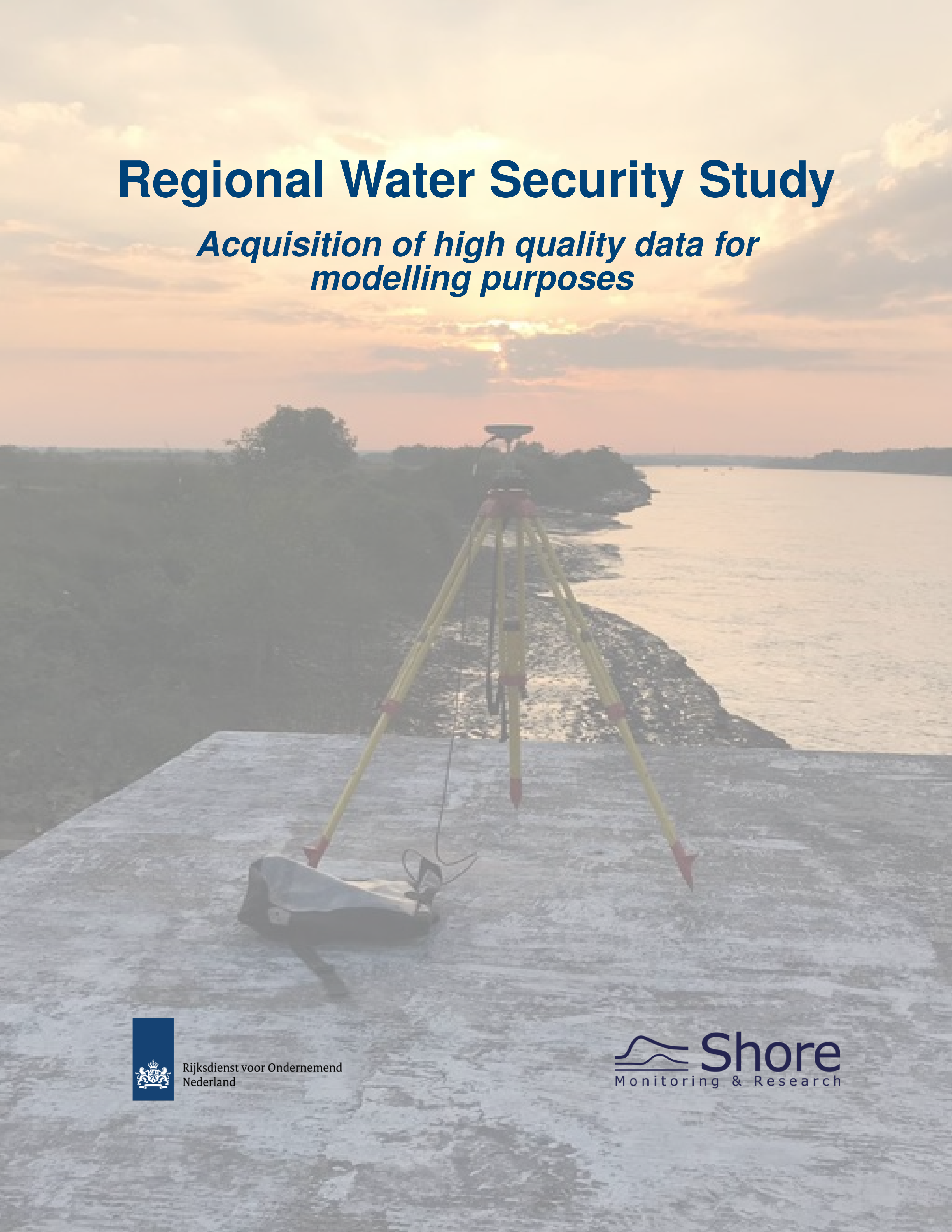
Regional Water Security Study

Acquisition of high quality data for modelling purposes



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Field report

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Contents

1 Introduction

1.1 Background

The Netherlands Enterprise Agency (herafter, RVO) comissioned Shore Monitoring & Research BV (hereafter, SHORE) to perform field measurements categorised by activities A - F (section 1.3. These activities focus on collecting data as input for a large regional model of the Yangon region in Myanmar which, ones completed, should provide insight into water security related problems.

Data quality has a large impact on the quality of subsequent modelling stages and therefore a clear and well documented approach has been followed. The activities contain transformation of existing (local) data to internationally acknowledged standards and additional surveys of areas where data was not available or from an inferior quality (i.e. not possible to transform to an acceptable level of quality).

1.2 Project location and survey area

The project location is the greater Yangon region mainly (Fig. 1.1) with the exception of hydraulic and bathymetric measurements in Pyay (Fig. 1.2). Hydraulic and bathymetric parameters are acquired from Pyay to Nyaungdon, at Hle Seik, from Nyaungdon to Yangon, the Twante Canal, the Bago river between Bago/Tawa and Yangon and the Estuary between the Gulf and Yangon. Figure 1.1 shows location of benchmarks (red markers), existing referenced water level scales (yellow markers), existing permanent (white markers), new permanent (green markers) and temporary water level loggers (blue markers), discharge measurement locations (cyan markers), as well as numerous cross-sections at which the elevation of the river bed was measured.

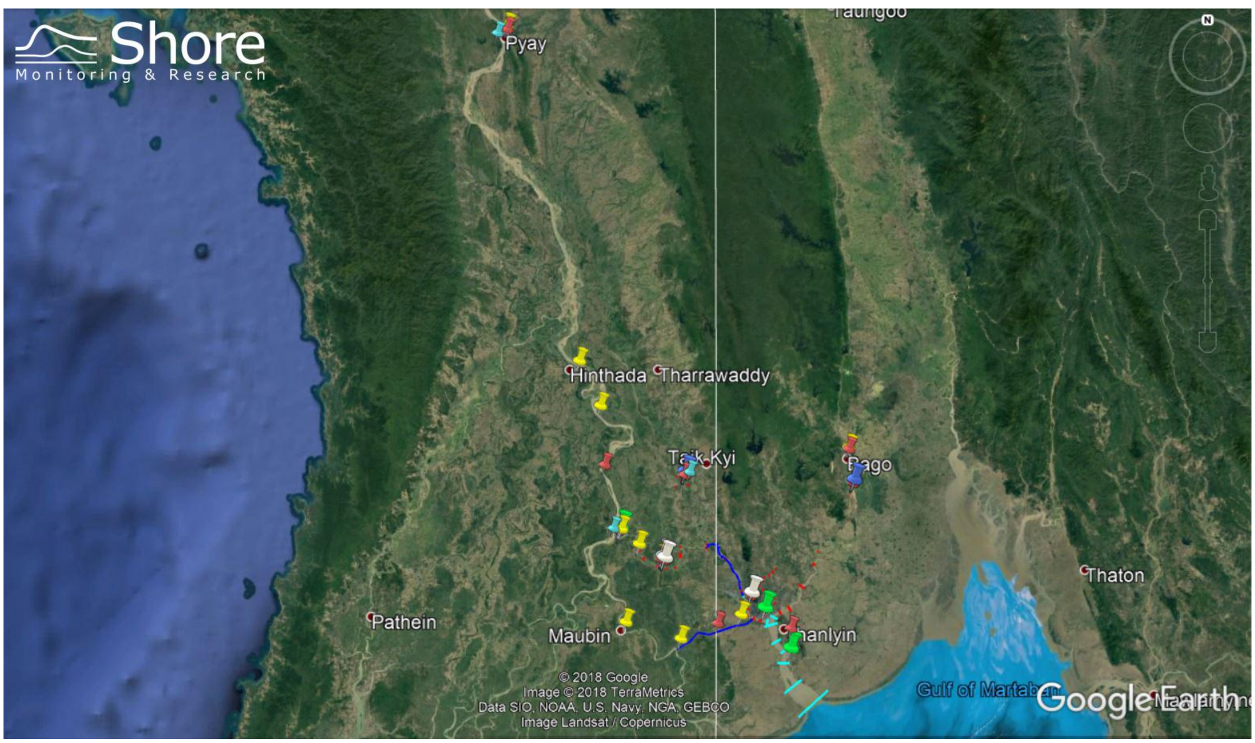

Figure 1.1: Overview data acquisition and project area. White vertical line indicates UTM 46N/47N boundary.

