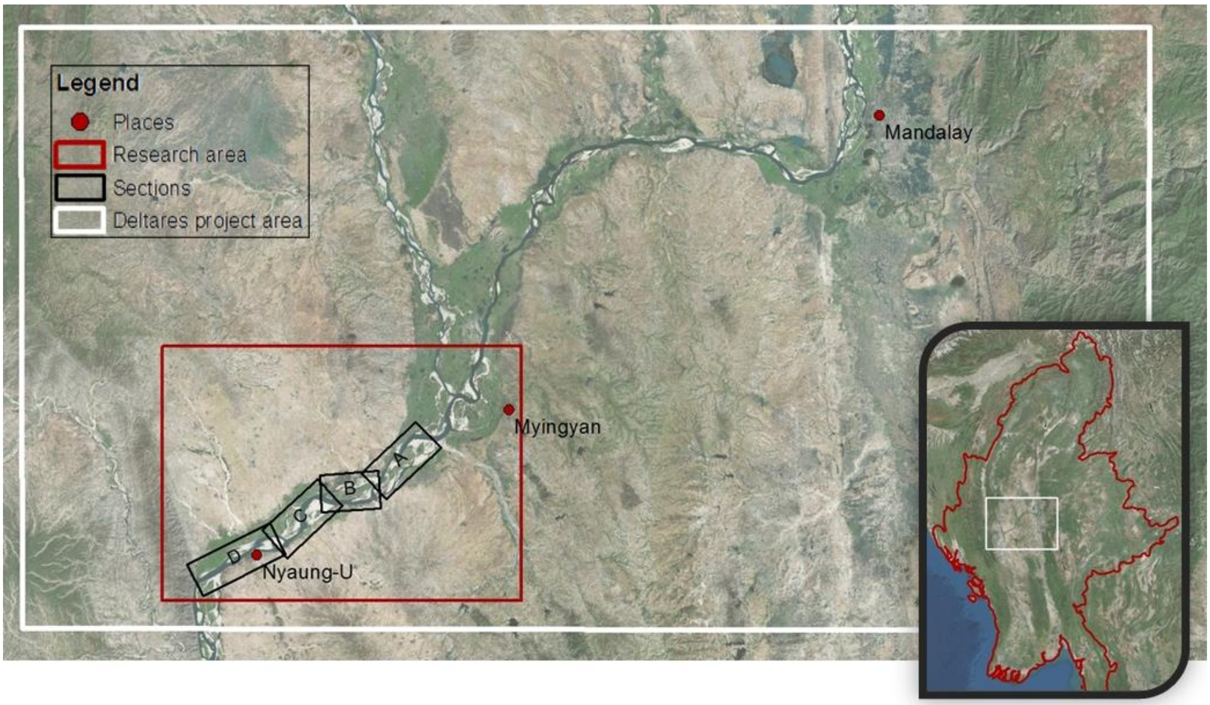

FIGURE 4.4 DELINEATION OF THE REGIONS DESCRIBED ON DIFFERENT SPATIAL SCALES. IN THE FIGURE RIGHT BELOW AN OVERVIEW OF MYANMAR WITH THE LOCATION OF THE DELTARES PROJECT AREA IS VISUALIZED.

First the entire drainage basin was reviewed. Discussing boundary conditions such as discharge regime, climate, tectonics and continental setting contributes to a profound understanding of the river system. The channel network was reviewed on drainage pattern and waterway transport changes. The next step focussed on the area as limited by the Deltares project. The river's planform pattern was described and the project requests and navigation requirements were examined. Based on the findings from the catchment description and project area review a smaller area was selected. The reach below the confluence with the Chindwin River is braided, highly dynamic and therefore less predictable. This meets the research objective to find out how the river's dynamic behaviour can contribute to adapting the river morphology for navigational purposes. Other reaches (upstream confluence) appear less dynamic and are straighter. The area of interest is expected to create the most difficulties for navigation. The entire Deltares project area was too large to investigate within a small timeframe. Within the research area a more extensive morphological description and a preliminary satellite image analysis focussed on the shift of the main channel through time, the stability of the river and planform change. This contributed to the recognition of different 'problems' or knowledge gaps for the next step. Four consecutive river sections within the area of interest were chosen for further investigation. The four sections are all dissimilar in their planform appearance and all required a separate research plan, based on conclusions from the prior larger scale satellite image analysis. The combination of a more detailed satellite image analysis, a geometry analysis and a model simulation gave answers to section specific questions and the interaction between the four sections. The two most important themes were bar behaviour and channel migration. Based on an understanding of these two subjects, predictions were made on future river changes.

4.3 MORPHODYNAMIC ANALYSIS OF SECTIONS

A variety of methods was used for morphodynamic analysis of the sections within the research area. A data analysis of the water level and discharge datasets provided information on the input of the river. A 10 year average of the water level and discharge datasets between 2005 and 2014 was used as an input for the simulations. Sediment size and sediment discharge for the past 35 years were reviewed together. Accuracy for the latter dataset is low, but sediment plays an important role in river morphodynamics. Satellite images were used for observing and visualizing planform changes through time. It also gave more insight in the locations of resistant river banks. For each separate section a more extensive satellite image analysis was carried out as well. Also two field trips in Myanmar contributed to analysing the active shift of the river. During the field survey on the Ayeyarwady River in March 2015 a GPS track was recorded and afterwards compared to another sailing track from November 2013 (Commandeur, 2013). This chapter gives more information on the research methods used for the four sections.

4.3.1 GEOMETRY MEASUREMENTS AND CHANGE DETECTION

The large dataset of satellite images was used for geometry measurements and a change detection of the river's planform. For this analysis a selection was made of Landsat images with cloud coverage less than 20% and in specific months of the year. Images from the months January to April were most suitable for morphological evaluation, since water levels are low and morphological features are exposed. Images from September, October and November provided more information on the river's appearance during high water levels.

GEOMETRY

The geometry measurements include all static measurement on the river contributing to a better classification, description and understanding of the river. Geometric measurements include:

- Number of (active) channels
- Bar shape
- Maximum and minimum width of the river
- Bend angle
- Confluence angle
- Sinuosity index or braiding index
- Number of old cut off channels visible

Most of these measurements were carried out manually within ArcGIS. Water- and island surface ratio and bar shape were determined automatically, using the shapefiles characteristics in the attribute table. When measuring geometry of the river it is important to bear in mind what the water level was at the date the satellite image was obtained, because a difference in water level results in a difference in i.e. width of the river or the number of active channels. Thus the measurements were carried out on the same satellite images for each section. This is a statistic method for describing and quantifying the planform of a river or river section and does not include analysis of change over multiple years. Geometry measurements were done for all sections and a more extensive description is given for sections B and D.

PLANFORM CHANGE

The planform change detection was an analysis of change of the river channels and bars. Relevant features and processes are:

- lateral accretion of bends
- life cycle of bars
- erosion velocity
- cutoff quantity

- channel migration
- bar migration
- changes in river width
- width ratio changes for two channels

The change detection with satellite images was a dynamic analysis of morphologic changes. The products of the analysis were visualizations of changing river planform through time, with a description of all (possible) related processes and features. Knowing the direction, rate and quantity of certain processes will help predict future behaviour of the river sections. For all sections separately and for the total research area an image analysis was carried out. The analysis of the total research area provided guidance for a focus on specific characteristics of each section. Also it supported in explaining the interactive processes between the different sections.

PLANFORM COMPONENT: BARS

River planform in braided rivers is largely controlled by bar formation and migration. Bars are in-channel accumulations of sediment. They emerge during low water, while they are invisible during high water when morphologic processes are most active. Bar shape depends on the width to depth ratio of the channel. There are many types of bars – a classification is given in Figure 4.5. The bars in the Ayeyarwady River are classified according to this scheme. A short literature review on this and other planform components is given in Appendix 4: Planform components – literature review

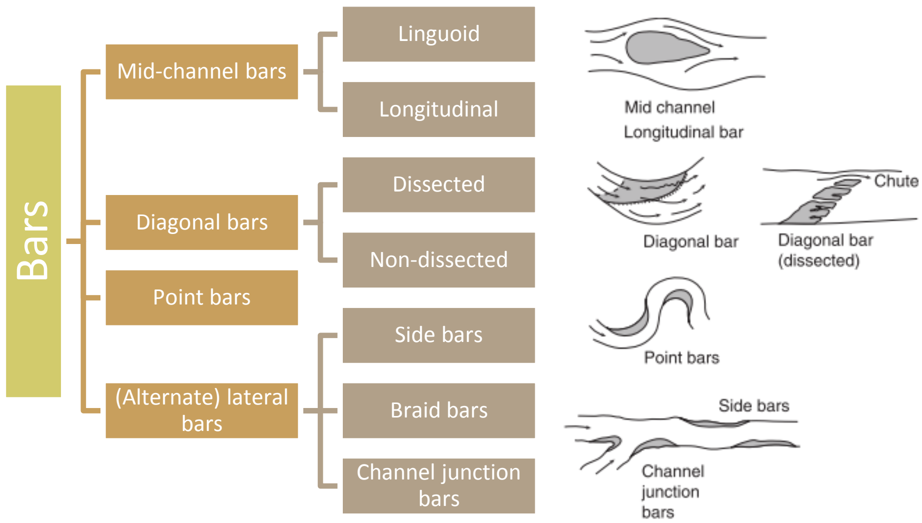

FIGURE 4.5 SCHEMATISATION OF POSSIBLE BAR TYPES IN THE RESEARCH AREA. WITH EXAMPLES FROM CHARLTON (2008)**, BASED ON** CHURCH & JONES (1982); CHURCH (1992); AND MORISAWA (1985)

4.3.2 COMPUTATIONAL MODEL SIMULATIONS

In order to increase the understanding of the active processes in the river and their effects on river bedform and planform, model simulations were executed of certain river sections in the area of interest. This is performed using the Deltares open software Delft3D-FLOW. Flow is a package focussing on 2D or 3D hydrodynamic and transport simulations. It calculates non-steady flow and transport phenomena on a predefined grid (Deltares, 2014b) (Appendix 2: Software). For initial bed level elevation the SRTM elevation map from February 2000 was used (U.S. Geological Survey (USGS), 2000). In 2000 the river planform was different from the current situation, causing the simulations to deviate from recent river planform observations on satellite images. Also the radar does not record below water surfaces. The initial river bed was therefore uniform and a pre-processing simulation was applied to obtain a realistic initial bed level. Other important input parameters are given in Table 4.2. For a more extensive description on the preparations and input of the model see Appendix 3: Delft3D simulation.

TABLE 4.2 BASIC INPUT PARAMETERS FOR THE SIMULATION IN THE 2D FLOW MODEL IN DELFT3D

Parameter	Description or input
Initial water level (non-uniform)	+/- 4 meters
Time frame	1 year
Morphological acceleration factor	5
Sediment	Bedload sand, 0.4 mm diameter
Manning roughness coefficient	0.04 (Arcement & Schneider, 1989; Chow, 1959)
Viscosity and diffusivity	1.35 [Pa/s] and [m^2/s] (Rodi, 1993; Tinkler & Wohl, 1998)
Transport equation	Engelund-Hansen (Engelund & Hansen, 1967)

River flow simulations of the Ayeyarwady River in FLOW provided more insight in the flow and sediment transport dynamics of the river. For complicated braiding rivers such as the Ayeyarwady it is difficult to obtain a result equal to reality. Predicting the exact migration of the channel or visualizing alternations in the river bathymetry was therefore not a realistic ambition. Though, with all boundary conditions and known systems variables included in the model, the processes taking place in the simulated river corresponded to real processes. With this locations of instability were recognized; the river thalweg was located; characteristic flow velocities and water depths were derived and bar formation was reviewed. Also reoccurring processes as were seen in the image analysis were easier to analyse with smaller time steps in the model. The simulation covers the full research area. For sections A, C and D the simulation results are discussed in more detail.

5 MORPHODYNAMICS OF THE RESEARCH AREA

The section between the confluence of the Ayeyarwady with the Chindwin and Nyaung-U (Figure 5.1) is highly dynamic. Here the river flows through multiple channels and island formation and migration is common. This braiding section is expected to have more depth variations than the single sinuous reaches upstream the confluence – and is thus expected to create more difficulties for navigation. In addition, straight or sinuous channels have been investigated extensively in literature and show relatively predictable behaviour, in contrast to the less understood braiding rivers. This chapter contains a description of boundary conditions, relevant processes and a channel change analysis.

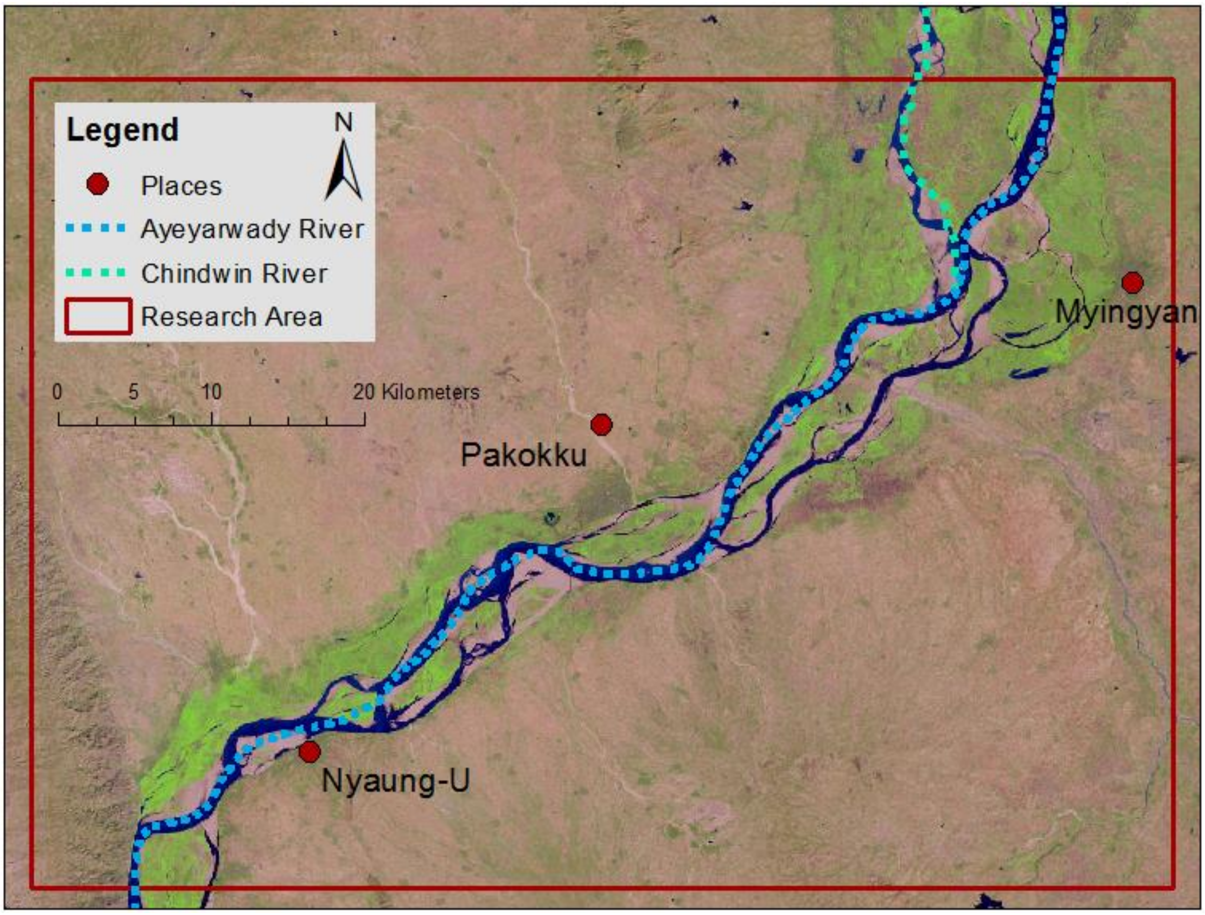

FIGURE 5.1 THE RESEARCH AREA INCLUDING THE CONFLUENCE POINT AND RELEVANT PLACES. THE RIVER COURSE LINES WERE CREATED BASED ON OLD SATELLITE IMAGES AND DO NOT REPRESENT THE CURRENT SITUATION. BASEMAP; 07-01-2015 LANDSAT 8

5.1 BOUNDARY CONDITIONS

5.1.1 WATER LEVELS

Both in Sagaing and Chauk minimum water levels have decreased over the past years (Figure 5.2). This could be caused by changes in river bed topography or by decreasing discharge. Bed erosion is not accounted for in the measurements and can affect the depth of the river at the measuring station without changes in water levels being present. Water level is determined based on water depth relative to a local reference level. Decreasing discharge can be explained by changes in rainfall, or by upstream installed dams. Different effects are counteracting and relative influence is not measurable. As mentioned in Data availability, the datasets are not accurate and are mostly interesting for visualizing annual trends and for computing multi-year averages. For further analysis averages are used from the most recent 10 years of measurements.

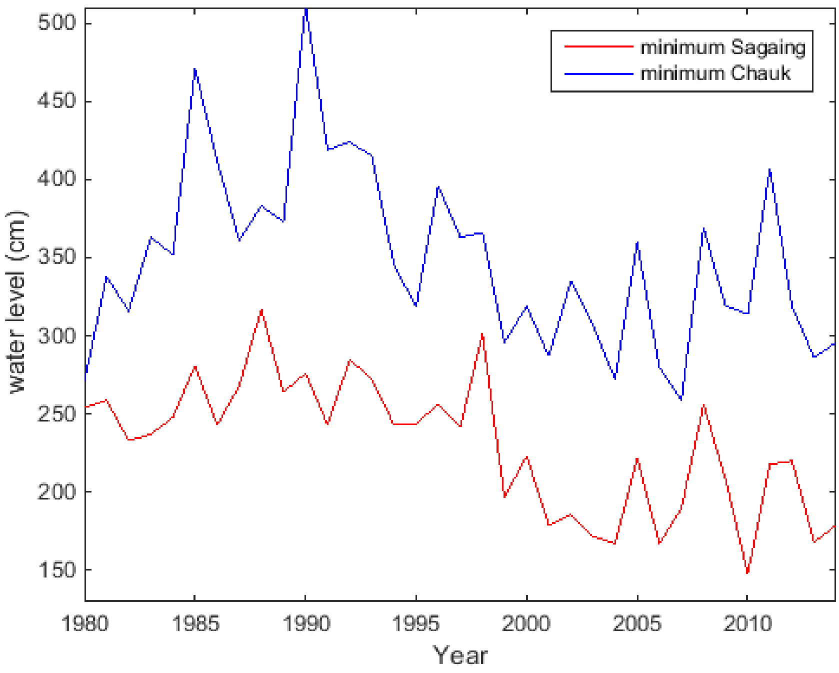

FIGURE 5.2 MINIMUM WATER LEVELS IN SAGAING AND CHAUK FOR THE PAST 35 YEARS. WATER LEVELS ARE GIVEN ACCORDING TO A LOCAL REFERENCE LEVEL. THE 4TH DEGREE POLYNOMAL IS FITTED AS A TRENDLINE VISUALISATION

5.1.2 Discharge

Normally the ratio between the discharge from the Ayeyarwady and the discharge from the Chindwin River is around 1.5. This indicates that the Ayeyarwady River gives 50% more discharge than the Chindwin in the months between July and February. In the months March, April, May and June the ratio increases, showing a relatively higher discharge from the Ayeyarwady River, up to 7 times as high as the Chindwin River. This peak from the Ayeyarwady is related to the high temperatures between March and May and the increasing rainfall in April and May. Snowmelt occurs in spring, but the Chindwin source mountain ranges do not contain as much snow as the mountains upstream the Ayeyarwady River. The changing ratio between the two river discharges affects the water inflow at the confluence point as well as the relative sediment discharge from both reaches.

