Dispersion in the Ayeyarwady River

A description of the mixing of tracers in the area of the Ayeyarwady River-Chindwin River confluence

Tije Bakker

TU Delft

The photo on the cover page is taken from the boat just after releasing the floaters into the Chindwin River, just upstream of the bridge (also visible) near Monywa. The ships in the picture are dredging ships, used for sand mining. Just a little later some of these ships have probably destroyed and stolen all 5 used GPS floaters at this location. Only 2 were found back. The photo is taken on 31 January 2017.

Dispersion in the Ayeyarwady River

A description of the mixing of tracers in the area of the Ayeyarwady River-Chindwin River confluence

Tije Bakker BSc

Supervisors:
Dr. Ir. M.M. (Martine) Rutten
Dr. Ir. K. (Kees) Sloff

June 2017

TU Delft

I. Preface

In this thesis report you will find the results of an effort made to describe the mixing of tracers in the Ayeyarwady River, Myanmar. This additional thesis report is made in the context of my Master Hydraulic Engineering at the Delft University of Technology (TU Delft). Part of this thesis was a stay in Myanmar together with Erik van Duijn to participate in a week of fieldwork at the Ayeyarwady River and a stay of five weeks at the Myanmar Maritime University (MMU).

Participating in the fieldwork on such location and in such circumstances was extraordinary. Although less data than hoped was collected due to the in this report described difficulties, some useful data, and definitely the experience was gained to make a future fieldwork more successful. During our stay at the MMU, Erik and I worked (mostly together) on elaborating the fieldwork results. Besides, we worked together with students and staff at the River and Coastal Department at the MMU in the context of a capacity building project, for example on the setup of course for learning the programming language Python.

Back in the Netherlands, setting up the Delft3D model and estimating the dispersion appeared to be more challenging than expected, mostly due to the limited available data. The trip to Myanmar was directly at the beginning of this research, meaning there was only little time to prepare. Looking back on all there are quite some things that I would have done differently now, but that's with today's knowledge. It would have definitely made a more accurate estimate of the dispersion easier and less time consuming, but that's for future projects. Nevertheless it was a very nice and educative experience in many ways and I'm very glad to have had the opportunity to do this.

Acknowledgements

I would like to thank my supervisors from the TU Delft Martine Rutten, especially for the guidance during the setup and writing of the report and Kees Sloff, especially for all the help with the setup of the Delft3D model. Besides, I would like to thank Thom Bogaard and Rolf Hut for the organisation of and sharing their expertise during the fieldwork and RVO Partners for Water for making the trip financially possible.

I also would like to thank Erik van Duijn and Boy-Santhos van der Sterre for the good times during our stay in Myanmar, all the friendly and helpful students and staff from MMU, especially Htike Htike and Wai Yan Moe Aye for everything which made our stay so much better and all others who helped with or made it possible to go to Myanmar and do this thesis.

II. Summary

The Ayeyarwady River (also called Irrawaddy River) is the most important river of Myanmar and due to the country's rapid development it is expected to become even more important. The river flows roughly from north to south through Myanmar and is very dynamic and mostly unregulated. With a length of 2170 km and an over the year average (highly seasonally varying) discharge of 13'000 m^3/s into the Andaman Sea (Bhardwaj, Owen, & Leinbach, 2012), the Ayeyarwady is one of the bigger rivers in Asia.

To more than before take into account the interests of different stakeholders, as well as ecological aspects, sustainable management of the river is needed. Understanding the key aspects of the river flow can be a first step to sustainable river management (Richter et al., 2003). Pollution due to a large variety of activities of different nature make that water quality monitoring is of high importance (Thanda Thatoe Nwe Win, Bogaard, & Van de Giesen, 2015).

For monitoring and modelling the water quality, information about the mixing of tracers trough the river is needed, which can be quantified with the use of dispersion coefficients. Little research has been done about the Ayeyarwady River in general considered its size and importance. Very limited data about the mixing of tracers and the parameters needed to estimate the mixing of tracers was available.

This research focuses on the situation around the Ayeyarwady-Chindwin confluence in the first week of February 2017 (dry season). Hence, there is a very different situation during for example wet season. For the water quality, mainly the mixing in the longitudinal direction (direction of the main river flow) is of interest, which can be quantified by a longitudinal dispersion coefficient (K_x).

First relevant parameters for estimating K_x were identified based on the theory. This appeared to be the discharge, roughness and bathymetry. Besides, K_x has to be calibrated by floater experiments. To get better insight into the magnitude of these parameters, flow velocity and depth measurements (needed for estimating the discharge, roughness and bathymetry) and floater experiments have been done during a week of fieldwork in the area. Due to loss, theft and destruction of floaters, less data was collected than planed. To get further insight in the mixing of tracers, a numerical model was made in the software Delft3D based on data collected during the fieldwork.

Based on the combined results of the theory, measurements done during the fieldwork and the Delft3D model, it is expected that the magnitude of K_x in the Ayeyarwady River is somewhere in between 50-500 m^2/s (best estimate: K_x~300 m^2/s), although this has to be confirmed by further research. When the found value is compared with values found for other bigger rivers this value for K_x appears to be somewhat on the low side.

From the Delft3D model runs follows that the longitudinal dispersion coefficient in the Chindwin River is higher than in the Ayeyarwady, possibly even a factor 10. Besides, insight in the effect of the different parameters on the dispersion was obtained, contributing to a better understanding of processes causing the mixing of tracers in the Ayeyarwady and Chindwin rivers.

Estimating the highly sensitive longitudinal dispersion coefficient (K_x) appeared to be challenging, mostly due to the remote and highly dynamic character of the area. To make a better estimate of K_x, the uncertainty in the parameters needed (discharge, roughness, bathymetry and spreading of floaters for calibration) has to be reduced. Although some modelling options in Delft3D could be tried to narrow the range of these parameters, the best option to reduce this uncertainty is collecting more (high quality) data in the field.

III. Table of contents

IV. Lists of figures and tables

List of figures

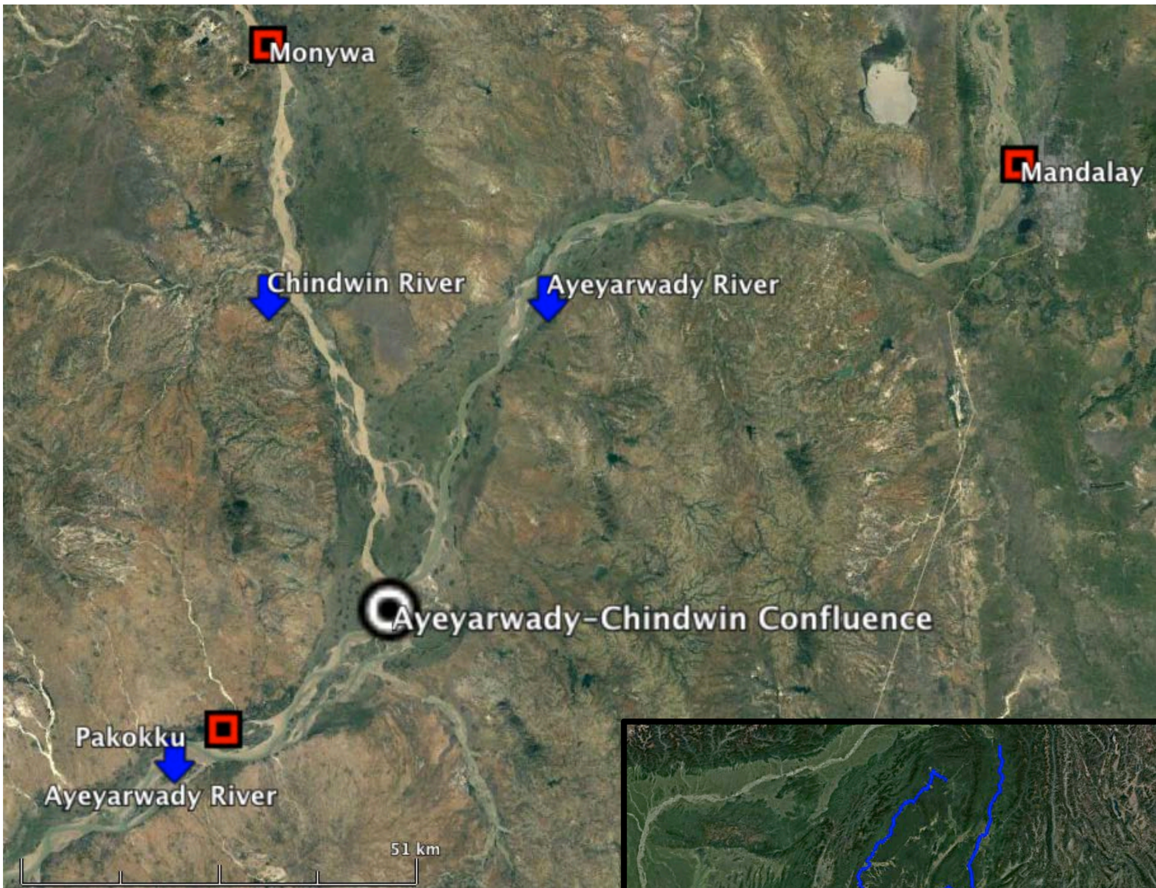
List of tables

1. Introduction

1.1 The importance of the Ayeyarwady River for Myanmar

The Ayeyarwady River (also called Irrawaddy River) is the most important river of Myanmar and due to the country's rapid development it is expected to become even more important. The river flows roughly from north to south through Myanmar (see map in Figure 1) and its basin covers 411'000 km^2 (Bhardwaj, Owen, & Leinbach, 2012). The river is used for many different purposes, as of which some examples are given in Figure 2.

The Ayeyarwady is a very dynamic and mostly unregulated river; the yearly displacement of the (main) channel can be in the order of hundreds of meters. With a length of 2170 km and an over the year average (highly seasonally varying) discharge of 13'000 m^3/s into the Andaman Sea (Bhardwaj, Owen, & Leinbach, 2012), the Ayeyarwady is one of the bigger rivers in Asia.



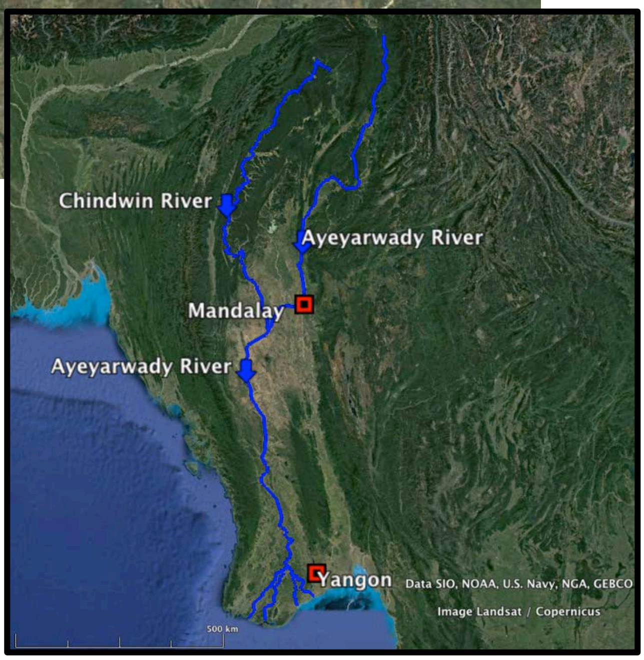


Figure 1: The location of the Ayeyarwady River and Chindwin River in Myanmar (right) and an overview of the area of the Ayeyarwady-Chindwin confluence (up).

The Ayeyarwady River has its origin in the foothills of the Himalayas. On its way it passes by Mandalay, confluences with the Chindwin River to finally enter the Andaman Sea in the Ayeyarwady Delta. Figures are made in Google Earth (2017).

Myanmar is a democratizing country, meaning it is important that different stakeholders can participate and feel they have a stake in developments (Thin Thin Aye, 2015). To take into account the stakes of different stakeholders, as well as ecological aspects, sustainable river management is needed. For sustainable river management, understanding the key aspects of the river flow can be a first step (Richter et al., 2003).

One of the subjects in this sustainable river use is the water quality. Chemical fertilizer used for agriculture, mining activities in the catchment area, wastewater effluents from the industries and communities and other development activities generate pollutants of different nature make that water quality monitoring is of high importance (Thanda Thatoe Nwe Win, Bogaard, & Van de Giesen, 2015). For monitoring and modelling the water quality, information about the mixing of tracers is needed.

Little research has been done about the Ayeyarwady River in general, considered its size and importance. No data about the mixing of tracers in the Ayeyarwady is available and only limited about the discharge and water levels is known. Van der Velden (2015) gives some insight in data provided by several institutions from Myanmar, but as mentioned before, the discharge is highly varying and meaning this information can only be used for a first estimate.

Figure 2: A large variation of activities happens on the river, among others the river is used for:

- *Drinking- and irrigation water.*
- *Transport (A), for example to cities as Mandalay and Monywa and transport of (valuable) teak wood (C) for export in downstream direction.*
- *Fishing (D) in and sand mining (by dredging vessels, (B) on the river.*
- *Water usage for mining in areas near the river.*

No recent data about the bathymetry was available. SRTM satellite data (USGS, 2000) gives some insight in the elevation (relative to the reference level EGM96) and thereby hydraulic gradient, but is from the year 2000 and therefore out-dated. Satellite images available in Google Earth give insight in the location of the riverbanks. In general, due to the dynamic behaviour of the Ayeyarwady and Chindwin rivers, data regarding all above-mentioned topics gets out-dated very fast.

In several other rivers research to dispersion and river mixing has been done. A good impression of the results of these researches is given by Rutherford (1994, pp. 193-197). One of the most intensively researched rivers is the River Rhine, in which tracer experiments have been done to estimate the dispersion and influence of various processes on the dispersion (Mazijk A. , 1996; Mazijk & Veling, 2004). However, most of these rivers are much smaller in terms of discharge, much more regulated and/or canalized making them less dynamic.

1.2 Objective

In this research, the main objective is to get insight in the how tracers (like pollutants) get spread out over the Ayeyarwady River. Mainly the mixing in the longitudinal direction (direction of the main flow) but also in the transversal direction (over the width of the river) is of interest.

One of the most dynamic parts of the Ayeyarwady River is the area around the confluence with the Chindwin River, making it an interesting case for research on mixing of tracers in rivers. The following main question is formulated:

- *How can the mixing of tracers around the confluence of the Ayeyarwady River and Chindwin River be described?*

As mentioned before, the circumstances in the river are highly seasonally varying. This research is done for the situation in the first week of February, meaning it was dry season in the area. Hence, there is a very different situation during for example wet season, when there is a much higher discharge and therefore different bathymetry, as the floodplains get flooded.

The mixing of tracers in a river is mainly caused by dispersion (see explanation in chapter 2). For the modelling of the mixing of tracers, dispersion coefficients are used. To be able to answer the above stated main question, the following sub questions are defined:

- Which parameters are important for the mixing of tracers and estimating the dispersion coefficient in the Ayeyarwady and Chindwin rivers?
- What is the magnitude of the parameters needed to describe the mixing of tracers and estimating the dispersion coefficient in the Ayeyarwady and Chindwin rivers?
- What are the flow patterns around the confluence of Ayeyarwady and Chindwin rivers?
- What is the estimated longitudinal dispersion coefficient(s) around the confluence of Ayeyarwady and Chindwin rivers?

The strategy used to achieve these objectives and be able to answer the main question is elaborated in the next section.

1.3 Setup of this research

First, some important concepts in the mixing of tracers (river mixing) are explained. Fisher (1979) gives an overview of the fundamental processes influencing the mixing of tracers. Also the work of Rutherford (1994) gives a good overview of the fundamentals and furthermore consists of somewhat more practical applications and examples on the mixing of tracers. A short overview of these concepts, for dispersion relevant parameters, a first estimate of the dispersion coefficients and some reference projects are given in chapter 2.

To get better insight in the mixing of tracers, a week of fieldwork has been done on the Ayeyarwady River and Chindwin River near the confluence. During this fieldwork a tracer experiment with floaters with GPS trackers and an experiment with simple floaters has been done. Moreover, depth and velocity measurements have been done, to get insight in the discharge, bathymetry and distribution of the flow velocities over the river. The set up and execution of this fieldwork is elaborated in chapter 3.

Based on these depth and velocity measurements done during the fieldwork, a numerical model in Delft3D is made. In this model, tracers have been modelled. This gives in principle the same type of results as the floater experiment done during the fieldwork, but in a model (without the complications of being in the field) much more tracers can be used and the floaters can be followed easier over a longer distance. However, also the model has its limitations. The setup of the model is elaborated in chapter 4.

The results of the theory, fieldwork and Delft3D model are presented in chapter 5. This includes floater paths from both the fieldwork and Delft3D model and an overview of the influence of different parameters on the dispersion resulting from the Delft3D model simulations. In chapter 6, all results and the limitations of the to obtain these results used theory, fieldwork and Delft3D model are discussed.

In chapter 7 the conclusions are presented, including their limitations and recommendations on how these limitations might be solved in further research. First, the sub questions outlined in the previous section are elaborated. Finally the main question is addressed, contributing to a better understanding of in the Ayeyarwady River and Chindwin River on going processes causing the mixing of tracers.

2. Theory and literature

In this chapter, first the basic terminology and theory regarding the mixing of tracers trough a river is elaborated. Important parameters are identified and a first estimate of the dispersion coefficient is given.

2.1 Terminology

The following definitions are used for the in this report used terms (alphabetically listed). See also Figure 3 to get insight in how the processes are linked.

Advection

Advection is the bodily movement of a parcel of fluid resulting from an imposed current. Advection transports any tracer which may be dissolved or suspended in the fluid and is clearly important in rivers because it carries tracer downstream away from a fixed source. Pure advection does not cause any changes in the concentrations in a particle cloud (Rutherford, 1994).

Dispersion

Dispersion is the mixing of tracers due to the combination of velocity distribution over cross section and turbulent diffusion (Rutherford, 1994).

Longitudinal

The longitudinal direction is in the direction of the main flow of the river.

Mixing

Diffusion, dispersion or any process that causes one parcel of water to be mingled with or diluted by another parcel of water (Fisher et al.,1979).

Mixing length

The mixing length is the length (of a river branch) before a tracer is well mixed over a certain domain. This domain can be the for example the depth or width of a river. This length can be calculated with Prandtl's mixing length hypothesis. The corresponding time needed for this mixing length is the mixing time.

Mixing time

The mixing time is the time needed before a tracer is well mixed over a certain domain. This domain can be the for example the depth or width of a river. The corresponding length needed for this mixing time is the mixing length.

Molecular diffusion

Molecular diffusion is the scattering of particles by random molecular motions. This can be described by use of Fick's law and the classical diffusion equation (Fisher et al.,1979). In rivers (turbulent) this process can normally be neglected, as the turbulent diffusion is of much more importance (Rutherford, 1994).

Tracers

Tracers are the subjects that are (eventually) spread out. They can be particles or dissolved matter.

Transversal

The transversal direction is in the direction of the width of the river.

Turbulent diffusion

Turbulent diffusion is the random scattering of tracers by turbulent motion (eddies). This is often modelled similar as molecular diffusion, but with (much larger) eddy diffusion coefficients (Fisher et al.,1979). In rivers this is an important process for the mixing of tracers (Rutherford, 1994).

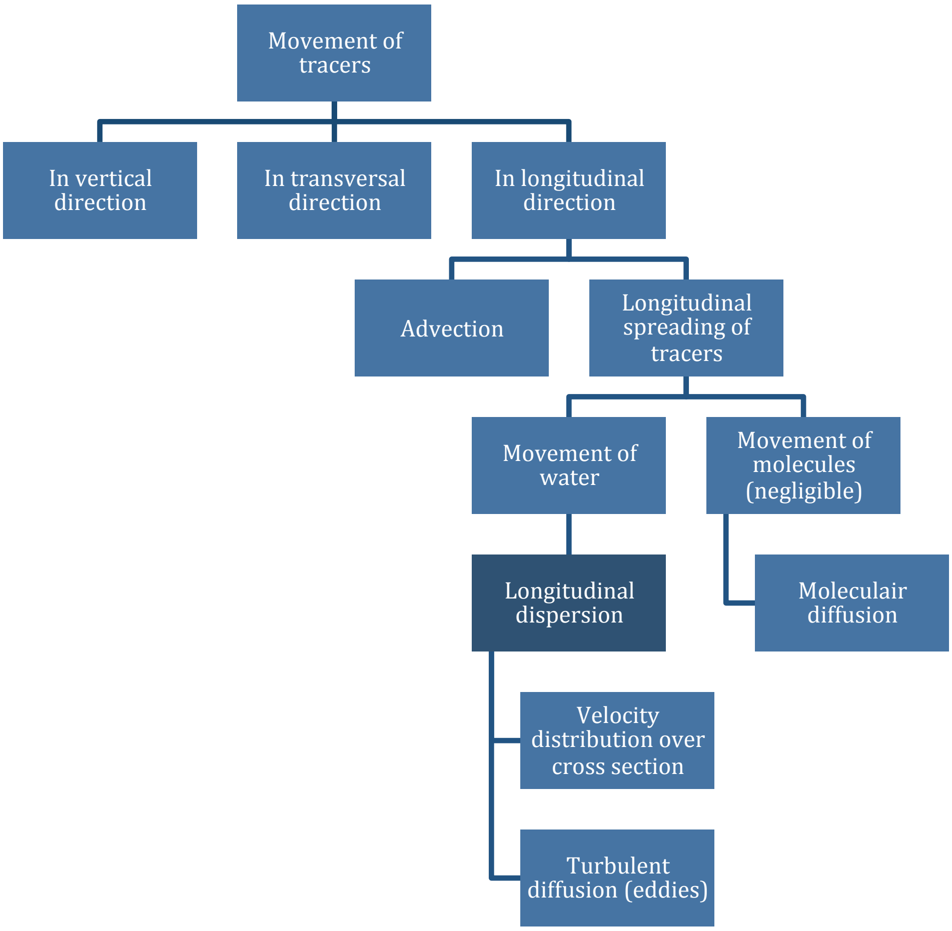


Figure 3: Overview of the in this report used terms and how they are connected. The process longitudinal dispersion (highlighted in dark blue) is the process of main interest in this report. The terms are explained in section 2.1.

2.2 Differentiating between different processes

The mixing of tracers in a river can be subdivided in the three categories according to Rutherford (1994):

- Near field: **vertical mixing** (mixing over the depth). The length scale of this process is relatively short. The mixing length (in longitudinal direction) for this process is in the order of 50 times the river depth, which is for the Ayeyarwady River in the order of 300 m.
- Mid field: **transversal mixing** (mixing over the width). The mixing length (in longitudinal direction) in the order of 100 to 300 times the river width for a point source in the middle of the river. For the Ayeyarwady River this is In the order of 100 km.
- Far field: **longitudinal mixing** (mixing over the length). The rate of longitudinal mixing depends mostly on the distribution of flow velocity over the cross section. Besides some other processes are important, see Figure 3. The length scale of this is basically the length of from tracer source to river mouth.

As shown, the length scales of these processes are different. Therefore it is possible to treat these categories separately. Main interest of this research is mixing in longitudinal direction. But for longitudinal mixing, tracers first have to be well mixed in vertical and transversal direction. As the vertical mixing length is very short compared to that of the longitudinal mixing, this can be neglected. Hence, transversal mixing is of some importance, as the length scale of order of 100 km cannot be neglected compared to the longitudinal length scale.

2.3 Longitudinal dispersion

2.3.1 Flow velocity distribution

The most important process causing longitudinal mixing is the variation in velocity over the width and depth of a river. This variation in velocity can have different causes, for example:

- Bottom fiction
- Bank friction
- Larger scale irregularities in bathymetry (shoals, etc.)
- River bends (spiral flow, gradient in bottom level)

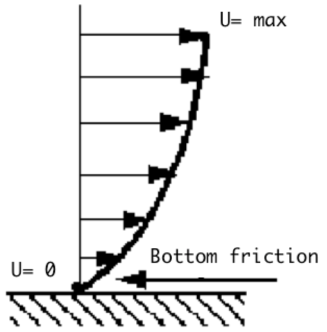


Figure 4: Effect of the river bottom on the flow velocity (u) distribution over the depth.

Bottom friction can be accounted for by a friction coefficient in combination with a depth and width. The effect of bottom friction on the flow velocity distribution is given in Figure 4. Hence, accounting for the effects of larger scale irregularities in vertical and horizontal direction is more complicated and information about the bathymetry is needed.

The tracer concentration distribution over a river in longitudinal direction corresponding to these idealized conditions is as shown in Figure 5. These theoretical concentrations follow a Gaussian distribution. However, tracer concentrations measured during experiments in various settings (both in the field and lab) have shown that the tail of this distribution is in reality much longer due to asymmetry in the flow velocity in for example bends and the 'catching of tracers' by dead zones (Rutherford, 1994). Turbulent diffusion counteracts the effects of velocity variations.

2.3.2 Longitudinal dispersion coefficient

According to Rutherford (1994), the one dimensional longitudinal dispersion coefficient (K_x) can be estimated with the following equation:

$$K_x = \alpha_x * \frac{u_x^2 * B^2}{d * u_*} \quad \text{(Eq. 1)}$$

In which the shear velocity u_* is:

$$u_* = u_x * \sqrt{g}/C \quad \text{(Eq. 2)}$$

With the following parameters:

- Longitudinal dispersion coefficient — K_x [m^2/s]
- Mean flow velocity — u_x [m/s]
- Width — B [m]
- Shear velocity — u_*[m/s]
- Roughness (Chezy) — C [m$^{1/2}$/s]
- Acceleration of gravity — g [m/s^2] (=9.81)
- Coefficient — α_x

As can be seen in equation 1, the width of the river is the parameter with the most influence, as it occurs squared in the equation. The u_x is not squared anymore when the equation for u_* is inserted. Estimating the values of u_x, d and C accurately is more challenging than estimating the value of B, which can be done from distance in a direct way by use of satellite images.

The coefficient α_x can be calibrated by tracer experiments. For a first estimate, the coefficient α_x can be replaced by a factor of 0.011 (Fisher et al., 1979) leading to:

$$K_x = 0.011 * \frac{u_x^2 * B^2}{d * u_*} \quad \text{(Eq. 3)}$$

The results of this equation appear to fit with observations within a factor 10, and deviations are mainly caused by effects of channel width, channel curvature and dead zones (Rutherford, 1994) which are not directly included in this formula. Hence, this also means (longitudinal) dispersion coefficients in practical river applications are complicated to determine accurate and do not always give the full picture, as 2D and 3D effects are not included in the equation while they are of great importance for the velocity distribution in a flow.

2.4 Theoretical longitudinal dispersion coefficient estimate

With use of equation 3, a theoretical estimate of the longitudinal dispersion coefficient is given for the Ayeyarwady River. As the mean flow velocity, mean width, Chezy coefficient and mean depth are not well known; some estimates have to be made. To make this easier, the flow velocity and equilibrium depth are calculated:

- The mean flow velocity (u_x) can be calculated with the Chezy equation for rivers with B>>d.

$$u_x = C * \sqrt{d * i} \quad \text{(Eq. 4)}$$

- The therefore needed mean water depth (d) can be calculated with the following equation for the equilibrium water depth (d_e).

$$d_e = \frac{Q^2}{B^2 C^2 i}^{1/3} \quad \text{(Eq. 5)}$$

When equation 4 and 5, are combined with equation 3, only the following parameters are left which are somewhat better known and can therefore be easier estimated:

- Discharge Q [m^3/s]
- Width B [m]
- Roughness (Chezy) C [$m^{1/2}/s$]
- Hydraulic gradient i [-]

To make an estimate of the longitudinal dispersion coefficient, these parameters have to be estimated. Only very limited data about the discharge is available, although Van der Velden (2015) gives some insight in the average discharge and the ratio between the discharge in the Ayeyarwady and Chindwin rivers based on data provided by several institutions from Myanmar. Based on this, an estimate is done (see Table 1). Furuichi, Win, & Wasson (2009) estimated the yearly average discharge between 1969 and 1996 at 12’000 ± 1500 m^3/s. The previously mentioned 13’000 m^3/s (Bhardwaj, Owen, & Leinbach, 2012) and average discharge by Van der Velden (2015) fall within this range.