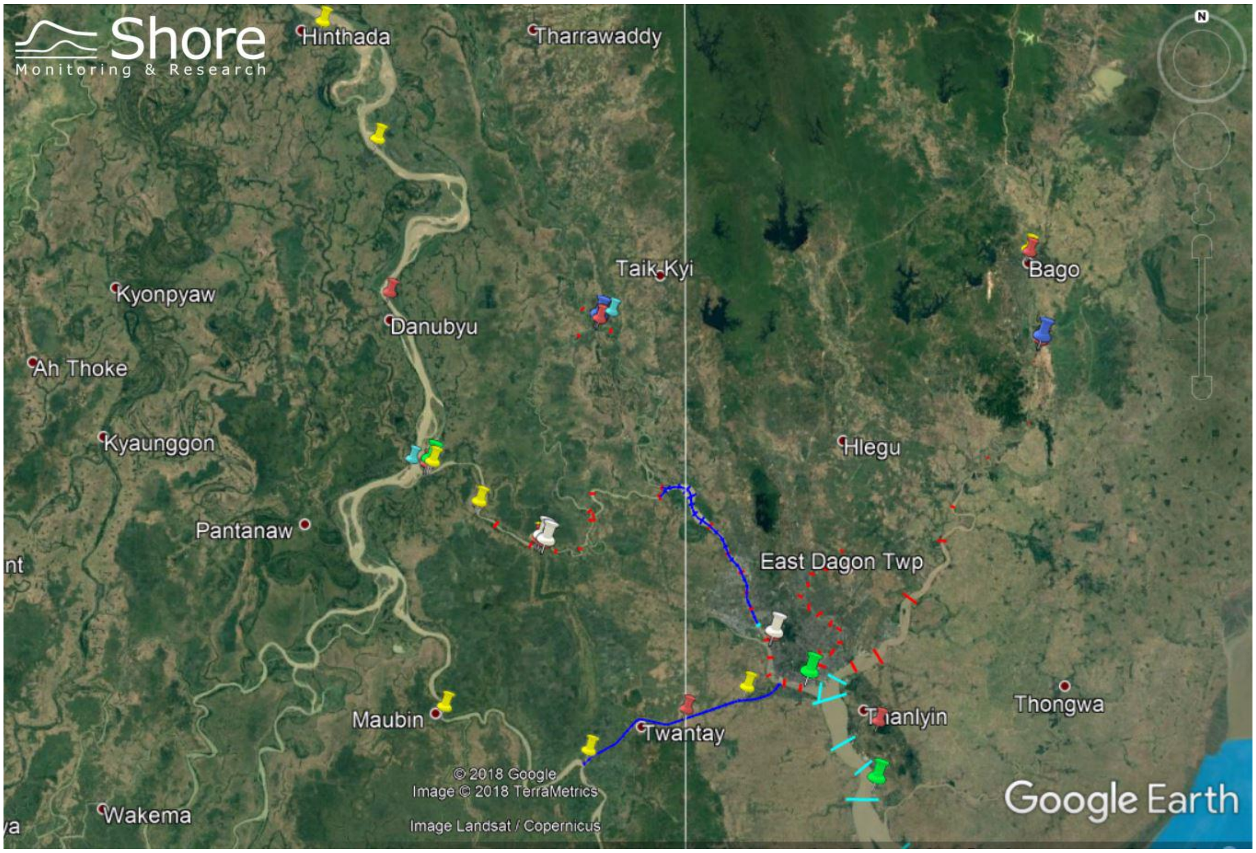

Figure 1.2: Overview data acquisition and project area. White vertical line indicates UTM 46N/47N boundary.

1.3 Setup of field campaign

Based on the requested measurements/activities, the field site investigation and with the modelling objectives in mind, SHORE has setup a field campaign consisting of the following elements:

A Investigating the presence of and/or creating GPS benchmarks
B Verification of available water level measurement time series
C Installation water level and salinity loggers
D Survey of strategic stretches to transform available bathymetric data
E Survey of 52 bathymetric cross-sections
F Measuring river discharges together with spatial current flow patterns

More detail on the above introduced measurements and results is provided in the coming chapters. Chapter 2 elaborates on the observed procedures and methodologies of local authorities. Subsequently, the created and surveyed benchmarks will be treated in chapter 3, whereas chapter 4 focuses on verification and referencing of available water level measurements. Next, chapters 5 and 6 will treat new water level locations, transformation of existing bathymetric data to EGM2008 and bathymetric survey of additional cross-sections respectively. This report is finalised with chapter 7 on discharge and spatial current measurements.

2 Assessing existing sites of local authorities

As part of the field campaign SHORE has assessed multiple existing benchmark and water level (scale) locations across the project area, and the measurement methodology of local authorities. The findings of the visits and interviews will be treated for the authorities DMH, IWUMD and DWIR in sections 2.2 to 2.4. However, this chapter starts with an introduction regarding locally available data and procedures.

2.1 Introduction

Local Myanmarese authorities collect, and have been collecting, data that potentially (possibly after correction) could be useful for the present modelling activities. Prior to, and during the field campaign, SHORE requested information on the location of benchmarks and water level scales. After being in Myanmar for one month, it proved to be very hard (impossible) to obtain documented data on locations, coordinates and methodology of existing benchmarks and water level scales. Only when locations of water level scales were physically visited together with the authorities, information was retrieved.

Mostly, local officers could show a schematic of the water level scale or benchmark, with elevations (no horizontal coordinates) related to a local chart datum: Reduced Level or Mean Sea Level in feet or meter, depending on location and authority. Though the origin and coordinates of for instance the benchmarks and the methodology how it had been created and related to that chart datum, was often not clear. Moreover, visiting a location did not always result in obtaining the important (historic) data.

The necessity to actually visit sites, limited the number of benchmarks/water level scales that have been assessed and converted to WGS84/EGM2008. Moreover, analysis of the visited benchmarks/ water level scales showed that it is not possible to derive general offsets that apply to all locations of the visited authorities, simply because too little data could be/ was shared by the authorities who all have their own methodology of measuring, recording and surveying.

By observation and interaction with the staff at the visited benchmarks and water level scales, as well as interviews with senior staff members in Yangon, some basic information was retrieved regarding the procedures and methodology of monitoring and surveying by the authorities. This is elaborated in the following sections.

2.2 DMH

2.2.1 Benchmarks and Chart Datum

Benchmarks of DMH were visited in Pyay, Zalun, Ngathaingchaung, Maubin and Bago. These were all related to measurement sites at offices of DMH, where a number of meteorologic and hydrologic parameters are measured every day (e.g: rainfall, temperature, evaporation, wind speed and direction, barometric pressure etc.). The benchmarks were always a concrete slab, with a bolt in the middle and either a marked/painted elevation in meters or date of creation or number. The elevation of the benchmark is known w.r.t. Mean Sea Level and listed in meters. However, how the elevation w.r.t. Mean Sea Level was established / derived was unclear and after many questions and interviews, remains unclear.

What did become clear, is that DMH uses Control Benchmarks (CBM) and derives local benchmarks (BM) from that CBM, mainly by total station or levelling techniques. SHORE was told that the CBM's were historically established by the British and used ever since to create BM's in the local surroundings, for instance at water level measurement sites, at a nearby riverbank.

2.2.2 Water level measurements

Water level measurements of DMH measurement location are performed in a uniform way, at all visited sites. The water level scale is constructed at the riverbank, either by poles on the embankment with clear marking on them, spanning the entire vertical distance from the lowest water level to the dike / levee flanking the river. Or by clear marks on a concrete structure (e.g. revetment) at the riverbank.

A local benchmark (BM) is usually present near the water level scale (also referred to as gauge station by DMH), which is used to create it. The water level scale's vertical marks and horizontal distance are documented in relation to the BM, though the height of the scale is not expressed in MSL (which is the chart datum of the BM) but the zero level (bottom end) of the scale, which is called **gauge zero / zero of gauge**. Only the gauge zero is expressed and documented in relation to MSL with the help of the BM's elevation. The section on referenced water level scales lists the offsets of the gauge zeros w.r.t. MSL of the visited and referenced existing water level scales.

Now, something important to realise when working with water level records is: water level records are manually measured and recorded relative to **gauge zero in centimetres** three times per day 6.30h, 12.30h and 18.30h local time (i.e. UTC +06.30) and communicated to the head office of DMH in Nay Pyi Taw, also w.r.t. **gauge zero** and **not MSL**. DMH head office knows the offsets of the gauge zeros w.r.t. MSL and applies these for their own work routines (forecasts, warnings etc.). At low lying gauge stations, the readings of the gauges are altered with an added (fictitious) water level to prevent the records from showing negative values during the dry season and low tide, because negative water levels are bad for communication to the public. For instance, to the gauge readings at Maubin an extra 3000 cm is added and recorded in the books!

Automatic water level measurements
Besides the manual water level measurements, DMH has installed radar gauges on most bridges in the delta region, which record water levels at intervals as small as 5 minutes. Data is streamed to the DMH head office in real time. SHORE was told that manual recordings are still continued for some years to calibrate the radar measurements.

2.2.3 Surveying

DMH performs very limited surveying works. No relevant information surfaced regarding their methodology, other than using levelling equipment to construct their water level scales. GNSS is not used, hence SHORE referenced their benchmarks, providing them with reliable coordinates.

2.3 IWUMD

2.3.1 Benchmarks and Chart Datum

IWUMD uses Reduced Level as Chart Datum, which is the same as Mean Sea Level of which the origin (zero datum) is defined at Kyaikkame, in Mon State. Benchmarks are mostly concrete slabs with a bolt in the center and either an elevation or number marked into the concrete. Elevations were encountered in both feet and meters. Benchmarks are created mostly without GNSS, given the fact that almost all encountered benchmarks were covered by bush or trees.

2.3.2 Water level measurements

IWUMD has the same type of water level scales as DMH, either poles on the embankment or scales on structures. However, scales can be in meters or feet (with a subdivision in 10ths of feet instead of inches). All scales are related to Reduced Level. IWUMD also has wells with an internal float marking the water level. However, not all of these are working at the moment and data is under embargo by Japanese.

2.3.3 Surveying

IWUMD performs surveying for the construction of irrigation works, installation of gauges and measurements of river cross-sections.

Bathymetric data is mainly obtained by their Hydrology Branch with auto level instruments and depth sounders, as well as the River Surveyor M9 for measuring river cross sections. Elevations are referenced to nearby benchmarks. SHORE hasn't received survey maps of IWUMD upon writing of this report.