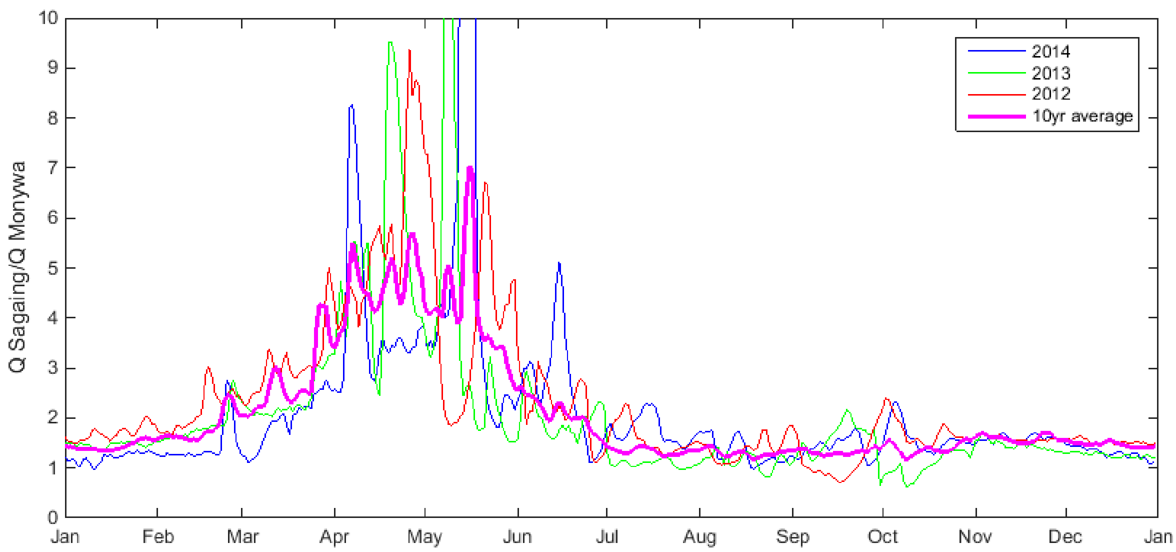

FIGURE 5.3 THE RATIO BETWEEN THE DISCHARGE FROM THE AYEYARWADY RIVER AND CHINDWIN RIVER IN 2012, 2013 AND 2014. ALSO A 10 YEAR AVERAGE FOR THE PERIOD 2005-2014 IS INCLUDED.

5.1.3 SEDIMENT

The majority of the samples obtained in November 2014 contained >90% sandy material (Table 5.1). Samples 11/12 and 23 contained more than 20% gravel. Also samples 14, 21 and 22 have relatively coarse material, although mostly still within the sand particle size range. Based on the sediment samples taken by Deltares in 2014, it can be concluded that bed material load from the Ayeyarwady River between Mandalay and Nyaung-U is sandy. All samples have a median grain diameter of around 0.3 mm and on specific locations sediment becomes coarser. At sample location 11/12 the river enters a narrower passage. Samples 5, 8, 14, 21, 22 and 23 were obtained in bends or narrow and deep sections of the river. Here flow velocities are expected to be higher and flow can carry coarser sediment. It is remarkable that sediment size does not decrease in downstream direction. This was also recognized by Commandeur (2014) based on the data from Haskoning et al. (1988) over a river stretch of 1000 km.

TABLE 5.1 RESULTS FROM THE PARTICLE SIZE ANALYSIS ON 23 SAMPLES FROM THE AYEYARWADY RIVER (MYAYARPIN ENGINEERING CO. & DELTARES, 2014)**. PARTICLE DISTRIBUTION IS GIVEN IN PERCENTAGES.**

Sample	Silt& clay (%)	Sand (%)	Gravel (%)	Sample	Silt& clay (%)	Sand (%)	Gravel (%)
1	0.97	99.03		**13**	0.15	99.66	0.18
2	0.52	93.17	6.31	**14**	0.07	95.37	4.56
3	0.11	99.89		**15**	0.17	98.72	1.11
4	0.40	99.60		**16**	0.18	96.14	3.69
5	0.21	91.65	8.14	**17**	0.04	98.01	1.95
6	0.01	97.88	2.12	**18**	0.30	98.79	0.91
7	0.08	99.92		**19**	0.04	96.08	3.89
8	0.14	92.19	7.67	**20**	0.18	97.95	1.87
9	0.24	98.68	1.07	**21**	0.19	96.36	3.44
10	0.09	97.85	2.06	**22**	6.87	83.46	9.67
11	0.30	71.10	28.61	**23**	0.38	78.49	21.13
12	0.12	71.32	28.57				

According to the rating curve and measured stages, sediment discharge in Chauk (downstream) ranges from 165 kg/s in winter to 18000 kg/s in the southwest monsoon period. During high discharge, at Chauk the river carries approximately 3 times as much sediment as in Sagaing (Department of Meteorology and Hydrology (DMH), 2014). The riverbed itself and the Chindwin are sediment suppliers. Also other smaller tributary rivers of the Ayeyarwady River, such as the one at Pakokku (Figure 5.5), supply bed material and wash load.

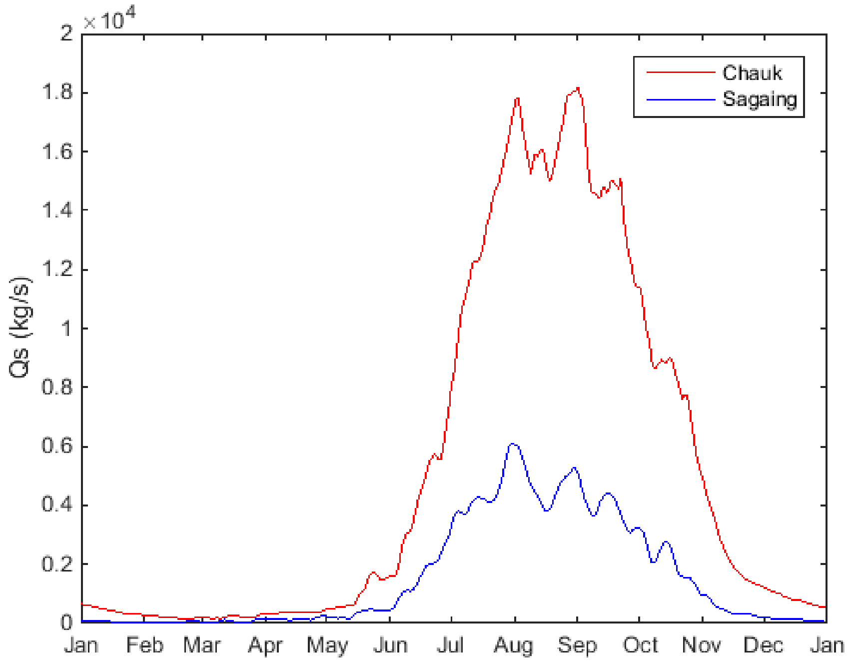

FIGURE 5.4 SEDIMENT DISCHARGE IN CHAUK AND SAGAING, 10 YEAR AVERAGE

In many satellite images of the confluence of the Chindwin and Ayeyarwady rivers it can be seen that the suspended sediment load of both rivers differs a lot The Chindwin River contains a high amount of fine sediment, making the river more reflective than the Ayeyarwady. The Ayeyarwady River shows a darker colour (low reflection), indicating low suspended sediment load. This is recognized in Figure 5.5 as a deviation in colour, which is visible in all months of the year, but most clear during low discharge. After the confluence near Myingyan, the two flows remain parted for up to 36 kilometres, after which the two flows finally mix up near Pakokku.

FIGURE 5.5 THE AYEYARWADY RIVER BETWEEN MYINGYAN AND PAKOKKU. THE DIVISION OF THE CHINDWIN AND AYEYARWADY RIVER IS STILL VISIBLE, WITH THE CHINDWIN FLOW BEING BRIGHTER THAN THE AYEYARWADY FLOW. BASE MAP; NOVEMBER 2009 (DIGITAL GLOBE, 2009)

5.2 PLANFORM CHANGES

The entire river stretch within the project area is very dynamic in its planform change. Figure 5.6 shows two recorded river tracks from field surveys projected on a satellite image. The satellite imagery is from November 2009, the lime green track from November 2013 and the pink track from March 2015. In box A it is visible that the river eroded almost 700 meters in the lower bend within 5.5 years. In Box B the river show a change to a more sinuous path, with erosion up to 500 meters in the outer bends.

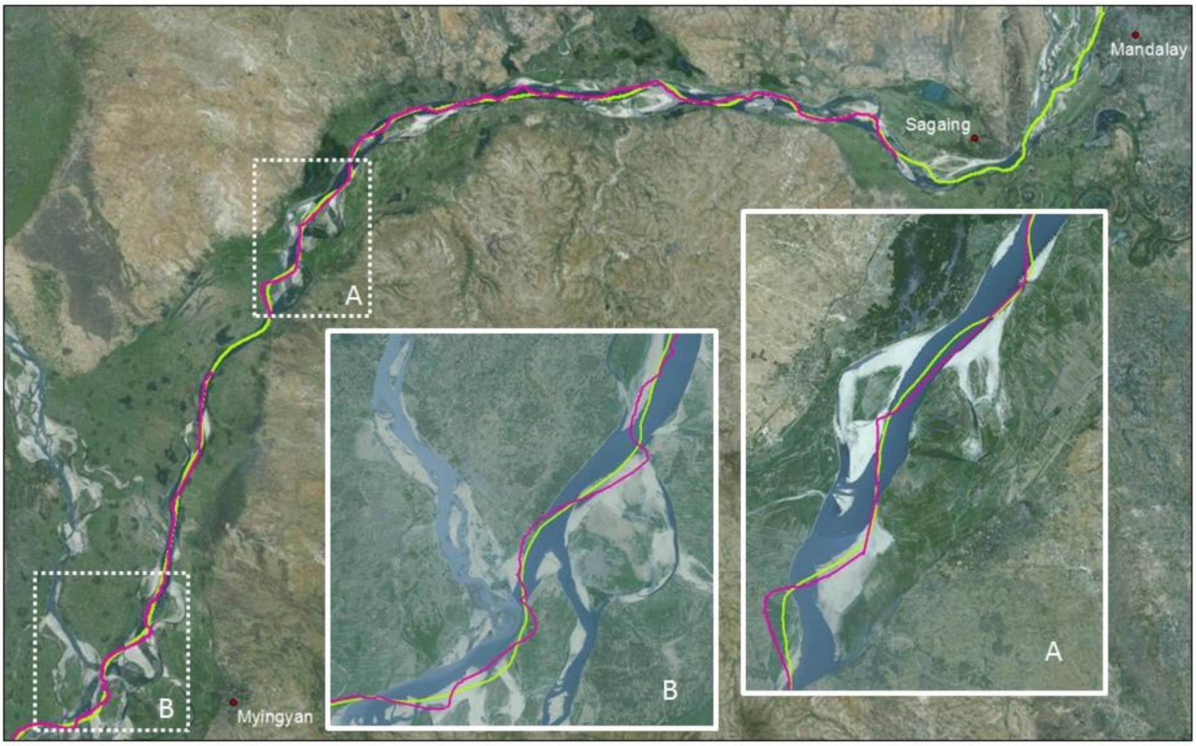

FIGURE 5.6 NAVIGATION ROUTES OF TWO BOAT TRIPS ALONG THE AYEYARWADY RIVER IN NOVEMBER 2013 (LIME GREEN) AND MARCH 2015 (PINK) BETWEEN MANDALAY AND MYINGYAN. TWO BOXES DISPLAY LOCATIONS WHERE LARGE CHANGES HAVE TAKEN PLACE. BASE MAP; NOVEMBER 2009 (DIGITAL GLOBE, 2009)

Compared to the section upstream the confluence, the river is even more dynamic in the research area. Figure 5.7 provides an overview of the changes in the main channels centreline through time. Figure 5.8 shows the different river paths of the Ayeyarwady River in three years: 1974, 1996 and 2013. In places where the river was active in multiple or all years, colours are darker.

Some sections are very stable, such as the section in the centre of the images, below Pakokku. In the visualized 14 years of Figure 5.7, the river has eroded less than 30 meters in southern direction and widens only during flood. This high stability was also identified on a longer timescale in Figure 5.8. In the three given years the main channel was situated along the river banks and did not shift. The same stability can be seen along the southern side of the river at Nyaung-U, albeit on a smaller scale. Both figures also show the stability of the incoming Ayeyarwady River before the confluence, and at what point the river becomes laterally active. Just northwest of Nyaung-U two evolving meander bends are visible (Figure 5.7). These bends have migrated between 2000 and 2014 with more than 3 kilometres in a downstream and lateral direction, making it more sinuous. Just downstream the confluence point of both rivers, northwest of Myingyan, the main channel has large sinuous bends in 2000 and in 2014. In the years in-between the river was still sinuous, but to a lesser extent. In both pictures the two parallel channels are visible. The location of the two channels is not stable due to the sinuous shifting, but its stability increases in downstream direction.

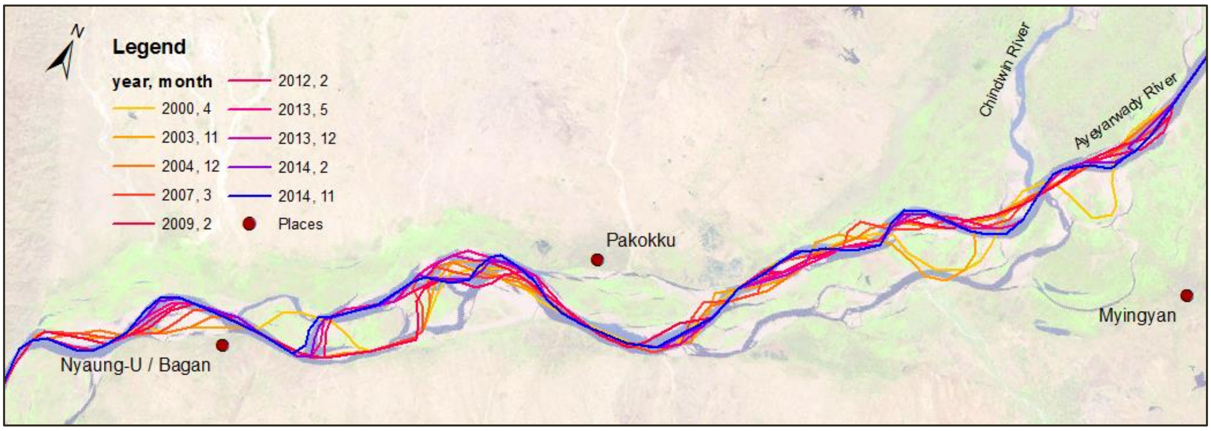

FIGURE 5.7 CHANGING MAIN CHANNEL CENTERLINES BETWEEN 2000 AND 2014, DOWNSTREAM THE CONFLUENCE WITH THE CHINDWIN RIVER. BASEMAP: FEBRUARY 2014

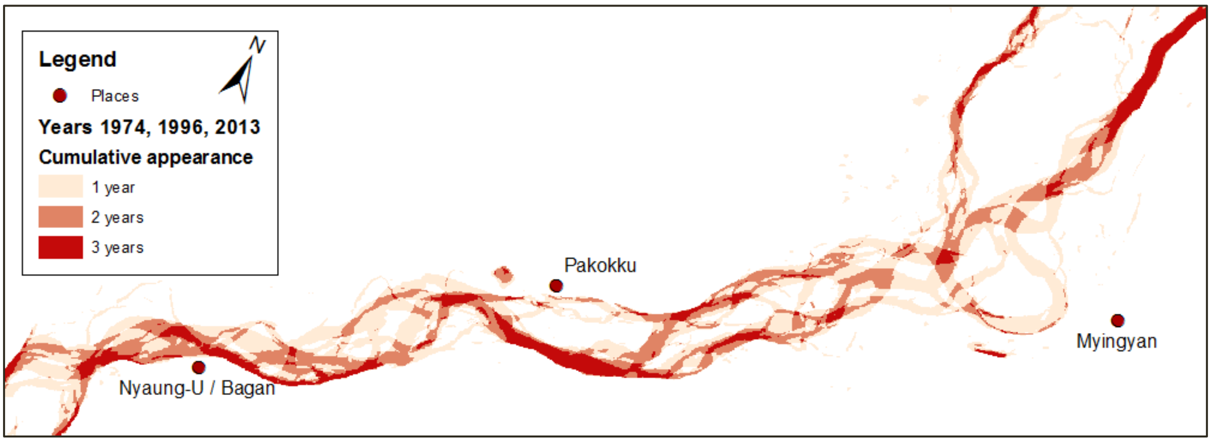

FIGURE 5.8 SUMMATION OF THE RIVER PATH OF THE AYEYARWADY RIVER DOWNSTREAM THE CONFLUENCE IN THREE YEARS. 25-01-1974 LANDSAT 1, 10-05-1996 AND 01-05-2013 LANDSAT 5. DARKER COLOURS INDICATE FREQUENTLY OCCUPIED AREAS, EQUIVALENT TO MORE STABLE RIVER SECTIONS

5.3 MORPHOLOGY

5.3.1 BARS AND ISLANDS

In March 2014 various types of bars were present in the research area (Figure 5.9). Lateral side bars and point bars are most common, as well as islands. Several lateral side bars have developed into point bars after the channel became more sinuous (west of location III in Figure 5.9). Also many islands are present, which have formed due to the stabilization of point-, braid- or mid channel bars. This stabilization is induced by vegetation and is enforced by sedimentation and related height increase when the river floods the island. In March 2014 only one longitudinal mid-channel was visible. The other mid-channel features are all stable islands.

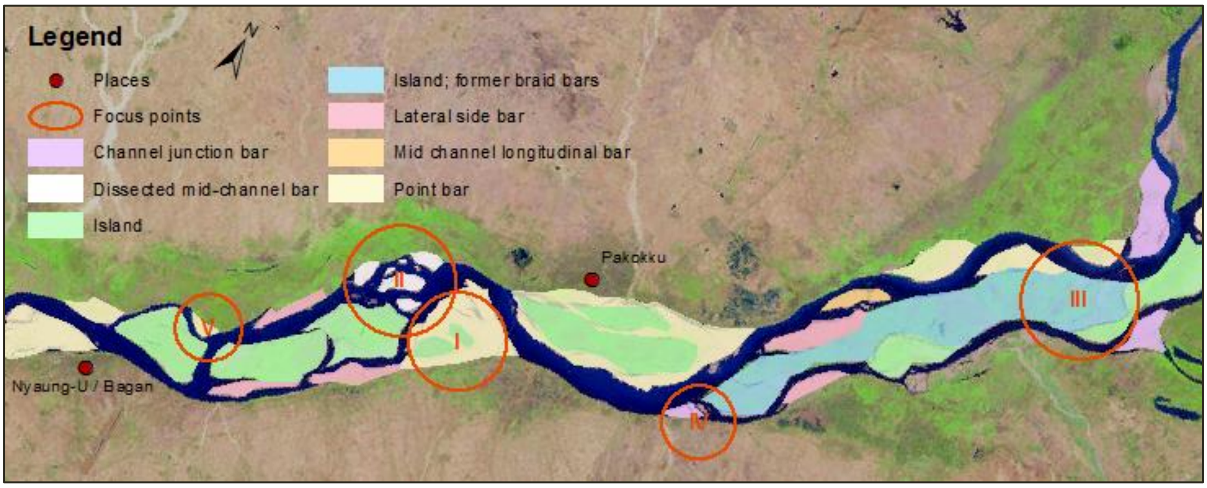

FIGURE 5.9 BAR TYPES AND ISLANDS IN THE RESEARCH AREA, BASED ON A SATELLITE IMAGE FROM 09-03-2014 LANDSAT 8. THE FOCUS POINTS ARE DISCUSSED IN THE TEXT.