The width of the Ayeyarwady River varies per location, and is estimated by measuring the river width at a few locations in the area on satellite images in Google Earth (2017). As there is no information available about the Chezy roughness coefficient of the Ayeyarwady River, values that are typical for rivers are taken (standard value Delft3D: C=65 $m^{1/2}/s$). The hydraulic gradient can be estimated based on the SRTM data (USGS, 2000) by taking the difference in elevation and divide this over the subsequent stretch of the river.

In Table 1 an overview of the estimated mean, lowest and highest values of the above-mentioned parameters (Q, B, C and i) is given. The longitudinal dispersion coefficient K_x is calculated for the mean values of these parameters, as well as for the combinations of these parameters leading to the lowest K_x and highest K_x. This results in a very wide range of longitudinal dispersion coefficients.

Table 1: Overview of the lowest, mean and highest estimated values of the discharge (Q), river width (B), Chezy coefficient (C) and hydraulic gradient (i). K_x is calculated with equation 3 for the mean values of these parameters, as well as for the combinations of these parameters leading to the lowest K_x and highest K_x.

Parameter	Lowest K_x	Mean	Highest K_x
Q [m^3/s]	3000	2000	1000
B [m]	300	400	500
C [$m^{1/2}/s$]	50	65	80
i [-]	$6*10^{-5}$	$8*10^{-5}$	10^{-4}
K_x [m^2/s]	2'000	10'000	41'000

For the estimated mean values from Table 1, a value for K_x of about 10'000 m^2/s is found. The corresponding tracer distribution after several times over an idealized (straight) river branch of 200 km with the properties as given in Table 1 can be found in Figure 5. The corresponding equilibrium depth is about 4.2 m and corresponding flow velocity is 1.2 m/s.

It has to be noted that no 2D and 3D effects are yet included in the calculation of these values for the longitudinal dispersion coefficient. This means that as earlier mentioned in section 2.3, the longitudinal dispersion coefficient can in the reality be a factor 10 lower or higher.

2.5 Longitudinal dispersion in other rivers

Most reported longitudinal dispersion coefficients in other rivers fall within the following range (Rutherford, 1994):

$$30 < \frac{K_x}{h * u_*} < 3000 \qquad \text{(Eq. 6)}$$

With use of equation 2 this can be rewritten as:

$$30 * \frac{Q\sqrt{g}}{B*C} < K_x < 3000 * \frac{Q\sqrt{g}}{B*C} \qquad \text{(Eq. 7)}$$

For the estimated 'mean' values of Q, B and C of Table 1 for the Ayeyarwady River, this would mean:

$$7.2 < K_x < 723 \text{ m}^2\text{/s}$$

These values of K_x are clearly lower than the in section 2.4 estimated values. The following reasons could explain this:

- The estimated value of the Q is to low or estimated values for the width and Chezy coefficient are too high.
- The dispersion coefficient falls out of the range of equation 6, which is possible as the range of equation 6 is mostly based on less dynamic and smaller rivers in terms of discharge (Rutherford, 1994, pp. 193-197).
- The dispersion coefficient is actually lower than estimated in the previous section.

However, this order of magnitude for the longitudinal dispersion coefficient found by equation 7 is comparable with the values found for the following bigger rivers:

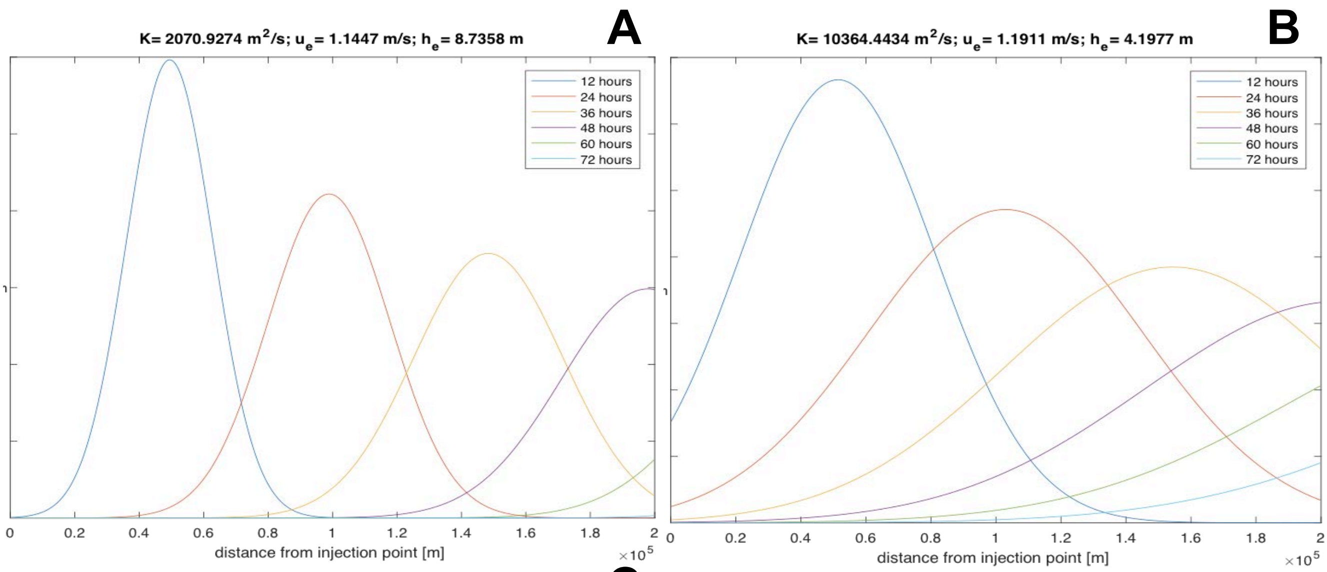
- Mississippi River: Q=22600 m^3/s gives K_x= 700 m^2/s (Rutherford, 1994).
- Missouri River: Q~900 m^3/s gives K_x= 800-1500 m^2/s (Rutherford, 1994).
- River Rhine between Kehl-Kronenhof and Lobith: Q~ 2500 m^3/s gives K_x~ 2500 m^2/s (Mazijk A. , 1996).

2.6 Conclusion

Al together this means that to get a better estimate of the dispersion, the following information is needed:

- More accurate estimate of α_x, by doing a tracer estimate.
- More accurate estimate of the discharge (Q), by measuring the depth and flow velocity in cross sections
- More accurate estimate of the Chezy coefficient. This can be calculated when the depth, flow velocity and hydraulic gradient are known at a certain location by equation 4.
- More accurate estimate of the hydraulic gradient by use of satellite data.
- Estimate of the bathymetry of the river, to be able to account for 3D effects with the use of a computer model.

The more accurate this information is, the better the estimate of the dispersion can be made. How this information is collected during the fieldwork and how the computer model is set up can be found in the respectively chapters 3 and 4.



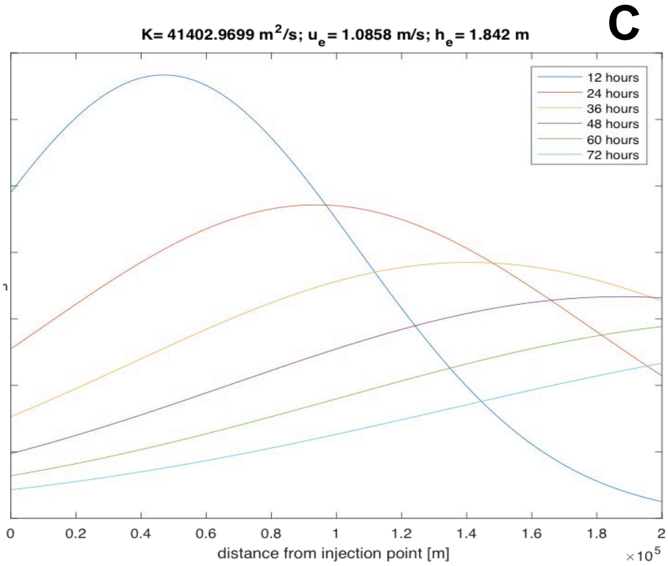


Figure 5: The distribution of a concentration of a tracer over a river branch of 200 km after multiples of 12 hours, for different values of the longitudinal dispersion coefficient corresponding to the values found in Table 1.

(A) K_x= 2071 m^2/s; (B) K_x=10364 m^2/s; (C) K_x= 41403 m^2/s.

3. Fieldwork experiments

In this chapter, a description of the execution of measurements done during the fieldwork and the procedure used for processing of the data collected is given.

3.1 General setup

In the week of 30 January to 3 February 2017 a week of fieldwork on the Ayeyarwady River has been done. All described measurements are done in that time window. In this week three groups of 4-5 researchers and students went on boats to do different kinds of measurements. The teams started at the following three locations (see Figure 1):

- Mandalay, a couple of kilometres upstream of the Inwa Bridge. This group looked at the Ayeyarwady River between Mandalay and the confluence with the Chindwin.
- Monywa, about 2 kilometres upstream of the nearby bridge over the Chindwin. This group looked at the Chindwin River between Monywa and the confluence with the Ayeyarwady River.
- Pakokku, just upstream of the bridge crossing the Ayeyarwady River. This group looked at the Ayeyarwady River downstream of the confluence, around Pakokku.

In addition, one small team has noted crossing times of simple floaters at the south bank of the Ayeyarwady, Northeast of the village of Sinde (N21.87279; E95.89574). Although the plan was that the above-mentioned groups would follow the floaters downstream during the full fieldwork week and meanwhile complete all other measurements, this appeared to be unrealistic due to difficulties during the fieldwork (see section 6.2.1). Therefore, from the third day onwards, the teams were regrouped as following:

- One group that did the tracer experiment around the confluence with GPS trackers.
- One group did measurements in for the river representative cross sections around the confluence.

In this way as much data as possible had been collected under the locally present conditions.

3.2 Floater experiments

To get insight in the mixing of tracers, two types of floaters have been used:

- 15 (5 per group) GPS trackers on floaters (see Figure 6), to have a continuous recording with precise measurements (but only for a limited number of floaters).
- 360 (120 per group) simple floaters (see Figure 6) to have data about a group of floaters, but not so precise and only at a few locations.

3.2.1 GPS Floaters

The GPS floaters move with the flow and save the GPS location and time every minute. Every 15 minutes the last 15 GPS locations with times are sent via GSM network to a database. The data is also saved locally on a micro SD card. It was possible to follow the floaters real-time via a website connected to this database. Limiting the influence of wind and waves has been taken into account in the design.

3.2.2 Simple Floaters

For the simple floaters the crossing times at bridges and other points had to be noted. Also takeout times and locations have been noted. The simple floaters are made of a (floating) coconut with a balloon attached with a small bicycle light (HEMA, type mini led lights, about 70 hours of light) and helium in it for visibility. All used materials, except the bicycle lights, are biodegradable. Different colours of lights and/or balloons were used for the different deployment locations to be able to distinguish which balloon came from the Chindwin and which balloon from the Ayeyarwady after t he confluence.

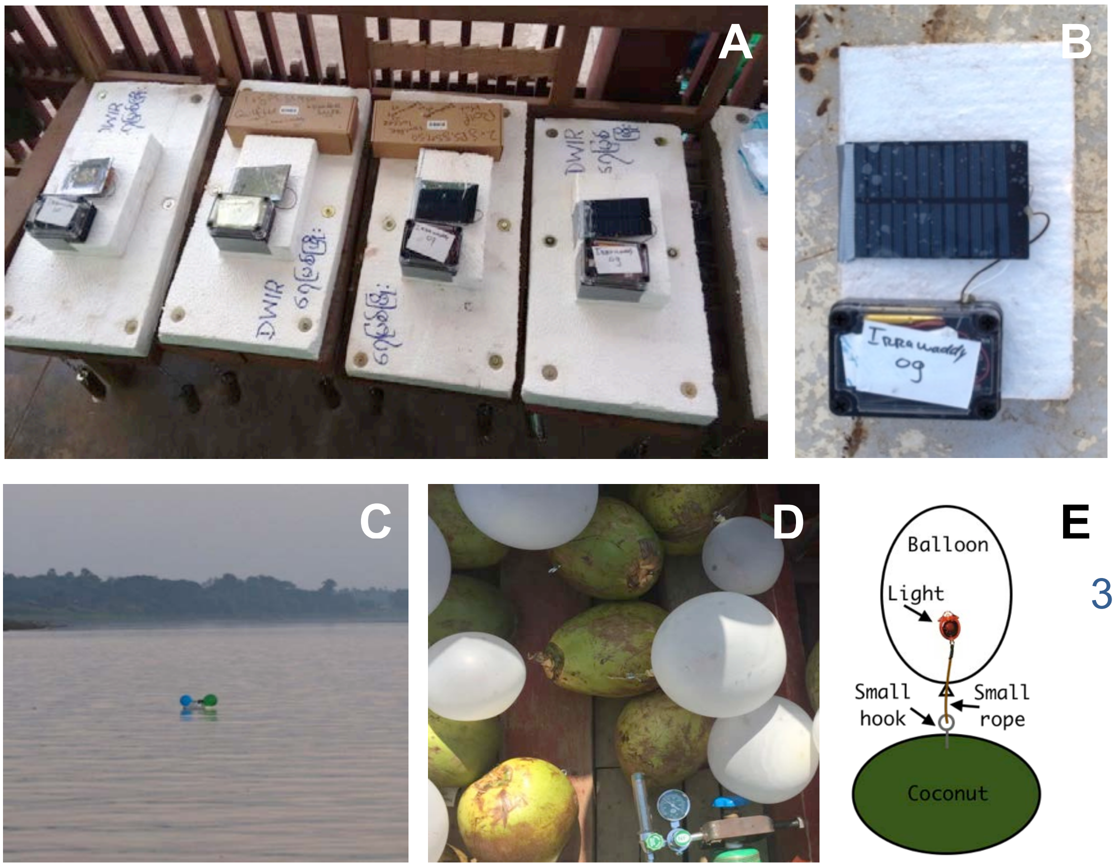


Figure 6: (A) Some of the GPS floaters ready for deployment. (B) Close-up of the top part of one of the floaters. (C) GPS floater in action at the end of the day; balloons with (bicycle) lights are already attached for visibility of the floater at night. (D) Some of the simple floaters before deployment. (E) Sketch of the design of the simple floaters; for the lights, small bicycle lights (HEMA, type mini led lights, about 70 hours of light) are used. See also the cover of this report, for the simple floaters in action.

3.3 Depth and flow velocity measurements in cross sections

In the Ayeyarwady and in the Chindwin near the confluence depth and velocity measurements have been done in for the river representative cross sections. The locations of these cross sections were chosen in such way that there was an “as clean as possible” cross section, meaning no obstacles such as islands increase the inaccuracy. Measurements were done on the Chindwin River and Ayeyarwady River upstream and downstream of the confluence.

To get as reliable data as possible within the restrictions of the fieldwork, all depth and flow velocity measurements have been done double. Two teams did measurements independent of each other, with different measurement equipment. However, both teams were on the same boat, and measured at the same time, which has an influence on the results. See section 6.3 and 6.4 for a more in depth discussion about the reliability and usefulness of the results.

3.3.1 Depth measurements in the cross sections

The depth has been measured with an echo sounder (Garmin Striker 4), doing constant depth measurements and marking them by means of waypoints with GPS coordinates. Besides, depth measurements by hand are done, to validate the echo sounder measurements. This was done with a portable sonar system (Norcross Hawkeye H22px).

In the Chindwin (except at the last few kilometres before the confluence) no echo sounder was available and only hand measurement have been done.

3.3.2 Flow velocity measurements in the cross sections

In the Ayeyarwady and Chindwin near the confluence also flow velocity measurements have been done. When possible the measurements were done at two and four meter depth. For these measurements two Valeport current meters have been used.

The measurements have been done in two independently operating groups, to have a back up in case of failure of one of the groups and to be able to compare the results afterwards. At the same time the location (by GPS) and the depth (once more) were noted to be able to approximate the velocity profile over the depth. See section 3.4 for how the collected data has been processed.

Because of difficulties with keeping the boat in a geographically steady position, it was chosen to measure at only one or two depths, whereas in the ideal case another measurement at the surface would have been included. For this reason also a measurement duration of 15 s was chosen (instead of the standard 30 s). A more detailed description can be found in Appendix A Here also the specifications of the used equipment can be found.

3.4 Processing of the collected data

The during the fieldwork collected data was not directly ready for use and had to be post processed according to the in this section described methods.

3.4.1 Flow velocities

Cross sections

For the flow velocity in the cross sections, at most locations and depths two measurements by independent groups had been done. In this case, the mean flow velocity of both measurements is taken. When there was an error in of the measurements, only the flow velocity of the other measurement has been taken.

Floaters

As the floater pats are returned as points with a date and time and a location, the mean velocity (at the surface) between to consecutive measurement point can be calculated according to the following principle:

$$u = \frac{\Delta \mathrm{x}\ [\mathrm{m}]}{\Delta t\ [s]} \qquad \text{(Eq. 8)}$$

To be able to apply equation 8, conversion of the units of $\Delta \mathrm{x}$ (from WGS 84 / UTM zone 46N coordinates to meters) had to be done. By also using the floater data in this way, much more information about the flow velocities has been obtained than would be the case with only the data collected with the current meter.

3.4.2 Discharge

For estimating the discharge, the measurements done in the cross sections are used. The following procedure is followed:

1. The cross section is split up over the width into parts. The boundaries of these parts are chosen such that they are in the middle of two consecutive flow measurement locations.
2. The mean depth in each part is calculated based on the echo sounder data, where after the surface (A_{part}) of each part is calculated.

3. The mean measured flow velocity is calculated. At each location, the velocity was measured at two depths. However, it appeared that there were measurement errors as a consequence of movement of the boat. A better approximation was obtained by combining the two measured flow velocities at a location. This is done by taking the mean of at one location, at 2 depths measured flow velocities, and assume this is the flow velocity at the mean of the depths where was measured. In this way 2 measurements are converted to one measurement. The validity of this assumption is elaborated in section 6.5.
4. For the flow velocities, a logarithmic flow velocity profile is assumed. For each of the parts the logarithmic profile is fitted with the in the previous step calculated velocity, for which also the depth is known.
5. The mean velocity ($u_{mean,part}$) of this logarithmic profile is calculated.
6. The total discharge in a cross section can be calculate by use of the following equation:

$$Q = \sum A_{part} * u_{mean,part} \quad \text{(Eq. 9)}$$

See Figure 7 for an example discharge calculation.

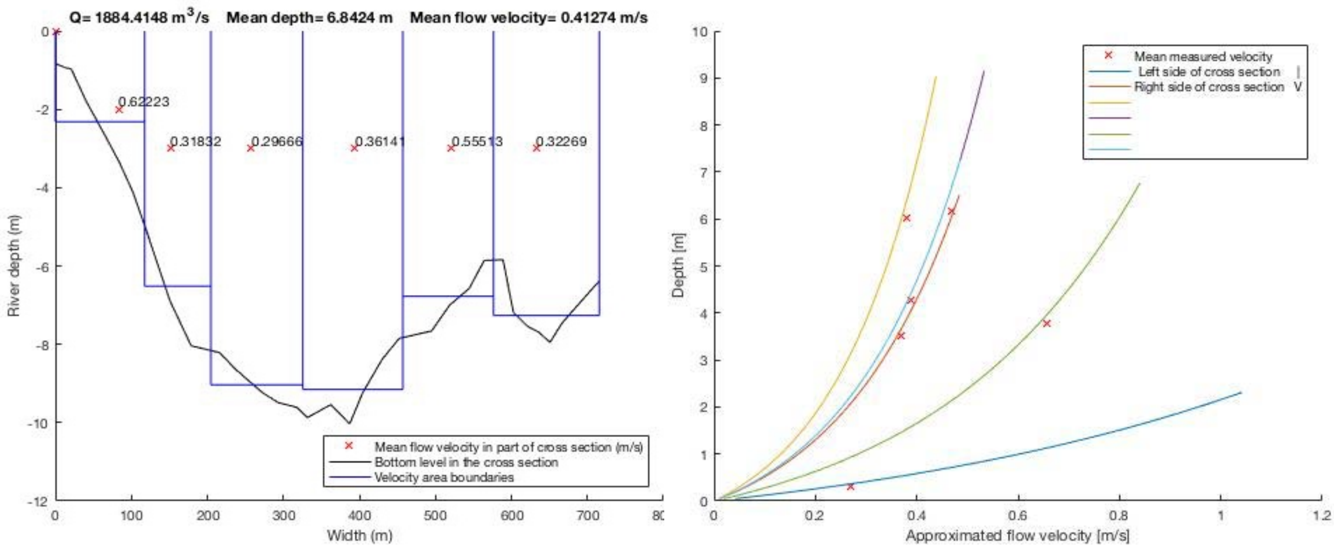


Figure 7: Example of a discharge calculation for one of the cross sections according to the steps of section 3.4.2. The cross section is split up over the width into parts and for each part the surface and mean flow velocity is calculated. Subsequently, the total discharge is calculated by taking the sum of all parts multiplied by their mean flow velocity.

3.4.3 Bathymetry

Echo sounder

As the echo sounder returns a depth and location, the data files could be almost immediately used. Only some file conversion had to be done.

Hand measurements

The hand measurements were noted in a logbook and were digitalized before the data could be used for estimating the bathymetry.

Floaters

When no other information at that location is available, it is assumed that the floaters follow roughly the deepest part of the river, meaning the paths of these floaters give some insight in where the main channel is located. This information can be used to approximate the bathymetry in the Delft3D model (see section 4.3.3).

4. Delft3D model

In this chapter, a description of the Delft3D model used for hydrodynamic simulations is given. First the used software is described, where after the setup of the model and simulations is described.

4.1 Software

4.1.1 Delft3D software

Delft3D (by Deltares) is a 3D modelling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments (Deltares - Delft3D, n.d.). For this model the modules GRID and FLOW are used.

The FLOW module is the core of Delft3D and is (in this research) used to do (horizontal) 2D hydrodynamic calculations. The GRID module can be used to create some of the input file for the FLOW module. Among others, a computational grid and bathymetry file can be made in this module.

4.1.2 MATLAB and Open Earth Tools in MATLAB

MATLAB (by Simulink) is a software package and programming language optimized for solving engineering and scientific problems (Mathworks, n.d.).

Open Earth Tools in MATLAB (by Deltares) is a free and open source initiative to deal with Data, Models and Tools in earth science & engineering projects, currently mainly marine & coastal (Deltares - Open Earth, n.d.).

MATLAB and the MATLAB scripts of Open Earth Tools are used for pre-processing of the files needed for Delft3D and post-processing of the results from the fieldwork and Delft3D model.

4.1.3 Google Earth

Google Earth (by Google) is an application in which maps and satellite images can be viewed. In this research, the software is used to visualize the results of the fieldwork and Delft3D model by the use of maps (Google Earth, 2017).

4.2 Objective and basic assumptions

The main objective of the model in Delft3D is to approximate the bathymetry and flow conditions around the confluence in the first week of February 2017 as good as possible.

As the model is made to get more insight in the dispersion, all for dispersion important parameters have to be included in the model as good and completely as possible. Already in the 1D approximation in section 2.4, the following (in the 1D approximation constant) parameters appeared to be of importance for the dispersion:

- Discharge
- Roughness
- Hydraulic gradient
- Width
- Depth

As a 2D model is made, also the influence of following parameters has to be treated:

- Bathymetry (which is in fact the combined depth, width and hydraulic gradient)

- Processes in bends (like spiral flow, dependent on curvature)
- Eddy viscosity
- Eddy diffusivity

Besides, the influence of some numerical parameters has to be addressed:

- Time step
- Grid properties

As the model is only targeting insight in the dispersion, no morphodynamic effects are included in the model, as the timescale of those processes is much larger than the timescale of the mixing of tracers. This leads to the following simplifications and boundaries in the model:

- Only the area that is 'wet' in the situation of the first week of February 2017 is modelled, as bank erosion can be excluded.
- The bathymetry is constant over the duration of the simulation.
- There is no sediment transport in the model.
- A relative short simulation period of only a few days or weeks (long enough for tracers to leave the model) is needed.

As only one specific situation (beginning of February 2017) is modelled, also the roughness and discharge are assumed constant over the simulation period. For the modelled area, 3 river branches are distinguished for parameters such as the discharge and hydraulic gradient:

- Ayeyarwady River upstream of the confluence.
- Chindwin River upstream of the confluence.
- Ayeyarwady River downstream of the confluence.

For the Ayeyarwady River downstream of the confluence, the main branch and the big secondary branch are seen as one branch for Delft3D modelling purposes, as they confluence again before the downstream boundary of the model and the same hydraulic gradient.

4.3 Setup of the model

4.3.1 Land boundaries

The land boundaries are a tool to make the grid and bathymetry in the GRID module of Delft3D. The land boundaries are approximated by drawing a polygon over the land-water boundaries on a satellite image of the area of 22-1-2017 in Google Earth (see Figure 8). This gives a good estimate of the land boundaries in the first week of February 2017.

Next, the polygon file created in Google Earth is converted with the use of Open Earth Tools to obtain the needed landboundary file with the coordinates in the correct notation for Delft3D (WGS 84 / UTM zone 46N).

4.3.2 Grid

For the computational grid, a curvilinear grid is chosen. The grid is made in such way, that the boundaries of the grid approximate the land boundaries are as good as possible.

A relative small gridcel size is used (in between 10^4-10^5 m^2), to be able to model important details in the bathymetry such as shoals and island. As only a short simulation period is needed, this is possible without getting to long calculation times.

Besides approximating the shape of the river as good as possible, the grid is orthogonalized to limit numerical errors. Special attention has gone to the area close to the confluence.