Topographic data is currently quite often acquired with RTK-GNSS. It is still uncertain until what level of detail GNSS equipment is programmed (e.g. antenna profiles, phase centre offsets, antenna reference points known). This introduces an uncertainty in the GNSS data in the order of 10 cm. Besides that, it is unclear if the relation between the WGS84 ellipsoid (GNSS standard) and Reduced Level is defined in a uniform way. It is assumed that GNSS base stations are positioned above a benchmark of which the elevation is read and programmed into the GNSS, instead of working with a predefined geoid model. This can be justified for small distances, but not for large areas, since the WGS84 ellipsoid is not a flat surface and the earths gravitational field shows quite some variation within the greater Yangon area (order meters w.r.t. WGS84).

2.4 DWIR

Although less benchmarks and water level scales of DWIR were encountered and referenced, an interview with Chief Surveyor of Yangon yielded insight in DWIR's methodology and Chart Datum.

2.4.1 Benchmarks and Chart Datum

DWIR uses another vertical referencing level (Chart Datum) than IWUMD and DMH: Lowest Water Level (LWL), which changes every 2 mile along the river. LWL is determined by measurements of the water level during one day, mostly prior to the day of surveying. The lowest water level of that day is set to LWL and used as Chart Datum for the following surveys. In March, when water levels in the river are generally lowest, the survey sites are visited again, to measure if the water level is lower than the previously established LWL. If so, the LWL is corrected to the lowest water level on that day in March and existing surveys are corrected for the lowering of the Chart Datum.

Benchmarks are usually concrete slabs, marked with a bolt and number and referenced to LWL. If a benchmark is somehow referenced to MSL, the offset to MSL is usually marked in the concrete and documented in the survey maps. SHORE has not observed this in the field.

DWIR also uses temporary benchmarks (TBM's) which are not always documented, but **are** used for surveying. These TBM's are corners of statue sockets, sidewalks or roads; geometrically recognisable objects.

Although SHORE encountered mainly benchmarks surrounded by trees or right next to buildings, DWIR is aware of the importance of clear sky visibility when working with GNSS.

2.4.2 Water level measurements

Water level measurements are mainly related to LWL as well, though not all. For instance the 3.5 mile station in the Twantay Canal is referenced to MSL. At the same time, staff at the 21 mile station could not show any documentation on referencing of their scale (LWL or MSL).

Water level scales are similar to DMH scales, though measurements are performed in feet (!) relative to the zero of the gauge (which is either referenced to LWL or MSL or not at all). This is very important to realise when working with DWIRs elevation data, since surveys of the riverbed and embankments are performed with GNSS, total station and water level equipment, which use a benchmark (or TBM), which is vertically referenced to the local Chart Datum which, in turn, is derived from the local water level. More info on the referenced DWIR water level measurement stations can be found in section 4.

2.4.3 Surveying

Other than DMH, DWIR performs a lot of survey work. Their methodology was researched for better understanding and use of existing data.

Bathymetry data is acquired mainly by a Garmin 80XS, which is a combination of a fish-finder and GNSS antenna. The systems automatically measures water depth and position. In surveying terms the horizontal accuracy of this system is poor (order tenths of meters) and the vertical accuracy worse. Consequently, the vertical component of the position is not used. As an alternative, the local water level is measured every 5 minutes, during survey. After survey the automatic water depth measurement of the Garmin 80XS are coupled to the recorded water level in time to obtain bed elevations w.r.t. the local Chart Datum (LWL), at the measured (horizontal) position of the vessel in time. Logging of the measurements is performed in the Garmin 80XS, exporting is done with Garmins Basecamp software. Correction to the measurements are performed in Microsoft Excel. Sound velocity in the water is **not** sampled or corrected for. Instead the manufacturers (Garmin) suggestion for appropriate sound velocity is used.

Topographic data is acquired by GNSS, water levelling and total station. The use of GNSS is limited to RTK and correction for antenna heights only. No post processing of GNSS data is performed. It remains unclear to what level antenna profiles with phase center offsets, Antenna Reference Points (ARP's) or internal coordinate reference systems are used. Assuming the equipment is delivered to DWIR with the right settings pre-programmed and consequently used by DWIR following the manufacturers instructions, measurements quality should be uniform. Still, without clear documentation on this, data should be treated with care.

Part of the initial scope of this study was transforming existing bathymetric data to readily useful data. Given the above, this is not a straightforward process. Moreover, after almost half a year of requesting this data from DWIR, by SHORE, RVO and the Dutch Embassy in Myanmar, no data was shared with SHORE, to perform the transformation. Therefore, this part of the study could not be performed.

3 GPS Benchmarks

3.1 Objectives

Clear documentation of the horizontal and vertical reference system of field measurements is very important to obtain generically useful data for any party that might be using it. Most often, (some) local data is available, though without a clear and reliable description of the referencing to horizontal and vertical reference systems. For instance, often, bathymetric measurements are related to the instantaneous water level during survey, for which is (or is not) corrected in post processing. Therefore, an important objective of this survey campaign was to create and use new benchmarks with reliable and accurate coordinates.

Section 3.2 introduces the used coordinate systems. Next, a distinction has been made between **new** SHORE benchmarks (section 3.3) and **existing** benchmarks that have been surveyed by SHORE (section 3.4).

3.2 Benchmark Coordinate Reference Systems

All benchmark coordinates are provided in X/Easting (m), Y/Northing (m) UTM projection of WGS84 and Z/elevation (m) WGS84 ellipsoidal height and EGM2008 geoid height.

3.3 SHORE benchmarks

3.3.1 Methodology

Benchmarks were created using a Leica GNSS receiver on a tripod, positioned above a marker (particular well recognisable geometric shape or feature, or special marker drilled into the surface). The Leica GNSS receiver has been logging raw observations for at least 8 hours. Raw observations were processed using AUSPOS GPS data processing. During subsequent days, a base station has been set up above the benchmark, sending RTK corrections to the rovers in the field. These benchmarks were often created on buildings (rooftops) for security reasons and guarantee on clear sky visibility (e.g. Fig. 3.1).

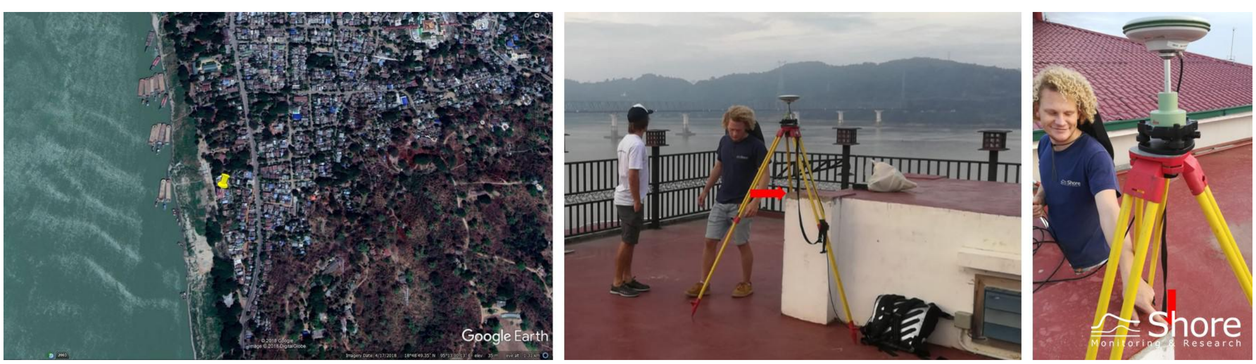

Figure 3.1: Example of GNSS base station set-up over a benchmark on a rooftop (Irrawaddy Hotel, Pyay)

When a convenient, safe and open space on a hard surface (road, quay, construction) was encountered, additional benchmarks were created by drilling a special marker into it and using RTK-GNSS corrections from the reference station on the rooftop. The coordinates of these points were determined by two consecutive measurements of the marker, each for at least 5 minutes, resulting in at least 600 observations in total (e.g. Fig. 3.2).

Figure 3.2: Example benchmark creation with marker (Hinthada Baseballfield)

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Details of the instrument used for creating the benchmarks are shown Tab. 3.1 below:

Table 3.1: Overview of instrument and corresponding accuracy used for creating benchmark. The accuracy is based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:
RTK-GNSS	Leica viva GS10	$\pm$ 2 cm + 1 mm/km
RTK-GNSS	Leica GX1230GG	$\pm$ 2 cm + 1 mm/km

3.3.2 Results and deliverables

In total the SHORE survey resulted in 34 reliable benchmarks (Fig. 3.3). Twenty (20) new SHORE benchmarks were created and used for the survey. Secondly, whenever present and accessible, existing DMH and DWIR benchmark were visited, of which 14 were successfully referenced.

Figure 3.3: Geographic overview of created and referenced benchmarks.

The benchmarks which were created by SHORE are listed in Table 3.2. The content of Table 3.2 is delivered to the client in a .txt file named:

- *SHORE NEW benchmarks RWSS v20181220.txt*

Table 3.2: Coordinates of newly created SHORE benchmarks.