At focus point I in Figure 5.9 a point bar is visible, formed by the upstream flow being forced in northwest direction due to high flow velocities, and hitting the opposite river bank before bending south. During flood the point bar is reduced in size and cut off (Figure 5.10 left), but its centre part is stabilized by vegetation and is not eroded. Although the chute cut-off has a theoretic channel gradient and length advantage, the cut-off has not developed as a permanent channel. This is caused by both the incoming angle of the river and the short flood period. At the opposite river bank (focus point II) multiple small islands are visible. Throughout the past 5 years this has been a mid-channel linguoid bar, with varying planform shapes. In 2013 the bar was dissected during high discharge and the small dissection bars have migrated in different directions. The initiation of this dissection was first visible in January 2013. The elongated island in the upstream section of the river at focus point III is formed by a sequence of alternate braid bars. The typical shape of these bars is still visible during high water (Figure 5.10 right).

At locations where two channels join channel junction bars have formed (focus point IV, Figure 5.9). This is caused by secondary flow and does not occur on a large scale in the research area. At the bifurcation at focus point V also a small bar has formed. The southern channel lies in line with the upstream channel, while this bifurcation channel is almost perpendicular. In the inner bend a point bar is formed.

The stability of the bar planform shape varies with the type of bar. Islands are most stable and maintain their approximate shape for more than 10 years. They erode at a constant but slow rate. Lateral side bars, braid bars and channel junction bars are evolving over a smaller time scale, because they depend on the stage of the river. Still, if one of these types of bars migrates, it occurs at a constant rate. They commonly form at logical locations and for braid- and side bars its lateral extension can be estimated based on the possible erosion of the opposite river bank. The mid channel bars are the most dynamic features. They migrate freely and its erosion is very unpredictable based on the satellite images. This is illustrated by the situation at focus point II.

 

FIGURE 5.10 BARS IN THE AYEYARWADY RIVER DURING FLOOD. LEFT: DOWNSTREAM PAKOKKU AND RIGHT: AT THE CONFLUENCE. BOTH PICTURES ARE OF THE SAME SCALE. 17-09-2014 LANDSAT 8

5.3.2 RESISTANT BANKS AND FLOODPLAINS

Channel migration takes place during high discharge. Water levels differ with up to 10 meters between April and August. When water levels start lowering again new bifurcation channels become visible. Channel migration can be seen as island erosion or as the reoccupation of old bifurcation channels in the floodplains of the river. Some borders of the river consist of a more resistant and elevated substrate. In the field survey this was recognized as old floodplains with clay banks. This material is composed of shales form the Tertiary Miocene or Pliocene era, and is part of the Irrawaddy Formation (Myanmar Geosciences Society, 2014). The shales are more resistant and cohesive than the Holocene alluvial deposits in the channel belt, and therefore confine the channel at its borders. In most of the research area the southern part of the river is confined (Figure 5.11). In the northern side of the channel the lower floodplains are visible, which are regularly flooded and/or reoccupied by new channels. At Pakokku a resistant riverbank borders the river as well. In the west of Figure 5.11 an active thrust fault is visible. This fault confines the channel and makes the river bend south past Nyaung-U.

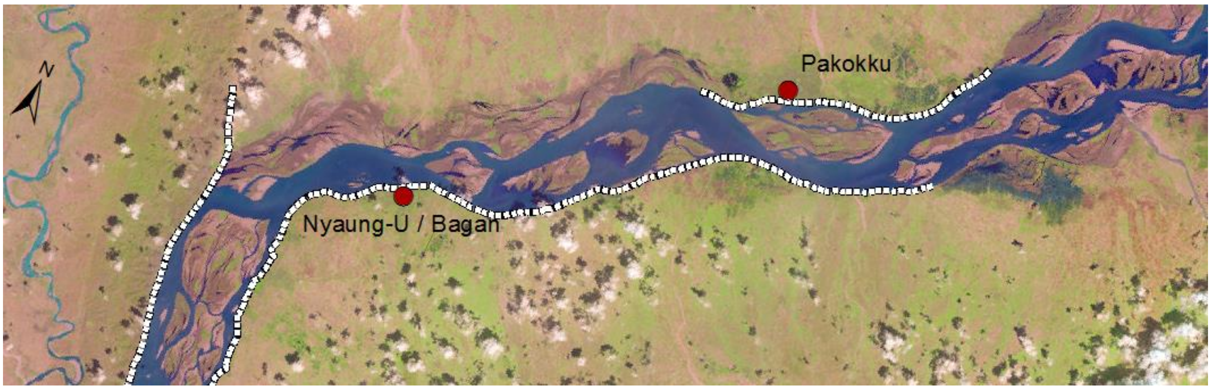

FIGURE 5.11 SATELLITE IMAGE OF THE RESEARCH AREA SHOWING THE LOCATIONS OF MORE RESISTANT SUBSTRATES AND THE EXTEND OF THE ANNUALY OCCUPIED FLOODPLAINS WITH OLD RIVER SIDE CHANNELS. 17-09-2014 LANDSAT 8

6 Morphodynamics of sections

All four of the sections selected for further research are very different. Section A consists of two intertwined channels. Section B is very stable. Section C is unstable, with large shifts and is expected to show large erosion and deposition differences throughout the year. In section D the river is sinuous and migrating at a constant rate. Despite these differences, these sections are all part of a river reach of only 55 kilometres. The first section is located 10 km downstream of the confluence, to out rule the effect of inflow ratio from the two rivers.

All sections are discussed separately, to identify the most important processes and boundary conditions causing the morphodynamic differences. Influence of up- and downstream sections is incorporated within the full model and by relating the outcomes of the four image analyses.

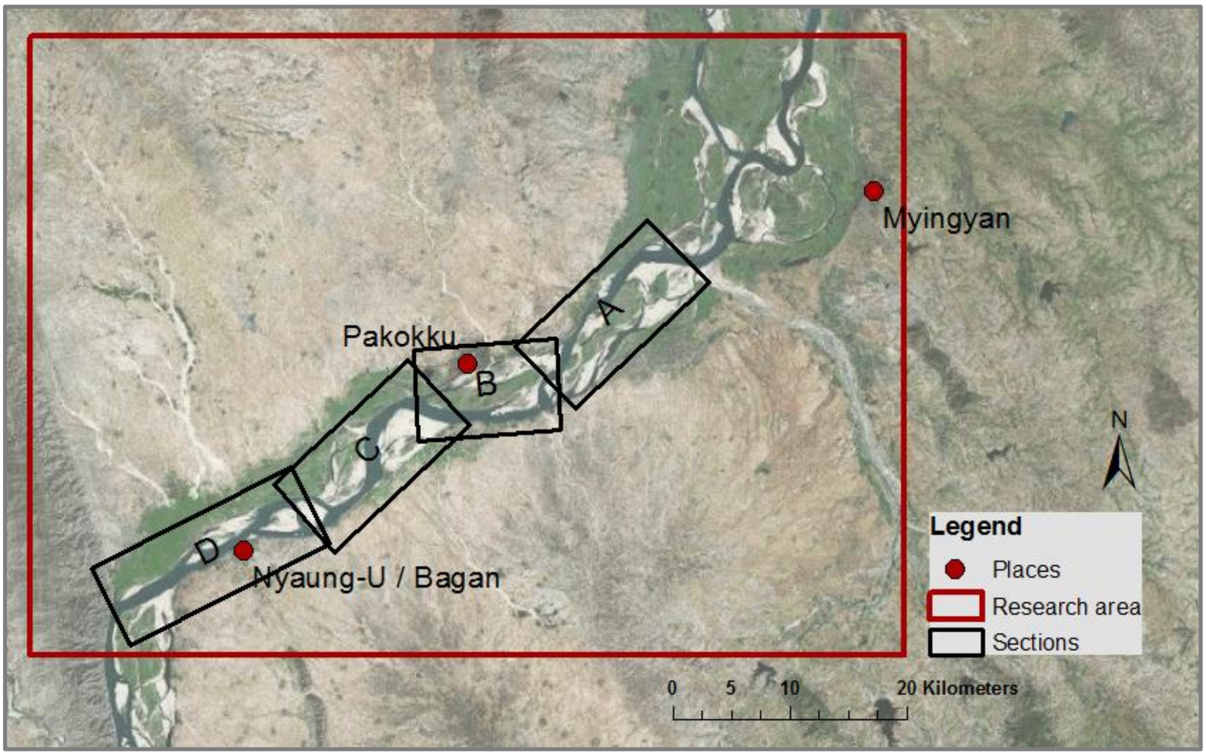

FIGURE 6.1 LOCATIONS OF THE FOUR RIVER SECTIONS WITHIN THE RESEARCH AREA.

6.1 Section A

6.1.1 Characteristics

This section can be characterized as highly complex, due to the two interacting channels and the braiding nature of the river at two scales: the two intertwining channels with large vegetated bars; and in-channel braiding bars which are not vegetated and very unstable. Although it shows small shifts, the location of the main channel has remained in the northern reach of the river, at least since 1999. Since 2011 the main channel became sinuous. Some connections between the main and secondary channel are formed by chutes and bifurcations.

TABLE 6.1 GEOMETRIC CHARACTERISTICS OF THE AYEYARWADY RIVER IN SECTION A, BASED ON SATELLITE IMAGES OF 16-04-2014 AND 17-09-2014 LANDSAT 8. MEASUREMENTS ARE TAKEN ALONG THE MOST REPRESENTATIVE COURSE OF THE RIVER IF NOT SPECIFIED OTHERWISE.

Measurement	Value (km, degrees or [-])
Number of active channels	2
Main bar shape (length/width)	26/3
Minimum width of the main channel	0.6
Maximum width of the main channel	1.8
Confined channel belt width	4.3
Sharpest bend angle	150°
Confluence angle main and sec. channel	60°
Braiding index	2.6
Number of large cut off channels visible	5

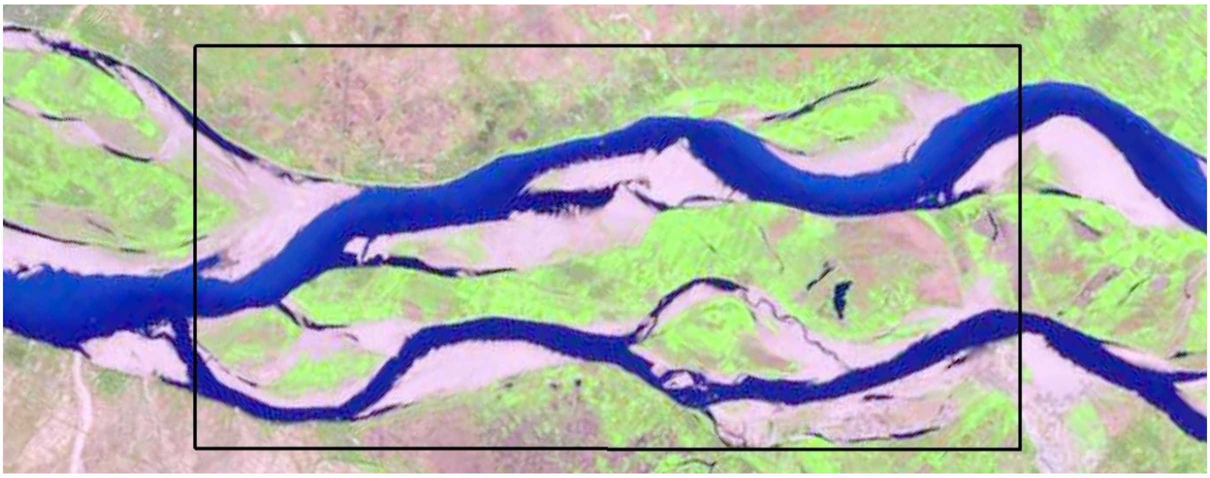

FIGURE 6.2 OUTLINE OF SECTION A IN THE AYEYARWADY RIVER, DELINEATED ON A SATELLITE IMAGE FROM 23-01-2015 LANDSAT 8

6.1.2 Planform change

Bar behaviour

The vegetated islands in-between the two large parallel channels (Figure 6.2) consist of connected alternate braid bars. Within the channels longitudinal bars, lateral alternate bars and dissected diagonal bars can be found. In the mixing zone between the Chindwin and the Ayeyarwady water small mid-channel bars form due to secondary flow. This is fundamental to the assumption that braiding rivers tend to form under highly variable discharges. The spatial migration pattern of the bars in section A is to a lesser extent predictable: alternate or point bars are cut-off; bars migrate downstream to the other side of the channel and reattach there; on its way the bars usually get dissected again.

The lifetime of bars depends highly on discharge variations and location within the channel. The large mid-channel island has existed in its present form since 2009. It has evolved from previous existing islands, thus age cannot be quantified.

CHANNEL SINUOSITY AND PLANFORM CHANGE

Although the main channel being part of a braided river section, the channel itself is sinuous. There are only few mid channel bars and multiple sidebars causing sinuosity. Also during flood the sinuosity of the channel is visible, explaining it to be more than only a sinuous thalweg within a braiding river. After 20 km it becomes straight again. This substantiates the theory of the sinuosity being induced by the upstream confluence direction. Before, when the channel was straight, also more mid channel bars were visible (Figure 6.3 2007/2009). Just past the first confluence point of Chindwin and Ayeyarwady River, the two partly separated channels split up and re-join multiple times. This region is highly dynamic, with many bifurcations and the main channel shifting from the south-eastern bend (Figure 6.3 2000) to the north-western straight channel (2009). Between 2000 and 2003 a large bifurcation emerged in the northern part, shortcutting the river bend previously mentioned. In the same period, a second bifurcation developed reoccupying the old channel between the meander bend and the secondary downstream channel. This causes the lower situated connection between the main channel and the secondary channel to fill in and close off.

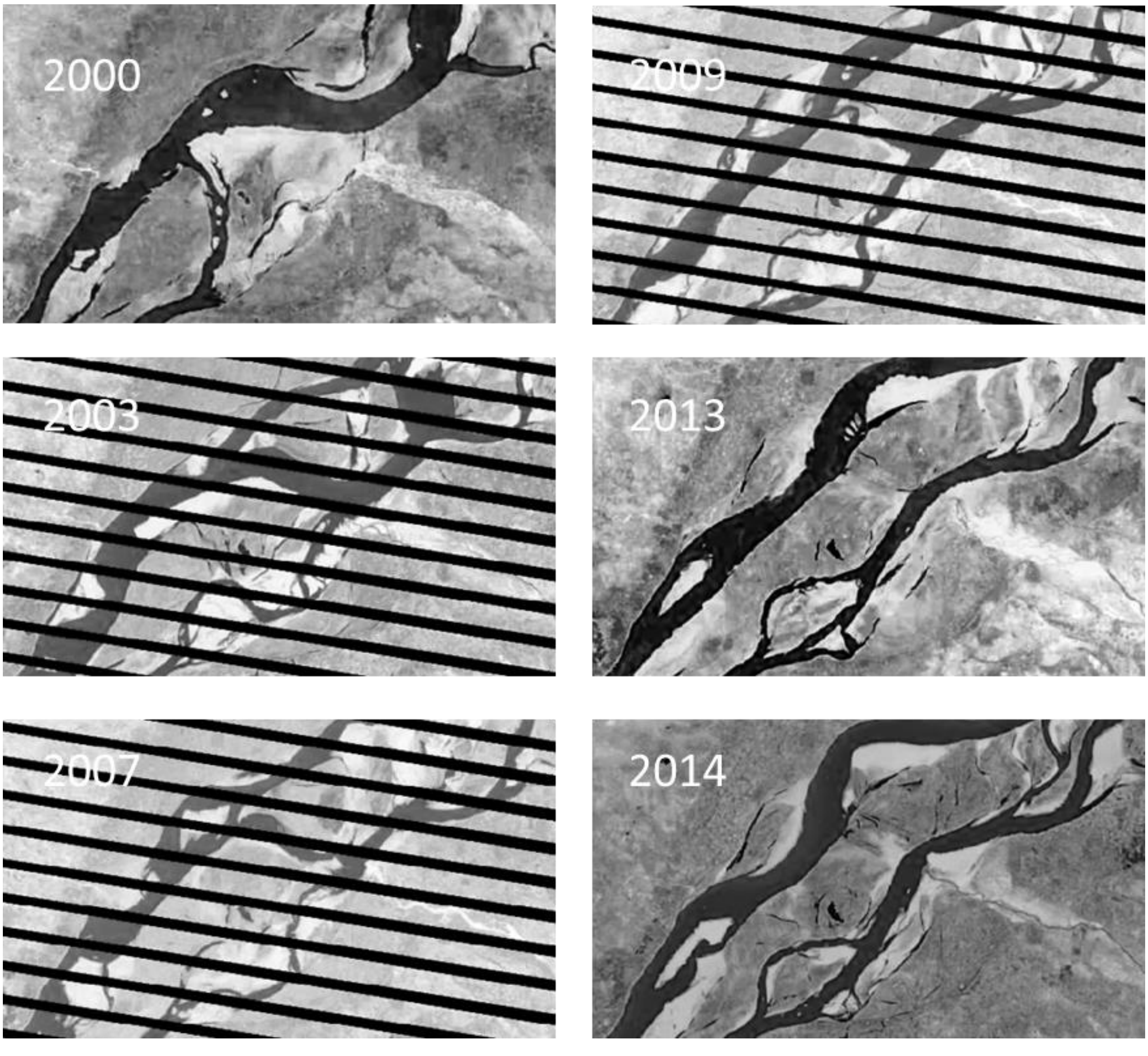

FIGURE 6.3 DEVELOPMENT OF THE TWO PARALLEL CHANNELS IN SECTION A. SATELLITE IMAGES 11-04-2000, 03-03-2003, 30-03-2007, 03-03-2009 LANDSAT 7 , AND 23-04-2013, 05-02-2014 LANDSAT 8

Between 2003 and 2007 (Figure 6.3) the major event taking place was the wide upstream part of the meander bend (north) closing off. Flow of the secondary channel was since fed by the pre-existing side channel, which is visible in the northeast corner of the image. This gave opportunity to the newly formed bifurcation (2000-2003) to be successful. Between 2009 and 2013 the connection between the main channel and the secondary channel reduced to an intermittent stream, leaving two parallel channels with a relatively small difference in channel width. Since the close off, more mid channel bars are formed with increased bar activity. The fact that the connection between the two channels has not closed off is explained by tributary flow at that point.