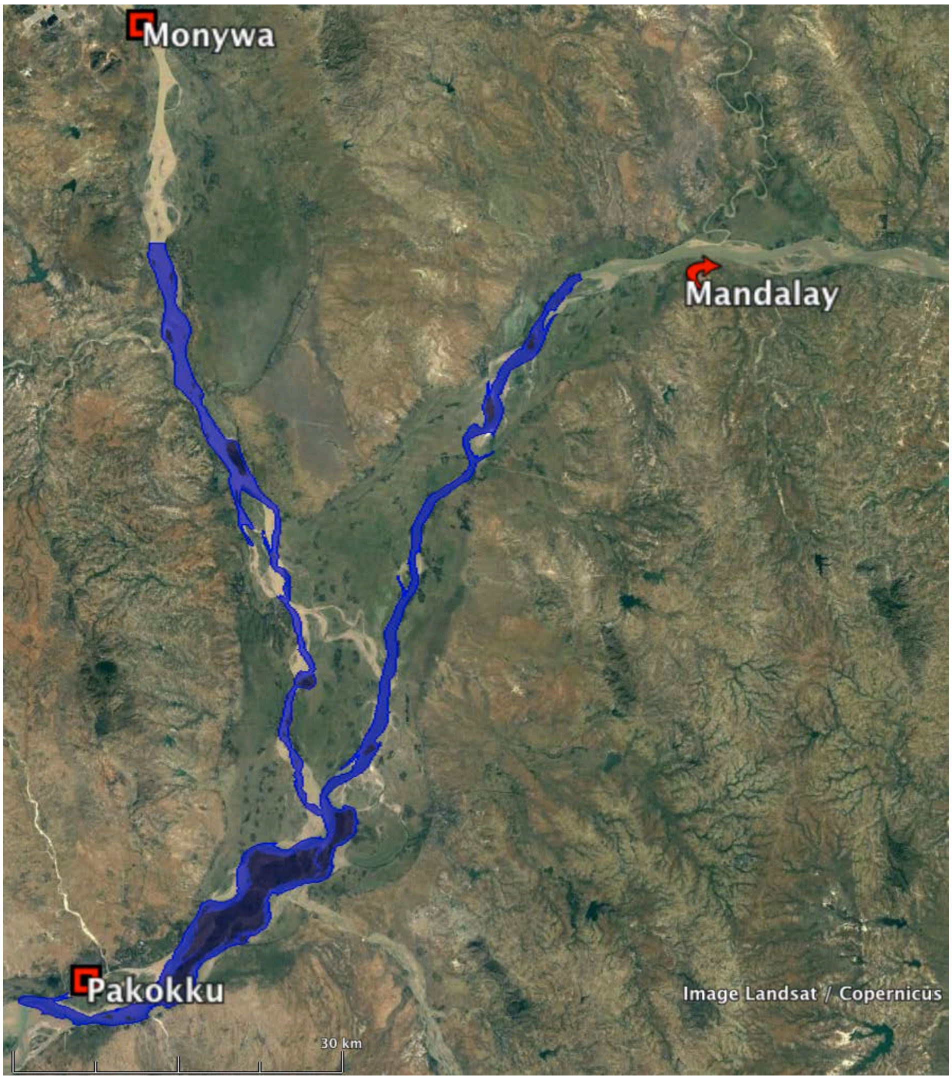


Figure 8: Overview of the area of the Ayeyarwady-Chindwin confluence with the area modelled in Delft3D (blue) including islands (black). Figure made with Google Earth (2017).

4.3.3 Bathymetry

As only the data collected during the fieldwork and satellite data (SRTM by USGS (2000) and images in Google Earth (2017)) are available, approximating the bathymetry was the main challenge in the Delft3D model. In each of the grid points, the depth has to be specified. The bathymetry has to be given relative to a reference level, and is therefore composed of three parts:

- **Water level relative to the reference level EGM96**, based on SRTM satellite data of 11-22 February 2000 (USGS, 2000).
- **Water depth**, based on data collected during the fieldwork and rough estimates by extrapolation methods.
- **Islands**, which are all given a height somewhat above the water level (5 m) to make sure they will not be flooded.

The height of the islands is first combined with the water depth, making the ‘water depth’ at the islands -5 m. When the water depth is then subtracted from the water level relative to the reference level EGM96, the bathymetry (bottom level relative to the reference level EGM96) is obtained. See Figure 9 for further clarification.

Water level relative to the reference level EGM96

The water level is based on SRTM satellite data. This data from the 11-22 February 2000 consists the surface elevation relative to the reference level EGM96 with a vertical accuracy of 1 m (USGS, 2000). As mentioned before, the Ayeyarwady River is very dynamic and its location has varied a lot between 2000 and 2017. Furthermore, the water surface is seen as the elevation, meaning that the elevation of the bottom (under water) cannot be derived from this data. Hence, it is not possible to derive the river's position and bathymetry from this data.

The hydraulic gradient however, can be approximated with this data, as the water level relative to the reference level EGM96 has probably not changed too much since 2000, as long as the data is from the same period in a year (February, dry season). By taking the water level relative to reference level EGM96 at both ands of each river branch, and then interpolate this for the whole modelled area, the hydraulic gradient is approximated.

Water depth - direct measurements

During the fieldwork, depth measurements have been done (see section 3.3). Although very useful, this data is not sufficient to be directly extrapolated for the whole model area. Therefore several methods are used to estimate the depth at other locations by indirectly extrapolating this data and using the floater paths.

Water depth - depth estimate with Chezy equation

Estimating the depth by use of equation 4 (Chezy equation) for stationary flow appeared to return inaccurate values but provides useful information about where the main channel is located (see section 3.4.3).

Water depth – depth estimate by constant cross section assumption

Basic assumption is that the surface (depth*width) of a cross section in a river branch is more or less constant as long as the discharge in a certain river branch is also constant. Hence, this is not such a strong assumption, as the flow velocity can also fluctuate over a branch, but it is the best available option. The validity of this assumption is discussed in section 6.3.2. Nevertheless it gives a better approximation of the bathymetry than just assuming a constant depth. The following procedure is followed:

- Approximate the depth in a measured cross section by a polynomial
- Take the coordinates of 2 points on the banks more upstream or downstream in the same river branch, where in between the new cross section has to be estimated.
- The ratio between the width of the original cross section and the new cross section is determined and used to scale the depth to get the same total surface for the original and new cross section.
- When wanted, the new cross section can be mirrored, for example when the original cross section was in a "left bend" and the new cross section is in a "right bend".
- New data points are calculated in between the earlier given coordinates. The new data points consist of latitude and longitude coordinates and a depth and are returned directly in a .xyz samples file as input for Delft3D. See Appendix B for the resulting sample points.

When all depth data is extrapolated, the depth in the whole modelled area can be estimated. The best data had been collected near the confluence, which is the area of interest, meaning that the bathymetry is approximated the best here. The further away from the confluence, the less accurate the depth estimate will be.

Islands

The islands are made by adding a depth of -5 m to the water level at the location of the islands.

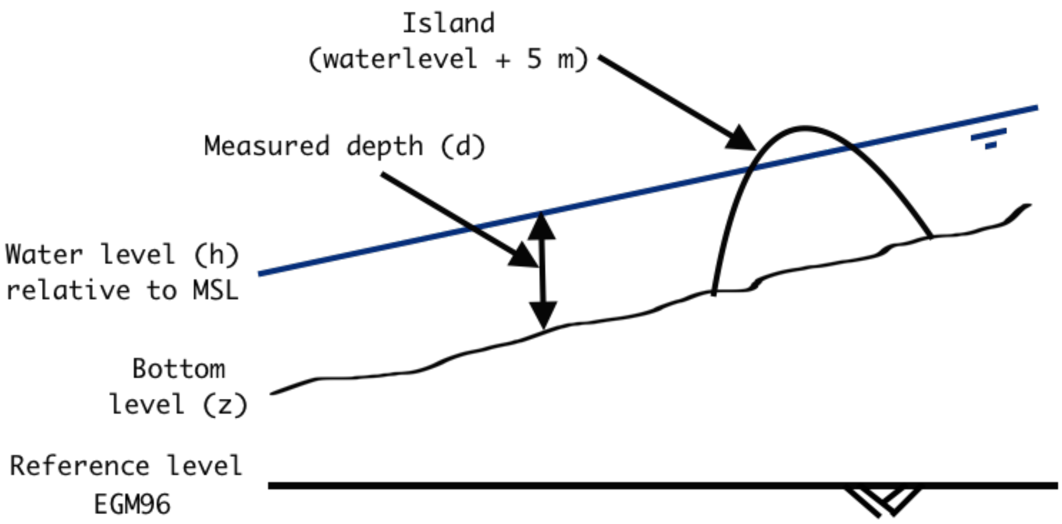


Figure 9: Overview of the construction of the bathymetry. The (during the fieldwork measured) depth (d) is extracted from the water level (h) relative to the reference level EGM96 (based on SRTM satellite data), where after the islands are added.

4.3.4 Boundary and initial conditions

Locations of the boundaries are chosen about 40-50 km upstream and downstream of the confluence. For the exact location of the boundary a cross section is chosen where only one, straight, channel is present, to limit the complexity of the boundary conditions and avoid errors.

There are two upstream boundaries in the model: one where the Chindwin flows in and one where the Ayeyarwady flows in. At these locations, the discharge is specified:

- Ayeyarwady River (upstream boundary): discharge= 1500 m^3/s
- Chindwin River (upstream boundary): discharge= 700 m^3/s

These values are estimates based on during the fieldwork collected data. See section 3.4.2 how this data is collected and section 5.2.4 for the resulting discharge. There is one downstream boundary, where the Ayeyarwady flows out. There, the water level (relative to the reference level EGM96) is specified, based on the SRTM satellite data (USGS, 2000).

- Ayeyarwady River (downstream boundary): water level= 49.5 m

For the initial conditions, the water level has to be specified everywhere in the model. This cannot be done easily in a direct way. Therefore a preliminary simulation is done just to get a file for the other simulations with the correct initial water levels (relative to the reference level EGM96) in the river.

To obtain the initial condition file (water levels in the whole model), a simulation is done with an initial water level of 65.9 m (equilibrium water level at the highest upstream boundary). At the downstream boundary the water level is linearly decreased from 65.9 m at the start of the simulation (equilibrium water level at the highest upstream boundary) to 49.5 m at the end of the simulation (equilibrium water level at the downstream boundary), see Figure 10. The water level at the end of the simulation is than saved in a file that can be used as initial condition for subsequent simulations.

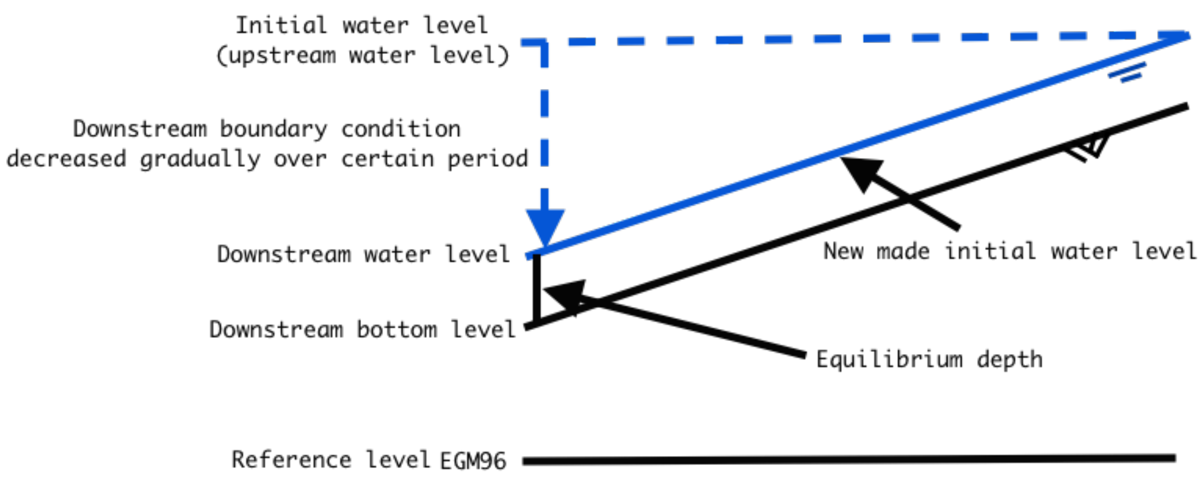


Figure 10: Overview of the construction of the initial water level file. First an initial water level and boundary condition (water level) at the level of the upstream equilibrium water level is assumed. Over a certain period, the level of the downstream boundary is decreased to the equilibrium water level downstream. The final water level in the model is saved and can now be used for the subsequent simulations.

4.3.5 Physical parameters

In the Delft3D model some physical parameters have to be specified:

- Water density (default: 1000 kg/m^3)
- Gravity (default: 9.81 m/s^2)
- Beta c (default: 0.5, parameter for secondary flow)
- Roughness (default: Chezy, uniform, 65 $m^{1/2}$/s)
- Eddy viscosity (default: uniform, 1 m^2/s)
- Eddy diffusivity (default: uniform, 10 m^2/s)

To model large eddies, the option HLES in Delft3D is used. All parameters needed are set to default except:

- Relaxation time set to 10 minutes
- Molecular diffusivity set to 1e-06 m^2/s

The influence of the option HLES is elaborated in section 6.7.

4.3.6 Numerical parameters

The following numerical parameters have been chosen:

- Simulation period of 2 weeks. This is sufficient (with margin) to let the floaters go through the model.
- Time step of 5 minutes.
- Values of the bathymetry are specified in the grid cell centres.
- All other numerical parameters are set to default.

4.3.7 Modelling of floaters

In the Delft3D model floaters can be modelled. For this purpose, the monitoring option ‘drogues’ is used. For each drogue, the starting location and starting time have to be specified. In the model, the following drogues are specified:

- 10 at the upstream boundary of the Ayeyarwady River.
- 10 at the upstream boundary of the Chindwin River.

They are distributed over the width of the river and are deployed after 3 days of the simulation period, when the flow is stationary. In this way disturbances due to the start up of the model are prevented. The drogues go with the flow, and can be seen as roughly similar to the floaters in the fieldwork experiment, although just as the fieldwork the model has it's limitations, as mentioned in chapter 6.

4.4 Influence of different parameters

To get better insight in the influence of different parameters on the dispersion in the Ayeyarwady, the following parameters are varied:

- Discharge (in both Ayeyarwady and Chindwin rivers)
- Roughness
- Eddy viscosity
- Eddy diffusivity

Besides, the effect of the inclusion of the Delft3D options secondary flow and HLES is elaborated. See Table 2 for an overview of the used values in different simulations. Although the range of the eddy viscosity and diffusivity is somewhat large, they provide insight in the influence of the parameter on the dispersion. The default values are probably more realistic than the extreme values.

The magnitude of the simulated values for the discharge is based on the results of the fieldwork (see Table 4). For the roughness, the in section 2.4 estimated values are tested. Besides, one simulation with a Manning coefficient is done. In this way, insight is obtained in the dependence of the roughness on the depth, as the depth is included in the Manning formula but not in the Chezy formula.

4.5 Overview of done simulations

All simulations done that have been done are listed below (Table 2).

Table 2: Overview of the done simulations.

Nr.	Sec. flow	Discharge Ayeyarwady River upstream [m^3/s]	Discharge Chindwin River upstream [m^3/s]	Roughness [Chezy: $m^{1/2}/s$; Manning: $s/(m^{1/3})$]	Eddy viscosity [m^2/s]	Eddy diffusivity [m^2/s]	Large eddy sim. (HLES)
0*	Yes	1500	700	Chezy: 65	1	10	No
1	Yes	1500	700	Chezy: 65	1	10	No
2	**No**	1500	700	Chezy: 65	1	10	No
3	Yes	**1000**	700	Chezy: 65	1	10	No
4	Yes	**1900**	700	Chezy: 65	1	10	No
5	Yes	1500	**1000**	Chezy: 65	1	10	No
6	Yes	1500	700	**Chezy: 50**	1	10	No
7	Yes	1500	700	**Chezy: 80**	1	10	No
8	Yes	1500	700	**Manning: 0.035**	1	10	No
9	Yes	1500	700	Chezy: 65	**0.1**	10	No
10	Yes	1500	700	Chezy: 65	**100**	10	No
11	Yes	1500	700	Chezy: 65	1	**1**	No
12	Yes	1500	700	Chezy: 65	1	**100**	No
13	Yes	1500	700	Chezy: 65	1	10	**Yes**

*To create the initial water level

The results of these simulations can be found in section 5.3.

5. Results

In this chapter, first the results from the theory are shortly repeated, where after the results of the fieldwork (chapter 3) and delft3D model (chapter 4) are presented.

5.1 Theoretical dispersion estimate

As already stated in section 2.4, the mean value calculated with equation 3 gives a longitudinal dispersion coefficient (K_x) of about 10'000 m^2/s. The minimal value found is around K_x= 2000 m^2/s and the maximum value as high as K_x= 41'000 m^2/s.

This is without the uncertainty due to in the equation 3 excluded 2D/3D effects caused by among others bathymetry and bends, which means there can be about a factor 4 error in these results.

5.2 Fieldwork

In this section, the results of the fieldwork are presented.

5.2.1 GPS floaters

An overview of the (GPS) floaters paths around the confluence is given in Figure 11. A close up of the point of the confluence is given in Figure 12. The dispersion due to velocity shear is clearly visible in Figure 13, where a section of the Ayeyarwady more upstream of the confluence, west (downstream) of Mandalay is presented. See section 5.4 for the resulting dispersion estimate.

Figure 11: The floater paths of different floaters around the confluence. Each colour represents one floater, although some floaters have been deployed multiple times. The line width is a measure for the magnitude of the flow velocity; the numbers (in white) are some values for the flow velocity (m/s) at that location. Figure made in Google Earth (2017).

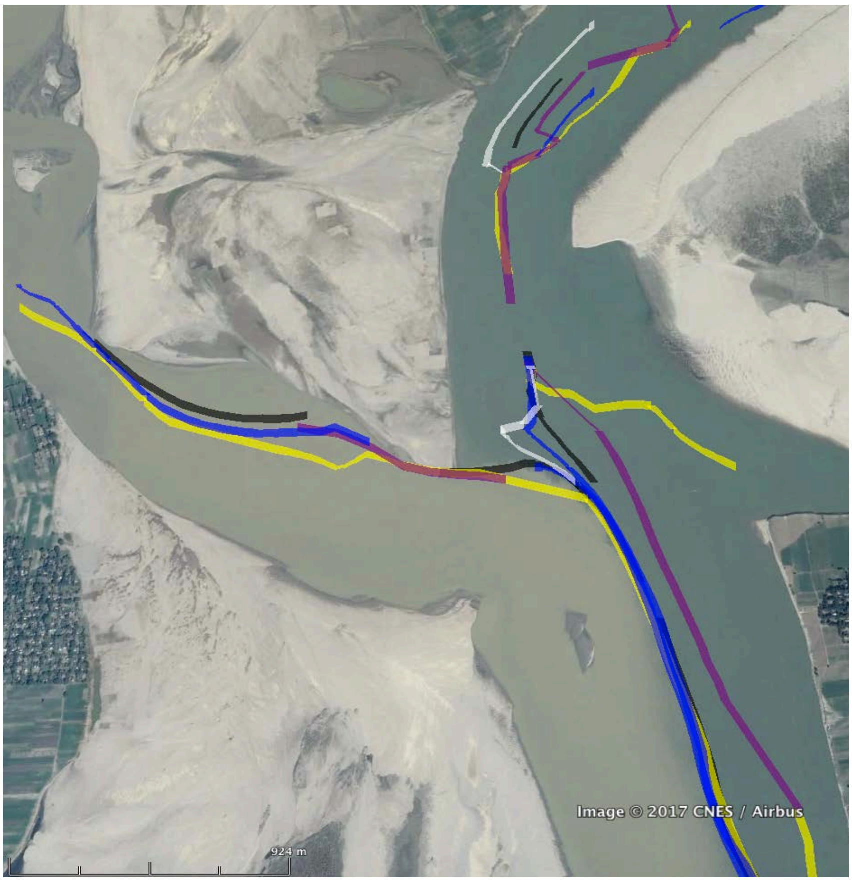


Figure 12: Close up of the confluence. Each colour represents one floater, although some floaters have been deployed multiple times; the line width is a measure for the magnitude of the flow velocity. The floaters coming from the Chindwin get very close to the point of the confluence. The floaters have velocities here as high as 1.8 m/s (not visible in figure). Interesting is the floater path marked in yellow, which is very close to the other floaters when it comes down the Ayeyarwady, but suddenly goes in the direction of the second branch instead of the main branch. Figure made in Google Earth (2017).

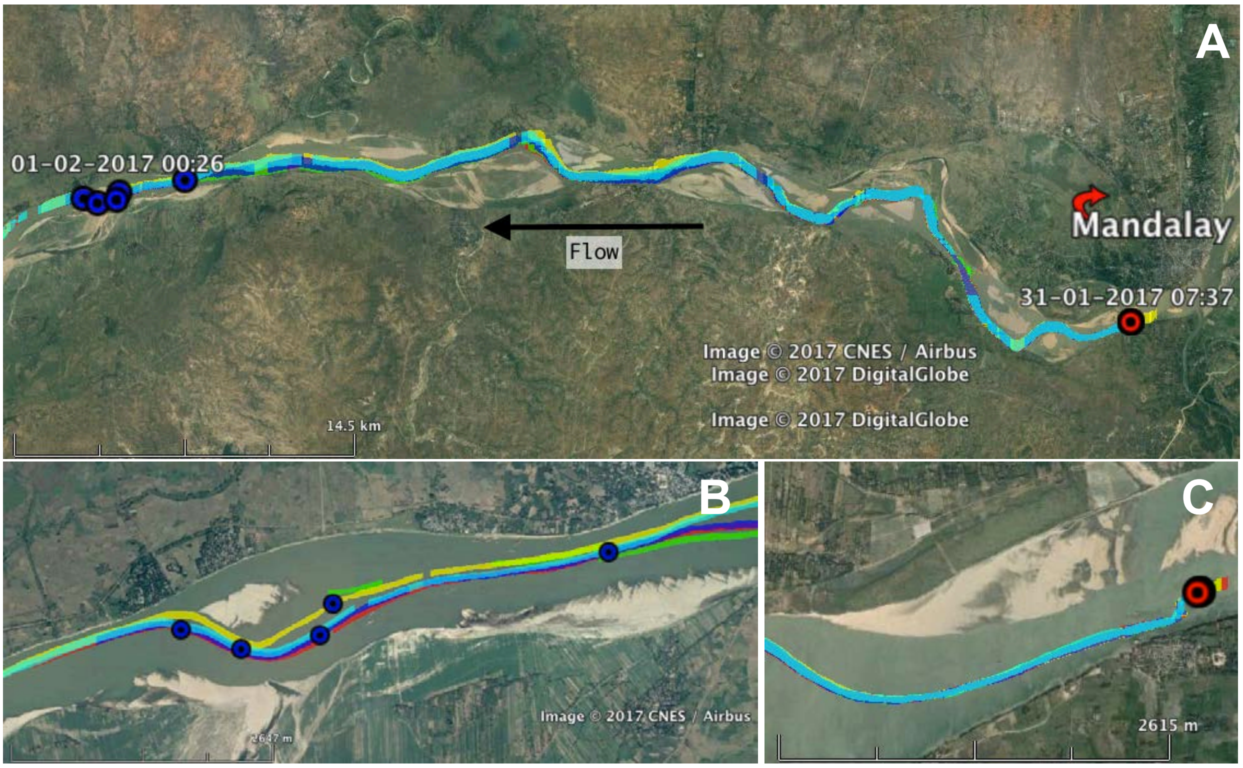


Figure 13: (A) Overview of floater paths in a section of the Ayeyarwady, west (downstream) of Mandalay. Each coloured line represents one floater. The red markers are the floater locations at release, at 31-01-2017 07:37. The blue markers are the floater locations 16:49 hours later, at 01-02-2017 00:26 (both UTM time). The mean distance travelled in that time is by the floaters is 50 km (distance between first and last floater 4.6 km; mean floater velocity 0.8 m/s).

(B) Close up of the floaters at 01-02-2017 00:26 (UTM time). (C) Close up of the floaters at 31-01-2017 07:37 (UTM time). The scale of (B) and (C) is the same. The both transversal and longitudinal dispersion are clearly visible. The longitudinal dispersion coefficient for this branch is estimated in section 5.4. Figure made in Google Earth (2017).

5.2.2 Simple floaters

Due to difficulties with the simple floaters (described in section 6.2.1), only at one location crossing times have been noted: at the south bank of the Ayeyarwady, Northeast of the village of Sinde (N21.87279; E95.89574) at 31 Jan 2017 between 16:00 and 17:25. This is about 9 km from deployment. See Figure 14 for the results.

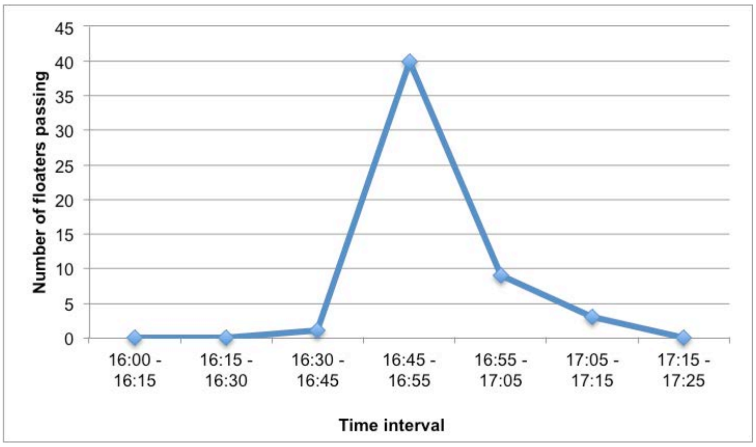


Figure 14: Number of simple floaters passing in each time interval.

With an estimated average floater speed in that area of about 0.8 m/s, this would mean that after 9 km the floaters are already spread out over about 3 km. See section 5.4 for the resulting dispersion estimate.

5.2.3 Flow velocity

Floaters

As the floaters go with the flow, they have roughly the same velocity as the surface flow velocity. See Figure 11 for the floater velocities around the confluence.

Cross sections

The mean flow velocity in the cross sections is calculated according to the in 3.4.1 described procedure. See Table 3 for the results.

Table 3: Mean flow velocities in the cross sections (CS), based on the fieldwork measurements. See Figure 15 for the locations of the cross sections.

Mean flow velocity Ayeyarwady upstream of the confluence [m/s]		Mean flow velocity Chindwin upstream of the confluence [m/s]		Mean flow velocity Ayeyarwady downstream of the confluence main branch [m/s]	
CS 5	0.25	CS 4	1.15	CS 1	0.62
CS 6	0.35			CS 2	0.58
CS 7	0.51			CS 3	0.60
CS 8	0.41				
Mean:	**0.38**	**Mean:**	**1.15**	**Mean:**	**0.58**

5.2.4 Discharge

The discharge is calculated based on data collected during the fieldwork (according to the procedure described in section 3.3). The method used for the calculations is described in section 3.4.2.

As the discharge in the second branch of the Ayeyarwady downstream of the confluence was not measured accurately, this discharge estimated based on the nearby-observed floater speeds, nearby measured depth and width based on satellite imagery. The following estimated discharge is obtained:

$Q=u_{mean}*d_{mean}*B_{mean}= 0.7*1.5*400= 400\ m^3/s$.

All resulting discharges are presented in Table 4. When the mass balance for the discharge upstream and downstream of the confluence is calculated, it appears that these values do not match. The possible reasons for this will be further elaborated in section 6.5.

Table 4: Mean discharge (Q) in the cross sections (CS), based on the fieldwork measurements. See Figure 15 for the locations of the cross sections. The calculated values do not match when the mass balance for upstream and downstream of the confluence is calculated. Therefore also the assumed real discharges as used in the Delft3D model are presented.