Name	X/Easting (m)	Y/Northing (m)	UTM zone	Z WGS84 (m)	Z EGM08 (m)
Pyay SHORE Rooftop	733454,531	2081649,459	46 N	4,700	55,029
Myanaung SHORE	745302,174	2023951,100	46 N	-28,011	22,370
Hinthada SHORE Pagoda	761219,694	1953476,779	46 N	-33,948	16,265
Hinthada SHORE Baseballfield	761296,591	1953304,933	46 N	-35,292	14,917
Hinthada SHORE Rooftop	761239,497	1953377,981	46 N	-19,423	30,789
Danubyu SHORE	774332,124	1912334,984	46 N	-42,148	7,499
Ngathaingchaung SHORE Rooftop	719531,297	1923904,490	46 N	-32,294	18,850
Pathein SHORE Rooftop	684699,332	1855693,838	46 N	-21,558	30,152
Pathein SHORE Boulevard	684424,975	1856285,516	46 N	-48,707	3,026
Nyaungdon S2 SHORE	780290,321	1887049,442	46 N	-39,061	10,186
Wakema SHORE	733114,599	1837271,834	46 N	-47,132	2,871
Pyapon SHORE Rooftop	786530,477	1803140,936	46 N	-27,180	21,064
KIP SHORE	192814,462	1861778,068	47 N	-41,731	5,507
Mezali S1 SHORE	797998,027	1875476,852	46 N	-40,043	8,473
Tawa SHORE	233660,689	1905111,120	47 N	-39,407	6,690
MMU SHORE	208452,562	1848790,373	47 N	-42,091	4,723
Hle seik SHORE	805706,205	1908966,845	46 N	-40,765	7,446
Twantay SHORE	819529,391	1851116,962	46 N	-42,119	5,385

3.4 Existing DMH and DWIR benchmarks

3.4.1 Methodology

Existing benchmarks of DMH and DWIR were referenced using RTK-GNSS with a reference station on a newly created SHORE benchmark. The coordinates of the existing benchmarks were determined by two consecutive measurements of each at least 5 minutes, resulting in at least 600 observations in total. The same instruments were used as for creating the SHORE benchmarks (Table 3.1).

Quite some existing benchmarks were found to be surrounded by trees or other obstacles, which theoretically is an unfavourable situation for using RTK-GNSS. However, often an attempt was made to reference the benchmark. An example is shown for benchmark (BM30.698) at the DMH office in Pyay (Fig. 3.4).

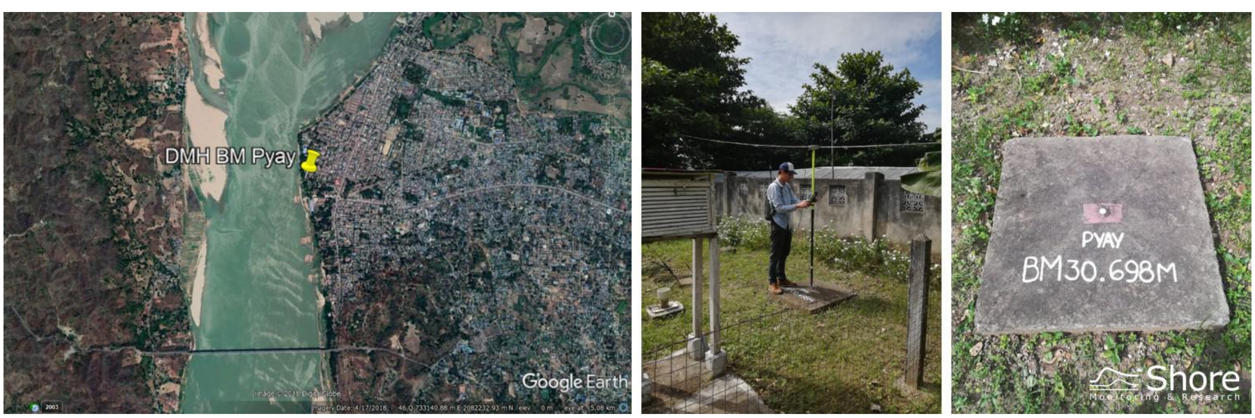

Figure 3.4: Example referencing existing benchmark at DMH office, Pyay.

3.4.2 Results and deliverables

The existing benchmarks of DMH, DWIR and IWUMD which were referenced by SHORE are listed in Table 3.3. The content of Table 3.3 is delivered to the client in a .txt file named:

- *SHORE Referenced Existing benchmarks RWSS v20181220.txt*

Table 3.3: Coordinates of referenced existing benchmarks.

Location name	X/easting (m)	Y/northing (m)	UTM zone	Z WGS84 (m)	Z EGM08 (m)
Pyay DMH office	733184,386	2082512,244	46 N	-18,904	31,427
Pyay DMH control BM	733191,287	2082770,333	46 N	-13,151	37,178
Zalun DMH Office	770965,951	1933885,911	46 N	-40,674	9,154
Zalun DMH WL scale	772125,373	1934888,107	46 N	-37,912	11,877
Zalun DWIR	772088,238	1934969,961	46 N	-37,921	11,870
Ngathaingchaung DMH	719851,560	1923781,601	46 N	-44,485	6,652
Nyaungdon DWIR	780258,102	1887023,799	46 N	-39,548	9,700
Maubin DMH 1	783316,666	1850795,539	46 N	-43,094	5,725
Maubin DMH 2	783104,755	1850659,482	46 N	-44,792	4,032
Samalauk IWUMD	788009,747	1881300,226	46 N	-41,028	7,909
Mezali IWUMD North sluice	796961,851	1876084,275	46 N	-40,456	8,105
Tawa IWUMD 1	233644,969	1905122,616	47 N	-39,556	6,542
Tawa IWUMD 2	233913,969	1905136,058	47 N	-37,848	8,241
Bago DMH	232193,001	1918241,142	47 N	-35,210	10,843

4 Verification and referencing of available water level measurement time series

4.1 Objectives

Based on previous survey campaigns and contact with local authorities, it was known that locally acquired water level time series exist. Potentially, these time series are very valuable because of the relatively long recording period. However, before this campaign the vertical referencing and accuracy of these measurements were unclear. SHORE visited these locations to:

- obtain insight in the local vertical reference levels (Chart Datum) used by MMR parties
- investigate the measurement methodology
- reference the scales with GNSS to WGS84 and EGM2008 elevation

The results can be used to transform existing water level records from local Chart Datum to EGM2008 water level records, which are valuable for future studies of the MMR water system.

4.2 Methodology

To be able to transform existing and future water level data from the local water level measurement installations, the measurement methodology of the local authorities was investigated and the water level gauge was referenced with RTK-GNSS.

Representatives of DMH, DWIR and IWUMD provided access to the water level measuring location, translated and further explained the local methodology. Schematisations and drawings of the water level scale (gauge) were explained to SHORE and photographed for documentation purposes. Subsequently the water level scale was referenced by:

1. placing the GNSS antenna or survey pole on a clear mark on the water level scale
2. photograph the above set up
3. document the local gauge zero (0 m mark of the scale), w.r.t. the locally used Mean Sea Level or other locally used Chart Datum
4. post process the GNSS measurement of the referenced mark on the scale to known coordinates in UTM WGS84 X/Easting and Y/Northing, and Z/elevation in WGS84 ellipsoidal height and EGM2008 geoid height.

The equipment that has been used for the referencing and transformation of existing water level measurements is presented in Tab. 4.1 below:

Table 4.1: Overview of instruments and corresponding accuracy used for the referencing of water level scales. The accuracy is based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:
RTK-GNSS	Leica viva GS10	± 2 cm + 1 mm/km
RTK-GNSS	Leica viva GS14	± 2 cm + 1 mm/km
RTK-GNSS	Leica GX1230GG	± 2 cm + 1 mm/km

4.3 Results and Deliverables

Results of the referencing are presented in a geographical overview (Fig. 4.1) and a table (Table 4.2) listing water level scale location, local authority, zero of the gauge w.r.t. WGS84 and EGM2008 and coordinates of the zero of the gauge w.r.t. to locally used Chart Datum (e.g. MSL) by the local authorities.

A more elaborate description of the local situation in Appendix B. The zero level of the water level scale is an important parameter and not straightforward for all locations, which is further discussed in Appendix B.