6.1.3 Simulated morphology

Thalweg formation

As described in the planform change analysis there are two large channels within this section. In Figure 6.4 both the main and the secondary are visible, with the northern channel being deepest and forming the river thalweg. The small side channels are very shallow. The river is most active in both erosion and sedimentation in the period from June to November/December, coherent with the months of highest discharge. In June water levels just start to rise and in end November and December flow is already low again. Channels are eroding downstream while water levels are lowering. This is called delayed scour, happening when the river is 'draining' after a high water period. The initial riverbed of the simulation was based on SRTM data with no bathymetry. Therefore the initial riverbed had wide and shallow channels. New channels were cut into the existing channels, making them deeper in the middle and silting up at the sides. This process was progressive in a downstream direction. The simulation product agrees to the real river planform (Figure 6.4). The channels upstream section A are more complicated and do not correspond to the real conditions.

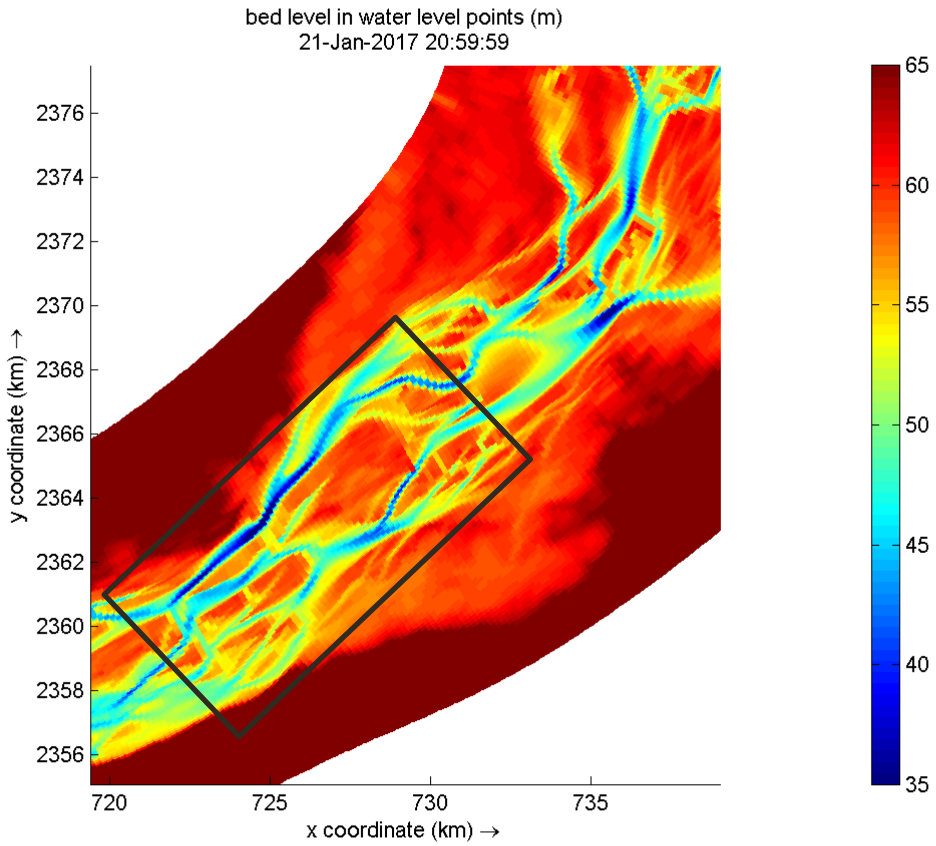

FIGURE 6.4 BED LEVEL (M) IN SECTION A (BLACK BOX) AFTER 5 YEARS OF SIMULATION. IN JANUARY DISCHARGE IS LOW. BED LEVEL IS GIVEN AS ELEVATION ABOVE SEA LEVEL

Bar and channel migration

Within the 5 year simulation (Figure 6.4) existing initial islands and bars are eroded, dissected or accreted. The bars/islands are actively involved in braided channel formation. In the simulation the river was more braiding than the real situation. The existing bars are dissected in a manner typical for braid bars, with cross-bar flow and tail formation (see also Appendix 4: Planform components – literature review). For both parallel channels the downstream part – within section A – is more stable than the channels coming in from the confluence point. The main channel is most stable with no lateral migration at all within the five simulation years. Channel migration is most active in the upstream parts of the channels, where the surrounding floodplains are eroded by cut-offs and channel migration (Figure 6.4 where the river enters section A). Most bars are migrating downstream, due to upstream eroding channels. For the large island in-between the main and secondary channel (centre of section A, Figure 6.4) the sedimentation zone at its tail is very small. The tail was formed by small bars attaching to the large island and further accretion at the downstream end. At the head of the island the sedimentation zone is much larger (yellowish colours upstream section A, Figure 6.4), but this sedimentation zone is eroded at its upstream boundary again due to a migrating channel.

6.1.4 Conclusions

The main channel is the northern channel, being deepest and most stable. The channel is suitable for navigation. However, bar behaviour is quite unpredictable. Lateral side bars are cut-off, start to migrate downstream and are eroded, dissected or reattaching to another riverbank. Migration and erosion rates are dependent on discharge and flow patterns. This should be investigated in further research more extensively to predict future changes in thalweg location or thalweg disturbance.

A shortcut between 2001 and 2003 caused a change in the upstream confluence angle. The river became more sinuous after the shift of the confluence point to the east creating upstream forcing. In 2011 side bars started to form and the channel's sinuosity increased. Towards the downstream end of this section the sinuosity is damped out. The elongated profile of this river section can be used as an advantage. Upstream adjustments will affect the entire reach along the island of 26 kilometres.

6.2 Section B

6.2.1 Characteristics

In this section the main channel remained stable in the past 14 years. This is explained by the presence of the more resistant and elevated geologic section in the south. There might also be additional explanations why the channel is this stable. There are only very small mid channel bars visible. The influence of the secondary channel (northern small channel, Figure 6.5) is not yet clear. It is very small and not always flooded. The location for inflow of this channel is ideal based on the upstream channel direction, though still it is not the main channel. This section is most interesting because of its stability. Understanding the causes of such constant and invariable behaviour contributes to application of this knowledge to other river sections. Stable channels are desirable for navigation management, with the river thalweg fixed to a certain position.

TABLE 6.2 GEOMETRIC CHARACTERISTICS OF THE AYEYARWADY RIVER IN SECTION B, BASED ON SATELLITE IMAGES OF 16-04-2014 AND 17-09-2014 LANDSAT 8. MEASUREMENTS ARE TAKEN ALONG THE MOST REPRESENTATIVE COURSE OF THE RIVER IF NOT SPECIFIED OTHERWISE.

Measurement	Value (km, degrees or [-])
Number of active channels	2
Main bar shape (length/width)	11.3/3.6
Minimum width of the main channel	1.2
Maximum width of the main channel	1.9
Confined channel belt width	5.6
Sharpest bend angle	135°
Confluence angle main and sec. channel	45°
Sinuosity index	1.3
Braiding index	1.8
Number of large cut off channels visible	2

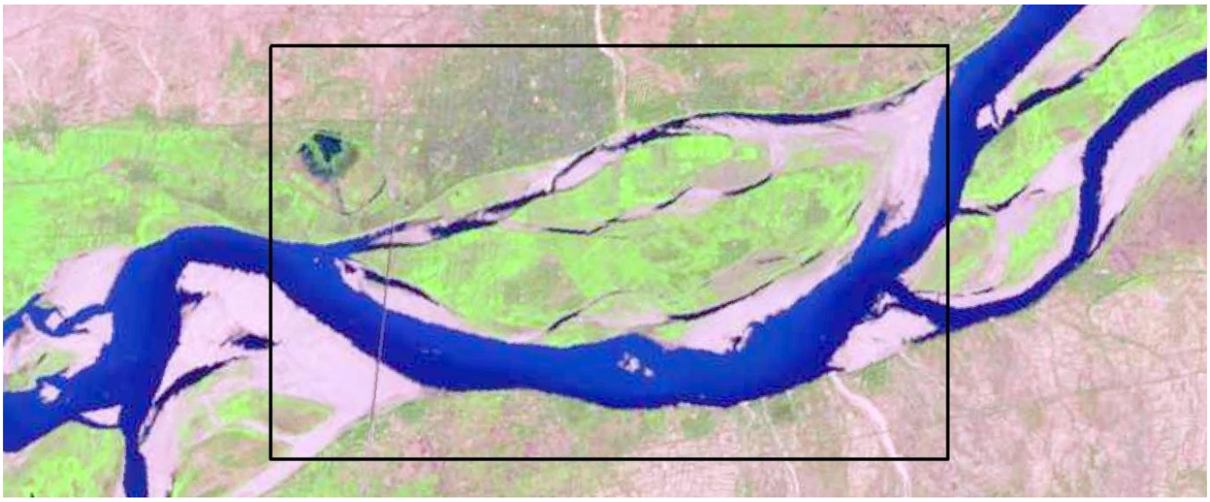

FIGURE 6.5 OUTLINE OF SECTION B IN THE AYEYARWADY RIVER, DELINEATED ON A SATELLITE IMAGE FROM 23-01-2015 LANDSAT 8

6.2.2 Planform change

Upstream channel

In 1989 there were two upstream channels flowing into two channels in section B (Figure 6.6). By that time, the northern channel was of similar size to the southern channel. In 1993 a cut-off formed which connected the northern incoming channel directly to the southern (current main) channel. The primary reason for this cut-off to take place and develop easily is that the northern upstream channel received more flow. Throughout the years this connection has developed as the main channel, leaving the northern channel within section B to become a “secondary channel”. Also the incoming southern channel has decreased in size to become the small side channel which it is now (2015 in Figure 6.6). Since 2010 there were no changes in the direction of the incoming main channel. In 2003 the entire planform of section B became more curved. The incoming channel angle reflected and affected the angle of downstream outflow. The current bend angle of the main channel in 2015 is 135° (Table 6.2). In the downstream part, the river flows in northwest direction and bifurcates into multiple channels where it hits the river banks (Section C). This bend extended in north-western direction since 2005 reoccupying the oxbow lake which was once an active channel (visible in 1993, Figure 6.6).

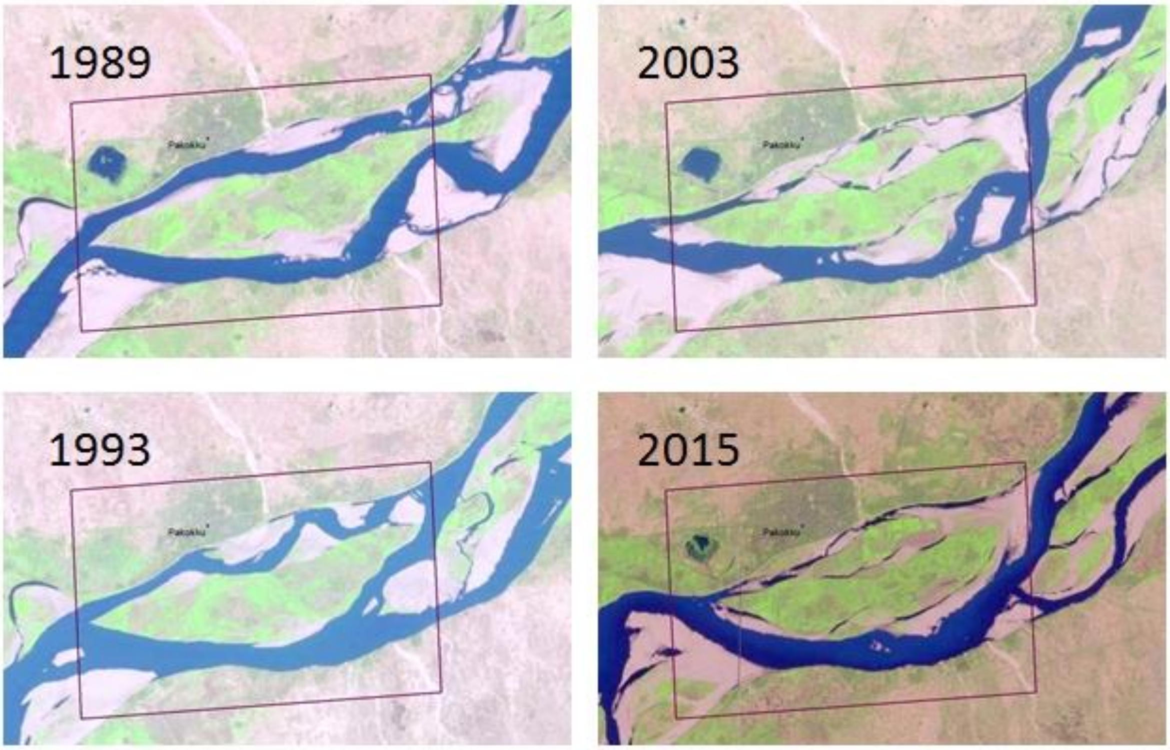

FIGURE 6.6 RIVER PLANFORM CHANGE IN SECTION B AND ITS UP AND DOWNSTREAM SECTIONS. 23-01-1989 LANDSAT 4, 27-02-1993 LANDSAT 5, 03-03-2003 LANDSAT 7 AND 07-01-2015 LANDSAT 8.

SECONDARY CHANNEL

The resistant bedrock at the river boundaries forms a “lobe” near the upstream border of section B, directing the flow to the southwest (Figure 6.6). If the angle of the upstream main channel changes the secondary channel can become more pronounced. Also if the incoming southern channel would receive more flow than the incoming northern channel, a connection with the secondary channel can be established again – like the situation in 1989 (Figure 6.6). Although the secondary channel decreases in size significantly during low flow in March and April, it is always active. The channel receives flow from a small tributary in the north.

BAR BEHAVIOUR

The most dominant bar in section B is the large island in the middle, with its surrounding sand bars. Its location is fixed by the direction of the incoming channels and by the small tributary flowing in at the secondary channel. The island is also stabilized by vegetation. Between 1993 and 2003 a smaller island has formed between the large island and the northern river bank (Figure 6.6). This island is currently not fully attached to the largest island, as water flows between the two islands during high discharge.

Mid-channel bars are formed by chute cut-offs of existing channel junction bars and side bars in the main channel. These bars migrate downstream towards the large island, where they attach and/or erode again. Very small mid-channel bars are formed during increasing water levels, when point and side bars are dissected (2015, Figure 6.6). These small bars are eroded very quickly and do not get the time to migrate downstream.

6.2.3 GEOMETRIC CHANGE

RATIO MAIN AND SECONDARY CHANNEL

During low water levels (low discharge) the ratio between the width of the main channel and the width of the secondary channel becomes larger (Figure 6.7). During high water the secondary channel is only 3 times smaller than the main channel, while during low water this ratio is 5 to 7. The secondary channel captures part of the discharge during high flow and does not capture discharge during low flow. This results in less variation in the inflow for the main channel throughout the year. The main channel does not vary its width to a large extend. It is much deeper than the secondary channel and has relatively steep banks on the southern side. The main channel has an asymmetric cross-section, with highest flow velocities along the outer banks of the river.

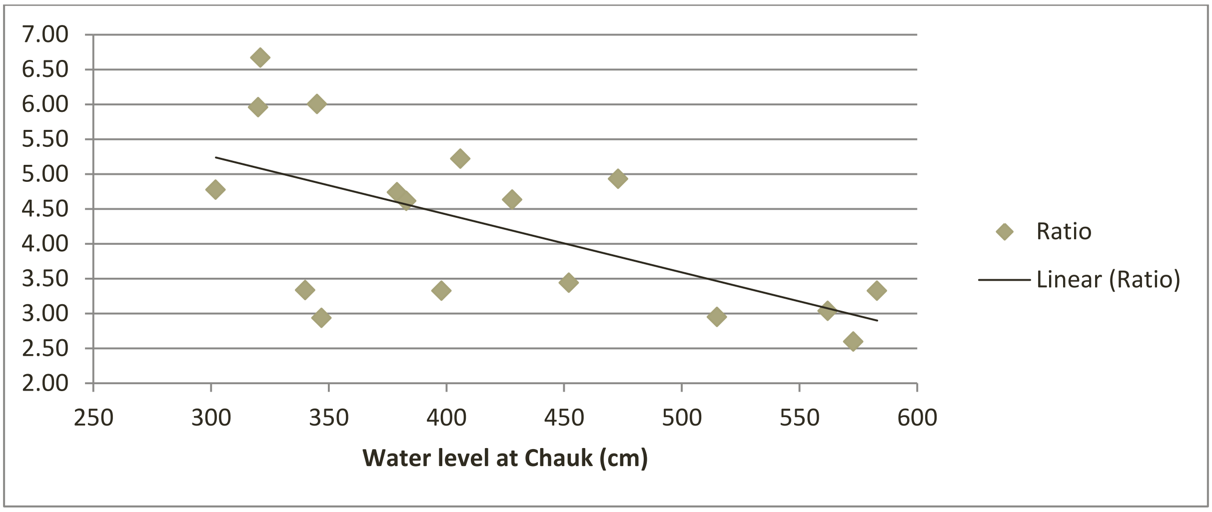

FIGURE 6.7 WIDTH RATIO OF THE MAIN AND SECONDARY CHANNEL IN SECTION B OF THE RESEARCH AREA, FOR GIVEN WATER LEVELS IN CHAUK. CHANNEL WIDTH MEASUREMENT LOCATIONS ARE GIVEN IN FIGURE 6.8

MAXIMUM EXTEND OF THE RIVER

The maximum extend of the river is 5.6 kilometres, measured for the 17th of September 2014 (Table 6.2). During this day the river was in flood stage and water levels at Chauk were around 987 cm. The channels are always located along the relatively steep and resistant sidewalls of the surrounding land. The maximum width of the river channel belt (5.6 km) is therefore always “occupied”, even during low water (Figure 6.8). The channel width of the main channel varies on average between 1.2 and 1.9 km. At some locations channel width even varies between dry and wet season with more than 1.5 kilometres. The erosion of the main channel concave bend is less than 30 meters (resolution satellite images).

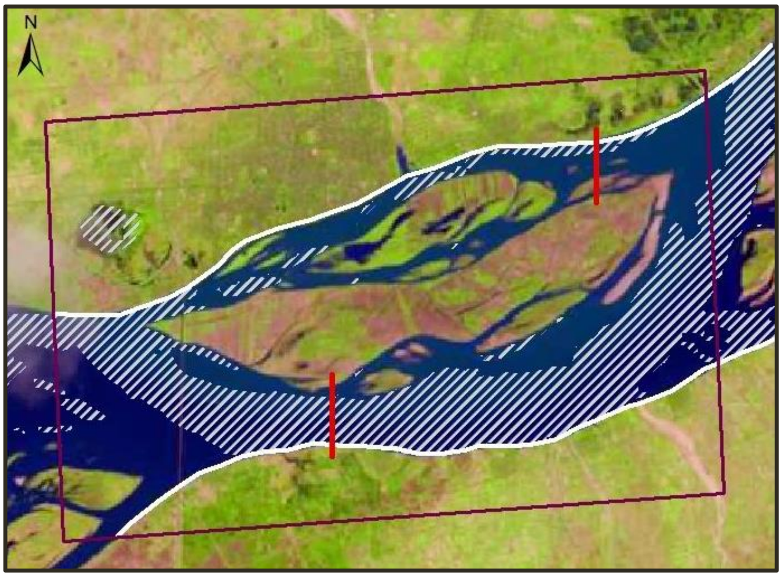

FIGURE 6.8 SECTION B, MEASUREMENT LOCATIONS FOR CHANNEL WIDTH (RED LINES) AND MAXIMUM EXTEND OF THE RIVER (WHITE LINES) 17-09-2014 LANDSAT 8. ALSO AN OVERLAY OF THE RIVER IN THE DRY SEASON OF 2014 IS GIVEN (GREY STRIPING PATCH) 21-02-2014 LANDSAT 8

UPSTREAM INCOMING ANGLE

In 2003 the incoming angle of the upstream channel was ~40°. Currently this angle is around 65°, which makes flow to the southern main channel more efficient. In the future this angle is not likely to change much, since the river path is now highly efficient, from the upstream northern outer bank, to the downstream southern outer bank in a very straight line (Figure 6.8). This channel reach can possibly migrate downstream in the future, eroding the island head. This will increase the bend angle of the main channel, since the downstream half of the channel is constraint from migration. It can also induce the secondary channel to receive more flow and enlarge. No clear evidence for this possible future shift is found though.