Q Ayeyarwady upstream of the confluence [m^3/s]		Q Chindwin upstream of the confluence [m^3/s]		Q Ayeyarwady downstream of the confluence main branch [m^3/s]		Q Ayeyarwady downstream of the confluence second branch [m^3/s]	
CS 5	976	CS 4	1054	CS 1	1541	Estimate	400
CS 6	1213			CS 2	1537		
CS 7	1602			CS 3	1742		
CS 8	1884						
Mean:	**1419**	**Mean:**	**1054**	**Mean:**	**1607**	**Mean:**	**400**
Total Q before confluence:			2473	Total Q after confluence:			2007
Mean total Q at downstream boundary:							2190
Total assumed Q before the confluence, after the confluence and at downstream boundary:							2200
Assumed real Q:	**1500**	**Assumed real Q:**	**700**	**Assumed real Q:**	**1800**	**Assumed real Q:**	**400**

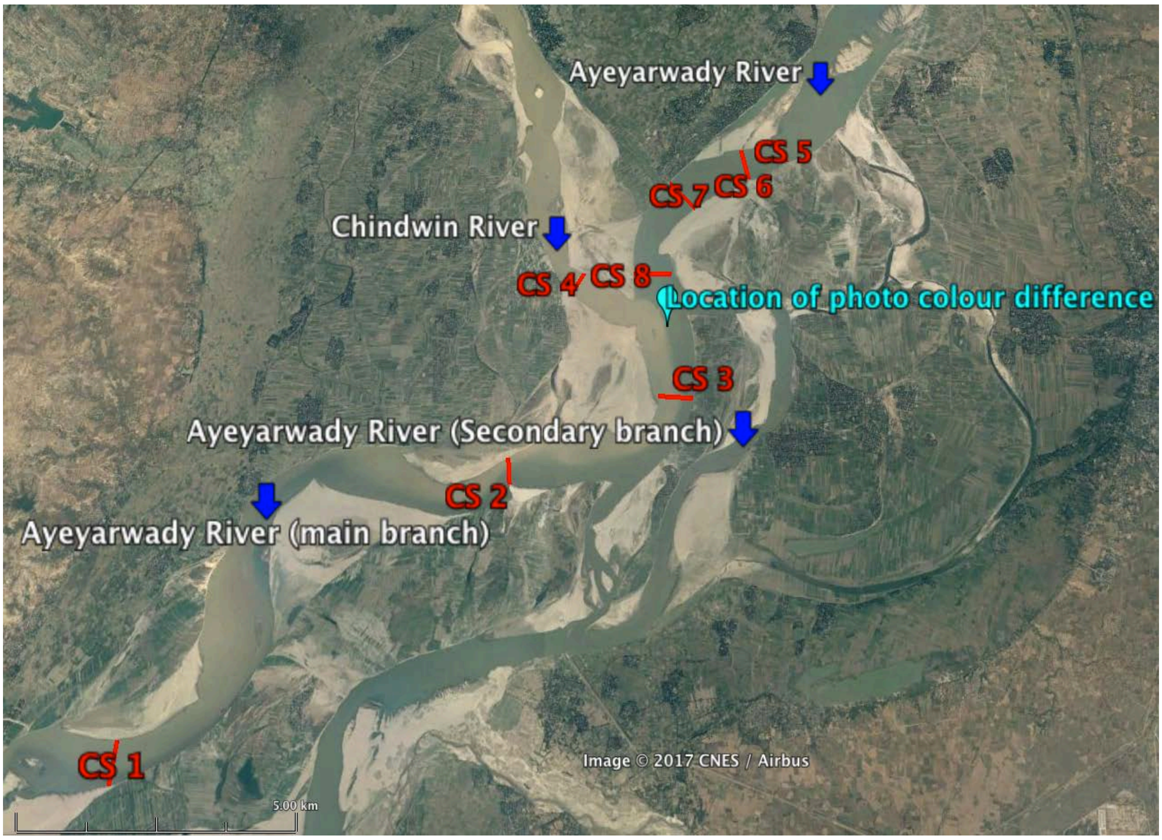


Figure 15: The colour difference near the confluence is clearly visible on a satellite image. The underlying satellite image (Google Earth, 2017) is taken on 22-1-2017. Besides, the locations of the cross sections (CS) and different branches are given. Also the location where figure 16 is taken (location of photo colour difference) is given. Figure made in Google Earth (2017).

As the Delft3D model needs the discharge in the Ayeyarwady River and Chindwin River as upstream boundary, the assumed real values of the discharge are also presented in Table 4. For this assumed real discharge, the relative low values of the discharge are raised and the relative high values of the discharge are lowered. Although this is based on analysing the quality of the measurements and field observations, there is still uncertainty in the reliability of these assumptions. Details about the calculation of the discharge in different cross sections can be found in Appendix A.

5.2.5 Bathymetry

The results of the depth are used to determine the bathymetry for the Delft3D model, as explained in section 4.3.3. The result of the actual measurements can be found in Appendix B.

5.2.6 Visual results

As can be seen in Figure 16 and also on the satellite image of Figure 15, there is a clear difference in colour between the Ayeyarwady water coming form upstream of the confluence (more blue) and Chindwin water (more brown). On the satellite image of Figure 15, the colour difference is still visible some tens of kilometres downstream of the confluence, being an indication that the transversal mixing length is indeed in the order of 100 km as stated already in section 2.2.

Figure 16: The difference in colour (and sediment concentration) between Ayeyarwady water and Chindwin water is clearly visible at the confluence. The Ayeyarwady water coming from upstream of the confluence (more blue) contains less sediment than the Chindwin water (more brown).

5.3 Delft3D model

In this section, the results of the drogue simulations in the Delft3D model are presented.

5.3.1 Floater paths of final model setup

In Figure 18, the results of simulation nr. 1 (according to Table 2) are given for different times:

- The floater locations 1000 minutes after release (yellow markers)
- The floater locations 1250 minutes after release (green markers)
- The floater locations 1500 minutes after release (purple markers)
- The floater locations 1750 minutes after release (cyan markers)

The longitudinal mixing (and thus dispersion) is clearly visible in Figure 18, as the groups of floaters are spread out more over the river the longer after they are released. The flow velocity in the Chindwin is clearly higher compared to the Ayeyarwady. Also the dispersion in the Chindwin is higher, as the floaters clearly get spread out in longitudinal direction faster.

In Figure 17, a close up of the Ayeyarwady and Chindwin from Figure 18 is given. The markers (yellow) are the floater locations 1000 minutes (16:40 hours) after release at the upstream boundary of the model. The influence of the difference in flow velocity (see section 2.3.1 and Figure 4) can be clearly seen, as the floaters in the middle of the river are already further downstream than those more near the banks. Beside, it can be clearly seen that the floaters in the Chindwin are more spread out in longitudinal direction, meaning the dispersion in the Chindwin is higher than in the Ayeyarwady.

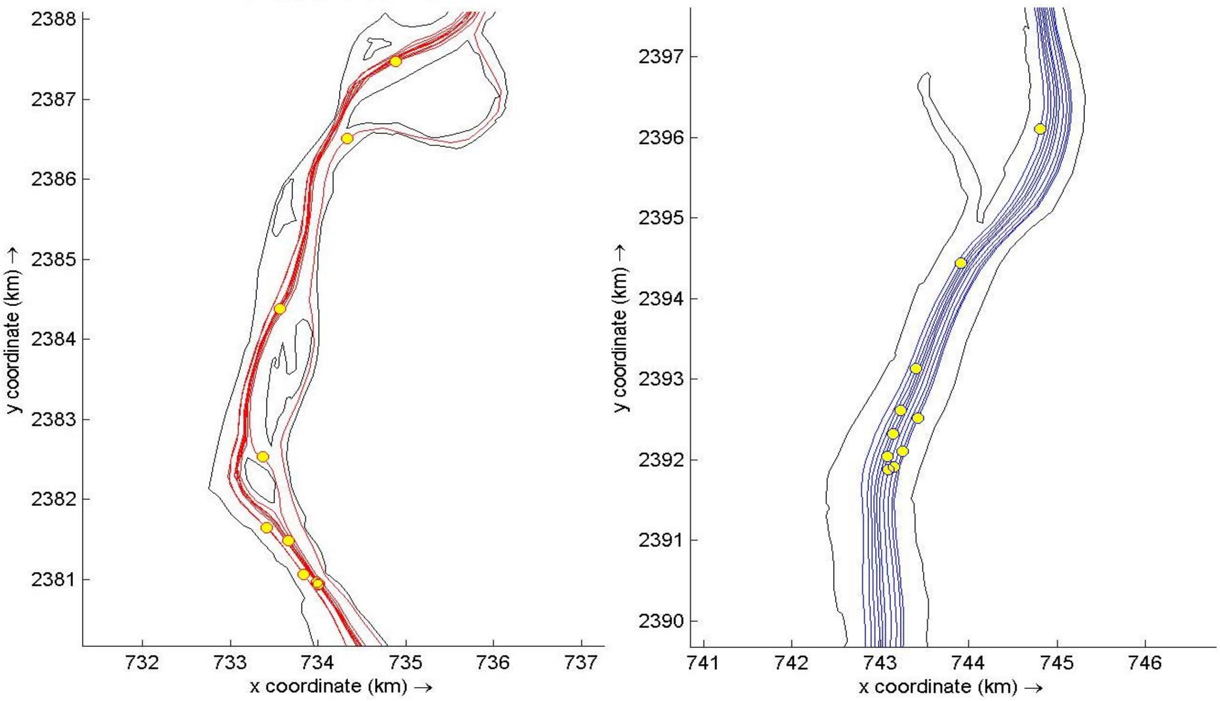


Figure 17: Close up of the paths of the floaters released in the Chindwin (left, red) and Ayeyarwady (right, blue). The floater locations 1000 minutes after release are given with the yellow markers. The scale of the both figures of the Chindwin and Ayeyarwady is the same. The dispersion is clearly higher in the Chindwin River, as the floaters are more spread out in longitudinal direction at the same time after deployment.

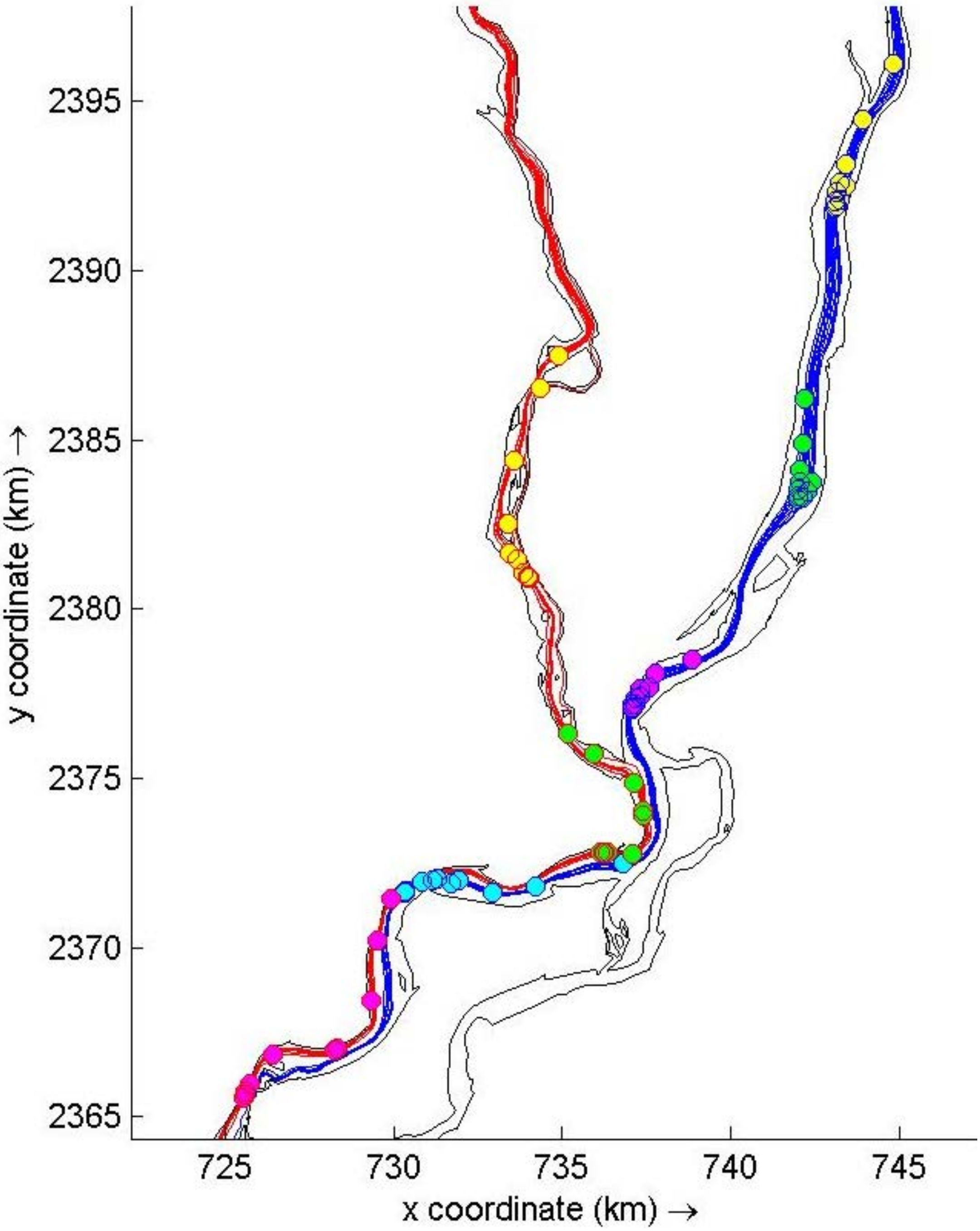


Figure 18: Floater paths of the floaters released in the Chindwin (red) and Ayeyarwady (blue). The flow velocity is clearly higher in the Chindwin River, as well as the dispersion, as the floaters get spread out in longitudinal direction faster.

5.3.2 Influence of different parameters

In this section, the effects of different parameters on the dispersion around the confluence are discussed. The results of the different simulations are presented. The simulation numbers are according to Table 2.

Influence of Discharge

As there was quite some variation in the calculated discharges, some simulations with different discharges at the upstream boundary have been done. The influence of the discharge can be seen in Figure 19, where the results of the following simulations are presented:

- Simulation nr. 1 Ayeyarwady 1500 m^3/s Chindwin 700 m^3/s (yellow markers)
- Simulation nr. 3: Ayeyarwady 1000 m^3/s Chindwin 700 m^3/s (green markers)
- Simulation nr. 4: Ayeyarwady 1900 m^3/s Chindwin 700 m^3/s (purple markers)
- Simulation nr. 5: Ayeyarwady 1500 m^3/s Chindwin 1000 m^3/s (cyan markers)

The discharge clearly has a significant impact on the dispersion rate. The results are as expected according to equation 1: when the discharge in either the Ayeyarwady or Chindwin is raised, the flow velocity and thus floater speed rises as well, leading to an increase in dispersion. The opposite happens for a decreased discharge.

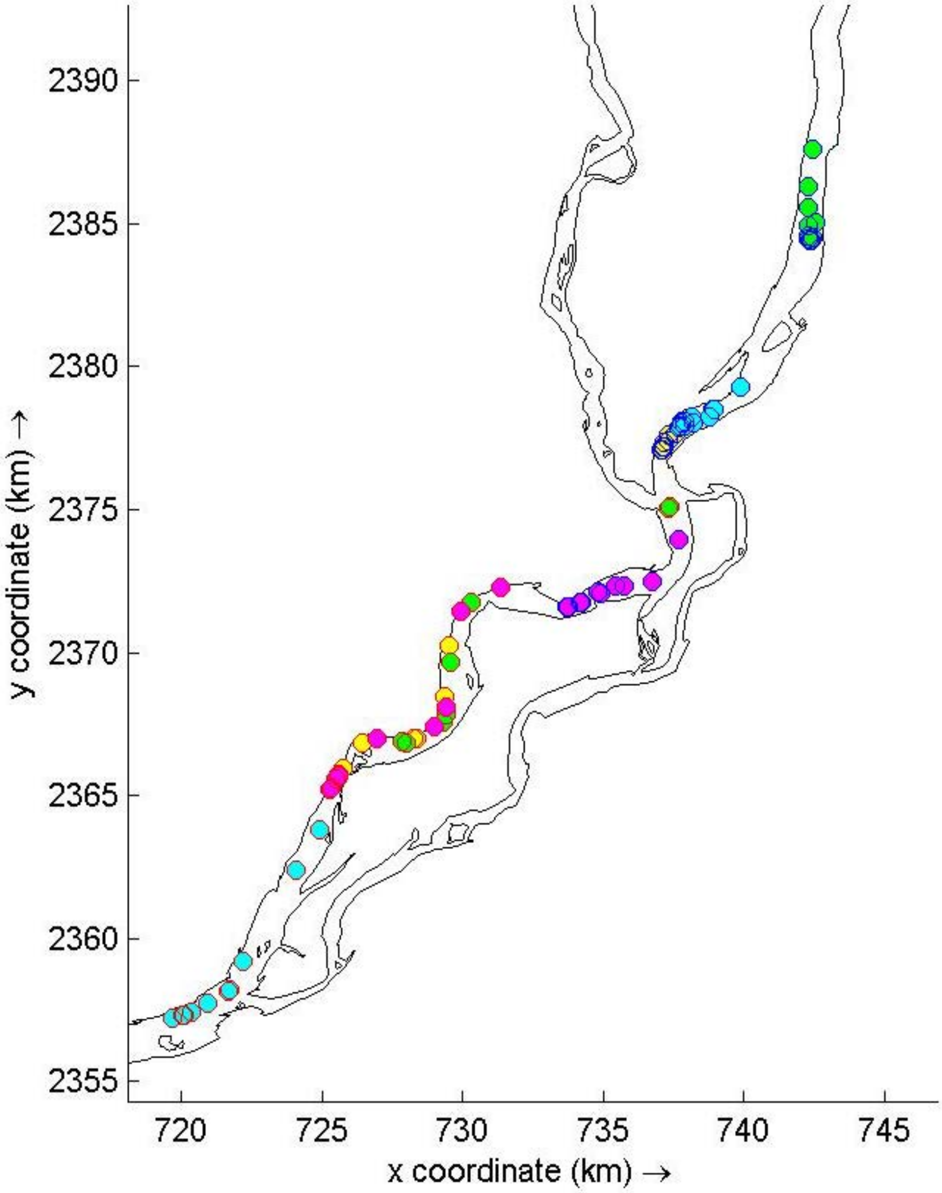


Figure 19: Influence of the discharge on the spreading of floaters and the floater speed. Floater markers with a blue edge are released in the Ayeyarwady; floaters with a red edge are released in the Chindwin. The markers represent the floater locations 1500 min after release.

Influence of Roughness

The influence of the roughness can be seen in Figure 20, where the results of the following simulations are presented:

- Simulation nr. 1: Chezy coefficient 65 $m^{1/2}/s$ (yellow markers)
- Simulation nr. 6: Chezy coefficient 50 $m^{1/2}/s$ (green markers)
- Simulation nr. 7: Chezy coefficient 80 $m^{1/2}/s$ (purple markers)
- Simulation nr. 8: Manning coefficient 0.035 $s/(m^{1/3})$] (cyan markers)

The roughness clearly has a significant impact on the dispersion rate. The results are as expected according to equation 1: when the Chezy coefficient is increased (meaning a smoother bed), the flow velocity and thus floater speed rises as well, leading to an increase in dispersion. The opposite happens for a lowered Chezy coefficient. Unlike the Chezy coefficient, the manning coefficient is dependent on the local water depth. Although the mean travelled distance of the floaters is lower than in simulation nr. 1, this spreading of the floaters (and thus dispersion) is higher.

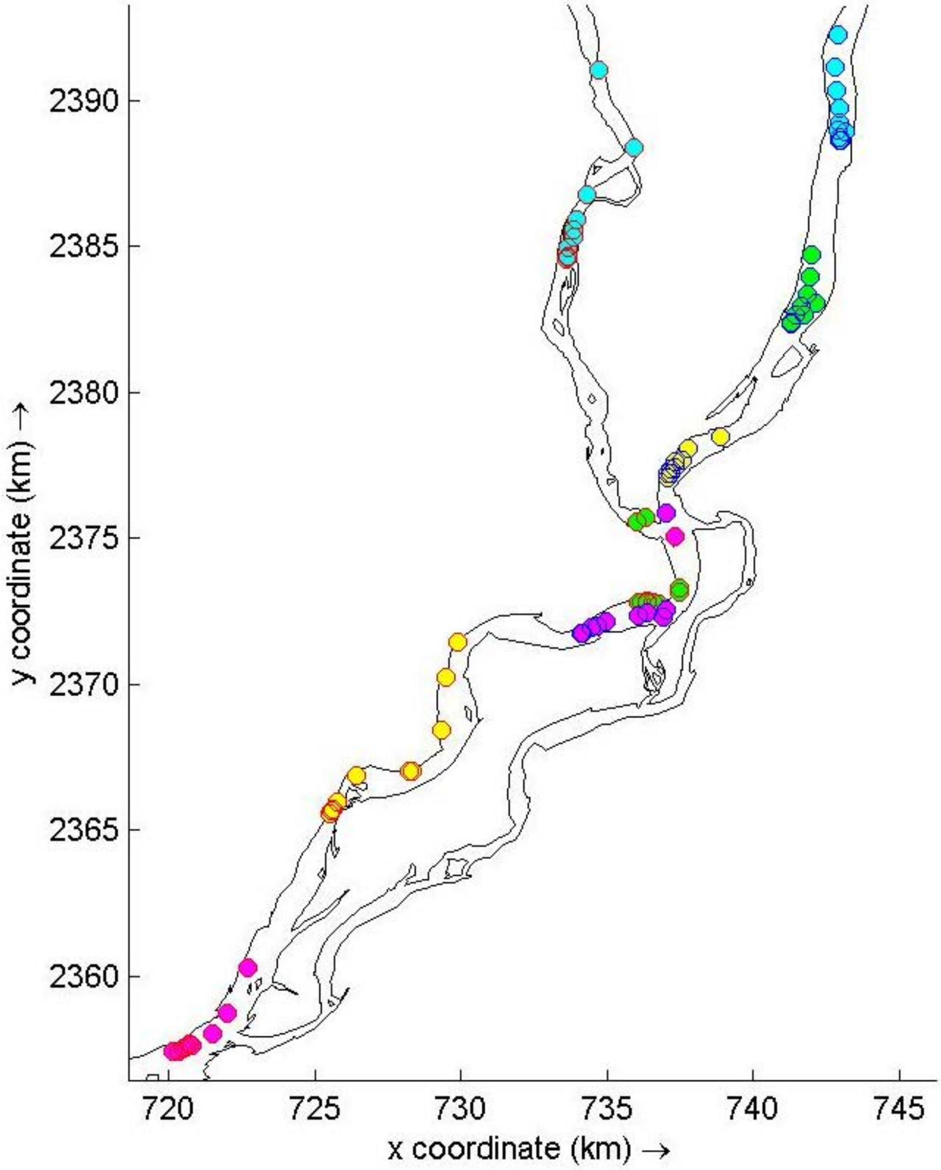


Figure 20: Influence of the roughness on the spreading of floaters and the floater speed. Floater markers with a blue edge are released in the Ayeyarwady; floaters with a red edge are released in the Chindwin. The markers represent the floater locations 1500 min after release.

Influence of Eddy viscosity and Eddy diffusivity

The influence of eddy viscosity and eddy diffusivity can be seen in Figure 21, where the results of the following simulations are presented:

- Simulation nr. 1: Eddy viscosity 1 m^2/s Eddy diffusivity 10 m^2/s (yellow markers)
- Simulation nr. 9: Eddy viscosity 0.1 m^2/s Eddy diffusivity 10 m^2/s (green markers)
- Simulation nr. 10: Eddy viscosity 100 m^2/s Eddy diffusivity 10 m^2/s (purple markers)
- Simulation nr. 11: Eddy viscosity 1 m^2/s Eddy diffusivity 1 m^2/s (cyan markers)
- Simulation nr. 12: Eddy viscosity 1 m^2/s Eddy diffusivity 100 m^2/s (black markers)

The influence of the eddy viscosity on the flow velocities and dispersion is very limited. Only when the eddy viscosity is increased to 100 m^2/s (purple markers) there is a clear difference. While the mean travelled distance of these floaters is lower, the distance between the floaters (and thus dispersion) is higher compared to the floaters from the other simulations.

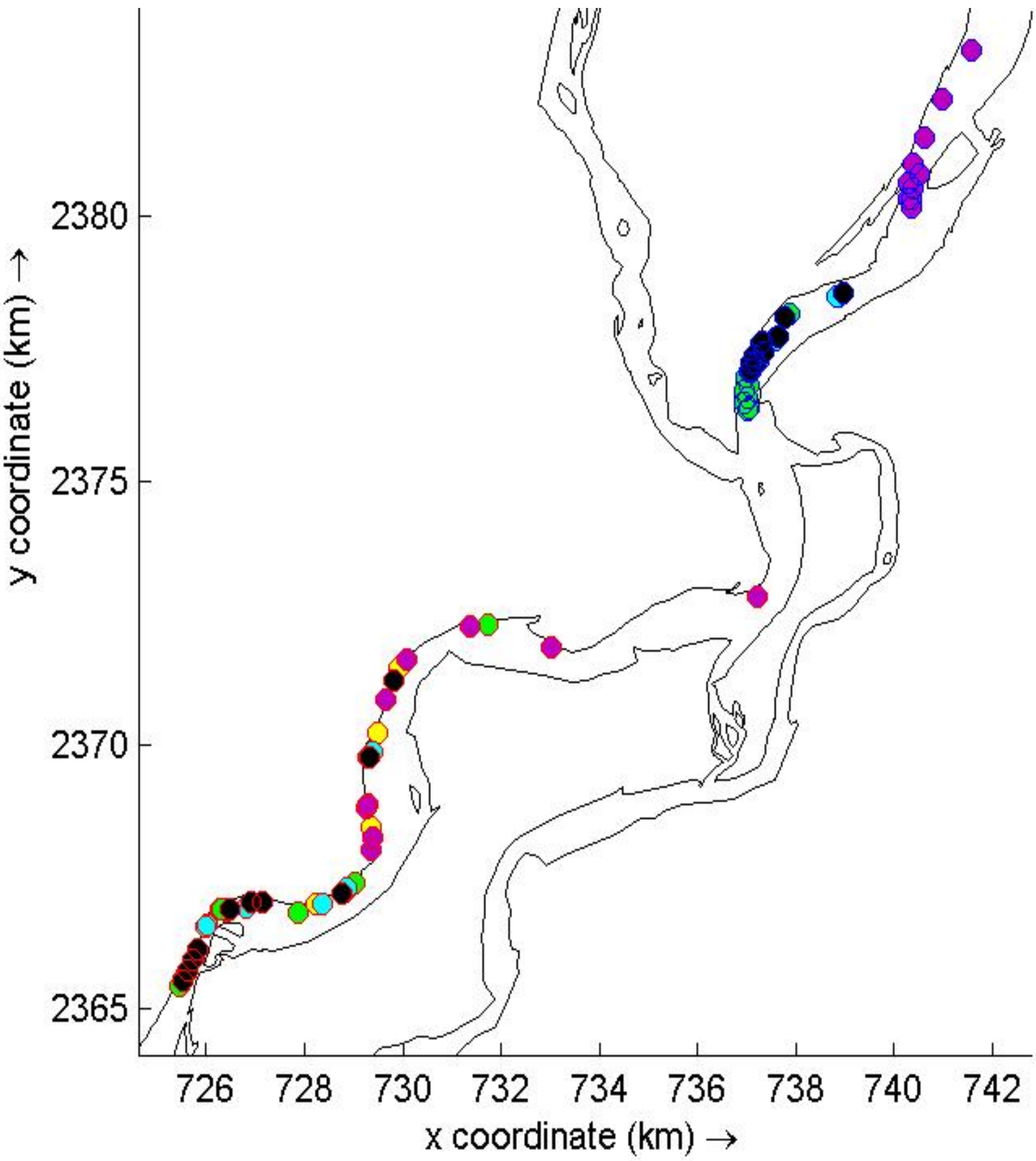


Figure 21: Influence of the eddy viscosity and eddy diffusivity on the spreading of floaters and the floater speed. Floater markers with a blue edge are released in the Ayeyarwady; floaters with a red edge are released in the Chindwin. The markers represent the floater locations 1500 min after release.