The content of Table 4.2 is delivered in a .txt file named:

- *SHORE Referenced Existing WL Scales of DMH IWUMD and DWIR RWSS v20181224.txt*

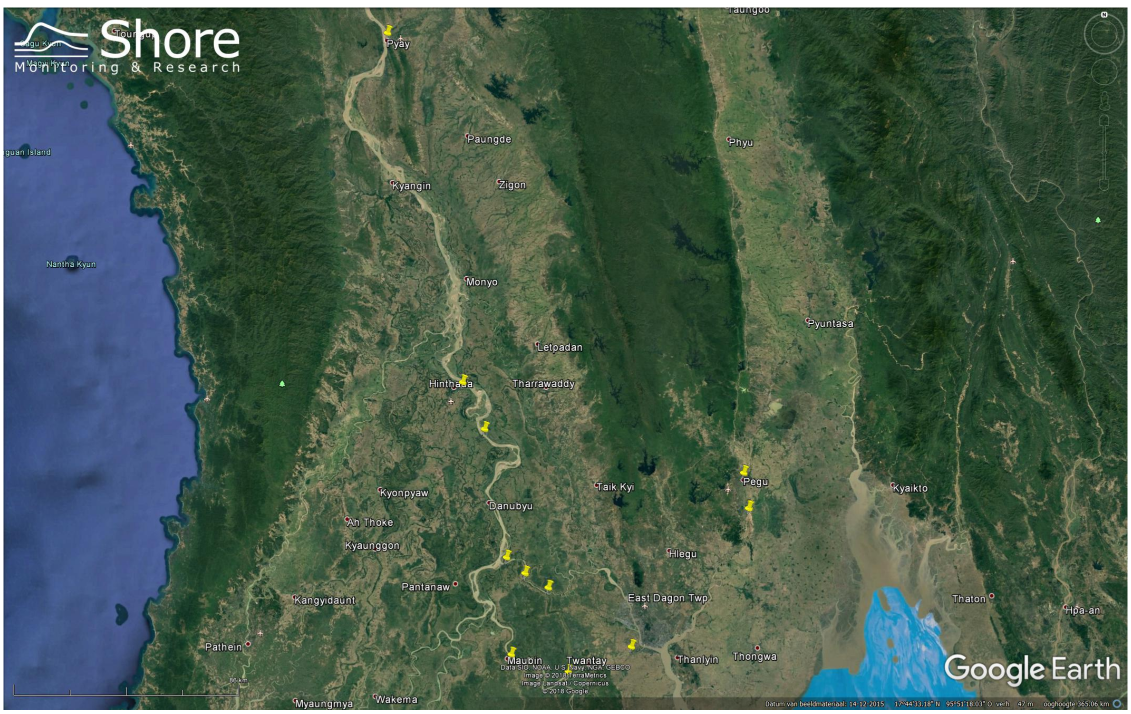

Figure 4.1: Overview of existing referenced water level measurement locations.

Table 4.2: Referenced Existing Water Level Scales

Name	X/Easting (m)	Y/Northing (m)	UTM zone	Z gauge zero WGS84 (m)	Z gauge zero EGM2008 (m)	Offset zero of gauge to local CD (m)
WL Scale DMH Bago	232007,041	1918438,619	47 N	-45,787	0,270	0,000
WL Scale IWUMD Tawa inside sluice	233895,511	1905330,447	47 N	-45,512	0,577	0,000
WL Scale IWUMD Tawa outside sluice	233848,278	1905253,915	47 N	-45,443	0,648	0,000
WL Scale IWUMD Tawa Bago river	233631,566	1905128,549	47 N	-39,316	0,582	0,000
WL Scale DWIR Twantay 3.5Mile	188757,559	1854075,293	47 N	-46,705	0,587	0,000
WL Scale IWUMD Samalauk inside	788052,316	1881351,588	46 N	-48,510	0,425	0,000
WL Scale IWUMD Samalauk outside	788098,808	1881336,460	46 N	-48,451	0,483	0,000
WL Scale IWUMD Mezali north sluice LL	796881,114	1876037,890	46 N	-48,680	-0,116	0,000
WL Scale IWUMD Mezali north sluice HL	796916,734	1876065,920	46 N	-48,051	0,512	0,000
WL Scale IWUMD Nyaungdon	781043,853	1887146,229	46 N	-48,638	0,583	0,000
WL Scale DWIR Twantay 21Mile	804967,946	1844576,074	46 N	-47,703	0,238	0,000
WL Scale DMH Maubin	783332,221	1850803,093	46 N	-51,158	-2,450	-3,000
WL Scale DMH Zalun	772115,905	1934949,134	46 N	-48,857	0,933	0,000
WL Scale DMH Hinthada	763653,372	1952276,944	46 N	-49,539	0,592	0,000
WL Scale DMH Pyay	733131,826	2082478,641	46 N	-49,169	0,935	0,171

The table gives the zero of the water level scale w.r.t. WGS84 and EGM2008 in column 5 and 6 respectively and the zero level of the water level scale in column 7. Next to the scales listed in Table B, SHORE visited DMH scales in Ngathaingchaung and Thabaung. Unfortunately, it was not possible to measure these locations with RTK due to nearby trees, but the offset of the zero of the gauge w.r.t. M.S.L. have been determined:

- Offset zero of gauge to local CD (M.S.L.) **Ngathaingchaung: -3.076m**
- Offset zero of gauge to local CD (M.S.L.) **Thabaung: -3.00m**

The above mentioned parameters are used to transform the existing water level records into EGM2008 water level records. Upon writing of this report, only records from Pyay, Zalun and Maubin were obtained from DMH, of which only Pyay actually contained water level records. This record has been transformed. For other locations requests are pending.

4.3.1 Example Referenced Water Level Scale Pyay

One example of referencing an existing water level measurement location is presented for the DMH location in Pyay (Fig. 4.2). The local officer presented the schematic of the scale, which was referenced to a local DMH benchmark, behind the office. The water level scale was created on a concrete structure with steps, of which some were numbered (SG1, P01 - P23).

Figure 4.2: Existing Water Level Scale Pyay. Geographical Location (top left), GNSS referencing P20 (top middle and right), Step/Pile number and corresponding elevation w.r.t. zero gauge (bottom left), manual reading with portable ruler (middle right), DMH benchmark with elevation w.r.t. MSL (bottom right)

The numbered steps have a certain height w.r.t. the zero level of the gauge (in centimetres), which in turn has an offset to MSL (+0.171 MSL). The water level is measured 3 times daily, at 6.30, 12.30 and 18.30, by placing a ruler (portable scale) on one of the numbered steps. The measurement with the ruler is added to the level of the step and consequently recorded and communicated to DMH headquarters in Nay Pyi Daw. NOTE: the **gauge reading** is communicated and documented, so without the correction for the offset of the gauge zero w.r.t. MSL.

To reference the zero of the gauge to WGS84 and EGM2008 elevations, the P20 step (2042 cm above gauge zero) was measured with RTK-GNSS. The resulting elevation of the gauge zero w.r.t. locally used MSL, WGS84 ellipsoidal height and EGM2008 height are listed in Table 4.2, together with the other referenced existing water level scales.

5 Installation of water level and salinity loggers

5.1 Objectives

The objective of the water level and salinity measurements is to gain more insight into the hydrodynamics and salt intrusion of River system. The data serves as a basis for further (numerical) study of the river system. Furthermore, time series of the water level and salinity measurements as initiated in this campaign, will ideally be continued for years, providing valuable temporal (and real time) data of the river system, for both irrigation and drainage purposes.

5.2 Methodology

Referencing of the CTD location has been carefully executed by creating and measuring a RTK-GNSS reference point on a fixed structure, directly above the CTD. This reference point is documented and measured in UTM 46 and 47 N Easting and Northing and WGS 84 ellipsoid and EGM2008 geoid height. Consequently, the vertical offset between the sensor and the RTK-GNSS reference point has been measured.

The equipment that has been used for the referencing and transformation of existing water level measurments is presented in Tab. 5.1 below:

Table 5.1: Overview of used instruments and corresponding accuracy. The accuracy is based on the manufacturer's declaration

Instrument:	Brand and type:	Accuracy:
Water level and salinity logger	Schlumberger CTD-diver	+/-2 cm
RTK-GNSS	Leica GS10/14 (or comparable)	± 2 cm + 1 mm/km

5.3 Results and deliverables

The final locations of the newly deployed water level and salinity loggers are presented in a geographical overview (Fig. 5.1) and a table (Table 5.2) listing water level logger locations, the measured GNSS-reference point and the offset from GNSS-reference point and the logger. More detail on the locations and way of deployment can be found in Appendix C.

Table 5.2: Coordinates and offsets of newly deployed water level and salinity loggers

Name	X / Easting(m)	Y/Northing (m)	UTM zone	Z (m) refpoint WGS84	Z (m) refpoint EGM2008	Z (m) offset
WL Logger Elephant point	207864,67	1839898,2	47N	-41,546	5,248	9,76
WL Logger Monkey point	197983,05	1855889,21	47N	-41,739	5,358	8,661
WL Logger Nyaungdon	781046,18	1887150,48	46N	-46,181	3,04	1,43
WL Logger Tawa	233624,05	1905123,41	47N	-43,037	3,061	2,03
WL Logger Hle Seik	805407,84	1908961,97	46N	-45,348	2,878	3,713

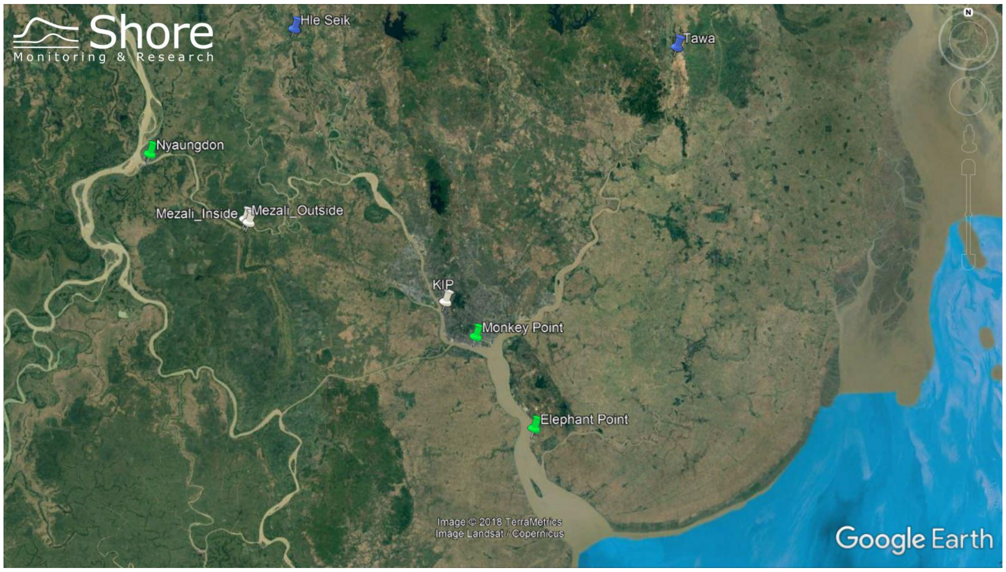

Figure 5.1: Geographical overview newly installed permanent (green markers) and temporary water level loggers (blue markers). Existing permanent loggers at Mezali (2) an KIP funded by RVO indicated with white markers.