6.2.4 CONCLUSIONS

Despite changes in upstream boundaries, the location of the main channel is very stable. Its stability only increased since the upstream main channel became relatively larger and the incoming angle became more efficient. The upstream direction of the river forces the river towards the rock wall. The channel is deep and constrained along the resistant river banks in the south. The sinuosity (bend angle) of the main channel has increased in the past 30 years.

There is no large bar development or migration present. The main channel attracts the major share of the discharge due to the large depth and high local flow velocities. Both river width and depth are sufficient for navigation. The secondary channel is always active. It transports a varying share of the total discharge and always drains the small tributary to its north. The tributary also brings in sediment, which has contributed to the formation of the smaller island in-between the large island and the northern river banks.

A channel shift can be caused by the upstream erosion of the island. That will increase the sinuosity of the main channel and can possibly induce a stream capturing of the secondary channel. Another possible change is the enlargement of the upstream incoming secondary channel. Also then the secondary channel in this section would become more pronounced. This should be kept in mind when choosing engineering solutions for the upstream section (Section A). Changes in discharge distribution over the two incoming channels can alter the system and undermine its stability.

6.3 Section C

6.3.1 Characteristics

In section C the river enters a more dynamic reach with continuous island formation and migration (Figure 6.9). Also chute cut-offs take place, as well as stream capturing. Changes in discharge and flow velocity induce changes in the planform of the river. Figure 6.10 visualizes the ever-changing planform of this section. The river flows into a relatively wide section with vast floodplains in the northwest. The large point bar in the south is always present, albeit in varying plan form and size (upstream end of the section, Figure 6.10). This is related to the incoming channel direction. The incoming angle is fixed and the channel is also in this section partly confined by the resistant river bank in the southeast. It is interesting to check whether the planform changes in this section show a regular pattern or if they are completely random.

TABLE 6.3 GEOMETRIC CHARACTERISTICS OF THE AYEYARWADY RIVER IN SECTION C, BASED ON SATELLITE IMAGES OF 16-04-2014 AND 17-09-2014 LANDSAT 8. MEASUREMENTS ARE TAKEN ALONG THE MOST REPRESENTATIVE COURSE OF THE RIVER IF NOT SPECIFIED OTHERWISE.

Measurement	Value (km, degrees or [-])
Number of active channels	1 upstream, 2 downstream
Main bar shape (length/width)	4.2/3.5 point bar, 9.8/2.3 other bar
Minimum width of the main channel	0.8
Maximum width of the main channel	1.5
Confined channel belt width	5.7
Sharpest bend angle	90°
Bifurcation angle main and sec. channel	90°
Braiding index	2
Number of large cut off channels visible	4

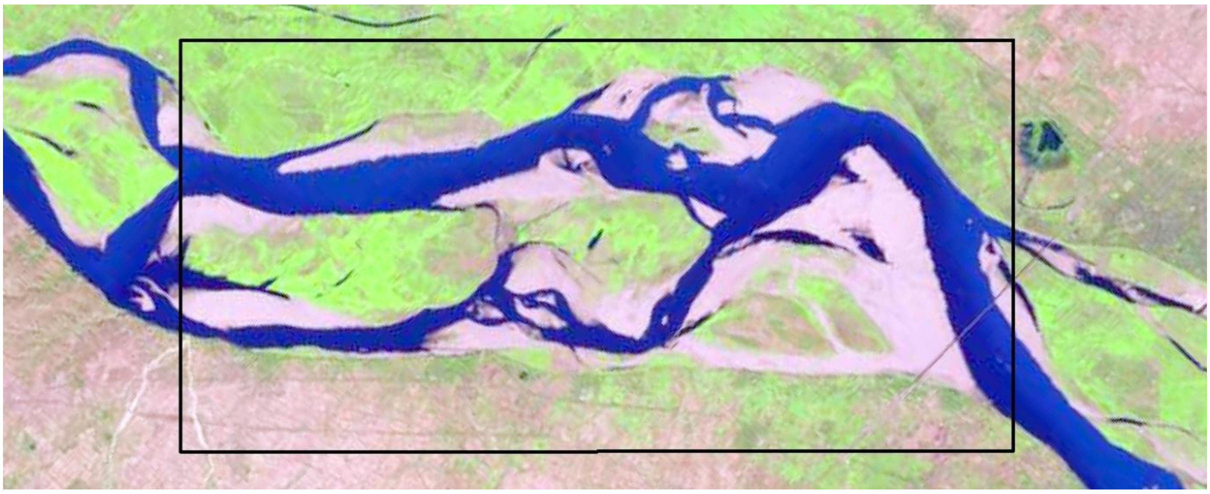

FIGURE 6.9 OUTLINE OF SECTION C IN THE AYEYARWADY RIVER, DELINEATED ON A SATELLITE IMAGE FROM 23-01-2015 LANDSAT 8

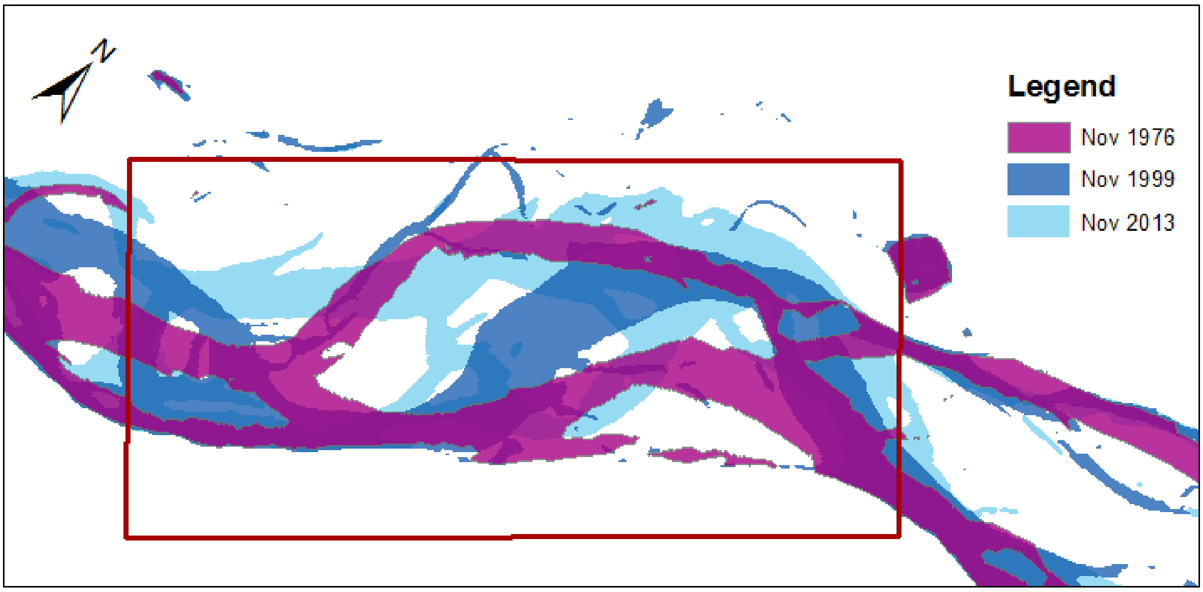

FIGURE 6.10 RIVER PLANFORM IN SECTION C IN THREE YEARS. THIS IMAGE IS CREATED USING OBIA. 15-11-1976 LANDSAT 2, 19-11-1999 LANDSAT 7, 17-11-2013 LANDSAT 8

6.3.2 PLANFORM CHANGE

Past the large bend at the upstream part of the section the river bifurcates into two channels. Upstream/next to this bifurcation, along the northern floodplains, a dissected point bar is visible (Figure 6.9) (described in 5.3.1 Bars and islands). The location of these island influences the discharge distribution over the two bifurcation channels. Also the fast migration of these islands induces a constant shift of the navigation route.

Northeast of Nyaung-U a large bifurcation development took place between 2000 and 2012 (Figure 6.11, downstream half of Section C). Around the year 2000 the bifurcation was initiated, probably during a river flood, reoccupying an old side channel. In 2003 this relatively small bifurcation channel connected to a downstream side-channel (or developed bifurcation). In 2004 they formed one side-channel (or bypass) together, with a meandering planform pattern. The connection with the main channel at the diversion in the centre was closed up (2004, Figure 6.11). In 2007 this bifurcation is choked and is filling in with sediment. The following years new bifurcations occur, reoccupying the old bifurcation path. In 2009 only the first half of the old channel was occupied and the channel reattached to the main channel at the old diversion point. By 2012 this channel has grown into a mature channel, shifting the main flow to this new route. In 2015 this channel is still the main channel (see also Figure 6.9).

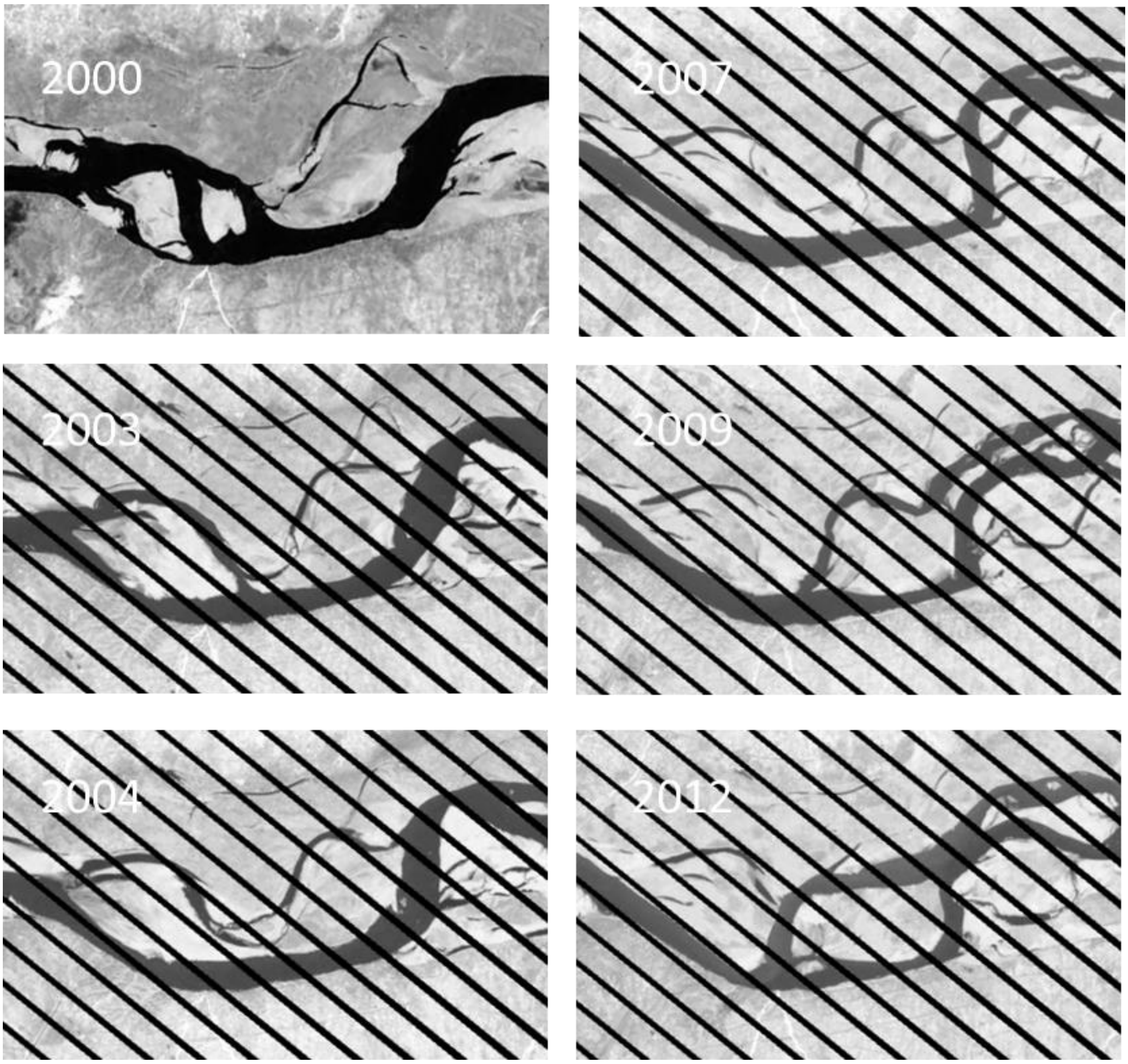

FIGURE 6.11 DEVELOPMENT OF A BIFURCATION NORTHEAST OF NYAUNG-U, IN THE DOWNSTREAM PART OF SECTION C, RESULTING IN A NEW MAIN CHANNEL. SATELLITE IMAGES 11-04-2000, 03-03-2003, 16-11-2004, 30-03-2007, 03-03-2009 AND 12-04-2012 LANDSAT 7

6.3.3 SIMULATED MORPHOLOGY

NORMAL CONDITIONS

Sediment transport is most active during the months June till November. In the simulations the incoming channel shows a repeating pattern of two stages (upstream half in Figure 6.12): The first is the channel flowing towards the northern floodplains and bending to the west. With this a large point bar forms in the inner bend, just like the real situation in recent years (Figure 6.10) but slightly smaller. The next stage is the cut off of this point bar and consequent straighter channel formation.

In the simulation the upstream large island from section B is very elongated. This causes the main incoming channel to be forced to flow southwest (Figure 6.12). Also the incoming secondary channel carries much more discharge than in reality, with consequent relatively high flow velocities. This together with the overall complexity of section C causes the simulation to be not accurate with real planform situations in the past 15 years. Still some relevant clues can be drawn from the model.

THALWEG

This braiding section of the river is very dynamic, with channels cutting off and reconnecting. But all channels do carry a sufficient water depth. Only the nodal points can be shallow in months with low flow stages. The dominant channel formed in the model simulation can be seen in Figure 6.12 in the middle of the river. Between 2000 and 2015 this course has never formed in reality. The flow direction appears to be very dependent on the upstream inflow ratio. Although this planform has never formed it can be a good option for navigation, since the thalweg is of sufficient depth (around 10 meters depth in January) and the channel is much straighter than the current situation (Figure 6.12). If the large natural bend at the inflow point is maintained, this straight channel can still be formed. It is possibly larger in reality than in the simulation, since the two current channels deviate a lot from the size of the simulated channel (Figure 6.12).

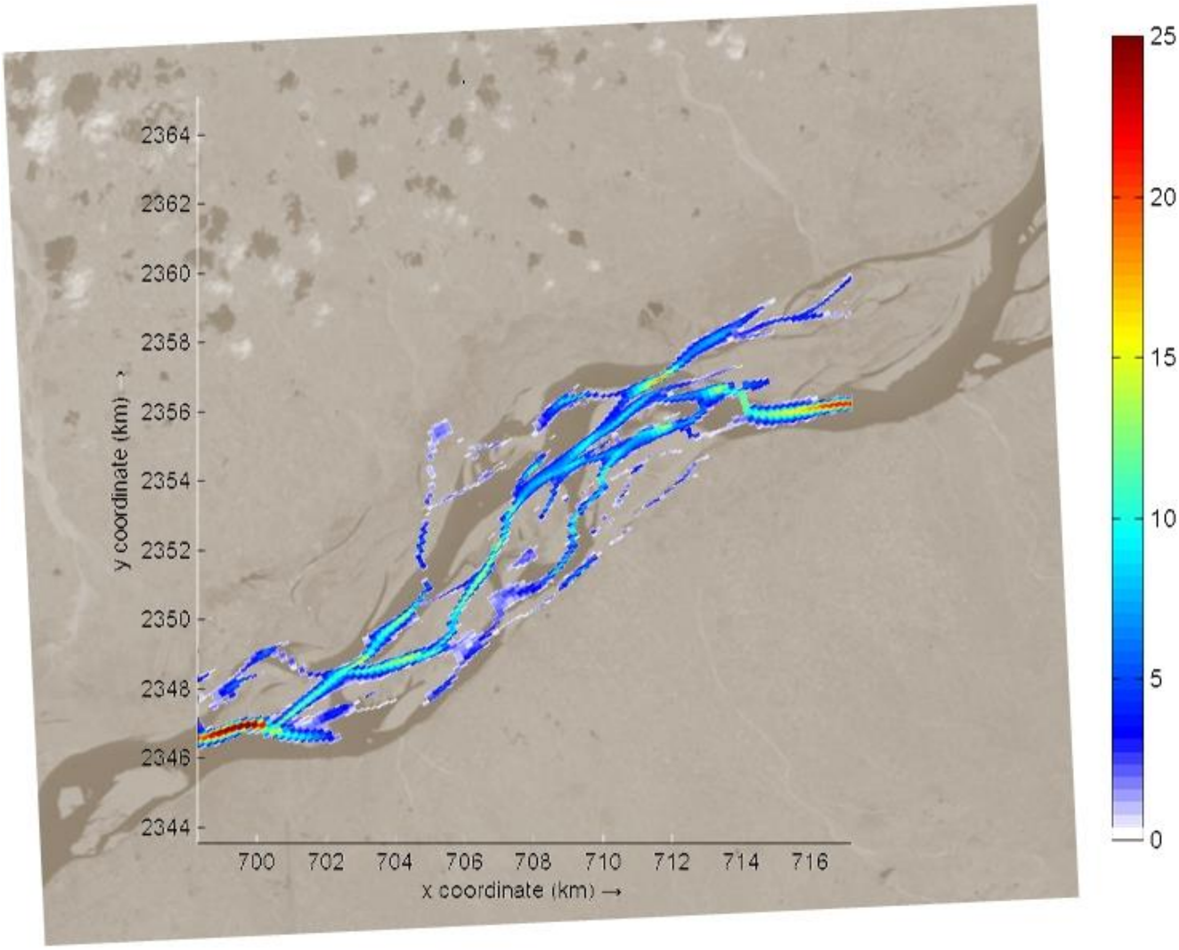

FIGURE 6.12 WATER DEPTH (M) OF SECTION C IN APRIL AFTER 2 YEARS OF SIMULATION. OVERLAY ON TOP OF A RECENT SATELLITE IMAGE 20-11-2014 LANDSAT 8

6.3.4 CONCLUSIONS

In the past 15 years this section of the river has been very dynamic in its planform development. The main incoming channel has forced the flow towards the northwest, creating a bend with a large point bar. The point bar is regularly cut-off during flood, but always reconnects to the riverbanks. Due to this more or less fixed bend, the flow in section C comes from a stable north-eastern direction, after which two channels bifurcate. The largest channel is formed along the northern floodplains, the smaller channel along the southern resistant riverbanks. Discharge distribution over these channels can be changed due to the location and shift of upstream bars. The large point bar along the northern floodplain was dissected in 2013 and most of these small bars are currently shifting through the channel.