Influence of secondary flow and HLES (large eddy modelling)

The influence of the options secondary flow and HLES (large eddy simulation) in Delft3D on the floater paths can be seen in Figure 22, where the results of the following simulations are presented:

- Simulation nr. 1 With secondary flow No HLES (yellow markers)
- Simulation nr. 2 No secondary flow No HLES (green markers)
- Simulation nr. 13 With secondary flow With HLES (purple markers)

Without the option secondary flow, the dispersion is clearly higher compared to simulation nr. 1. This is not straightforward, as the option secondary flow accounts processes like spiral flow in bends for example, of process that is expected to increase the dispersion. With HLES (large eddy modelling), the dispersion decreases. This is in agreement with the theory by Rutherford (1994) that says turbulent diffusion (large eddies) counteracts the effects of velocity variations and leads to less dispersion (see also section 2.3.1).

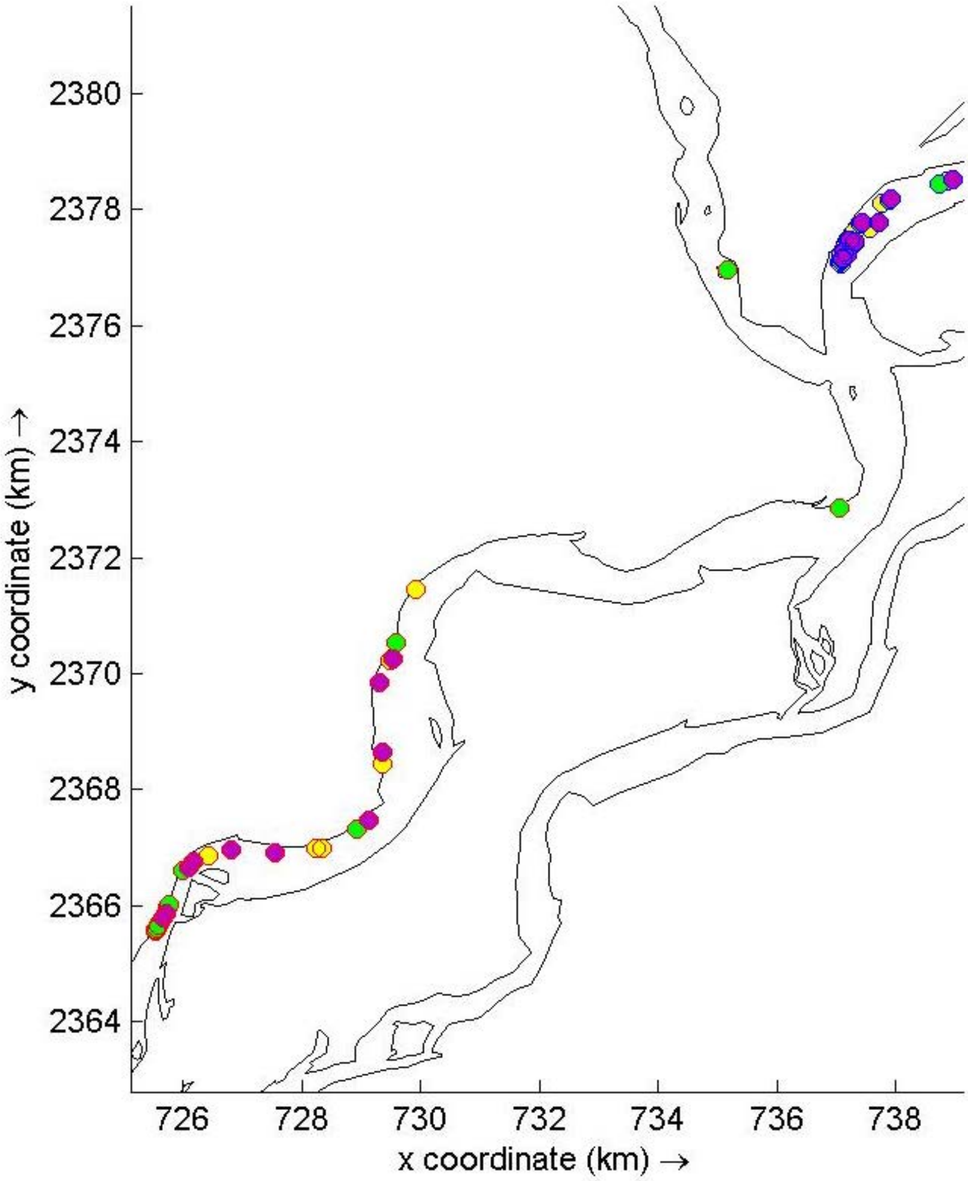


Figure 22: Influence of the modelling options secondary flow and HLES (large eddy modelling) on the spreading of floaters and the floater speed. Floater markers with a blue edge are released in the Ayeyarwady; floaters with a red edge are released in the Chindwin. The markers represent the floater locations 1500 min after release.

5.4 Dispersion

In Figure 23 the travelled distance (in longitudinal direction) of the GPS floaters from Figure 13, the simple floaters of Figure 14, and the Delft3D floaters of simulation 1 after 1500 minutes are plotted. Besides, the theoretical distribution of a tracer concentration over the river for the values of the longitudinal dispersion coefficient K_x= 10’000, 5000, 1000 and 500 m^2/s is plotted. In this way the observed spreading of the floaters can be compared with the theoretical dispersion corresponding to some values of the dispersion coefficient.

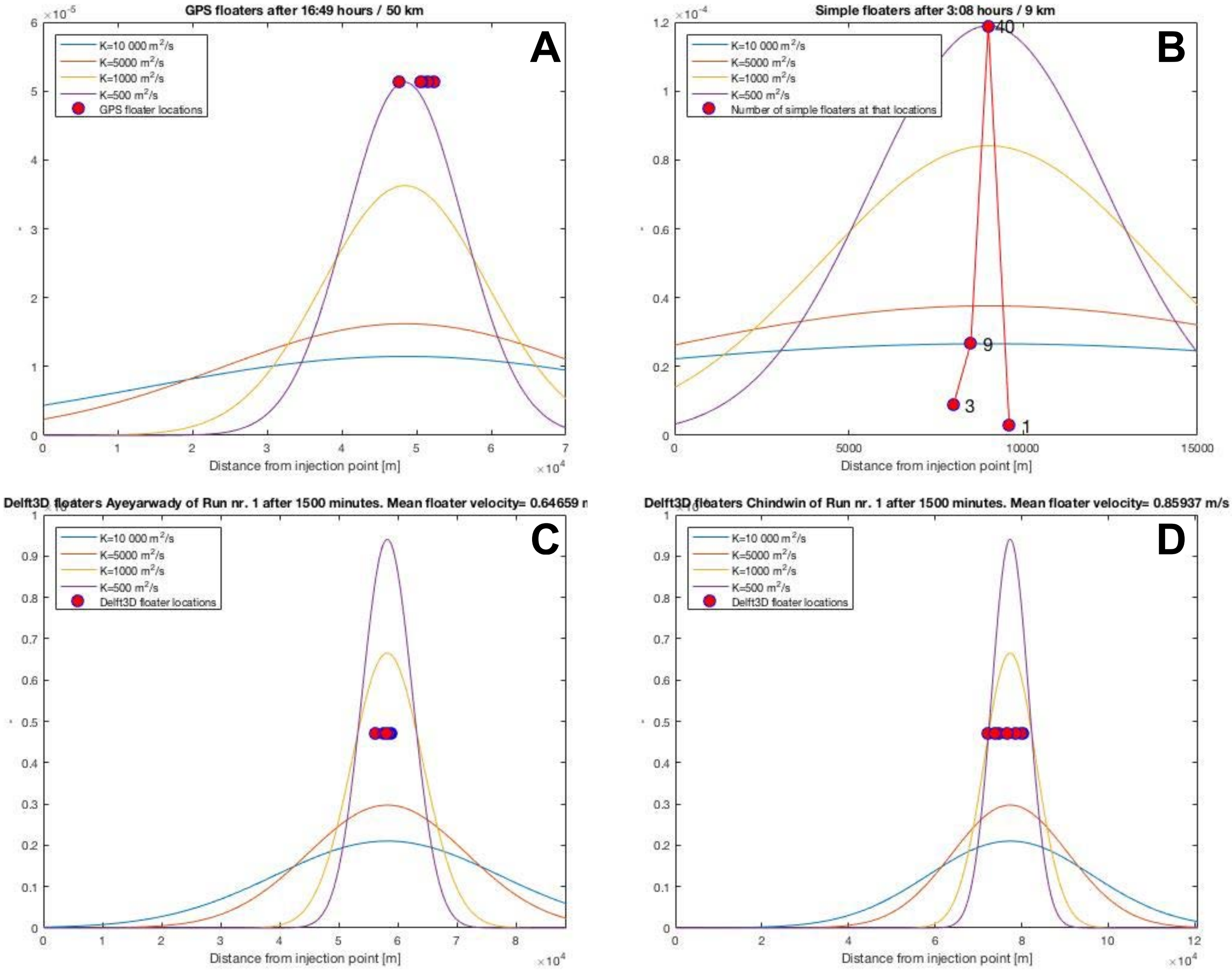


Figure 23: Comparison of the travelled distance and spreading of the floaters from the fieldwork and Delft3D simulation nr 1 with the theoretical concentration distribution. The theoretical concentration distribution corresponding to the values of the K_x= 10’000, 5000, 1000 and 500 m^2/s is plotted.

(A) Distance travelled by the GPS floaters after 16:49 hours or on average 50 km (standard deviation 1730 m) in the Ayeyarwady River west of Mandalay (for location see Figure 13).

(B) Estimated travelled distance of the simple floaters after 3:09 hours or on average 9 km (see section 5.2.2).

(C) Distance travelled by the Delft3D floaters from the upstream boundary in run 1 (see Table 2) in the Ayeyarwady after 25 hours or on average 58.2 km (standard deviation 779 m).

(D) Distance travelled by the Delft3D floaters from the upstream boundary in run 1 (see Table 2) in the Chindwin River after 25 hours or on average 77.3 km (standard deviation 2978 m).

In Figure 23 (A) and (B) it can be clearly seen that the fieldwork floaters get less spread out than expected according to the theory, as in section 2.4 it was expected that the floaters would be spread according to the distribution of a concentration belonging to K_x=10'000 m^2/s. After 50 km or 16:49 hours, the standard deviation for the GPS floaters Ayeyarwady in travelled distance is 1730 m. This corresponds to a longitudinal dispersion coefficient K_x= 70 m^2/s, a much lower value than expected based on the theory of section 2.4.

Also the simple floaters expected (after about on average 9 km or 3:08 hours) got spread out much less than when the distribution of simple floaters is compared to the theoretical concentration distribution. However, there are several reasons why value of the dispersion coefficient based on the GPS and simple floaters is probably an underestimation of the dispersion coefficient, this will be elaborated in section 6.8.

In figure 23 (C) the distance travelled by the Delft3D floaters in the Ayeyarwady is shown. When compared to the theoretical tracer concentration distribution, the dispersion is much lower. This is in agreement with the floaters from fieldwork. For the Chindwin (Figure 23 (D)) however, the dispersion is more in agreement with the theoretical tracer concentration distribution corresponding to K_x= 500 m^2/s.

For the Delft3D floaters of all 13 simulations in both Ayeyarwady and Chindwin rivers the mean, min and max distance travelled by the floaters in 1500 minutes (25 hours) is calculated. Besides, the standard deviation of the travelled distance is calculated. The results are shown in Table 5.

Table 5: Overview of the (mean, min and max) distance travelled by the Delft3D floaters after 1500 minutes (25 hours) for all runs (see Table 2 for the details of these runs) and the standard deviations in travelled distance. Both in the Ayeyarwady and Chindwin 10 floaters are used. Also the mean distance travelled and the mean standard deviation of all runs is calculated. When the travelled distances and standard deviations of the Chindwin and Ayeyarwady are compared, it can be clearly seen that the flow velocities in the Chindwin are higher and the dispersion is also higher.

	Ayeyarwady River				**Chindwin River**			
Simulation nr.	Mean distance travelled [m]	First Floater travelled distance [m]	Last floater travelled distance [m]	Standard deviation travelled distance [m]	Mean distance travelled [m]	First Floater travelled distance [m]	Last floater travelled distance [m]	Standard deviation travelled distance [m]
1	58'194	58'795	56'276	779	77'343	80'313	72'073	2978
2	58'126	58'735	56'500	711	74'954	80'313	58'589	7813
3	48'329	49'029	46'114	950	71'751	78'255	61'142	6920
4	66'187	67'935	62'348	1754	77'373	80'679	70'016	3819
5	57'011	57'706	54'884	879	88'649	91'242	83'416	2748
6	50'652	51'521	48'933	858	62'603	63'993	59'413	1580
7	65'374	67'546	60'048	2276	86'836	90'871	60'738	9253
8	43'754	44'701	41'363	1125	46'896	48'631	41'281	2406
9	58'905	59'519	57'397	667	77'856	80'522	69'899	3274
10	53'207	54'040	50'815	1052	71'545	74'842	63'197	3740
11	58'204	58'797	56'349	760	77'895	80'351	73'747	2531
12	58'172	58'770	56'165	801	77'764	80'358	73'071	2680
13	58'103	58'658	57'005	584	76'901	78'313	74'361	1411
Mean	56'478	57'366	54'169	1015	74'490	77'591	66'226	3935

There is a clear influence of most parameters; this will be further elaborated in chapter 6. Based on the in Table 5 calculated dispersion standard deviations, the corresponding dispersion coefficient is estimated. This is done by calculating the dispersion coefficient corresponding to a tracer concentration distribution with the same standard deviation as found for the Delft3D floaters:

- The mean standard deviation of all the Delft3D floaters (all simulations) in the Ayeyarwady River leads to a longitudinal dispersion coefficient K_x= 25 m^2/s
- The mean standard deviation of all the Delft3D floaters (all simulations) in the Chindwin River leads to a longitudinal dispersion coefficient K_x= 350 m^2/s

Just like with the floaters from the fieldwork, there are several reasons why value of the dispersion coefficient based on the GPS and simple floaters is probably an underestimation of the dispersion coefficient, this will be elaborated in section 6.8. In Appendix C the distance travelled by the Delft3D floaters in all other simulations (1-13) is plotted for both the Ayeyarwady and Chindwin. In this way

6. Discussion

In this section, the in chapter 2, 3 and 4 described methods, the assumptions made and subsequent results described in chapter 5 are discussed.

6.1 Theoretical longitudinal dispersion coefficient

In chapter 2, it has been shown that the dispersion coefficient is highly sensitive to various parameters, especially for width, but also the discharge, roughness and hydraulic gradient play an important role and are more complex to estimate. To include 3D effects, the bathymetry has to be known and the coefficient α_x has to be estimated by tracer experiments. This sensitivity means, data of high accuracy is needed for al these parameters. As already mentioned before and elaborated below, collecting and processing this data appeared to be challenging.

The in section 2.4 estimated range of longitudinal dispersion coefficients (2000-41’000 m^2/s, mean 10’000 m^2/s) appeared to very high when compared to the usual range (7.2-723 m^2/s, section 2.5). This was confirmed by the fieldwork and Delft3D simulation results.

6.2 Floaters

The floater experiment forms the core of the efforts done during the fieldwork to estimate the dispersion. However, as described below, serious problems occurred during the experiment, leading the limited data collection and thereby usefulness of the data.

6.2. Execution of the floater experiment

The GPS floaters worked well and mostly the data was sent without problems, so the track of each floater could be followed real time on a website. The design was robust enough, as they did not break due to currents and waves of ships etc. As there was very limited wind during the experiment, it is unlikely that wind will have significantly influenced the floater paths. However, the following problems occurred:

- Main problem was that the floaters got stolen and/or destroyed, probably because of the lack of knowledge among other river users about where they were used. They look expensive, are easily dissembled and get quite some attention because of their size and the electronics on top.
- Some technical issues with the solar panels destroyed some of the trackers already before the floaters were deployed.

The simple floaters performed somewhat less than hoped for, although the basic idea of a mostly biodegradable and cheap, but good recognizable floater is very nice. The following problems in both design of the floater and execution of the experiment occurred:

- Many balloons popped due to the heat of the sun, nails or wood on the boat and incautious handling. The rough rope trough the balloon knot to attach the light to the coconut also destroyed some balloons already before deployment.
- The helium leaked out of the balloons, probably due to the porosity of the balloon material and because of the rope going through the knot of the balloon.
- The original simple floater design consisted a brick under the coconut to create drag, but already before deployment this appeared to be too heavy. Although the coconut was quite low in the water, the wind had more influence in this way.
- Obviously, coconuts are food, and the balloons make them very visible. Most other river users do not know for what reason the coconuts are in the river and take the coconuts out to eat, see Figure 24.

Figure 24: Simple floaters look like free coconut with balloons, and are taken out of the water by fishermen (and put back in after asking them to do so).

Due to the problems mentioned above, only at one location the passing times for the simple floaters have been noted, while in the original plan this would be every few tens of km. Also, with the GPS floaters significantly less data was collected than planed, as only part of the floaters could be used as the rest was almost immediately broken or stolen. For this reason the fieldwork has been more concentrated on the direct area around the confluence than was desired.

6.2.2 Usefulness and limitations of the collected data

The GPS floater experiment gives useful insight in the flow patterns and speeds around the confluence. No simple floaters were counted around the confluence. Due to the limited number of GPS floaters and short measurement times, the GPS floater paths appeared to be of little use for calculating the dispersion at close to the confluence. However, the floater paths around the confluence have been useful for validating the Delft3D model, as the floater speeds and paths observed in the field were compared to those of the Delft3D model.

More upstream, west of Mandalay (see Figure 13), 5 GPS floaters have collected data for more than 50 km. Besides, the crossing times of 53 simple floaters were noted after about 9 km in the water at the same river section. As has been shown in section 5.2.6 in accordance with the theory of section 2.2, the transversal mixing length is in the order of 100 km. This means that at the moment of noting the passing times, the floaters were probably not yet fully transversally mixed, leading to an underestimation of the dispersion.

The some holds for the GPS floaters: especially around the confluence they were deployed only for a short period and distance, and therefor not well transversally mixed. More upstream the floaters were mixed better, although in figure 13 it is visible that the floaters get also after 50 km more transversally spread out after every river bend, and thus also for this location the floaters are probably not fully transversally mixed. This leads to an underestimation of the dispersion coefficient (further elaborated in section 6.8).

On both rivers but mostly on the Ayeyarwady, ships might have significantly distorted the track of the both types of floaters due to waves and secondary currents, especially as both ships and floaters tend to follow the deepest part of the river.

6.2.3 Recommendations for future floater experiments

When the original plan with both types of floaters could have been executed, this would probably have led to enough floater data to make a much more accurate estimate of the dispersion. Nevertheless the use of more GPS floaters (10 for example) at one location would make this estimate even better.

Although unforeseen events will always occur during fieldwork and focussing on the confluence was probably the best option after the loss of most of the floaters, more intensive testing of the floaters and more practising on small scale could improve a setup of a fieldwork on this scale. Solutions could be either a more robust or a more camouflaged (GPS) floater design to prevent theft and destruction.

Keeping the floaters in sight is anyway recommended, faster and easy manoeuvrable boats could make this easier. A more intensive campaign upfront to create awareness among the other river users might also help, but can be complicated due to the remoteness of the area.

6.2.4 Comparison of fieldwork and Delft3D floater paths

When Figures 11 and 12 (fieldwork floater paths) are compared with Figures 17 and 18 (Delft3D floater paths), the following things can be noted:

- The floaters in Delft3D much more follow streamlines; the paths of the floaters do not cross each other, while the paths of the floaters in the fieldwork cross regularly and the floaters do not follow straight streamlines. That this is not visible in Delft3D is a model artefact. The consequence is that the dispersion will be underestimated.
- Near the confluence, the floaters coming from the Chindwin first go quit far to the east into the Ayeyarwady. This is visible in the floater paths of the fieldwork and Delft3D model. This is an indication that the modelled bathymetry and discharge (at least the Ayeyarwady-Chindwin discharge ratio) are similar to the reality.

6.3 Bathymetry

6.3.1 Depth measurements

Both depth measurements with the echo sounder and the hand measurements are expected to be quite accurate. Measurement errors due to not measuring from exactly the water surface (leading to an lower measured depth than actual depth) will give the highest inaccuracy. It is expected that deviations are in general less than 10 cm, possibly with a few outliers of a few decimetres. The depth measurements are used to estimate a bathymetry for the Delft3D model. Measurement errors can be considered negligible considered the much higher inaccuracy in the following:

- The interpolation of the depth measurements with a very low spatial density in most parts of the river.
- Assumptions regarding the bed level in the more upstream parts of the modelled area where no data at all was available.
- The very dynamic character of the river, meaning the bed level and depth are rapidly varying.

In case the data would be used for other purposes, this consideration regarding measurement errors has to be made again. An overview of all depth measurements can be found in Appendix B.

6.3.2 Constructing the bathymetry for Delft3D

Due to the already mentioned data availability, there is a high uncertainty in the used bathymetry in Delft3D, especially in the Chindwin River; the deviation can be in the order of meters. The assumptions made to create the bathymetry were already shortly described in section 4.3.3:

- Cross section surface (depth times width) is roughly constant over the length of a branch. Unfortunately this is not such a strong assumption, as the flow velocity can also fluctuate over a branch, but it is the best available option due to the limited data availability.
- The hydraulic gradient is more or less constant over a branch, and did not significantly change since the year 2000. Although there can be local deviations, it is expected that the inaccuracy in this assumption is much smaller than of the above-mentioned assumption.
- Basic principles for the bathymetry in river bends are applicable, roughly meaning higher depths in the outer bends and lower depths in the inner bends. This was the case in the measured cross sections and as the river is only very limited controlled, this is expected to be a good assumption.
- The river can be divided in 3 branches (Ayeyarwady upstream of the confluence, Chindwin (upstream of the confluence), and Ayeyarwady downstream of the confluence) in which parameters like discharge, roughness, hydraulic gradient and cross section surface can be assumed constant.

The influence of (eventual errors in) the bathymetry has not been included in the analysis of the influence of different parameters in the Delft3D model and can therefore be seen as one of the main uncertainties in the used Delft3D model and corresponding dispersion coefficient estimate. An overview of the resulting bathymetry used in the Delft3D model can be found in Appendix B.

6.3.3 Recommendations

To be able to optimally use the floater data, a Delft3D model can be very useful. It would be very interesting to do a Delft3D model run with another bathymetry constructed to the same principles to see the influence of the bathymetry is indeed of major influence on the floater paths and dispersion as expected.

When this is the case, the bathymetry should be measured in more detail, for example by letting a boat make cross section every few hundred meters in the river section of interest. Another option for improvement could be to include morphodynamic effects in the Delft3D model and let the model run for a much longer period to create an equilibrium bathymetry.

6.4 Flow velocities

6.4.1 Flow velocity measurements in the cross sections

To get as reliable data as possible within the restrictions of the fieldwork, all depth and flow velocity measurements have been done double. The flow velocity was measured at two depths. Two teams did measurements independent of each other, with different measurement equipment. In general, the measurements of both teams agreed well and otherwise a satisfying explanation for the deviation was found. When the deviation was small, the average flow velocity was taken, otherwise the value of the correct measurement.

However, instead of from a geographically stable point (like a bridge) the measurements were done from a (moving) boat. Although best efforts have been done to guarantee that the boat was on a steady position during the measurements, it appeared that the measurement error due to this was significant:

- During the first measurements (closest to the surface) the boat was still moving in upstream direction, leading to an overestimation of the flow velocities.
- During the second measurements (closest to the bottom) the boat was still moving in downstream direction, leading to an underestimation of the flow velocities.

As both teams were on the same boat and measured at the same time, measurements from both teams have this deviation. When the assumed logarithmic profile was fitted to the flow velocity, this appeared not to fit. A better approximation of the flow velocity appeared to be the average of the two measured flow velocities at the average depth of the measurements, see Figure 25 for further clarification.

Fitting the logarithmic profile to this new flow velocity point and than calculating the mean flow velocity worked well. It has to be noted however, that in this way quite some assumptions had to be made to come to a reasonable flow velocity estimate:

- The measured flow velocities are representative for (that part of) the river.
- The flow velocity has a logarithmic profile over the depth.
- The absolute deviations of the measured flow velocities at the 2 depths are equal.

As can be seen in Figure 25, the last of these assumptions leads to a high uncertainty in the calculated flow velocity, as it can be a factor of the order 2 lower and higher than calculated based on this assumption. The consequences of this uncertainty in the flow velocity are clearly visible in the section 6.5; there is a large variation in the calculated discharge based on these flow velocities.

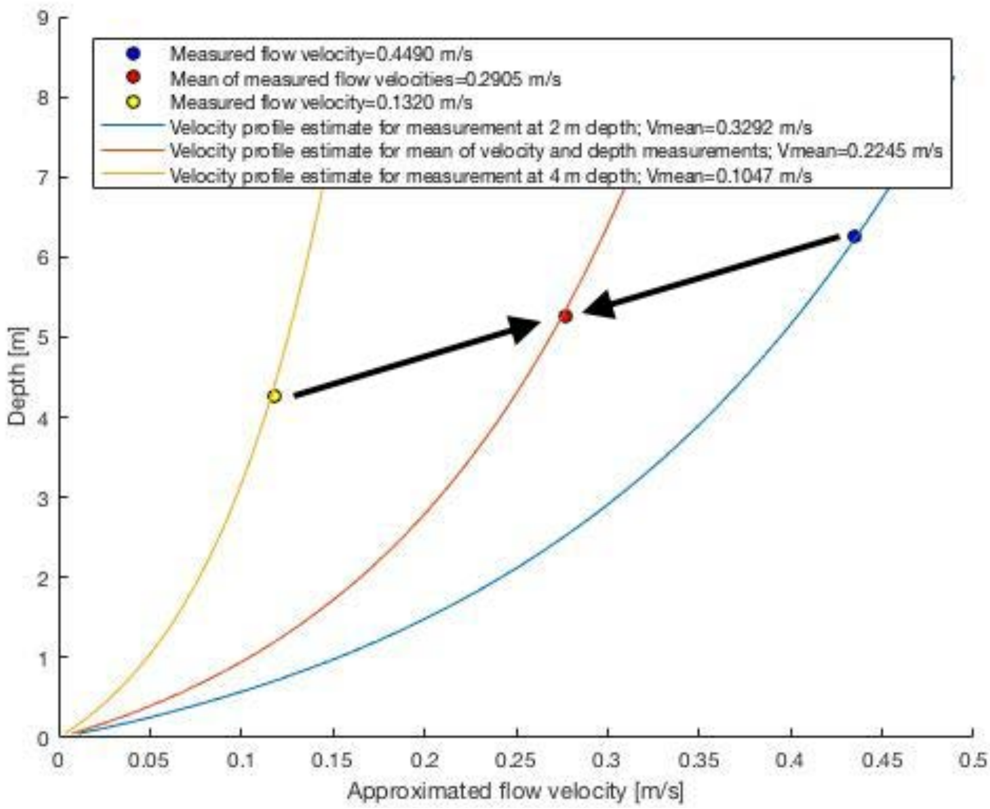


Figure 25: Explanation and accuracy estimate of the mean floater velocity. A logarithmic profile doesn't fit to the velocities measured at 2 m depth (blue) and 4 m depth (yellow). When the 2 measurements are combined, the point marked in red is obtained. For this point it is possible to fit a logarithmic profile. Next the depth averaged flow velocity (Vmean in figure) can be calculated for each profile.

There is clearly an high uncertainty in the calculated depth flow velocity, as the mean calculated depth averaged flow velocity=0.22 m/s is now assumed, while in reality the depth averaged flow velocity will be somewhere in between the 2 boundaries (0.10 m/s and 0.33 m/s; a factor 2 lower and higher).