Of the above listed loggers, the loggers Elephant Point, Monkey Point and Nyaungdon are connected to a modem that enables daily data transmission of the measured water levels. These loggers will continue sending data till two years after installation. The loggers in Tawa and Hle Seik are not connected to a modem and the data collected by these loggers will be obtained in the beginning of 2019.

The data of the loggers with a modem has been plotted in Fig. 5.2 together with data of three earlier installed water level loggers (KIP, Mezali Outside sluice and Mezali Inside sluice). Evaluating from sea in landward direction, the loggers can be observed in the following order:

1. Elephant Point
2. Monkey Point
3. KIP
4. Mezali Outside/Inside
5. Nyaungdon

Analysis of Fig. 5.2 shows that the acquired water level correspond to what is expected. The loggers closest to the sea (i.e. Elephant Point, Monkey Point, KIP) have the highest amplitude (also, note the amplification of tidal amplitude at Monkey Point). Further upstream, the amplitude decreases. Also phase shifts between the locations seem logical.

The only exception is the Mezali Inside logger which has a lower amplitude and peaks later than the Nyaungdon logger that is located further land inward. However, the observed behaviour of this logger can be explained by its location which is in a sluice that serves as water control structure. Therefore, the water level deviates from what would occur based on natural forcing.

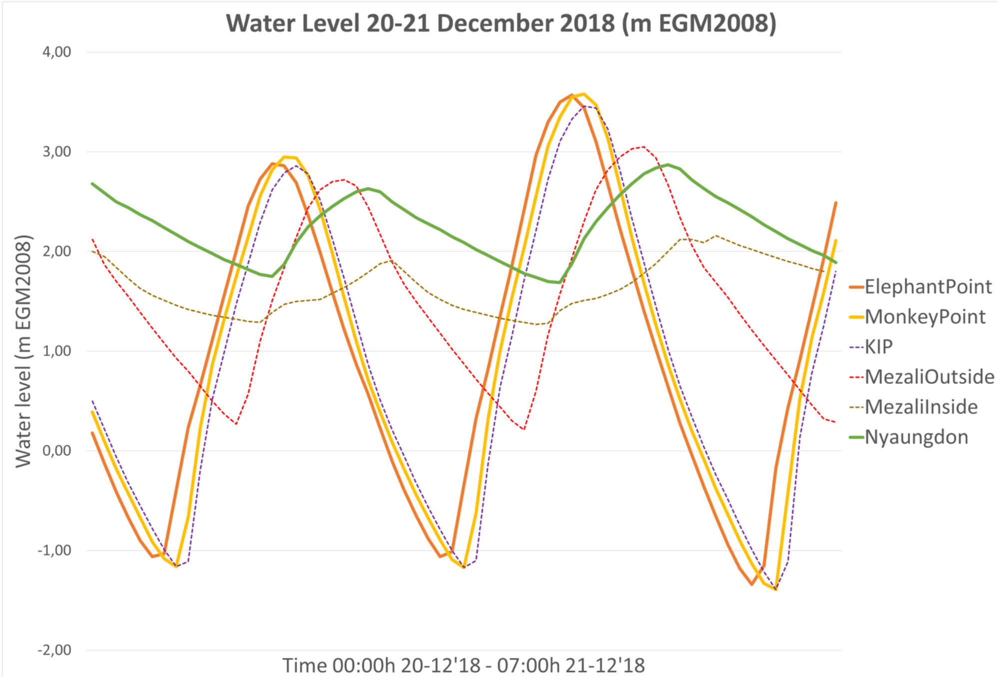

Figure 5.2: Preview of obtained data between UTC 00:00h on 20-12-2018 and 07:00h on 21-12-2018.

NOTE: the elephant point logger was installed on the most seaward located jetty in the estuary which allowed installation: the IBTT jetty (still under construction). More seaward than this, no suitable location was found. Other options were small coastal town approximately 80 km westward from the estuary, which, from a modelling point of view, would cost increased effort to include this area and processes in the model. Therefore, the IBTT jetty was selected as most suitable option for recording water levels, although the tide will already by influenced by the estuaries geometry and river discharge.

Deliverables are:

1. Monthly .csv-files until November 2020 containing water level (EGM2008) and salinity (PSU) measurements (daily updated for current month) for locations Elephant Point, Monkey Point and Nyaungdon, with times in UTC.
2. .csv file with water level (EGM2008) and salinity (PSU) measurements of approximately one month of data for locations Hle Seik and Tawa, with time in UTC.

6 Bathymetric data

6.1 Objectives

Providing bathymetric input for the development of the regional hydrodynamic model (to be developed in 2019) of the greater Yangon area is the main objective. In the RWSS scoping[1] 52 cross-sections were defined to acquire new, reliable and well referenced bathymetric data (Fig. 6.1, red lines). Secondly, existing bathymetric data from DWIR was obtained of which the vertical reference level and reliability was unclear. Therefore, two (2) objectives are formulated for the current survey and data study:

1. assess (and possibly transform) existing bathymetric DWIR data to EGM08 elevation data, including strategic surveying in these areas
2. survey 52 cross-sections referenced to WGS84 and EGM08 elevation

An overview of the 52 cross-sections survey (red lines) and strategic survey (blue lines) is presented in Fig. 6.1)

Figure 6.1: Geographical overview of 52 cross-sections (red lines) and strategic surveying to transform existing data (blue lines)

6.2 Methodology

6.2.1 Existing Bathymetric Data

Earlier in 2008 SHORE had already transformed DWIR data to EGM08 data for the Nyaungdon area[2], by correlating overlapping recent SHORE survey data to the data from DWIR. The same methodology

[1] ScopingStudy_RegionalWaterSecurity_Yangon_v1.0-Final.pdf
[2] SHORE_Memo_Transformation of SHORE's WGS84 and DWIR's Reduced Level elevation data to EGM2008.pdf

was planned for the current assessment and transformation of existing data from DWIR, combined with the latest insights into DWIRs survey methodology (see section 2). Therefore, in addition to the 52 cross-sections, extra cross-sections and a longitudinal transect were defined in areas with existing bathymetric data (Fig. 6.1, blue lines) for comparison with DWIR data. A short recap on the assessment and transformation procedure is presented below:

1. extract all DWIR data points from the autocad drawing. These are points which can be read from the autocad drawings and correspond to the survey points as measured and drawn by DWIR. They are horizontally referenced to WGS84 by UTM 46 and 47 N projection (depending on location)
2. interpolate the DWIR data points to a gridded surface (DTM) 10 x 10 m $Z_{Dwir.DTM}$
3. select all SHORE survey points (referenced to WGS84) overlapping this area
4. interpolate the elevation from this DTM at the location of SHORE's survey points $Z_{Dwir.at.Shore.x,y}$
5. determine the differences between the SHORE elevation Z_{Shore} and the interpolated DWIR elevation Z_{diff} for all SHORE survey points
6. inspect the histogram of the differences and determine the mean of all differences
7. inspect the spatial distribution of the differences, by plotting Z_{diff} minus the mean difference at all SHORE survey points
8. transform DWIR data to match the SHORE WGS84 data with a single vertical offset value, being the mean of all differnces
9. transform the matched DWIR data to EGM008 elevation

However, after almost half a year of requesting the existing data from DWIR by SHORE, RVO and the Dutch Embassy in Myanmar, no data was shared with SHORE, to perform the transformation. Therefore, this part of the study could not be performed.

6.2.2 New Bathymetric Data

The used bathymetric survey system is a combination of multiple instruments that together form a modular survey kit that can be used on a variety of vessels. The modular character of the system increases the flexibility as the type of vessel can be selected based on specific local conditions and is not restricted to fixed setups. First the details of the survey system will be explained. The set up used for this project will be presented thereafter.

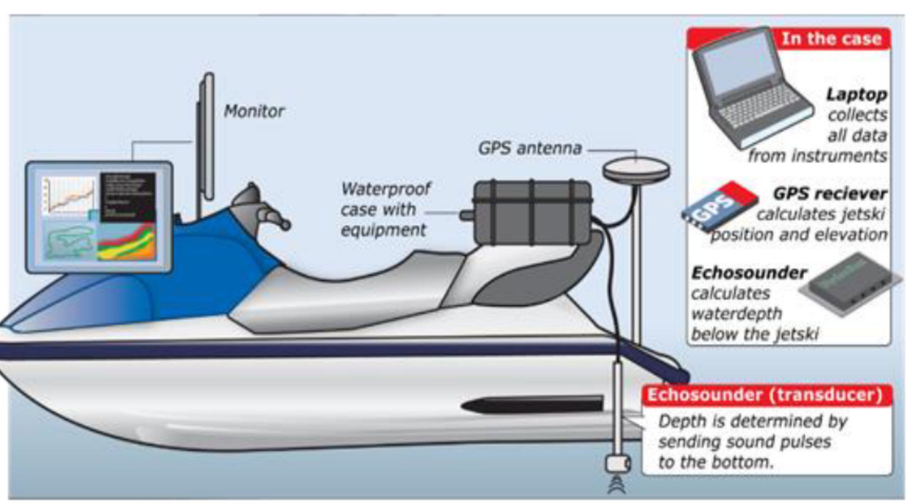

Figure 6.2: The instrument setup for a bathymetric survey. Example of deployment on a vessel

The water depth under the vessel is measured with a Hydrobox Single Beam Echo Sounder (SBES, frequency 10 Hz). The SBES sends sound pulses towards the bottom which reflect and are received back by the SBES sounder. From the time between sending and receiving a pulse and the speed of sound through water, the water depth under the echo sounder can be determined.