From the simulation it can be concluded that the incoming channels determine whether a bend is formed in the upstream half of the section. If the incoming channel comes from a north-eastern direction, no large bend is formed and only one main channel develops with small side channels. This channel would be sufficient in depth for navigation and straighter than the current real situation. The current situation with the large bend and two parallel channels can be stable, but would require intensive maintenance of shifting bars.

6.4 SECTION D

6.4.1 CHARACTERISTICS

In this section migrating sinuous river bends are visible. The bends are extending and translating downstream. This process is taking place at a stable and predictable rate, but is highly dependent on both up- and downstream conditions. Downstream of Section A, the main channel is confined along the western river banks. The secondary channel is confined along the eastern banks and in line with the current direction of the river bend (in the middle of section A, Figure 6.13). On the upstream side of the section there are two incoming channels with a confluence and a bifurcation point close to each other. At the southern border the river is confined by resistant river banks. In the northern floodplains old river courses can be recognized as scars in the floodplain. These scars can tell more on historic river migration and cut-offs. If the shift of the river is predictable, navigation management plans are much easier to make.

TABLE 6.4 GEOMETRIC CHARACTERISTICS OF THE AYEYARWADY RIVER IN SECTION D, BASED ON SATELLITE IMAGES OF 16-04-2014 AND 17-09-2014 LANDSAT 8. MEASUREMENTS ARE TAKEN ALONG THE MOST REPRESENTATIVE COURSE OF THE RIVER IF NOT SPECIFIED OTHERWISE.

Measurement	Value (km, degrees or [-])
Number of active channels	1
Main bar shape (length/width)	4.8/2
Minimum width of the main channel	0.8
Maximum width of the main channel	2
Confined channel belt width	3.3
Sharpest bend angle	110°
Confluence angle main and sec. channel	65°
Sinuosity index	1.2
Number of large cut off channels visible	1

FIGURE 6.13 OUTLINE OF SECTION D IN THE AYEYARWADY RIVER, DELINEATED ON A SATELLITE IMAGE FROM 23-01-2015 LANDSAT 8

6.4.2 PLANFORM CHANGE

When comparing the river planform of the years 2001 and 2014 (Figure 6.14), it can be seen that the river has some 'constant' elements: at the upstream boundary the river stays attached to the resistant southern floodplain; at the downstream end the channel crosses from east to west to reattach to the resistant banks in the west. Also the river has always consisted of only one channel for most of this section.

There are three bends, referred to as upstream, middle and downstream bend. In the past 10 years all bends did translate in a downstream direction and the middle and downstream bends were also extending in a lateral direction. In the downstream bend though, the channel migrated less than 30 meters (image resolution) since January 2013. This is caused by the resistant rock it has “reached/touched” (red line in Figure 6.14B). The upstream bend has been in that same situation for a longer period; since 2003 no extension was possible (white line in Figure 6.14B). The middle bend is most active, being able to erode the less resistant floodplain in the northwest (yellow dotted line, Figure 6.14B). Between March 2014 and February 2015 this bend has eroded almost 175 m in western direction. This refers to an erosion rate of almost 0.5 m per day.

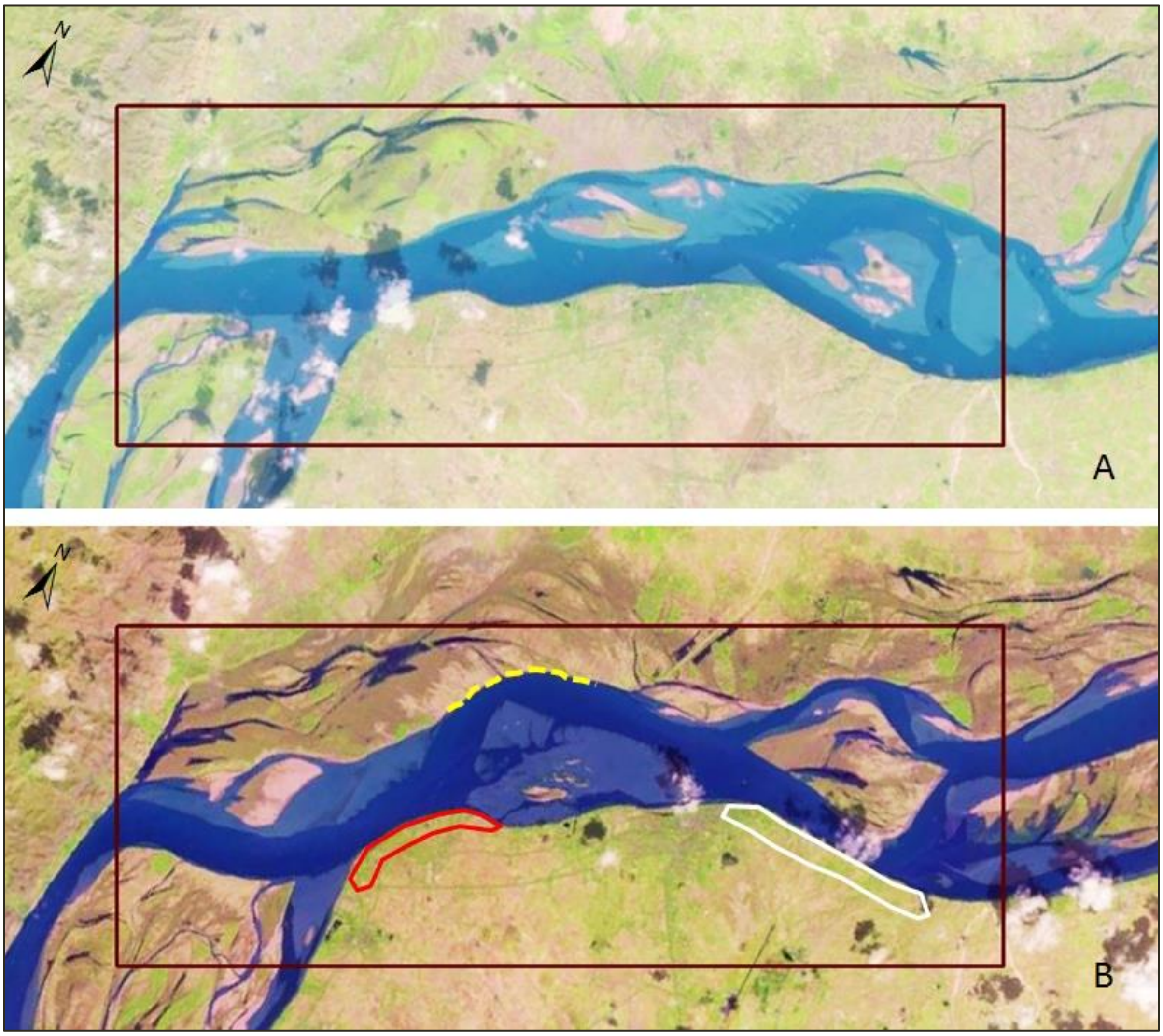

FIGURE 6.14 RIVER PLANFORM IN SECTION D IN 2001 AND 2014. DARKER COLORS WITHIN THE RIVER INDICATE THE RIVER COURSE DURING LOW WATER. A: 23-10-2001 AND OVERLAY 24-01-2001 LANDSAT 7, B: 17-09-2014 AND OVERLAY 22-12-2014 LANDSAT 8

In the years before 2001 the river was almost straight in this section (Figure 6.14A). In 2014 a secondary channel is formed due to the mid-channel island. This channel started developing in 2011 by a slow cut-off of the formed point bar at that location. If this channel will receive most flow in the future, the incoming angle of the channel will be straighter. Likely, the entire channel section will become much straighter again in that case (see blue line in Figure 6.15). If this bifurcation closes off again, the sinuous middle bend will develop further in western direction. This might lead to the stream capturing the bypass channel in the south, past Nyaung-U (See the pink and consecutive orange line in Figure 6.15).

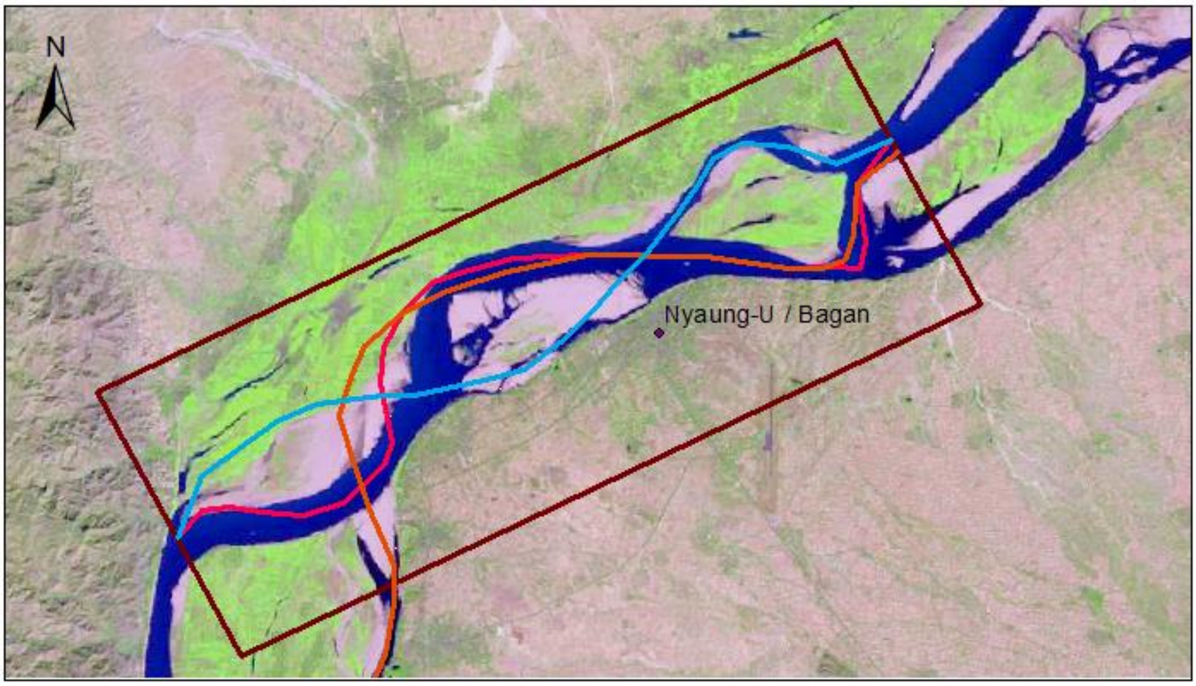

FIGURE 6.15 POSSIBLE FUTURE FLOW DIRECTIONS IN SECTION D, WITH PINK AND ORANGE BEING CONSECUTIVE AND BLUE BEING THE ALTERNATIVE ROUTE. BASE MAP 22-12-2014 LANDSAT 8

6.4.3 SIMULATED MORPHOLOGY

In the model simulation the river follows a route similar to the 2001 situation (Figure 6.16). This is expected since the models initial bed level is based on an elevation dataset of 2000 (SRTM). Migration of sinuous bends as in the current situation can therefore not be discussed based on the simulations. The inflow location is very variable and changes within years. In the simulation a large incoming channel has formed on a location in the middle between the current incoming channels (Figure 6.16, upstream end). The entire channel is straight because the incoming angle is dominantly north-east.

FUTURE CHANGES

The channel is very deep and stable (Figure 6.16). Based on only river planform it might be expected that the river will in the near future shift to the downstream secondary channel. Based on sediment transport and flow velocity simulations it appears that the channel along the western river banks attracts most of the flow and transport. The deep channel is located next to the resistant rock wall in the west. Both local depth and flow velocity create suction, making it the fastest route for water to flow. The secondary channel can neither provide high flow velocities nor accommodation for large volumes of water. However, if the river follows the route of the orange line (Figure 6.15), it is inevitable that the secondary channel will be occupied, albeit only for a few kilometres before crossing to the western banks again.

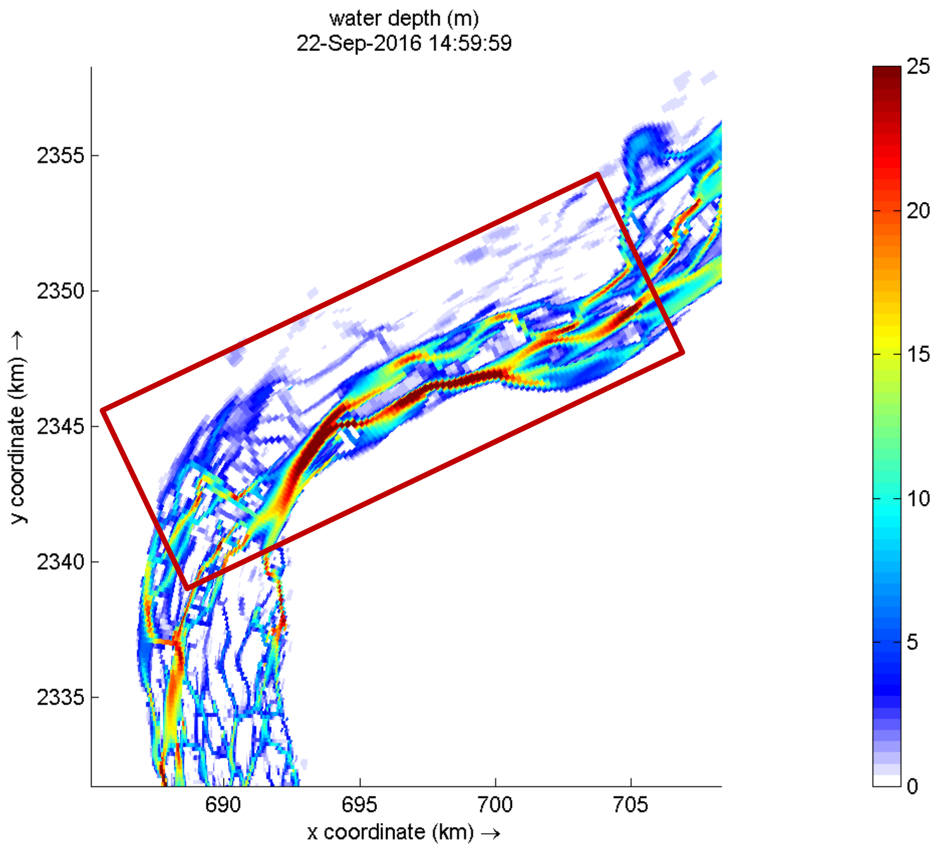

FIGURE 6.16 WATER DEPTHS IN SECTION D AFTER ALMOST FOUR YEARS OF SIMULATION

6.4.4 Conclusions

Within the last 15 years the river transformed from a straight channel to a sinuous channel. Only the middle bend of the river is currently capable of lateral migration. In the south the river is confined by resistant river banks. The incoming channel has changed its angle and has bifurcated into two channels from different directions. The discharge ratio of the two incoming channels determines the dominant flow direction and planform in the rest of this section, and with that determines the degree of sinuosity and related erosion of less resistant floodplains. The river will behave like a classic sinuous river when the incoming flow from the eastern direction is strongest, and behave like a straight channel when the incoming angle from the north-east is dominant. The physical boundaries of the river are evidently the resistant riverbanks, making the effects of the boundaries on free migration easy to predict. The outflow location is fixed at its current location, unless the incoming channel migrates to an angle as presented in Figure 6.15 orange line.

7 DISCUSSION

7.1 PLANFORM INTERACTION

The river within the research area mostly consists of two parallel channels; one along the southern resistant river banks and one along the northern floodplains. Only in section D the river forms one single channel. At locations where curved channels are confined by resistant river banks, the channels have an asymmetric cross section. Secondary flow in the channel does not scour the resistant outer banks but erodes the channel bed, making the channel deeper. These deep and relatively narrow channels attract a large part of the total flow and flow velocities are higher. This together with the resistant banks makes the channel more stable. There are two locations visible where the river is confined by the river banks and forced to bend north again due to curvature of the river bank. These two locations correspond to the locations where no channel migration was visible in the change analysis in chapter 5.3.2 and can be found in sections B and D. Parallel channels are found along the floodplains, where channels can freely migrate in lateral direction and tend to form a sinuous pattern.

The channel thalweg also forms a sinuous pattern on a larger scale. The thalweg wanders from along the northern floodplains to along the southern resistant river banks (Figure 7.1). This large scale pattern also induces the connected river sections to be highly dependent on its up and downstream channels. Changes in discharge ratio over two parallel channels can induce changes in the river planform for over 55 kilometres. The upstream northern channel in section A (Figure 6.3) received more flow since 2003. As a result a cut-off took place in section B, making the southern channel the main channel (Figure 6.6). The secondary channel in section B became smaller. For engineering solutions these relations should be considered as well. For instance: a single straight channel in section C is wanted, which seemed possible based on the simulation results. Therefore the upstream secondary channel in section B should be enlarged, so that it flow comes in from a straighter angle. This can be obtained by increasing flow in the secondary channel in section A. Changing the system on such a large scale is not recommended though. River management structures should be adjustable according to the ever-changing morphology of the river. It is expected that the AIRBM project team will have to update their model simulations regularly with new data, if available, and new observations from the first pilots in the river. The river is subject to change and therefore the management plan is as well. In order to anticipate on the dynamic nature of the river and the large downstream effects of changes in the system, adjustable river management structures should be used.

7.2 GENERAL MORPHOLOGICAL PROCESSES

In the entire research area the (parallel) channels tend towards a sinuous planform. These sinuous channels are more predictable than the straighter channels with much bar activity. The river bends along the floodplains can erode up to 0.5 meters per day, but channel depth is sufficient for navigation. Erosion takes place on a slow and predictable rate. In other sections the river is confined and (partly) stabilized. Planform changes are least predictable in section C, because of its extensive bar migration and non-sinuous planform. The dynamic planform in section C is caused by bar migration. Bars in front of a bifurcation affect discharge distribution by reducing the inflow channel size of one or both of the channels, and by changing the inflow angle. During high water flooded bars migrate through the channel. Bar migration results in changes in the discharge distribution, which in its turn results in a changing planform of the downstream channels. To prevent this change in the future the bars can be removed or stabilized to prevent them from migrating. Both natural vegetation and human-cultivated crops grow quickly and stabilize the sediment on the bar, making it an island. Natural vegetation occupies the bars in the river which are in the same location for multiple years or can be planted as part of the river management plan. Vegetated islands do not migrate unless eroded by river bends from the side.

7.3 RIVER MANAGEMENT OPTIONS IN EACH SECTION

In section A there is one preferential channel (main channel Section A, Figure 7.1) with increasing sinuosity since 2009. Sinuosity decreases in downstream direction. There are lateral side bars and some mid channel bars in the downstream end. If sinuosity is increased less mid channel bar formation would occur and the thalweg would be clear. Also discharge and related water depth in the main channel can be increased for the benefit of navigation. The channels would become deeper and less laterally active. Both sinuosity and discharge increase in the main channel can be obtained by increasing roughness of the secondary channel or dredging the main channel. The bifurcation point is located directly at the confluence point of the Ayeyarwady and Chindwin River. Closing off of the secondary channel is not recommended. This would affect the downstream sections in an unpredictable manner and also the river would form a new bifurcation at another location. A bifurcation point located more downstream (channel shift at confluence, Figure 7.1) would improve river management, by making the bifurcation planform simpler. Then the placement of an island in front of the bifurcation would be a natural solution to manage the discharge distribution over the two channels.