6.4.2 Interpretation of the flow velocities in the cross sections

From section 5.2.1 and Table 3, it can be concluded that the flow velocities are widely varying, from as high as 2 m/s to locally even 'negative' flow in the opposite direction of the main flow.

However, it can be said that the measured flow velocities in the Chindwin where on average 1.15 m/s and thereby significantly higher than the flow velocities in the Ayeyarwady (both upstream and downstream of the confluence). This is as expected, considered that the hydraulic gradient in the Chindwin is also higher.

Interesting to see that the flow velocities measured in the Ayeyarwady downstream (mean: 0.58 m/s) are higher than upstream of the confluence (mean: 0.38 m/s), although the hydraulic gradient downstream of the confluence is lower.

6.4.3 Comparison fieldwork and Delft3D floater velocities

As can be seen in Figures 11, 12 and 13, the floater velocities measured during the fieldwork are highly spatially varying. Interesting to see is that the flow velocities in the outer bends are as expected in general higher compared to the inner bend. The floaters are carried by the flow at the surface where the flow velocity is higher than the average floater velocity. This is confirmed when the floater velocities are compared with the mean flow velocities based on the measurements in the cross sections.

The floater velocities in the Delft3D model are somewhat lower than those measured in the fieldwork:

- Mean GPS floater velocity Ayeyarwady at the section west of Mandalay (Figure 23 (A)): 0.8 m/s.
- Mean Delft3D floater velocity at the Ayeyarwady upstream of the confluence in simulation nr. 1 (Figure 23 (C)): 0.65 m/s.

This is probably due to the fact that the GPS floaters are not yet well transversally mixed, leading to an overrepresentation of the fast flow in the deepest part of the river where the GPS floaters are carried. Besides, the discharge in the Delft3D model can be somewhat underestimated.

6.5 Discharge

6.5.1 Discharge measurements

As can be seen in Table 4, there is a high variation in the calculated discharges in different cross sections. Especially in the Ayeyarwady upstream of the confluence there is a high variation in calculated discharges with almost a factor 2 between the lowest and highest calculated discharge. There are several possible reasons for this:

- Measurement errors in the flow velocity, mostly due to movement of the boat (see section 6.4).
- The flow velocities are not representative for part of the cross section in which they are assumed to be.
- Assumption of a logarithmic velocity profile is (partly) wrong (see section 6.4).
- The flow velocities and depth measurements are not always done in exactly the same cross section (difference in location in the order of 100 m longitudinal).

Nevertheless, the (on the measurements based) assumed discharge gives reasonable results when the flow velocities and water depths of the fieldwork are compared with the Delft3D model. To be able to make a better calculation of the dispersion coefficient, more accurate discharge measurements would be strongly favourable due to the sensitivity of the used formula (equation 3).

6.5.2 Influence of the discharge on the dispersion

As can be seen in Figure 19, the floaters are more spread out after the same time in the runs with a higher discharge in one of the branches. The floaters are also more downstream, meaning the flow velocities are higher. This is in accordance with the theory elaborated in chapter 2; a higher discharge leads to a higher dispersion coefficient.

6.5.3 Recommendations

The magnitude of the mixing of the tracers (and thus dispersion coefficient) varies significantly, while all modelled discharges are well within the margin of the uncertainty of the discharge. From comparison of the mean GPS and Delft3D floater velocities in the Ayeyarwady (see section 6.4.3) follows that the discharge in the Ayeyarwady might be somewhat underestimated now.

A more accurate discharge estimate leads to a better dispersion estimate. To decrease the uncertainty in the discharge, flow velocity measurements from geographically stable points, like bridges could be executed, in combination with depth measurements at that location.

6.6 Roughness

At the locations of the cross sections the depth, flow velocity and hydraulic gradient are known, meaning that with some assumptions, theoretically equation 4 (Chezy equation) could be used to estimate the Chezy coefficient (C). When applied to the different locations, a very large spreading in values of C appeared ranging from C<1 $m^{1/2}$/ to C>100 $m^{1/2}$/s.

When the roughness is calculated based on the average values of the depth , flow velocity and hydraulic gradient in the branches, very low values of C are found. In the Ayeyarwady upstream of the confluence for example:

- mean depth 6.69 m;
- mean flow velocity 0.38 m/s;
- mean hydraulic gradient i= $8*10^{-5}$;
- leads to C~15 $m^{1/2}$/s.

This means the bed would be very rough. Unfortunately, again the same problems with the inaccuracy of the flow velocity play a role (see section 6.4). As shown in Figure 20, the roughness plays an important role in the flow velocities and dispersion.

Al together it has to be said that the roughness is not yet known well enough, but that the values of 65 and 50 are on the high side. It would be interesting to also try values of the Chezy coefficient in between 10 and 50 m^2/s in the Delft3D model. More accurate measurements (of depth and flow velocity) would also be useful to get a better estimate of the roughness.

Unlike the Chezy coefficient, the manning coefficient is dependent on the local water depth. In Table 5 it can be seen that with the manning coefficient the mean floater velocity is lower while the spreading of the floaters (and thus dispersion) is higher. Considered the much higher theoretically estimated (section 2.4) dispersion coefficients than the observed coefficients (section 5.4), this could be a more realistic representation of the reality, but this has to follow from more simulations with the manning coefficient.

6.7 Delft3D model parameters

As can be seen in Figure 21, the eddy viscosity and eddy diffusivity have significant influence on the mixing of tracers in the model as can be seen in Table 5, although it has to be noted that a large range for these coefficients has been used. At first sight, values around the default look to better approximate the reality in terms of flow velocities.

Although the model is 2D (no layers in vertical direction), including secondary flow gives different floater paths, see Figure 22. At first sight the model results look better when accounted for secondary flow. The option HLES looks less promising, especially as it is very expensive in terms of simulation time, however changing the settings of the parameters specified could lead to different results.

As mentioned above, there are many uncertainties in the used (physical) parameters. This makes it with the currently available data complicated if not impossible to estimate the values of the in this section elaborated parameters. Though the influence of the parameters is clearly visible, it is recommended to first put efforts into improving the physical parameters before addressing these further.

6.8 Longitudinal dispersion coefficient

6.8.1 Based on Theory

From the theory in chapter 2 follows that the first order estimated longitudinal dispersion coefficient can be best estimated as K_x= 10’000 m^2/s, although the range of the estimated coefficients is between K_x= 2000 m^2/s and K_x= 41’000 m^2/s.

This seems rather high, when compared to the normal range of dispersion coefficients for a river of this size, which is $7.2 < K_x < 723$ m^2/s.

6.8.2 Based on GPS and simple floaters

Based on the GPS floaters in the Ayeyarwady west of Mandalay (see Figure 13), the longitudinal dispersion coefficient can be estimated as K_x= 70 m^2/s. This is a much lower value than expected based on the theory, but confirmed by the results of the simple floaters. However, due to the too short measurement distance this dispersion coefficient is probably an underestimation.

It is likely that the floaters were not fully transversally mixed as the mixing length is in the order of 100 km while the floaters travelled only 50 km. It can be assumed that the floaters are only transversally mixed over about half the total river width after 50 km (conservative assumption when compared with the floater paths of Figure 13). With use of equation 1, where the width B is squared, this would lead to an increase of the dispersion with a factor 4, leading to K_x= 280 m^2/s. This does not yet account for the fact that the mean width over which the floaters were spread during this 50 km was even smaller, leading again to an increase of the dispersion coefficient.

It has to be noted that the estimate of the dispersion coefficient was only based on 5 GPS floaters, limiting the accuracy of the estimate. Besides, this dispersion coefficient is estimated at a different location (more upstream, not at the confluence). The Ayeyarwady is less dynamic at this location, which again leads to a higher dispersion coefficient near the confluence.

6.8.3 Based on Delft3D floaters

The estimated longitudinal dispersion coefficient based on the Delft3D floaters (all simulations) in the Ayeyarwady River leads to K_x= 25 m^2/s and for the Chindwin River this lead to K_x= 350 m^2/s. Again these values are much lower than found based on the theory, where K_x was calculated for the Ayeyarwady River. Again, this is most likely an underestimation of the dispersion coefficient due to the following reasons:

- The bathymetry (especially further away from the confluence) is assumed relatively smooth due to interpolation of very limited data points. As in reality the bed will likely be less smooth (more shoals, etc.) this will in reality likely cause large-scale turbulence (eddies), which is not included in the Delft3D model. The influence of large-scale turbulence is clearly visible in the floater paths of GPS floaters (see Figure 13) and its absence in the Delft3D model likely leads to a significant underestimation of the dispersion coefficient.

- The roughness is likely underestimated in the Delft3D model. Especially when a higher roughness is modelled by the depth dependent roughness (manning) coefficient, this leads to a higher value of the dispersion coefficient. When a Chezy value of 20 instead of 65 (~ factor 3) is assumed (based on section 6.6), K_x increases as well with a factor 3 according to equation 1.
- The floater speed somewhat to low in the Delft3D model, probably due to an underestimation of the discharge. A higher discharge leads to more dispersion in the Delft3D model. There is a large uncertainty in the magnitude of the discharge (~ factor 2, see section 6.5).

The sum of all above-mentioned effects can lead to the following (very rough) estimate in which effects of large scale turbulence are not yet included: K_x calculated (25)* factor for roughness (3) * factor for discharge (1.5) leads to K_x = 110 m^2/s.

Al these uncertainties in the Delft3D model combined make it reasonable to assume that the order of magnitude of K_x for the Ayeyarwady is more similar to the one resulting from the fieldwork. Besides, it has to be noted that the estimate of the dispersion coefficient in the Ayeyarwady was only based on 10 Delft3D floaters, limiting the accuracy of the estimate.

Based on the Delft3D floaters, it can be concluded that the dispersion in the Chindwin is significantly higher. From the model runs it follows that the dispersion coefficient can be in the order of a factor 10 higher than in the Ayeyarwady.

7. Conclusion and recommendations

In this research the parameters needed for describing the dispersion around the confluence of the Ayeyarwady and Chindwin rivers and their magnitude has been investigated. The following main question was formulated:

- *How can the mixing of tracers around the confluence of the Ayeyarwady River and Chindwin River be described?*

First, a theoretical estimate of the mixing of tracers in the Ayeyarwady River has been made. This was done by estimating the longitudinal dispersion coefficient (K_x) for the Ayeyarwady River. From the theory it followed that mainly the discharge, roughness and bathymetry (including width, depth and hydraulic gradient) in the river are of importance to make a good estimate of the longitudinal dispersion coefficient. Besides, floater experiments appeared to be necessary for calibration of the formula used to calculate the dispersion coefficient, for which the coefficient α_x is used.

During the fieldwork done in the area, as much data as possible had been collected, although various unforeseen difficulties limited the effectiveness of the fieldwork. Conclusions regarding the magnitude of the parameters needed for the dispersion including the limitations of the used data and recommendations for increasing the accuracy are outlined below. Based on this, the main question is addressed in the last section.

Discharge and roughness (based on the flow velocities)

To calculate the discharge, the flow velocities and depth (see next section) are needed. The magnitude of measured flow velocities is widely varying, from as high as 2 m/s to locally even 'negative' flow in the opposite direction of the main flow. Due to measuring from a moving boat, the measured flow velocities are not very accurate and could be a factor 2 lower or higher, but the calculated mean flow velocity is probably more accurate as it is the average of different measurements. The calculated mean flow velocities can be found in Table 6.

Due to the uncertainty in the measured flow velocities, there is a high uncertainty (factor 2) in the magnitude of the calculated discharges, of which the mean values are shown in Table 6. From the Delft3D model it appeared that these values are probably somewhat on the low side. For the roughness in the Delft3D model a Chezy coefficient of 50, 65 and 80 was tested while the Delft3D model, supported by a hand calculation, shows that lower Chezy coefficients are more likely (C~30 $m^{1/2}/s$).

To further improve the estimates of the discharge and roughness, it is recommended to do some detailed flow velocity and depth measurements from geographically stable points (like bridges). In this way, a more accurate estimate of the discharge and roughness can be calculated. Trying values of the Chezy coefficient (around C~30 $m^{1/2}/s$) or comparable depth dependent Manning coefficients in the Delft3D would also be interesting.

Table 6: Overview of the found values of the estimated flow velocities and discharge in the different branches during the first week of February 2017.

	Ayeyarwady upstream of the confluence	Chindwin upstream of the confluence	Ayeyarwady downstream of the confluence main branch	Ayeyarwady downstream of the confluence second branch
Estimated average flow velocity (m/s)	0.38	1.15	0.58	
Estimated discharge (m^3/s)	1500	700	1800	400

Bathymetry

The bathymetry is probably of major importance for the mixing of tracers, as the bathymetry induces larger scale eddies and differences in flow velocity over the width. Only in a very limited number of locations depth measurements have been done, showing that the depth is highly spatially varying. In some cross section depth measurements were done to be able to calculate the discharge. From comparison with hand measurements follows that the collected data was of good quality.

The depth measurements are used to construct the bathymetry in the Delft3D model. Due to the very limited number of depth measurement locations, there is a high uncertainty in the bathymetry used in the Delft3D model. The inaccuracy in the depth in the model can be in the order of meters. The influence of the bathymetry is not investigated in the Delft3D model runs, which would be a logical next step to get a feeling of its importance.

When the bathymetry is indeed of major influence as expected, the bathymetry should be measured in more detail, for example by letting a boat make cross section every few hundred meters. Another option for improvement could be to include morphodynamic effects in the Delft3D model and let the model run for a much longer period to create an equilibrium bathymetry.

Floater experiment

Insight in the magnitude of the spreading of floaters can be used to calculate the dispersion coefficient at a certain location. When the dispersion is known at one location and time for which also the other above mentioned parameters are known, the coefficient α_x used in the formula to calculate the dispersion coefficient can be calibrated. To estimate the longitudinal dispersion coefficient, 3 types of floater experiments have been done. Simple floaters and GPS floaters were used in the field and the option ‘drogues’ in the Delft3D model.

The especially for this floater experiment designed floaters (by Rolf Hut) worked technically mostly well. Unfortunately, loss, theft and destruction of the floaters made the obtained data limited. The best data was obtained west of Mandalay, where 5 GPS floaters were carried with the flow over a section of 50 km. Both transversal and longitudinal dispersion are clearly visible, and the dispersion coefficient has been calculated based on these results (see next section).

Besides, crossing times of simple floater were noted in this area, confirming the GPS floater results. Unfortunately, both the GPS and simple floaters were to short in the water to get transversally mixed, leading to an underestimation of the calculated dispersion coefficient. To prevent very long transversal mixing lengths in future floater experiments when mostly the longitudinal dispersion is of interest, it can be useful to do spread the floaters directly over the width at the injection point.

From comparison of the GPS floaters paths from the fieldwork and Delft3D model floater paths follows that the Delft3D model does not account well for the large turbulence (eddies), while the GPS floater paths show that this is an important process. This led to an underestimation of the dispersion in the Delft3D model. To model the large-scale turbulence better, the option HLES (large eddy simulation) in Delft3D has been tried, but with the used parameters the effect was hardly visible. Trying other settings for HLES might lead to better results and could be worth trying. Nevertheless, the Delft3D floater paths give useful insight in the relative influence of different parameters.

Although unforeseen events will always occur during fieldwork, more practising and intensive testing on small scale could improve a setup of a fieldwork on larger scale. Solutions should be searched in the direction of either a more robust or a more camouflaged (GPS) floater design. Keeping the floaters in sight is anyway recommended, faster and easy manoeuvrable boats could make this easier. A more intensive campaign upfront to create awareness among the other river users might also help, but can be complicated due to the remoteness of the area.

Dispersion

The mixing of tracers around the Ayeyarwady-Chindwin confluence can be described with the use of dispersion coefficients, for which the discharge, roughness and bathymetry are the parameters of main importance. Based on the combined information of the theory, measurements done during the fieldwork and the Delft3D model, it is expected that the magnitude of the longitudinal dispersion coefficient in the Ayeyarwady River is somewhere in between K_x~50-500 m^2/s (best estimate: K_x~300 m^2/s), although this has to be confirmed by further research.

This is the dispersion coefficient for the circumstances present during the first week of February 2017. During the wet season it is expected that the dispersion will be higher. When the found value is compared with values found for other bigger rivers (see section 2.5), this value for K_x appears to be somewhat on the low side. From the Delft3D model runs follows that the longitudinal dispersion coefficient in the Chindwin is higher than in the Ayeyarwady, possibly even a factor 10.

The dispersion coefficient is highly sensitive and it is complicated to determine the magnitude of the needed parameters accurately, especially in a remote and highly dynamic area as the confluence of the Ayeyarwady and Chindwin rivers. To make a better estimate of the dispersion coefficient, the uncertainty in the parameters needed has to be reduced. Although some modelling options in Delft3D could be tried to narrow the range of these parameters, the best option to reduce this uncertainty is collecting more (high quality) data in the field.

Bibliography

Bhardwaj, S., Owen, L., & Leinbach, T. (2012, 3 9). *Irrawaddy River.* Retrieved 6 27, 2017 from Encyclopedaedia Britannica: https://www.britannica.com/place/Irrawaddy-River

Deltares - Delft3D. (n.d.). *About Delft3D*. Retrieved 5 14, 2017 from Delft3D Open Source Community: https://oss.deltares.nl/web/delft3d/about

Deltares - Open Earth. (n.d.). *Publicwiki OpenEarth*. Retrieved 5 14, 2017 from What is OpenEarth?: https://publicwiki.deltares.nl/display/OET/OpenEarth

Deltares. (2014). *Delft3D-FGFGRID User Manual.* Delft: Deltares.

Deltares. (2014). *Delft3D-FLOW User Manual.* Delft: Deltares.

Deltares. (2014). *Delft3D-QUICKIN User Manual.* Delft: Deltares.

Fisher, H., List, E., Koh, R., Imberger, J., & Brooks, N. (1979). *Mixing in Inland and Coastal Waters.* San Diego, California: Academic Press.

Furuichi, T., Win, Z., & Wasson, T. (2009). Discharge and suspended sediment transport in the Ayeyarwady River, Myanmar: Centennial and decadal changes. *Hydrological Processes* (23), 1631-1641.

Google Earth. (2017). *Google Earth Products*. Retrieved 5 14, 2017 from Google Earth: https://www.google.nl/intl/nl/earth/explore/products/

HEMA. (n.d.). *Set mini led lampjes*. Retrieved 7 1, 2017 from HEMA.nl: https://www.hema.nl/winkel/vrije-tijd-kantoor/fietsen/fietsaccessoires/fietsverlichting/set-mini-led-lampjes-(41155070)?variant=41155070

Mathworks. (n.d.). *The Language of Technical Computing*. Retrieved 5 14, 2017 from Mathworks: https://nl.mathworks.com/products/matlab.html

Mazijk, A. (1996). *One-dimensional approach of transport phenomena of dissolved matter in rivers.* Delft: TU Delft.

Mazijk, A., & Veling, E. (2004). Tracer experiments in the Rhine Basin: evaluation of the skewness of observed concentration distributions. *Journal of Hydrology* (307), 60-78.

Richter, B., Mathews, R., Harrison, D., & Wigington, R. (2003). Ecologically sustainable water management: managing river flows for ecological integrity. *Ecological Applications* (13(1)), 206-224.

Rutherford, J. (1994). *River Mixing.* Chichester, England: John Wiley and Sons.

Thanda Thatoe Nwe Win, T., Bogaard, T., & Van de Giesen, N. (2015). Water Quality Assessment of Ayeyarwady River in Myanmar. *Geophysical Research Abstracts.* Delft, Netherlands: EGU.

Thin Thin Aye. (2015). The Role of Civil Society in Myanmar's Democratization. *Burma/Myanmar in Transition: Connectivity, Changes and Challenges.* Chiang Mai University, Thailand: University Academic Service Centre (UNISERV).

USGS. (2000, 2 11-22). *Shuttle Radar Topography Mission (SRTM)*. Retrieved 7 1, 2017 from U.S. Geological Survey: https://lta.cr.usgs.gov/SRTM

Van der Velden, J. (2015). *Understanding river dynamics of the Ayeyarwady River, Myanmar.* Utrecht University. Utrecht: Utrecht University.

Appendix A: Cross section measurements and calculations

In this appendix the details of used equipment, locations and results of the measurements in the cross sections are given. Also the subsequent information used for the flow velocity and discharge calculations and is given, including the resulting flow velocities and discharges in the different cross sections.

A.1 Used equipment

In Table A.1 the details the used equipment for flow velocity measurements is given.

Table A.1: Details of the used equipment for the flow velocity measurements in the cross sections at the Ayeyarwady and Chindwin rivers.

Measurement team 1	Measurement team 2
Velocity measurement of 15 s	Velocity measurement of 15 s
Calibration checked and OK (calibration 1)	Calibration checked and OK (calibration 1)
Current meter Valeport BFM001 S-N 3401	Current meter Valeport BFM001 S-N 3364
Impeller number 8011-4564	Impeller number 8011-4564

A.2 Cross section locations

In Figure A.1 the locations of all cross sections are given.

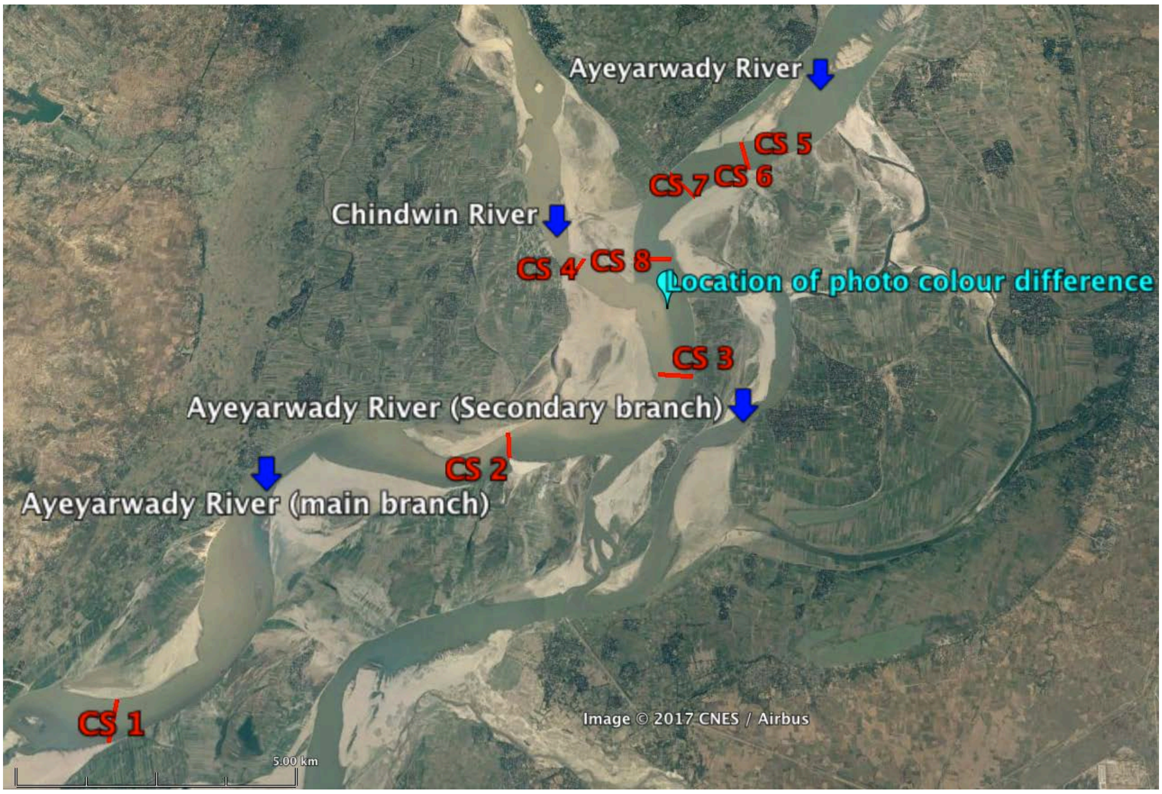
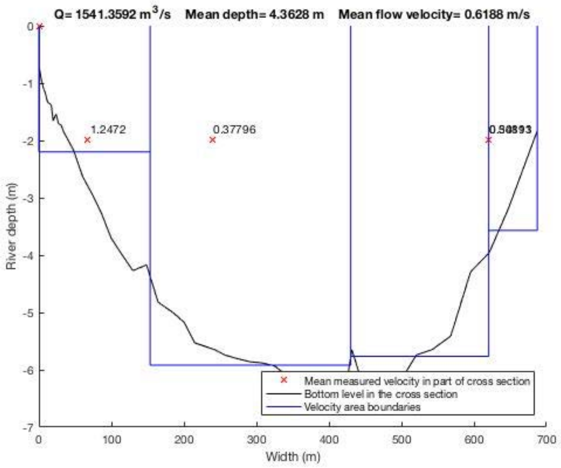


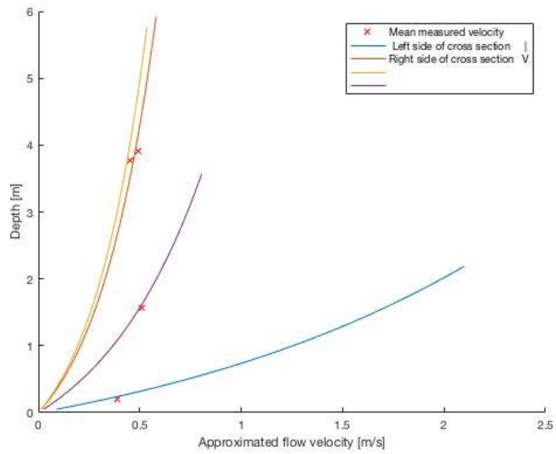
Figure A.1: The locations of the cross sections (CS) and different distinguished river branches. Figure made in Google Earth (2017).

A.3 Overview of the cross sections

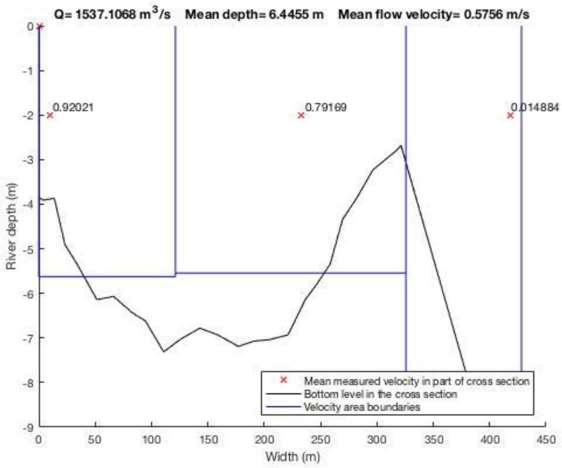
In Figure A.2 for each cross section, the (mean) depth, boundaries of the parts used for the discharge calculation and estimated (mean) flow velocities are given.