The speed of sound through water varies based on differences in water temperature and salinity. Therefore, CTD-measurements are performed multiple times during a survey to collect the necessary information. Locations of CTD-measurements are carefully selected, based on expected spatial gradients in the speed of sound among the surveyed area.

The survey system is equipped with a motion sensor to log movement (pitch / roll) of the vessel. The logged movements are used to correct/reject the depth measurements for pitch and roll. For further details reference is made to Appendix D.2.1.

A dual frequency (L1/L2) RTK GPS and GLONASS (GNSS) receiver with real time radio/GPRS/3G connection with a GNSS base station has been used. Its antenna is placed in one vertical axis with the SBES transducer of which the offset is measured carefully before deployment of the survey system on a 'new' vessel. The GNSS receiver logs the X,Y,Z position of the vessel at 2 Hz. RTK technique is used to obtain centimetre positional accuracy.

The latency between the instruments is calculated from the correlation between the time series of the vessel's GPS elevation and the sounding depths below the vessel. The presence of waves results in vertical movement (heave) in the vessel elevation, which is reflected in an equal variation in the depth measured below the vessel. The time shift to correlate maxima of both signals is the resulting latency, with which the sounding depths are corrected. For further details reference is made to Appendix D.2.2.

The final measurement of the elevation of the bed level is then obtained from the elevation of the GNSS (z_{GNSS}) subtracted with the vertical offset between the GNSS antenna and SBES (z_{offset}) and the depth measured by the SBES (d):

$$z_{bedlevel} = z_{GNSS} - z_{offset} - d \tag{6.1}$$

The above is illustrated in Fig. 6.3 below.

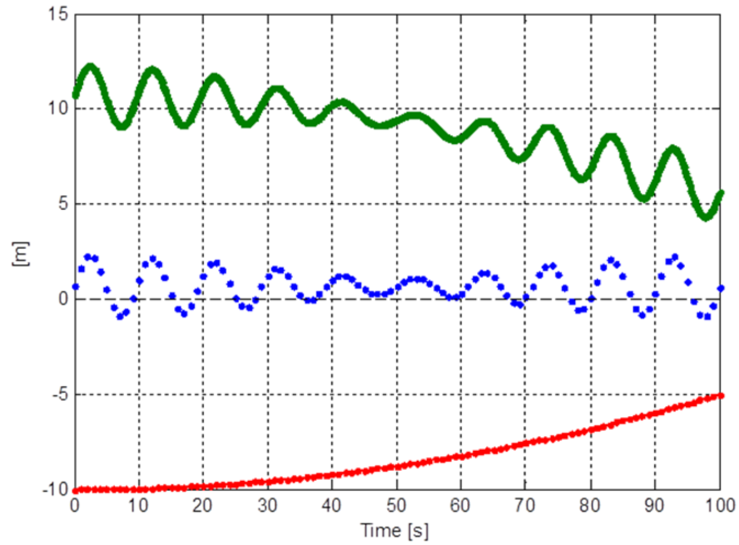

Figure 6.3: Calculation of the bed level. The green line shows the 10 Hz measurements of depth under the SBES. The blue points correspond to the 2 Hz RTK-GPS elevation of the vessel *at the bottom of the SBES* ($z_{GNSS} - z_{offset}$). The resulting bottom level (2 Hz) is obtained by subtracting both signals and is shown in red.

Details of the instruments of the survey system are summarized in Tab. 6.1 below:

Table 6.1: Overview of instruments and corresponding accuracy used for bathymetric survey. The accuracy is based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:
SBES	Syqwest Hydrobox 210kHz	$\pm$ 0.01 m +/- 1% depth
RTK-GNSS	Leica GX1230GG	$\pm$ 2 cm + 1 mm/km
Speed of sound sensor	YSI Castaway CTD	$\pm$ 0.15m/s
Motion sensor	Xsens MTi 300 AHRS	Gyro bias stability 10°/h, Roll/Pitch 0.2°, Yaw 1.0°

The survey system is completed with a wireless monitor kit and waterproof case containing hardware and a rugged laptop which collects and visualises the survey data real-time. The monitor shows the operator all data needed for a safe, accurate and effective survey: real-time sensor status, speed, position, depth, GNSS statistics, survey tracks, sailed tracks, background drawings etc.

6.2.3 Setup bathymetric survey system during execution of survey

The survey system has been mounted on locally rented boats (Fig. 6.4). For each different boat set up, the offset between SBES transducer and GNSS antenna was documented.

Figure 6.4: Instrument setup modular SBES system on a local boat.

6.3 RTK and GNSS post processing

Every morning the GNSS base station was set up over a benchmark (section 3) and dismantled in the evening. Connection between base and rover (the GNSS on the vessel) was established by UHF radios. Due to the distance between rovers and base station, connection couldn't always be maintained. Part of SHORE's quality assurance procedure is to log raw satellite observations on all GNSS receivers with 2Hz, enabling post processing of all GNSS data with 2 Hz.

6.3.1 Postprocessing Bathymetric Data

Postprocessing of the GNSS and SBES data was performed on a daily basis to monitor quality and progress of the survey. Data processing follows a strict procedure:

1. Automatic filtering and cleaning of sounding depths
2. Manual inspection of the filtered sounding depths
3. Latency inspection and correction
4. Correcting sounding depths with measured speed of sound
5. Rejecting sounding depths based on motion sensor data
6. Correcting vertical offset GNSS and SBES
7. Post processing of rover GNSS positions with local base station data
8. Rejection of points without fixed phase (L1 + L2) solution
9. Combining only RTK fixed positions with cleaned echosounder signal
10. Converting WGS84 Lat, Lon to UTM Easting and Northing coordinates (site specific)
11. Inspection of bed level elevation at crossings of the survey paths
12. Visualization of survey points in GIS or Google Earth
13. Writing ascii file containing all points that passed the post processing and quality control procedure (X/Easting (m); Y/Northing (m); Z/elevation (m) w.r.t. a generic reference level (WGS84 ellipsoid, CD, etc.)

Reference is made to Appendix D for more details on the above steps.

6.4 Results and deliverables

Note to users of the data: the survey area lies in two (2) UTM zones: 46 and 47 northern hemisphere. Therefore, results are delivered in separate files for each UTM zone.

6.4.1 Existing Bathymetric Data

After almost half a year of requesting the existing data from DWIR by SHORE, RVO and the Dutch Embassy in Myanmar, no data was shared with SHORE, to perform the transformation. Therefore, this part of the study could not be performed.

6.4.2 New Bathymetric Data

Results are presented by Google Earth maps containing the final bathymetric survey data, without DWIR data (Fig. 6.5 - 6.13). The data is delivered in ascii files containing all points in X/Easting UTM 46N (m); Y/Northing UTM 46/47N (m); Z/elevation (m) w.r.t. EGM2008 geoid coordinates

Bathymetric survey data was obtained until water depths of approximately 1 m. In case survey paths show no data, the water was to shallow to sail through and measure the depth.
To facilitate easy use of the data, the results of the 52 cross-sections survey and the cross-sections of the strategic survey have been combined in one file. Another file, containing **all** data, including the longitudinal transects and extra surveypaths is also delivered. Both files are ascii .txt files containing all points that passed post processing and quality control procedure (X/Easting UTM 46N (m); Y/Northing UTM 46N (m); Z/elevation (m) w.r.t. WGS84 ellipsoid and EGM2008 geoid). Due to anomalies in the graviational field it is advised to use the EGM2008 geoid for all modelling purposes.