In section B the main channel is stable situated along the resistant river banks in the south (main channel Section B, Figure 7.1). The channel is deep and has high flow velocities. This is favourable for navigation. The secondary channel is small but always active. If the incoming southern channel from section A enlarges too much, it would reconnect to the small secondary channel in this section and alter the planform in all downstream sections (channel shift in Section A, Figure 7.1). Therefore it is important to keep the incoming discharge distributed over the two channels as it currently is. The main channel in section B can in the future erode the head of the large vegetated island. This can be prevented with riverbank protection structures.

In section C there are two large channels and many smaller side channels. The northern channel is currently the main channel, but this can shift in the future. The inflow direction is determined by the location of the bend on the upstream end in section C. This bend eroded the northern floodplains with almost 0.35 per day in the period between 2011 and 2015. With bank protection the bend can be prevented from further migration and can make river management in this section much easier. Past the bend a large bifurcation is active (bifurcation point Section C). The discharge distribution over this bifurcation is constantly changing under influence of the dissected point bars migration through the channel. Removing the dissected islands would make the northern straight channel ever straighter, but this is not a sustainable solution, since the channel has a tendency towards lateral migration. Stabilizing the point bar however, would simulate sinuosity of the main channel and leave opportunity to manage the discharge distribution over the two parallel channels. Then the northern channel can become sinuous and thus more predictable in its behaviour. Also with discharge distribution water levels can be increased, extending the sufficient water depth period for navigation.

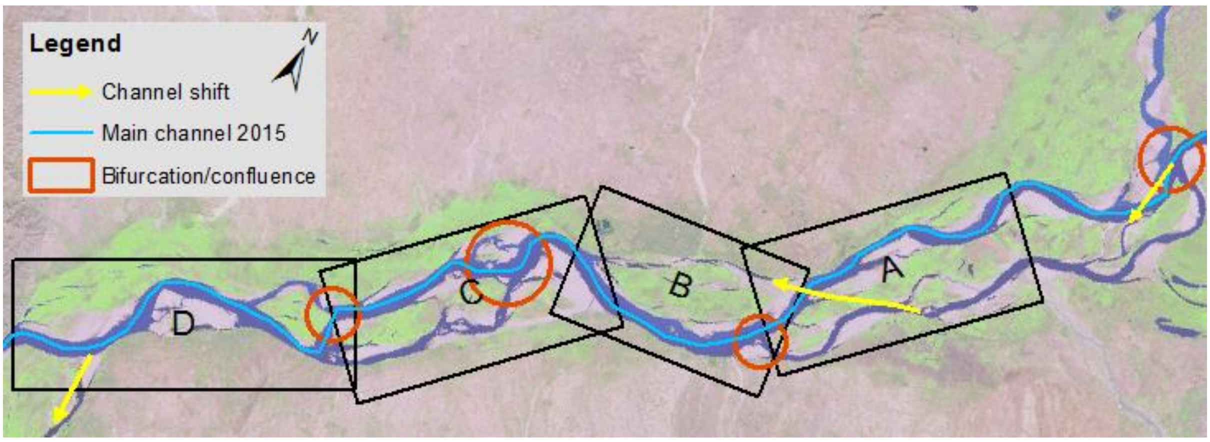

FIGURE 7.1 RIVER PLANFORM IN JANUARY 2015. LOCATIONS OF SHIFT AND BIFURCATIONS/CONFLUENCES ARE DISCUSSED IN THE TEXT. BASEMAP 23-01-2015 LANDSAT 8

In section D there are two future options for the channel thalweg. Both options are sinuous, but are mirroring each other. When the current situation is maintained, the downstream flow would shift towards the eastern banks (channel shift in Section D, Figure 7.1) and become less stable than it is now. To maintain the outflow location at a fixed position the discharge distribution around the upstream island (bifurcation point Section D) should be altered. If the bypass channel here develops into a mature channel, the river in section D will mirror its current planform and would become less sinuous. This can be obtained by dredging the bypass channel and increasing roughness in the main upstream channel.

8 CONCLUSIONS AND RECOMMENDATIONS

This research describes the planform change of the Ayeyarwady River in the past 15 years and reveals the effects of possible future changes. The research area is connected in its morphodynamic changes. When adjusting the planform of one section of the river, morphological changes will be stimulated for more than 50 kilometres downstream. This domino effect of the river system should be used in the advantage of river engineering.

From satellite image analysis it is concluded that the channel thalweg of the river follows a sinuous pattern. It alternates from along the resistant river banks in the south to along the floodplains in the north. For the first 50 kilometres of the river in the research area secondary channels lie parallel along the main channel. Important properties to bear in mind are;

- The secondary channels discharge part of the flow and with that contributes to less variation in discharge in the main channel.
- At a confluence the angle and discharge ratio of two channels determines what the main flow direction downstream is.
- Resistant river banks confine and stabilize the channel, which results in higher flow velocities and larger water depths.
- At a bifurcation discharge distribution and channel angle influences the river planform downstream. The upstream channels and bars in front of a bifurcation affect this discharge distribution.
- At locations where there are two channels but both not confined by resistant river banks channels are shallower and bar migration is more active.

Morphology simulations revealed that water depth in the main channel is sufficient throughout the year. Bar migration and channel shift are the major problems for navigation. In the reach between Pakokku and Nyaung-U these processes are most active. Also in other sections of the river channel cut-offs occur during high discharge in the period June-November. Based on simulations it can be concluded that discharge distribution over two bifurcating channels is the most important process to manage in order to keep the main channel deep enough for navigation and to prevent extensive bar formation. Though, the model simulations of the river require time and more input data is necessary to be able to represent the natural situation. In the future a new SRTM dataset can contribute to a model more similar to the current situation. A local bathymetry and elevation survey of the river and its surrounding floodplains would be the best source for an initial bed level in the model, making it both detailed and up-to-date.

In a dynamic system like the Ayeyarwady it is best not to use many large hard structures for river engineering. This and other research on this river is not sufficient enough to guarantee the long term effects. The structures should be adaptable to the ever-changing river dynamics, preferably even on a 5-year timescale. It is recommended to start the first Deltares project pilot in the upstream parts of the river and review its upstream hydrologic and downstream morphologic effects with model simulations combined with past planform changes. The effect analysis can be used to update the morphodynamic models of the river. Also for the final structures (next step in the AIRBM project) it is recommended to start building and adjusting upstream and work in a downstream direction.

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APPENDIX 1: SATELLITE IMAGERY

Overview table of all available Landsat satellite images, meeting the requirements: cloud coverage <20%, path 134, row 45. For 1976 path is 144, due to a different path-row raster at that time. For the years between 1980 and 2014 water level is given for measuring station Chauk.

Nr.	ID	Year	Day nr	Receiving station	Landsat satellite	Day	Month	Water level (cm)
1	LM1	1974	25	AAA05	L1-5 MSS	25	Jan	
2	LM2	1976	330	AAA03	L1-5 MSS	25	Nov	
3	LT4	1989	23	AAA01	L4-5 TM	23	Jan	443
4	LT4	1989	39	XXX09	L4-5 TM	8	Feb	408
5	LT5	1993	58	ISP00	L4-5 TM	27	Feb	606
6	LT5	1996	131	CLT00	L1-5 MSS	10	May	547
7	LE7	1999	323	SGS00	L7 ETM+ SLC-on	19	Nov	758
8	LE7	2000	102	SGS00	L7 ETM+ SLC-on	11	April	381
9	LE7	2001	24	SGS00	L7 ETM+ SLC-on	24	Jan	423
10	LE7	2001	88	SGS00	L7 ETM+ SLC-on	29	March	290
11	LE7	2001	296	SGS00	L7 ETM+ SLC-on	23	Oct	980
12	LE7	2002	11	SGS00	L7 ETM+ SLC-on	11	Jan	498
13	LE7	2002	59	SGS00	L7 ETM+ SLC-on	28	Feb	347
14	LE7	2002	107	SGS00	L7 ETM+ SLC-on	17	April	349
15	LE7	2003	30	SGS00	L7 ETM+ SLC-on	30	Jan	315
16	LE7	2003	62	SGS00	L7 ETM+ SLC-on	3	March	350
17	LE7	2003	78	SGS00	L7 ETM+ SLC-on	19	March	340
18	LE7	2004	1	ASN01	L7 ETM+ SLC-off	1	Jan	473
19	LE7	2004	17	ASN01	L7 ETM+ SLC-off	17	Jan	428
20	LE7	2004	65	ASN02	L7 ETM+ SLC-off	5	March	272
21	LE7	2004	113	ASN01	L7 ETM+ SLC-off	22	April	398
22	LE7	2004	321	PFS01	L7 EMT+ SLC-off	16	Nov	885
23	LE7	2005	3	EDC00	L7 ETM+ SLC-off	3	Jan	637
24	LE7	2005	19	EDC00	L7 ETM+ SLC-off	19	Jan	537
25	LE7	2005	35	EDC00	L7 ETM+ SLC-off	4	Feb	406
26	LE7	2005	67	PFS00	L7 ETM+ SLC-off	8	March	397
27	LE7	2005	83	PFS00	L7 ETM+ SLC-off	24	March	477
28	LE7	2005	99	PFS00	L7 ETM+ SLC-off	9	April	515
29	LE7	2006	22	EDC00	L7 ETM+ SLC-off	22	Jan	360
30	LE7	2006	38	EDC00	L7 ETM+ SLC-off	7	Feb	312
31	LT5	2006	46	BKT00	L4-5 TM	15	Feb	293
32	LE7	2006	54	PFS00	L7 ETM+ SLC-off	23	Feb	280
33	LT5	2006	62	BKT00	L4-5 TM	3	March	290
34	LT5	2006	94	BKT00	L4-5 TM	4	April	336
35	LT5	2006	110	BKT00	L4-5 TM	20	April	392
36	LT5	2007	1	BKT00	L4-5 TM	1	Jan	398

37	LE7	2007	9	EDC00	L7 ETM+ SLC-off	9	Jan	361
38	LE7	2007	25	SGS00	L7 ETM+ SLC-off	25	Jan	295
39	LE7	2007	41	EDC00	L7 ETM+ SLC-off	10	Feb	283
40	LT5	2007	49	BKT00	L4-5 TM	18	Feb	315
41	LE7	2007	57	SGS00	L7 ETM+ SLC-off	26	Feb	336
42	LT5	2007	65	BKT00	L4-5 TM	6	March	319
43	LE7	2007	73	SGS00	L7 ETM+ SLC-off	14	March	320
44	LT5	2007	81	BKT00	L4-5 TM	22	March	305
45	LE7	2007	89	SGS00	L7 ETM+ SLC-off	30	March	320
46	LT5	2007	97	BKT00	L4-5 TM	7	April	337
47	LT5	2007	113	BKT00	L4-5 TM	23	April	375
48	LE7	2008	12	EDC00	L7 ETM+ SLC-off	12	Jan	452
49	LT5	2008	36	BKT00	L4-5 TM	5	Feb	427
50	LE7	2008	44	SGS00	L7 ETM+ SLC-off	13	Feb	419
51	LE7	2008	60	SGS00	L7 ETM+ SLC-off	29	Feb	390
52	LT5	2008	68	BKT00	L4-5 TM	8	March	384
53	LT5	2008	100	BKT00	L4-5 TM	9	April	402
54	LE7	2008	108	SGS00	L7 ETM+ SLC-off	17	April	396
55	LT5	2008	116	BKT00	L4-5 TM	25	April	393
56	LE7	2009	14	EDC00	L7 ETM+ SLC-off	14	Jan	375
57	LE7	2009	30	SGS00	L7 ETM+ SLC-off	30	Jan	350
58	LE7	2009	46	SGS00	L7 ETM+ SLC-off	15	Feb	338
59	LE7	2009	62	SGS00	L7 ETM+ SLC-off	3	March	321
60	LE7	2009	94	SGS00	L7 ETM+ SLC-off	4	April	325
61	LE7	2009	110	EDC00	L7 ETM+ SLC-off	20	April	345
62	LT5	2009	118	BKT00	L4-5 TM	28	April	354
63	LE7	2010	1	PFS00	L7 ETM+ SLC-off	1	Jan	408
64	LT5	2010	25	BKT00	L4-5 TM	25	Jan	362
65	LT5	2010	41	BKT00	L4-5 TM	10	Feb	328
66	LT5	2010	57	BKT00	L4-5 TM	26	Feb	335
67	LE7	2010	65	SGS00	L7 ETM+ SLC-off	6	March	359
68	LE7	2010	81	PFS00	L7 ETM+ SLC-off	22	March	436
69	LE7	2010	97	SGS00	L7 ETM+ SLC-off	7	April	562
70	LE7	2010	113	PFS00	L7 ETM+ SLC-off	23	April	600
71	LE7	2011	20	PFS00	L7 ETM+ SLC-off	20	Jan	583
72	LT5	2011	28	BKT00	L4-5 TM	28	Jan	596
73	LE7	2011	36	PFS00	L7 ETM+ SLC-off	5	Feb	573
74	LT5	2011	44	BKT01	L4-5 TM	13	Feb	521
75	LE7	2011	52	PFS00	L7 ETM+ SLC-off	21	Feb	482
76	LE7	2011	68	ASN00	L7 ETM+ SLC-off	9	March	447
77	LT5	2011	76	BKT00	L4-5 TM	17	March	430
78	LE7	2011	84	PFS00	L7 ETM+ SLC-off	25	March	410
79	LT5	2011	92	BKT01	L4-5 TM	2	April	487

80	LE7	2011	100	PFS00	L7 ETM+ SLC-off	10	April	453
81	LE7	2012	39	EDC00	L7 ETM+ SLC-off	8	Feb	358
82	LE7	2012	55	EDC00	L7 ETM+ SLC-off	24	Feb	340
83	LE7	2012	71	PFS00	L7 ETM+ SLC-off	11	March	331
84	LE7	2012	87	PFS00	L7 ETM+ SLC-off	27	March	325
85	LE7	2012	103	PFS00	L7 ETM+ SLC-off	12	April	347
86	LE7	2013	9	EDC00	L7 ETM+ SLC-off	9	Jan	425
87	LE7	2013	25	PFS00	L7 ETM+ SLC-off	25	Jan	379
88	LE7	2013	41	PFS00	L7 ETM+ SLC-off	10	Feb	338
89	LE7	2013	57	EDC00	L7 ETM+ SLC-off	26	Feb	305
90	LE7	2013	73	EDC00	L7 ETM+ SLC-off	14	March	292
91	LE7	2013	89	EDC00	L7 ETM+ SLC-off	30	March	304
92	LE7	2013	105	SG100	L7 ETM+ SLC-off	15	April	354
93	LC8	2013	113	LGN01	L8 OLI/TIRS	23	April	403
94	LC8	2013	305	LGN00	L8 OLI/TIRS	1	Nov	850
95	LC8	2013	321	LGN00	L8 OLI/TIRS	17	Nov	625
96	LC8	2014	4	LGN00	L8 OLI/TIRS	4	Jan	419
97	LE7	2014	12	EDC00	L7 ETM+ SLC-off	12	Jan	398
98	LC8	2014	20	LGN00	L8 OLI/TIRS	20	Jan	387
99	LE7	2014	28	EDC00	L7 ETM+ SLC-off	28	Jan	375
100	LC8	2014	36	LGN00	L8 OLI/TIRS	5	Feb	365
101	LE7	2014	44	EDC00	L7 ETM+ SLC-off	13	Feb	358
102	LC8	2014	52	LGN00	L8 OLI/TIRS	21	Feb	345
103	LE7	2014	60	EDC00	L7 ETM+ SLC-off	1	March	411
104	LC8	2014	68	LGN00	L8 OLI/TIRS	9	March	383
105	LE7	2014	76	SG100	L7 ETM+ SLC-off	17	March	367
106	LC8	2014	84	LGN00	L8 OLI/TIRS	25	March	356
107	LE7	2014	92	SG100	L7 ETM+ SLC-off	2	April	353
108	LC8	2014	100	LGN00	L8 OLI/TIRS	10	April	393
109	LE7	2014	108	PFS00	L7 ETM+ SLC-off	18	April	311
110	LC8	2014	116	LGN00	L8 OLI/TIRS	26	April	302
111	LC8	2014	260	LGN00	L8 OLI/TIRS	17	Sept	987
112	LC8	2014	324	LGN00	L8 OLI/TIRS	20	Nov	536
113	LC8	2014	356	LGN00	L8 OLI/TIRS	22	Dec	431
114	LC8	2015	7	LGN00	L8 OLI/TIRS	7	Jan	
115	LC8	2015	23	LGN00	L8 OLI/TIRS	23	Jan	
116	LE7	2015	31	EDC00	L7 ETM+ SLC-off	31	Jan	
117	LC8	2015	39	LGN00	L8 OLI/TIRS	8	Feb	
118	LE7	2015	47	EDC00	L7 ETM+ SLC-off	16	Feb	

Appendix 2: Software

ESRI ArcGIS

'A geographic information system (GIS) is a system used to describe and characterize the earth and other geographies for the purpose of visualizing and analysing geographically referenced information. ArcGIS software is used for the following: Creating and using maps; compiling geographic data; analysing mapped information; sharing and discovering geographic information; using maps and geographic information in a range of applications; managing geographic information in a database.' (ESRI, 2013) In this research ArcGIS is used for image transformation into shapefiles, geometry measurements and river morphology change analysis. Other than the research applications for each section, ArcGIS is used for visualizations of river stability and overviewing locations of historic river paths in the entire research area.

USGS LandsatLook Viewer (online)

'The LandsatLook Viewer is a prototype tool that was developed to allow rapid online viewing and access to the USGS Landsat image archives. The LandsatLook Viewer displays the LandsatLook Natural Color image product for all Landsat 1-8 images in the USGS archive and was designed primarily for visualization purposes.

The imagery within this Viewer will be of value to anyone who wants to quickly see the full Landsat record for an area, along with major image features or obvious changes to Earth's surface through time. An area of interest may be extracted and downloaded as a simple graphic file directly through the viewer, and the original full image tile is also available if needed. Any downloaded LandsatLook image product is a georeferenced file and will be compatible within most GIS and Web mapping applications.

If the user needs to perform detailed technical analysis, the full bands of Landsat source data may also be accessed through direct links provided on the LandsatLook Viewer.

This viewer allows you to:

- Interactively explore the Landsat archive at up to full resolution directly from a common Web browser
- Search for specific Landsat images based on area of interest, acquisition date, or cloud cover
- Compare image features and view changes through time
- Display configurable map information layers in combination with the Landsat imagery
- Create a customized image display and export as a simple graphic file
- View metadata and download the full-band source imagery'

(U.S. Geological Survey (USGS), 2014b)

Delft3D

'Delft3D-FLOW is a multi-dimensional (2D or 3D) hydrodynamic and transport simulation program which calculates non-steady flow and transport phenomena that result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. It can carry out simulations of flows, sediment transports, waves, water quality, morphological developments and ecology.' (Deltares, 2014b)

Appendix 3: Delft3D simulation

In this appendix the five preparatory steps for the simulation model are explained. Next the full model input is given and the model products and its applications are described more extensively.