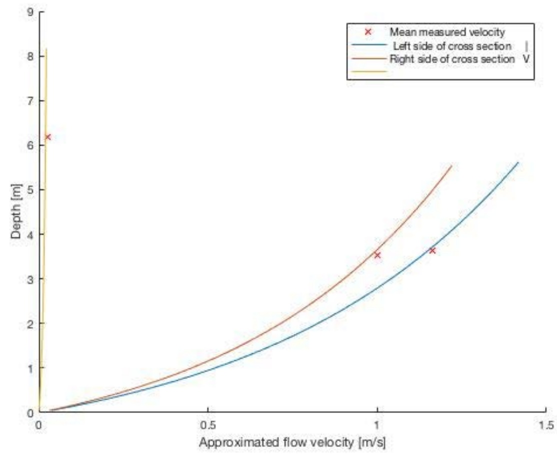
Cross section 1: Ayeyarwady most downstream



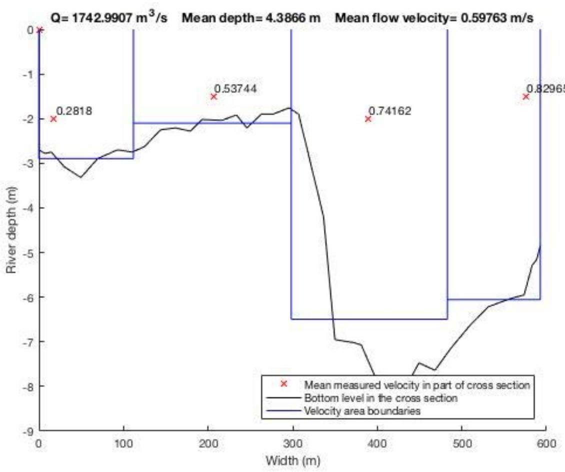


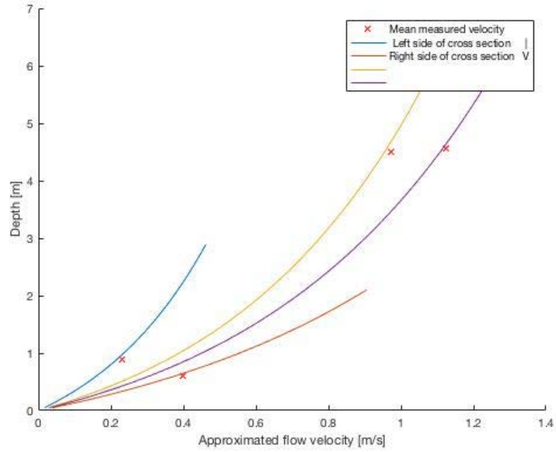
Cross section 2: in between 1 and 3



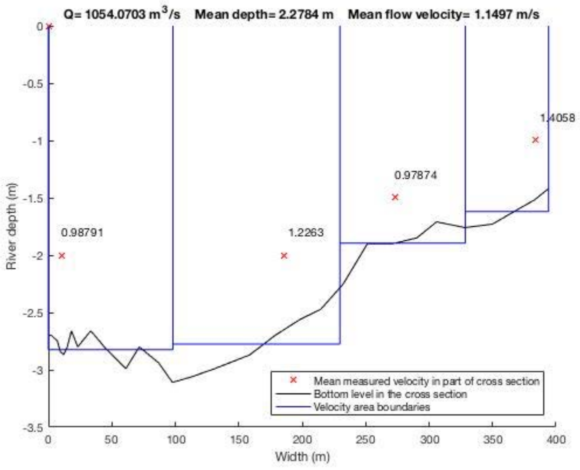


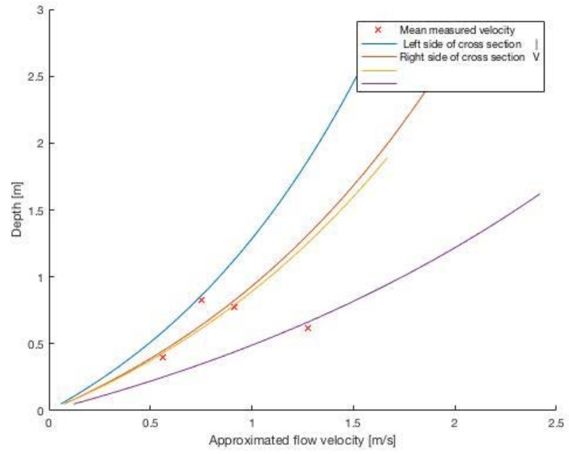
Cross section 3: Ayeyarwady just downstream of the confluence



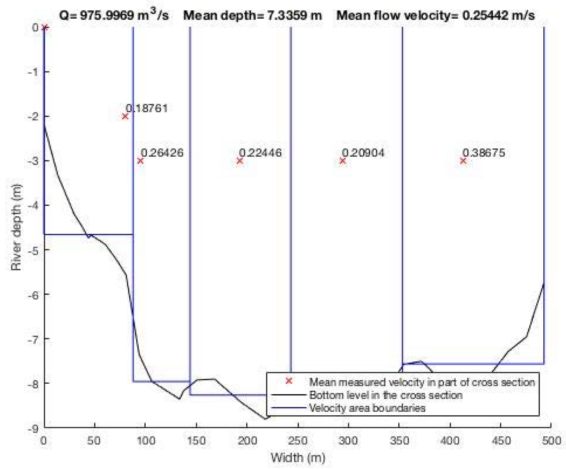


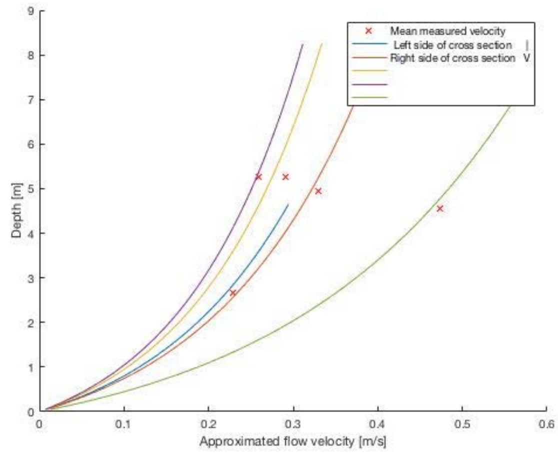
Cross section 4: Chindwin



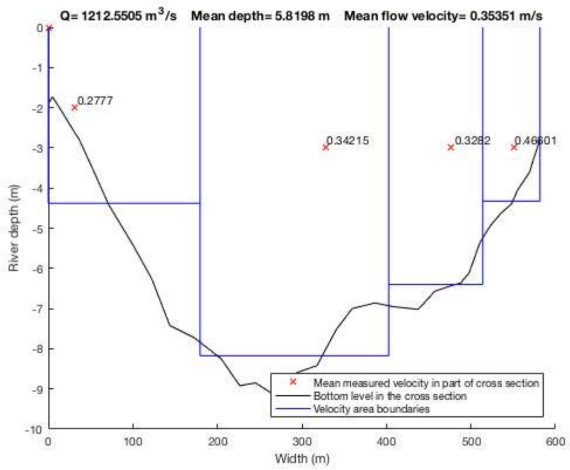


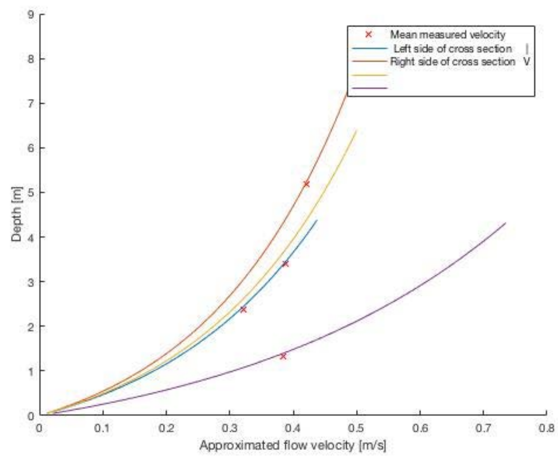
Cross section 5: Ayeyarwady most upstream





Cross section 6: in between 5 and 7





Cross section 7: in between 6 and 8

Cross section 8: Ayeyarwady just upstream of confluence

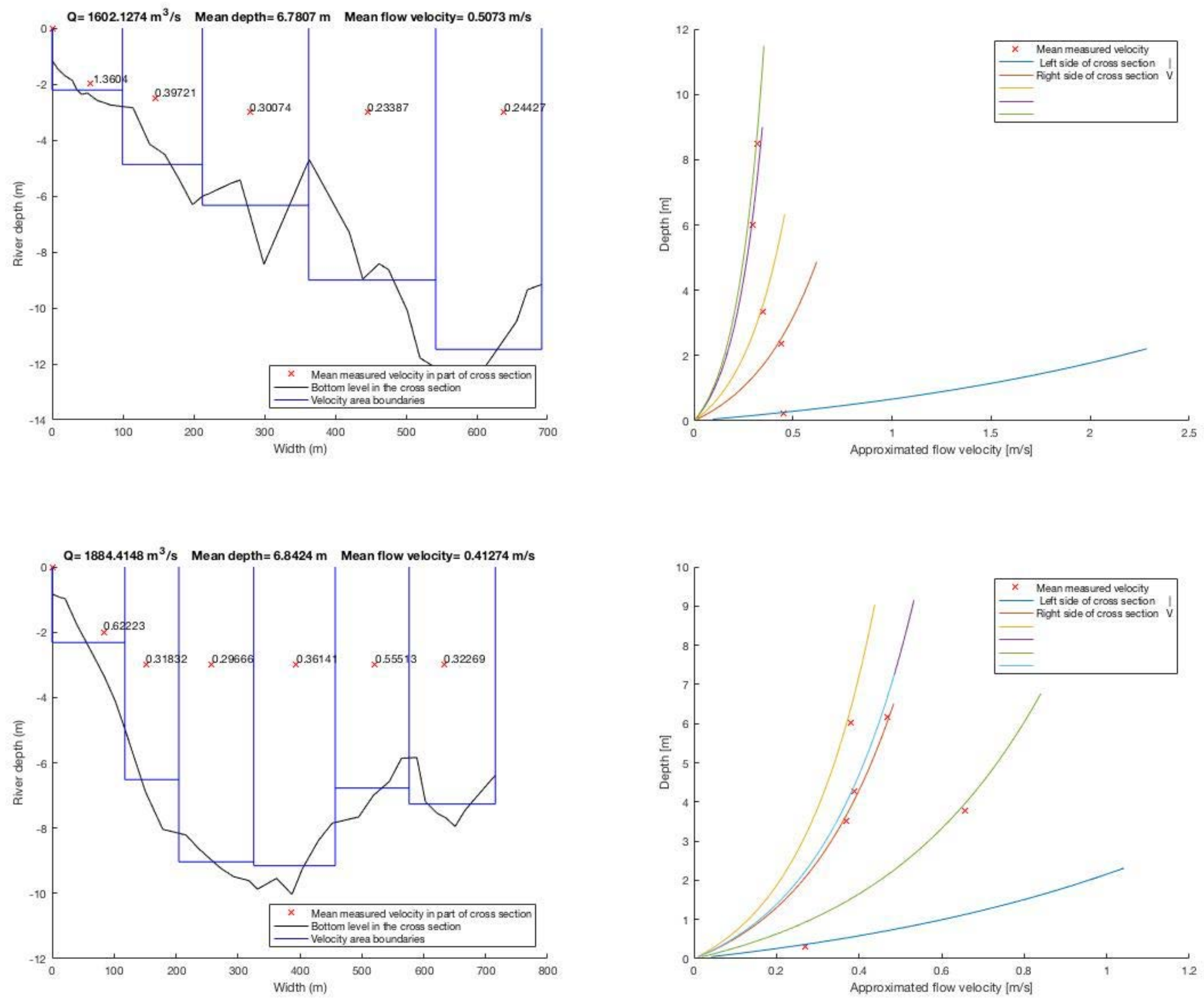


Figure A.2: Overview of all the cross sections.

A.4 Resulting flow velocities and discharges

In Table A.2 the results for the flow velocities are summarized. In Table A.3 the results for the discharge are summarized.

Table A.2: Mean flow velocities in the cross sections (CS), based on the fieldwork measurements. See Figure A.1 for the locations of the cross sections.

Mean flow velocity Ayeyarwady upstream of the confluence [m/s]		Mean flow velocity Chindwin upstream of the confluence [m/s]		Mean flow velocity Ayeyarwady downstream of the confluence main branch [m/s]	
CS 5	0.25	CS 4	1.15	CS 1	0.62
CS 6	0.35			CS 2	0.58
CS 7	0.51			CS 3	0.60
CS 8	0.41				
Mean:	**0.38**	**Mean:**	**1.15**	**Mean:**	**0.58**

Table A.3: Mean discharge (Q) in the cross sections (CS), based on the fieldwork measurements. See Figure A.1 for the locations of the cross sections. The calculated values do not match when the mass balance for upstream and downstream of the confluence is calculated. Therefore also the assumed real discharges as used in the Delft3D model are presented.

Q Ayeyarwady upstream of the confluence [m^3/s]		Q Chindwin upstream of the confluence [m^3/s]		Q Ayeyarwady downstream of the confluence main branch [m^3/s]		Q Ayeyarwady downstream of the confluence second branch [m^3/s]	
CS 5	976	CS 4	1054	CS 1	1541	Estimate	400
CS 6	1213			CS 2	1537		
CS 7	1602			CS 3	1742		
CS 8	1884						
Mean:	**1419**	**Mean:**	**1054**	**Mean:**	**1607**	**Mean:**	**400**
Total Q before confluence:			2473	Total Q after confluence:			2007
Mean total Q at downstream boundary:							2190
Total assumed Q before the confluence, after the confluence and at downstream boundary:							2200
Assumed real Q:	**1500**	**Assumed real Q:**	**700**	**Assumed real Q:**	**1800**	**Assumed real Q:**	**400**

Appendix B: Bathymetry

During the fieldwork done depth measurements are used to determine the bathymetry for the Delft3D model. In Figure B.1 an overview of the depth measurements is presented. In Figure B.2 an overview of the new constructed depth sample point created according to the procedure described in section 4.3.3 is given. In Figure B.3 the bathymetry (relative to the reference level EGM96) used for the Delft3D model is given, which is constructed based on the sample points given in Figure B.1 and B.2.

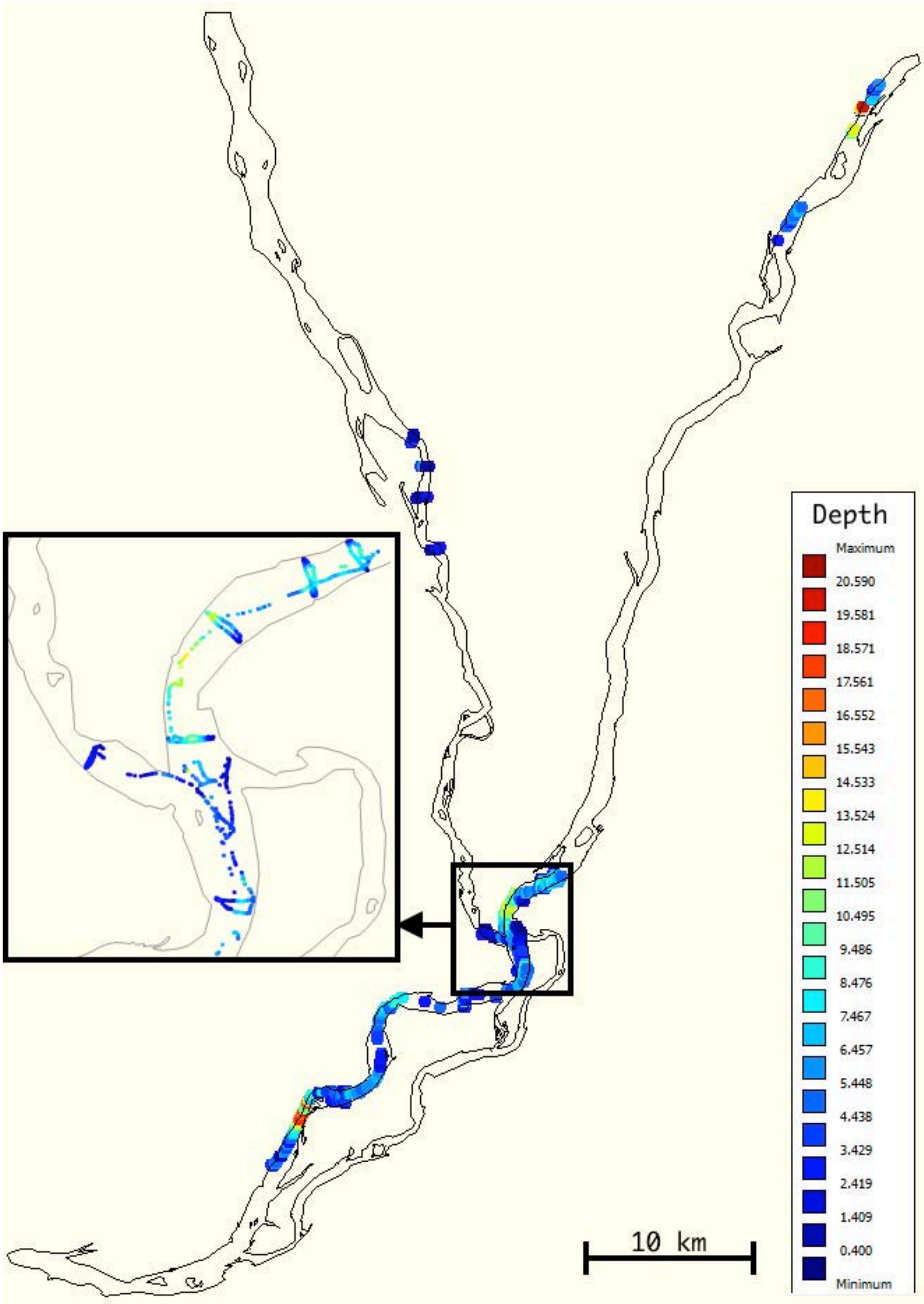


Figure B.1: Overview of all depth (m) measurements done during the fieldwork in the area modelled with Delft3D. All measurements are done with the echo sounder, except group of measurements more upstream in the Chindwin, those are hand measurements.

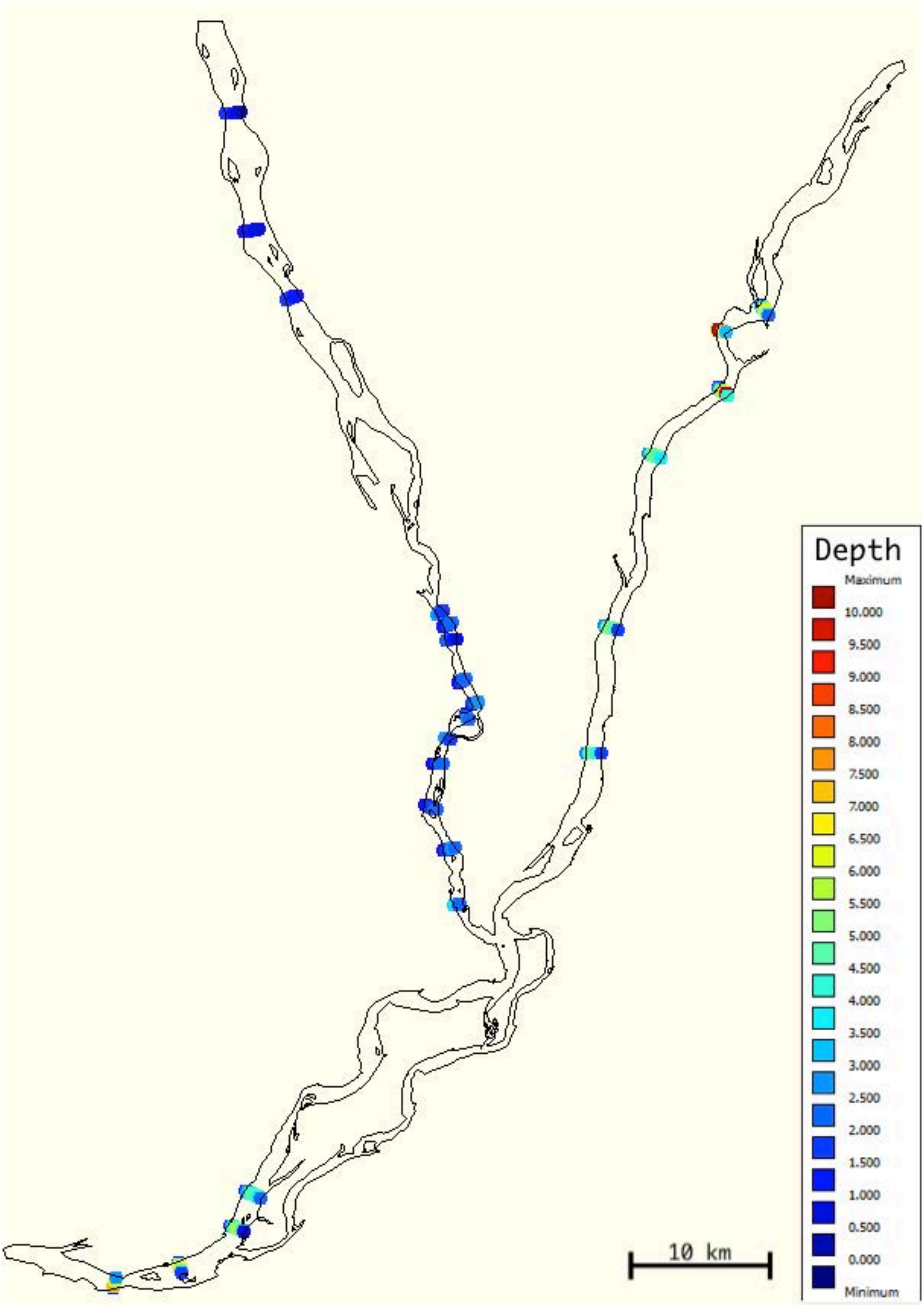


Figure B.2: Overview of all new constructed depth (m) sample point according to the procedure described in section 4.3.3.

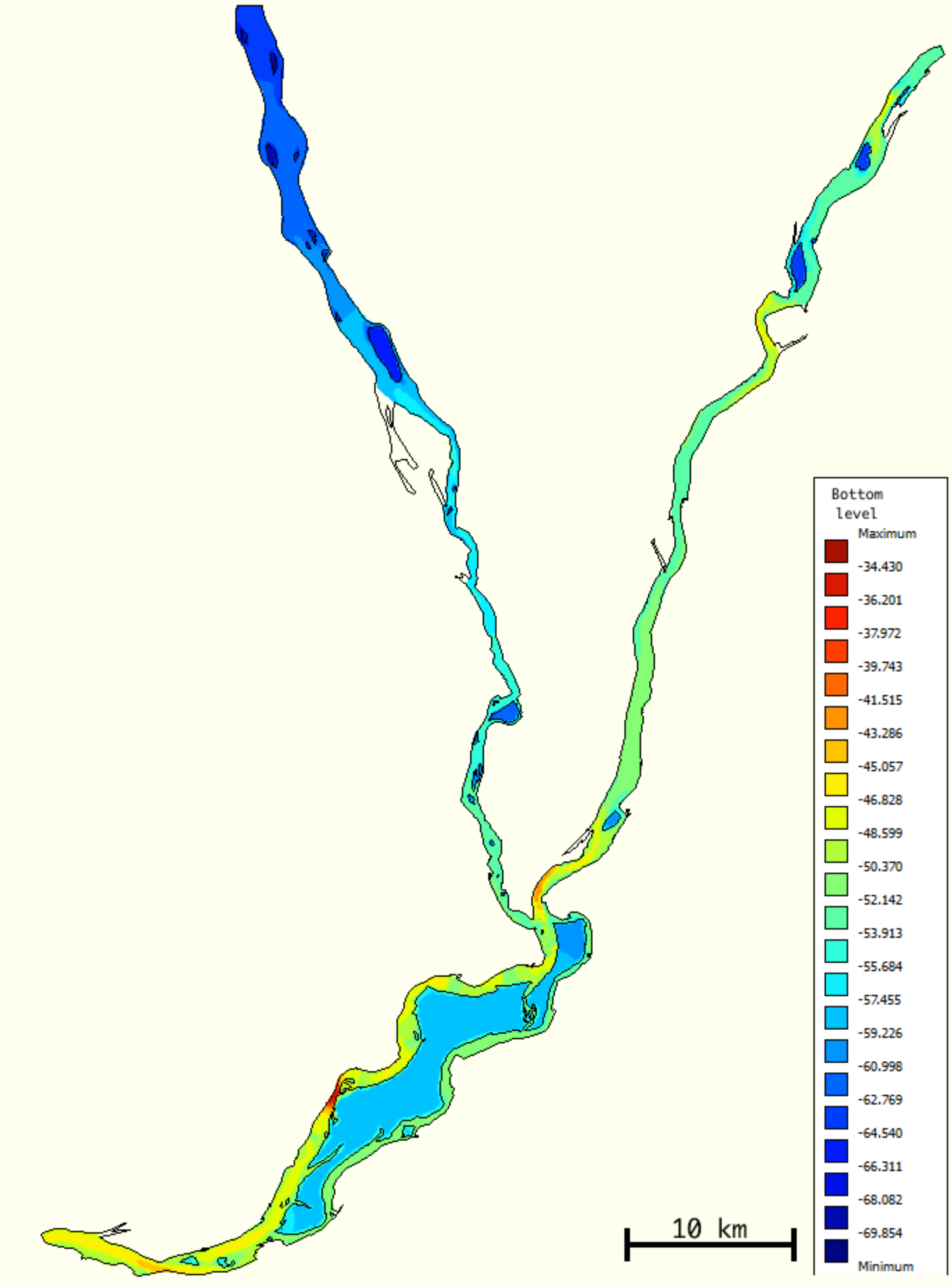
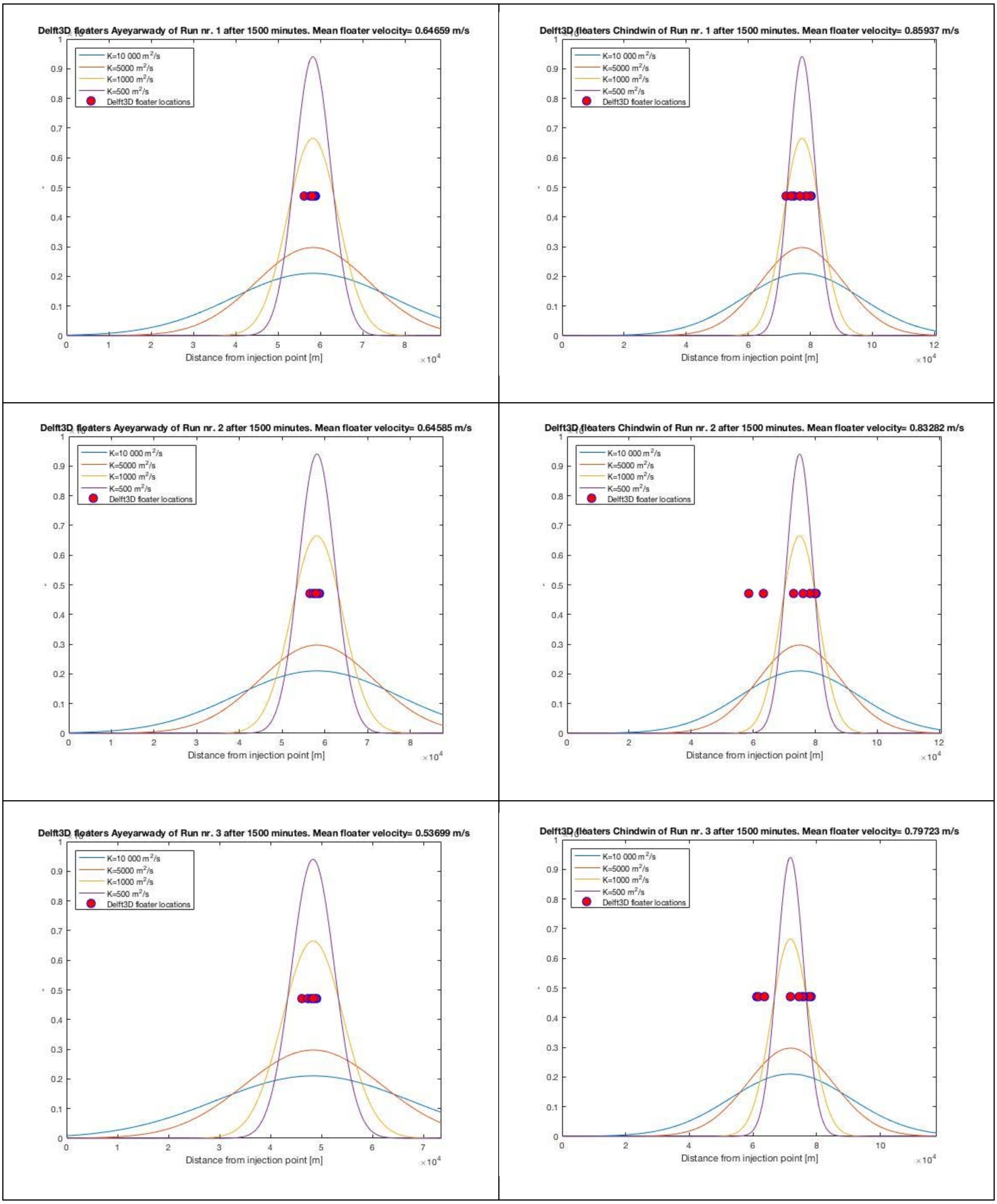
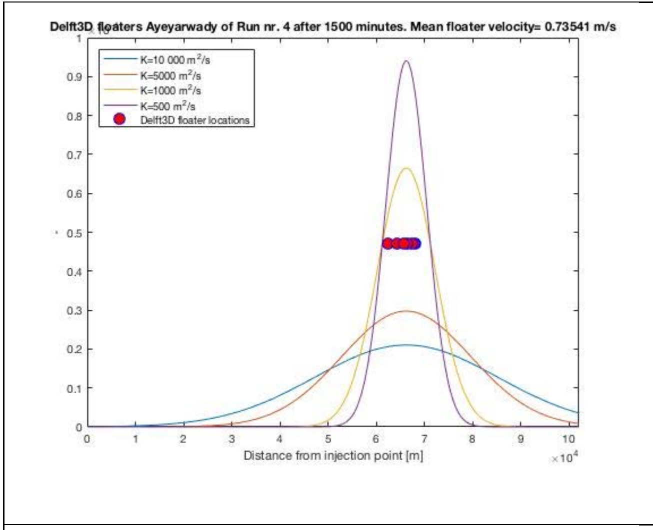


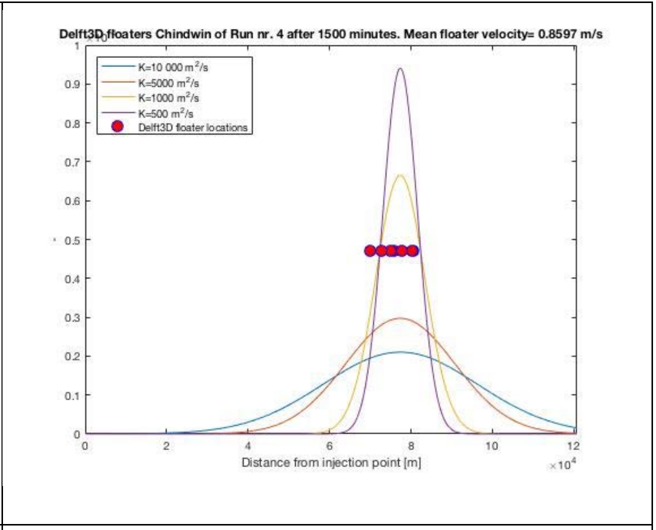
Figure B.3: Overview of the bathymetry (relative to the reference level EGM96) used in the Delft3D model. The bathymetry is constructed with the depth (see figure B.1), the water level relative to reference level EGM96 (from SRTM satellite data (USGS, 2000)) and the islands (water level +5 m). The depth sample points shown in Figure B.2 are used for interpolation of the depth measurements. When this figure is compared to figure B.1, it can be clearly seen that assumptions had to be made for the depth in large parts of the modelled area.

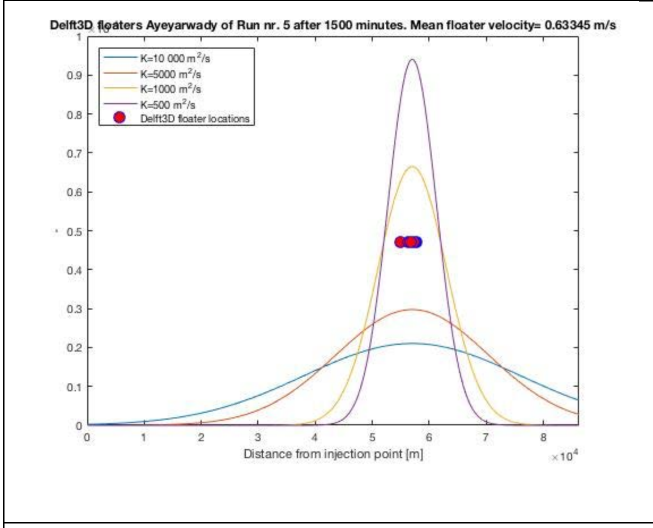
Appendix C: Delft3D Floaters dispersion

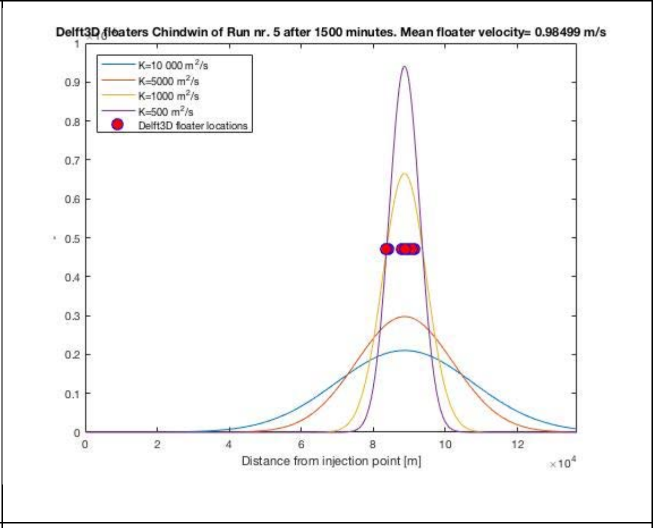
In Figure C.1 the floater locations of all Delft3D simulations are presented. The floater locations of the floaters released in the Chindwin and Ayeyarwady rivers are plotted in different graphs. It can be clearly seen that the dispersion of floaters is higher in the Chindwin River than in the

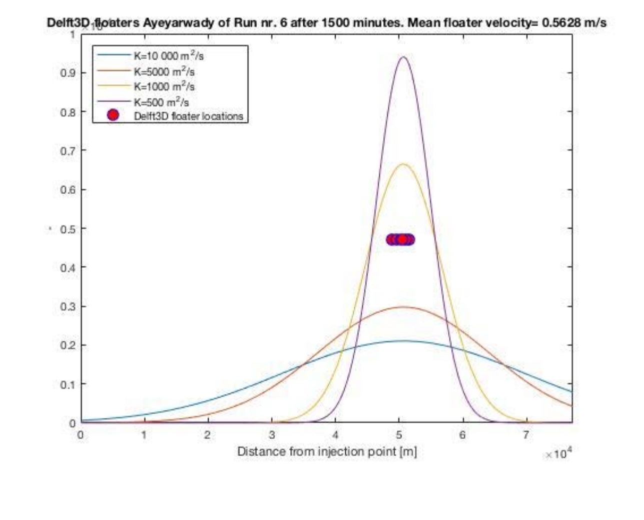


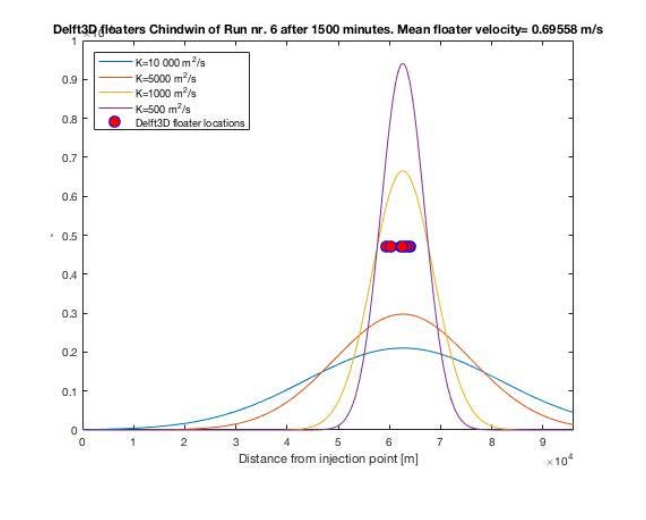

Delft3D floaters Ayeyarwady of Run nr. 4 after 1500 minutes. Mean floater velocity= 0.73541 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

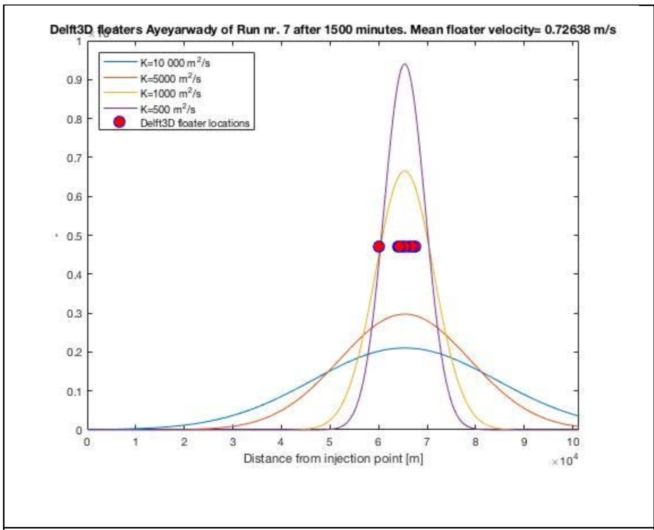

Delft3D floaters Chindwin of Run nr. 4 after 1500 minutes. Mean floater velocity= 0.8597 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

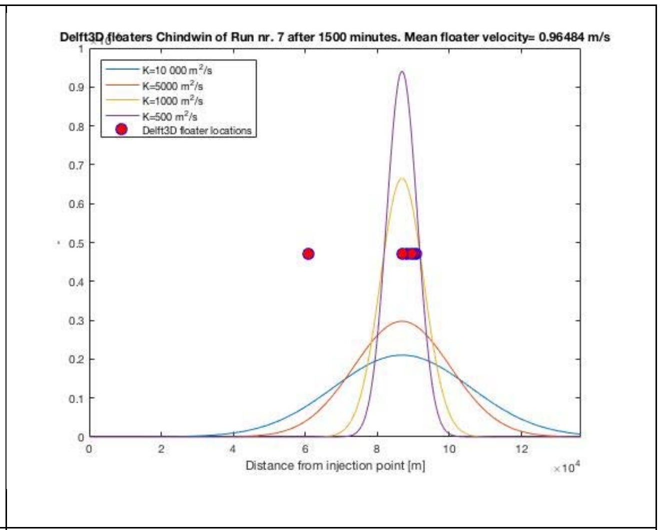

Delft3D floaters Ayeyarwady of Run nr. 5 after 1500 minutes. Mean floater velocity= 0.63345 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

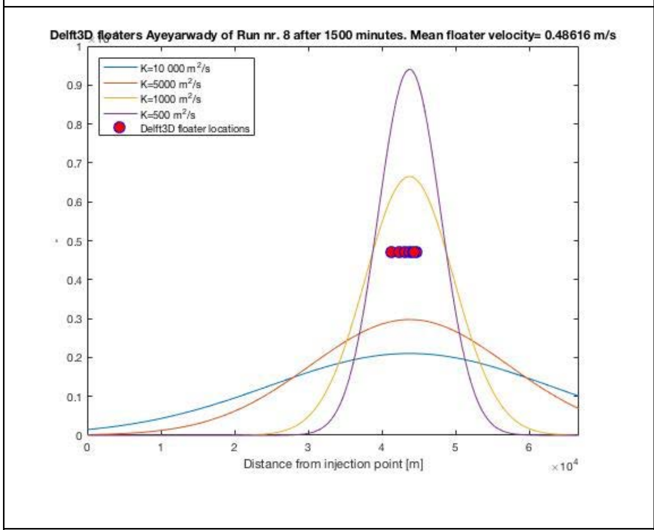

Delft3D floaters Chindwin of Run nr. 5 after 1500 minutes. Mean floater velocity= 0.98499 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

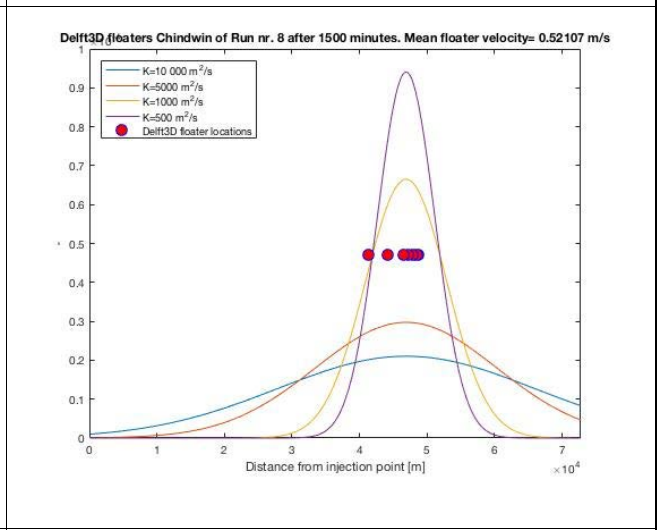

Delft3D floaters Ayeyarwady of Run nr. 6 after 1500 minutes. Mean floater velocity= 0.5628 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

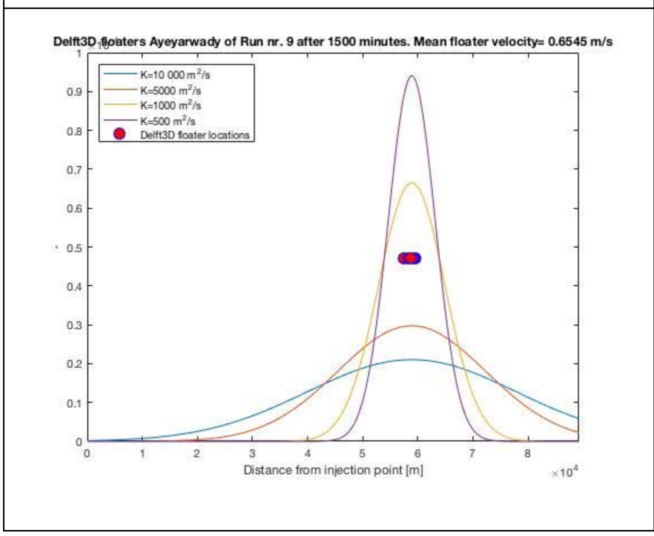

Delft3D floaters Chindwin of Run nr. 6 after 1500 minutes. Mean floater velocity= 0.69558 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

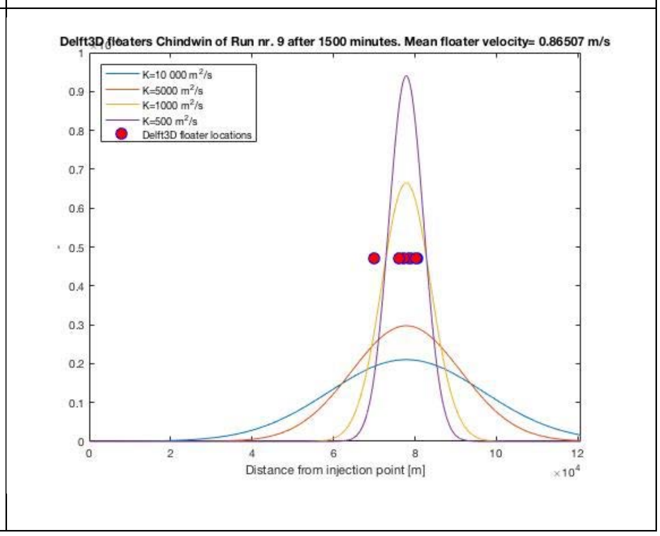

Delft3D floaters Ayeyarwady of Run nr. 7 after 1500 minutes. Mean floater velocity= 0.72638 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

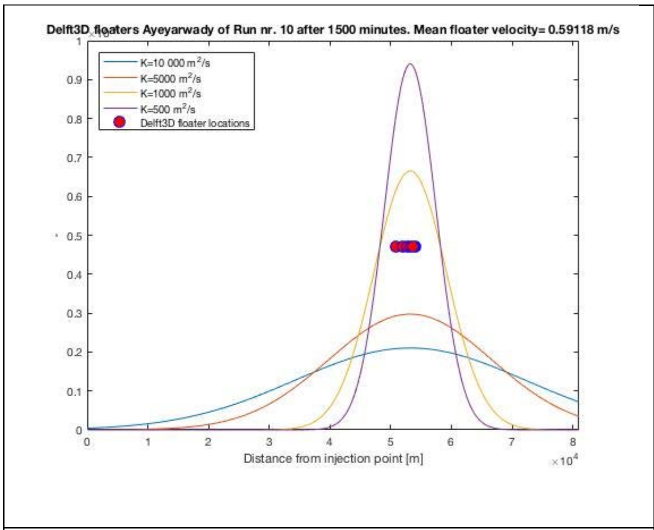

Delft3D floaters Chindwin of Run nr. 7 after 1500 minutes. Mean floater velocity= 0.96484 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

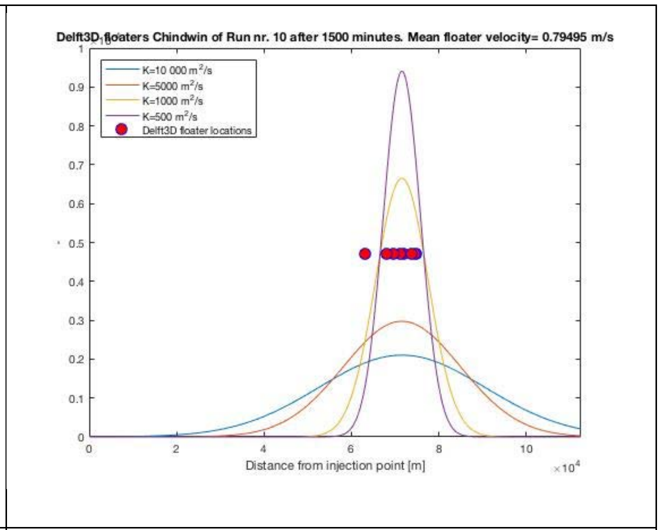

Delft3D floaters Ayeyarwady of Run nr. 8 after 1500 minutes. Mean floater velocity= 0.48616 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

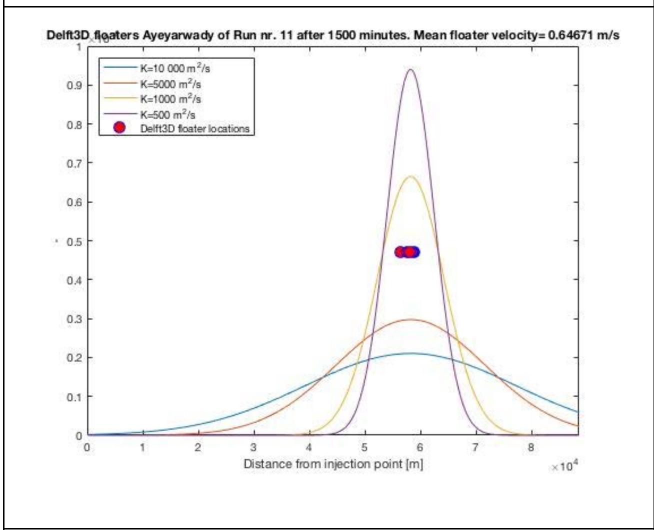

Delft3D floaters Chindwin of Run nr. 8 after 1500 minutes. Mean floater velocity= 0.52107 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

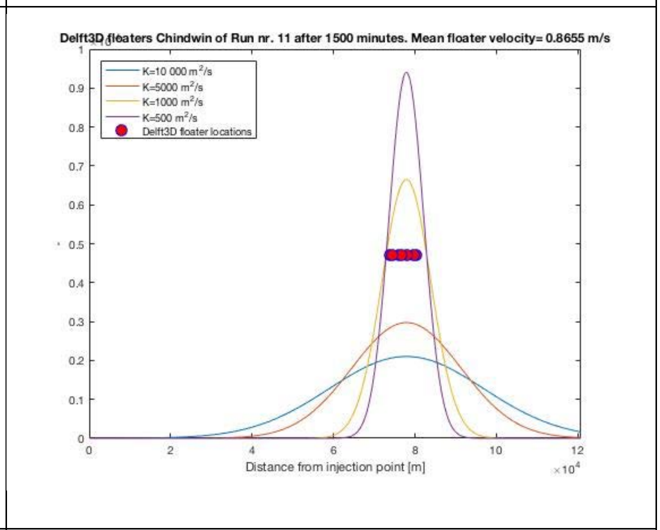

Delft3D floaters Ayeyarwady of Run nr. 9 after 1500 minutes. Mean floater velocity= 0.6545 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

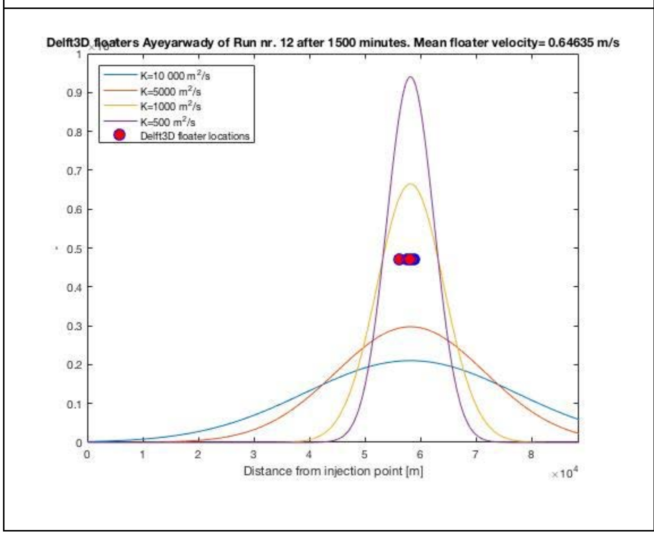

Delft3D floaters Chindwin of Run nr. 9 after 1500 minutes. Mean floater velocity= 0.86507 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

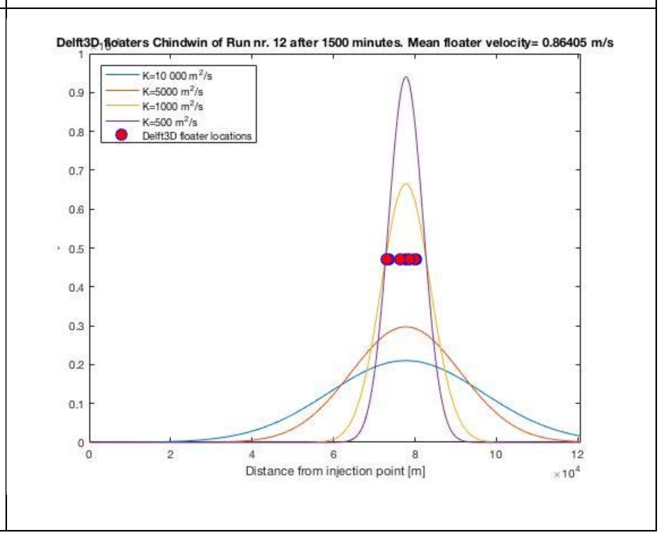

Delft3D floaters Ayeyarwady of Run nr. 10 after 1500 minutes. Mean floater velocity= 0.59118 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴


Delft3D floaters Chindwin of Run nr. 10 after 1500 minutes. Mean floater velocity= 0.79495 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴


Delft3D floaters Ayeyarwady of Run nr. 11 after 1500 minutes. Mean floater velocity= 0.64671 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴


Delft3D floaters Chindwin of Run nr. 11 after 1500 minutes. Mean floater velocity= 0.8655 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴


Delft3D floaters Ayeyarwady of Run nr. 12 after 1500 minutes. Mean floater velocity= 0.64635 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴


Delft3D floaters Chindwin of Run nr. 12 after 1500 minutes. Mean floater velocity= 0.86405 m/s
K=10 000 m²/s
K=5000 m²/s
K=1000 m²/s
K=500 m²/s
Delft3D floater locations
Distance from injection point [m]
×10⁴

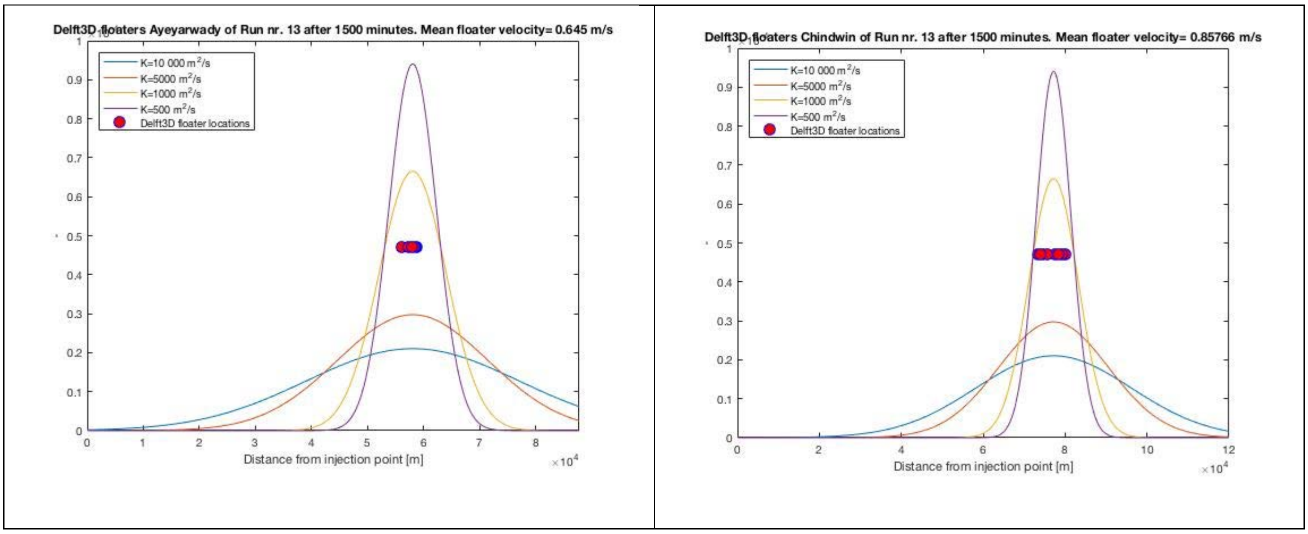


Figure C.1: Overview of the Delft3D floater distances after 1500 minutes for all different model simulations of which the details can be found in Table 2 (section 4.5). Besides, the theoretical dispersion at that location for different values of the dispersion coefficient K_x (10'000, 5000, 1000 and 500 m^2/s) is plotted. The red markers show the locations of the 10 released floaters after 1500 minutes. If the width of the red markers is similar to the width of the theoretical dispersion, the dispersion coefficient is also similar order of magnitude as the one belonging to that line. It can be clearly seen that the dispersion in the Chindwin River is higher than in the Ayeyarwady River as the floaters are more spread out in longitudinal direction.