Model preparations

A curvilinear grid is created for the research area including the confluence with the Chindwin River. For elevation data input, an SRTM dataset is used. The shuttle radar topography mission data was obtained in February 2000, with a spatial resolution of 90x90 meters. With the Delft3D QUICKIN toolbox the depth data is averaged per grid cell for the larger grid cells (borders) and smoothed for the smallest grid cells in the middle of the river. This smoothing does not affect the accuracy of the bathymetry, since the river bathymetry is initially flat; radar measurements do not penetrate water. Due to the low spatial resolution and the initial flat river bathymetry, no identical replica of the real situation can be made. Still, much can be learned from simulations of situations similar to the real situation.

After step one, the preparation of the model still consists of several steps:

1. Create grid and depth file based on SRTM data
2. Determine boundary conditions (Q, Qs and WL)
3. Create restart file for initial water level
4. Create river bathymetry
5. Create a new restart file for initial water level

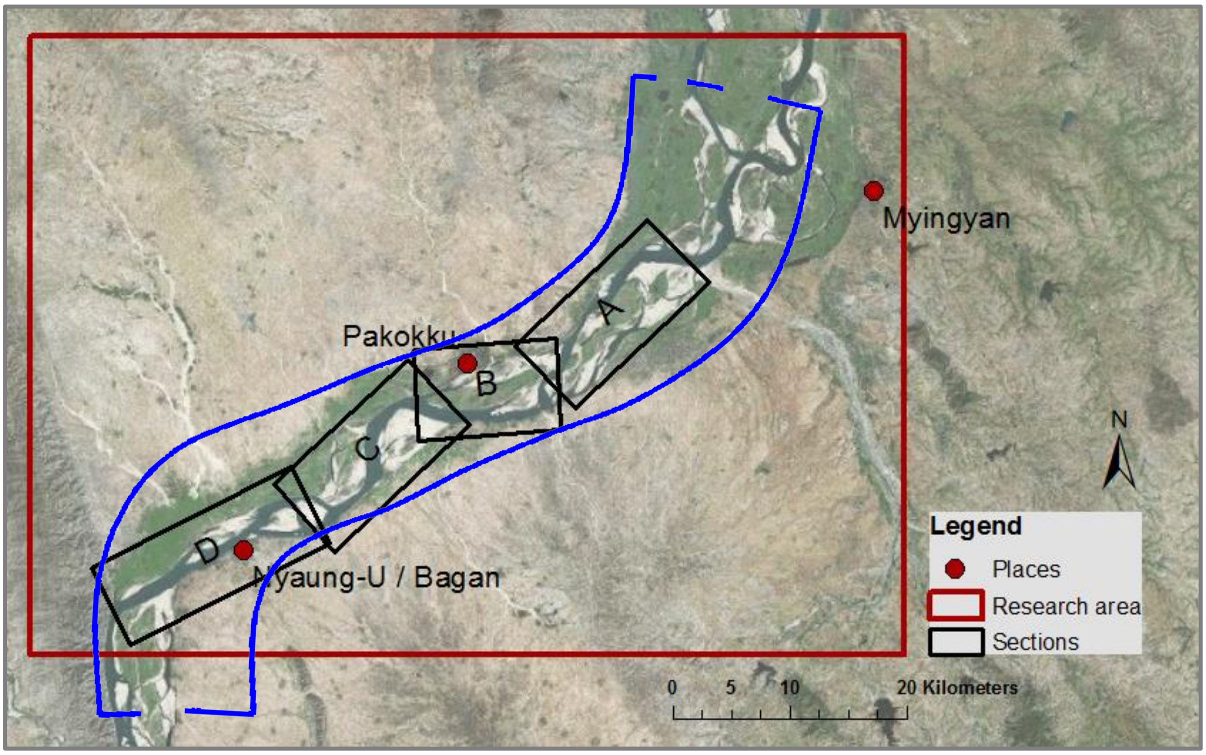

FIGURE 0.1 LOCATION OF THE MODEL GRID, RELATIVE TO THE LOCATION OF THE SECTIONS.

Boundary conditions

Open boundaries are defined at the Ayeyarwady inflow, the Chindwin inflow and the Ayeyarwady outflow. The inflow conditions are total discharge time series, which is a daily discharge file based on averaged existing flow measurement carried out by the DWIR between 1980 and 2014. For the Chindwin River discharge at Monywa are used, for the Ayeyarwady River discharge at Sagaing is used.

The discharge data is averaged over the last 10 years (2005-2014). It is averaged because: 1. It is not aimed to make an exact copy of reality so extreme events may be filtered out and 2. Annually repeating processes can be recognized and explained more easily when input is the same every year. The smaller time period of 10 years – while 34 years of data is available – is chosen based on a significant decrease in low water levels since 1980. The last 10 years are more representative for the current situation.

The outflow open boundary is of type Water Level time series. This file contains daily water level data corresponding to the discharge given at inflow, based on a Q/h relation obtained from the last 10 years of data. For this Q/h relation the downstream measuring station in Chauk is used as reference. See also 5.1 Boundary conditions.

Restart file

In Delft3D Flow, initial water level is given as a level above datum (sea level). Choosing the downstream boundary as a reference point would leave the upstream section dry (see pink line in Figure 0.2). Choosing the upstream boundary as a reference would flood the whole grid defined area with a uniform water level (see horizontal intermittent blue line in Figure 0.2). Downstream water depths are way too high. To create a uniform water depth (≠ uniform water level) the research area should be drained from all excess water. The product of this simple simulation is a restart file containing an initial water level for every grid cell (blue line).

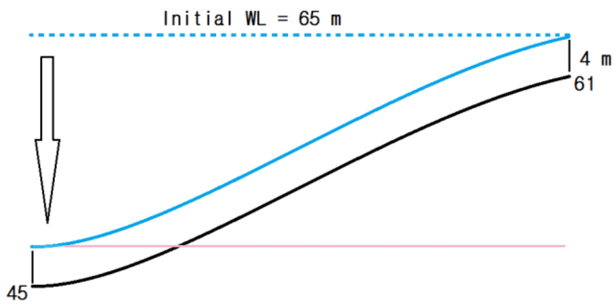

FIGURE 0.2 VISUALIZATION OF THE EFFECT OF A UNIFORM INITIAL WATER LEVEL AND THE SITUATION AFTER DRAINING, CREATING A RESTART FILE. THE BLACK LINE REPRESENTS THE BED LEVEL.

River bathymetry

As just explained the river itself does have a flat bathymetry when using the SRTM data as input. In order to make the simulation as realistic as possible a river bathymetry is created. In this model the discharge is set to uniform high (but realistic) values for one month: Ayeyarwady 15000 m^3/s and Chindwin 10000 m^3/s, with corresponding downstream water levels. The morphologic factor in Delft3D flow is set to 60, resulting in a morphologic simulation period of 5 years (60*1 month). Figure 0.3 displays the results of a 5 year simulation with high discharge.

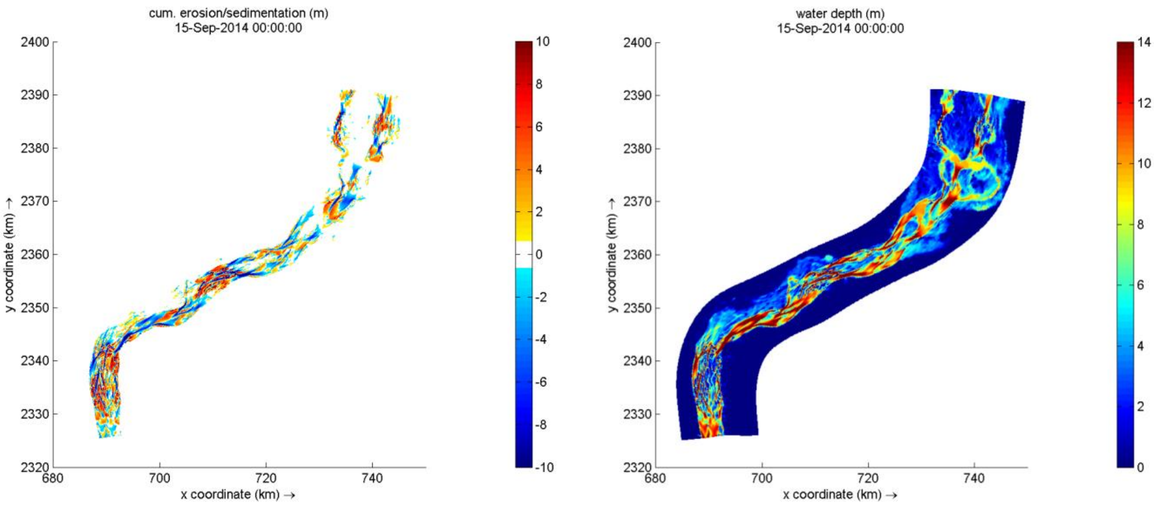

FIGURE 0.3 RESULTS OF STEP 4: CREATE RIVER BATHYMETRY, AFTER A FIVE YEAR SIMULATION WITH HIGH DISCHARGE. THE LEFT FIGURE SHOWS CUMULATIVE EROSION AND SEDIMENTATION (M), THE RIGHT FIGURE SHOWS WATER DEPTH (M).

New restart file

Another restart file is created as input for the final simulation. The previous restart file corresponds to a high discharge of 25000 m^3/s (Ayeyarwady + Chindwin), while the input for the full model should refer to discharge at the 1st of January. In January total discharge is typically around 2125 m^3/s. Corresponding water depth is ~4 meters.

It is also important to note the change in bed level elevation at the downstream end. After bathymetry is "created" the bed level has decreased by ~4 meters (from 45 m to 41 m above datum).

Parameter	Value	Unit	Note
Initial discharge Ayeyarwady	1244	[m^3/s]	
Initial discharge Chindwin	875.1	[m^3/s]	
Initial downstream water level	44.985855	[m]	= 41 + 3.985855

MODEL INPUT

Domain

Within Delft3D-FLOW the grid and bathymetry files are loaded and located at 55 decimal degrees latitude. Note that the new bathymetry file is chosen, based on step 3 in the preparations. No dry points and thin dams are defined.

Time frame

Simulation time runs from 01-01-2013 to 31-12-2014 with a time step of 2 minutes.

Processes

In Processes only secondary flow is checked. The model does also contain sediment transport, but only bed load sand transport. For this to be implemented correctly, both morphology and sediment settings have to be adjusted.

Sediment input (values other than default)

Parameter	Value	Unit	Note
Name	#Sediment-sand#		Name of sediment fraction
SedTyp	Bedload		Must be 'sand', 'mud' or 'bedload'
SedDia	4.000e-4	[m]	Median sediment diameter
IniSedThick	20	[m]	Initial sediment layer thickness at bed

Sediment size is assumed 0.4 mm, based on outcomes of the sieve analysis test on sediment samples obtained in November 2014 (Myayarpin Engineering Co. & Deltares, 2014) and based on the normal median diameter of sand. For more information on the sediment samples see 4.1.1 Sediment samples.

Morphology input (values other than default)

Parameter	Value	Unit	Note
MorFac	5	[-]	Morphological scale factor
MorStt	180	[min]	Spin-up interval from TStart till start of morphological changes
Thresh	5.000e-2	[m]	Threshold sediment thickness for transport and erosion reduction

The morphological scale factor is set to 5, referring to a morphological time 5 times as fast as hydrological time. This is done to reduce computation time. In order to let the hydrologic input correspond to the morphological time, 5 hydrological cycles (=years) are played within each of the two years. Thus in total 10 morphological years are computed within two years of computation.

Initial conditions

Initial water level is defined by the new restart file, based on total discharge on the 1st of January and the Q/h relation in Chauk. This file also contains values for secondary flow, which value initially was 0.2 m/s.

Boundaries

At the upstream boundaries the 10 year averaged daily discharge time series is used. The Ayeyarwady discharge at Sagaing varies between 730 and 16500 m^3/s. The Chindwin discharge at Monywa varies between 310 and 12500 m^3/s.

At the downstream boundary water levels are given based on total daily discharge (Ayeyarwady plus Chindwin) and the Q/h relation in Chauk.

Physical parameters

Parameter	Value	Unit	Note
Manning	0.040	[-]	Uniform (Arcement & Schneider, 1989; Chow, 1959)
Water density	1000	[kg/m^3]	Fresh water
Gravity	9.81	[m/s^2]	
Beta-c	0.5	[-]	Default
Viscosity	1.35	[Pa/s]	(Rodi, 1993; Tinkler & Wohl, 1998)
Diffusivity	1.35	[m^2/s]	(Rodi, 1993; Tinkler & Wohl, 1998)

Beta-c is the fraction of the shear stress due to secondary flow taken into account in the momentum equation. Secondary flow (spiral motion) is important for changes of the river bed and dispersion of matter. Spiral intensity can be computed with

- Advection – diffusion
- Equilibrium state

The latter assumes steady flow, which is not the case in our model.

Depth averaged eddy viscosity or diffusivity is "reasonably well correlated" with the product of shear velocity and water depth. This is expressed in SI unit m^2/s. For this model both parameters are assumed for high discharge conditions. Water depth during high discharge is ~11 m. This water depth is earlier used for the morphology run (step 3 – run 2). Shear stress during that run was ~ 15 N^2/m.

Viscosity or diffusivity $\approx U_* * h$

Shear velocity $U_* = \sqrt{\frac{\tau}{\rho}}$

With τ = 15, ρ = 1000 and h = 11. This gives a viscosity or diffusivity of 1.35 m^2/s

Numerical parameters

In the numerical parameters section, threshold depth is set to 0.1 m. All other options are left in default.

Operations

No extra discharges are added.

Monitoring

Four observation points are placed – one in each river research section – and three cross sections are lined at the upstream, downstream end and in the middle.

Additional parameters

An additional parameter is one of the possible sand transport formulations in Delft3D. The formula used is the Engelund & Hansen (1967) formula for transport of bedload (and possible suspended load) in alluvial streams.

Output

Parameter	Value	Unit	Note
Map result interval	360	[min]	6 hours
Restart interval	43800	[min]	Each month
History interval	360	[min]	6 hours

PRODUCTS

The Delft3D Flow simulation produces a planform view of changes in i.e. flow velocity or water level. In a time lapse, values are given in the entire river section, for each (defined) time step and for each defined cell. The software also computes changes in the morphology of the river, resulting in alterations of the bathymetry.

Relevant output datasets are

- Bed level
- Flow velocity
- Cumulative erosion/deposition
- Water level
- Water depth
- Froude number
- Bed load transport
- Secondary flow

For easy visualization, flow velocity and bed load transport are given as an arrow (longer is higher value), and other non-directional datasets are shown with a colour map.

The combined product of flow velocity, bedload transport and bed level shows the direct relation between active processes and bedform changes. Its outcomes will be used for understanding and describing this relation. Since the model does not represent the exact situation in the Ayeyarwady River but only an approximation of reality, it is mostly used to support or explain observations from the image analysis. More specifically, patterns in bar and channel migration can be recognized and linked to situations in reality. Also more general conclusions are drawn for all sections together.

With these simulations, effects of changing discharge and flood events can be researched more effectively. While in aerial images changes in water levels and its effects are only seen as static pictures and interpreted as dynamic processes, Delft3D can actually visualize the process itself. Response to changes is directly visualized, making quantification of the processes also possible.

In short, the visualizations containing information on both flow velocity and bathymetry will be used

- to understand the general relation between flow and bedform changes
- to visualise the effect of changes in discharge on morphology in smaller steps
- to help quantify processes which are recognized in the real situation as well

APPENDIX 4: PLANFORM COMPONENTS – LITERATURE REVIEW

Point bars and lateral bars are bank-attached, respectively in sinuous and relatively straight channels. Lateral bars commonly alternate from bank to bank (Schmidt, 2013). The alternate braid bar is formed when a double row of alternate bars exists in a channel. An increase in sediment supply and consequent bedform alternations results in flow divergence and bar initiation. Following lateral accretion and preferential scour of one anabranch occurs. This is influenced by the location of upstream lateral bars and also results in the formation of bars adjacent to the mid channel bar. In the final stages, cross bar flow and tail formation lead to bar dissection. (Ashworth, Best, Roden, Bristow, & Klaassen, 2000) Typical alternate braid bars form in a dune/oxbow shape, which can be dissected in various directions (Figure 0.4).

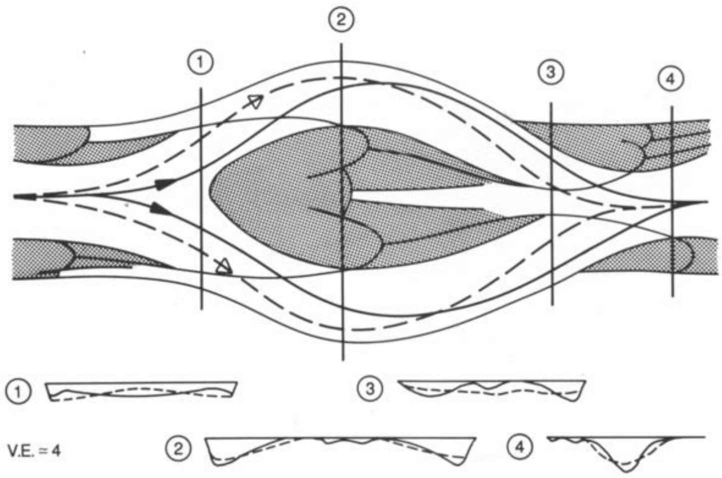

FIGURE 0.4 IDEALIZED GEOMETRY FOR A SIMPLE BRAIDED CHANNEL BAR (BRIDGE, 1993)

The location of bars influences the flow in channels, since flow separation occurs around an obstruction such as a bar and at a bend of a river (Morisawa, 1985) and influences erosion or deposition patterns. Formation and erosion of bars can initiate braid development. Depositional mechanisms are: central bar development where coarse material is deposited where flow is incompetent of carrying after scouring it from the upstream end of the flow convergence point (Ashmore, 1991; Charlton, 2008; Knighton, 1998); and transverse bar conversion where fine sediments eroded due to scour at the convergence are transported in the chute after the confluence. Past the chute the sediments are deposited in sheets in the wider section after the chute (Ashmore, 1991). Both mechanisms result in flow divergence around the downstream bar when bar height increases. Erosional mechanisms are: chute cut-off, formed by flow over a point bar and progressive enlargement of the channel as it captures more flow via this more direct route (Ashmore, 1991; Ferguson, 1993); and multiple bar dissection, when flow across linguoid bars is concentrated into multiple chutes (Charlton, 2008; Knighton, 1998).

Another important characteristic of braiding rivers is the development of bifurcations and confluences. A bifurcation is the division of a river channel into two or more channels. Changes in the relative importance of bifurcated channels are determined basically by the distributions of discharge and sediment transport at the bifurcation (Klaassen, Mosselman, & Bruhl, 1993). Important factors effecting these distributions are gradient advantage, bifurcation asymmetry and incoming angle. Channels with a gradient advantage are likely to capture more discharge, have higher flow velocities and enlarge (Kleinhans, Ferguson, Lane, & Hardy, 2013). The probability of channel abandonment increases with the deflection angle of the bifurcation (Klaassen et al., 1993). The angle of the channel upstream the bifurcation effects transverse flow in the channel and stimulates sedimentation of the inner bend. Of the two downstream channels, the one at the inner bend is shallower and will therefore capture less flow (Bolla Pittaluga, Repetto, & Tubino, 2003; Kleinhans, Jagers, Mosselman, & Sloff, 2008). The shape and location of bars upstream a bifurcation effect the angle of the incoming channel.