- All cross sections:
  - *SHORE_survey_points_RWSS_Crosssections_XYZ_***UTM46N***_WGS84_EGM08.txt*
  - *SHORE_survey_points_RWSS_Crosssections_XYZ_***UTM47N***_WGS84_EGM08.txt*
- All data, including longitudinal transects:
  - *SHORE_survey_points_RWSS_Alldata_XYZ_***UTM46N***_WGS84_EGM08.txt*
  - *SHORE_survey_points_RWSS_Alldata_XYZ_***UTM47N***_WGS84_EGM08.txt*

Overview total area

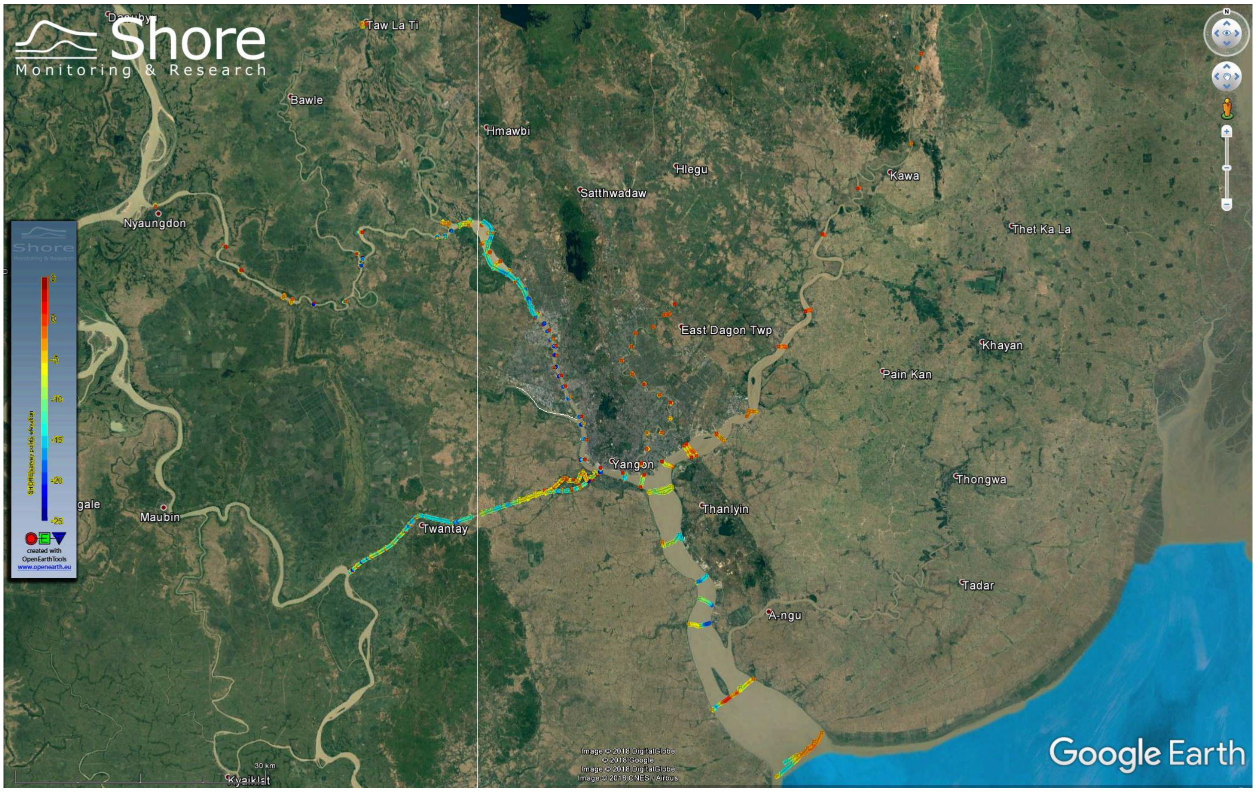

Figure 6.5: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Greater Yangon

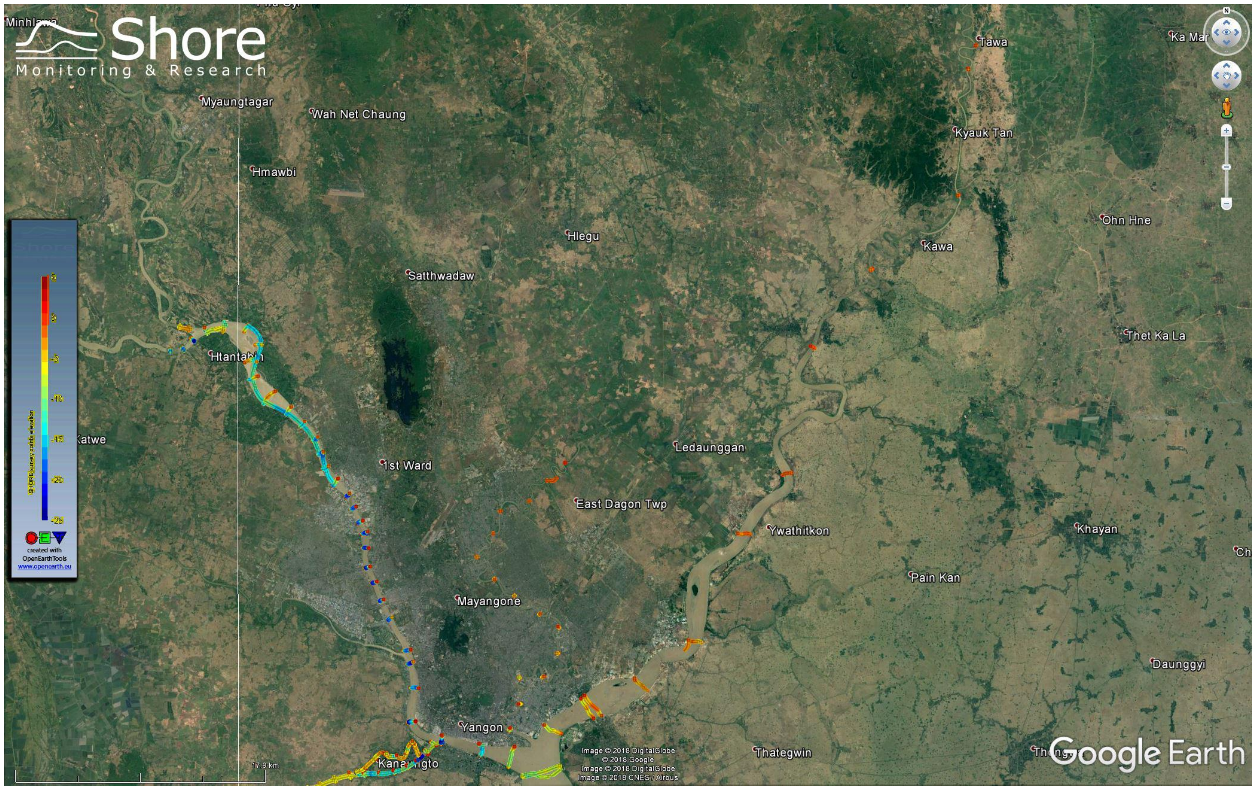

Figure 6.6: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Yangon

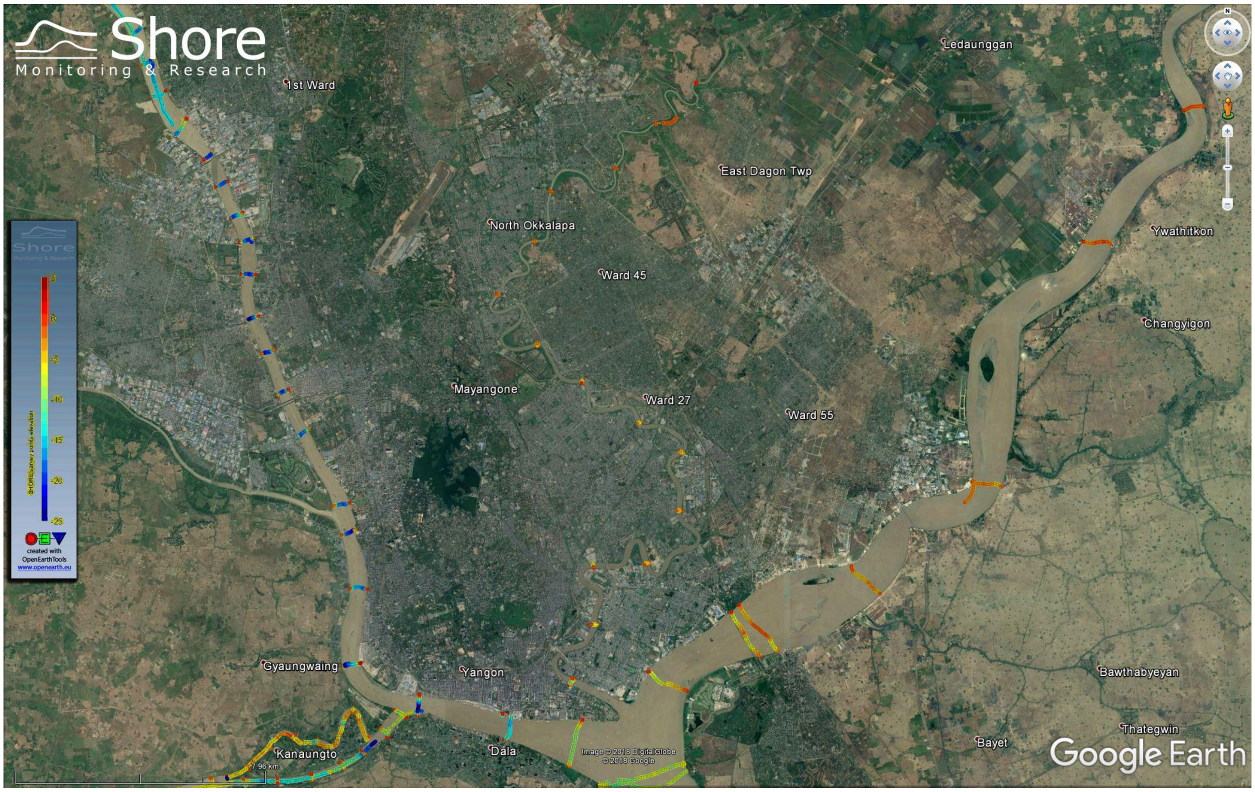

Figure 6.7: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Twantay Canal

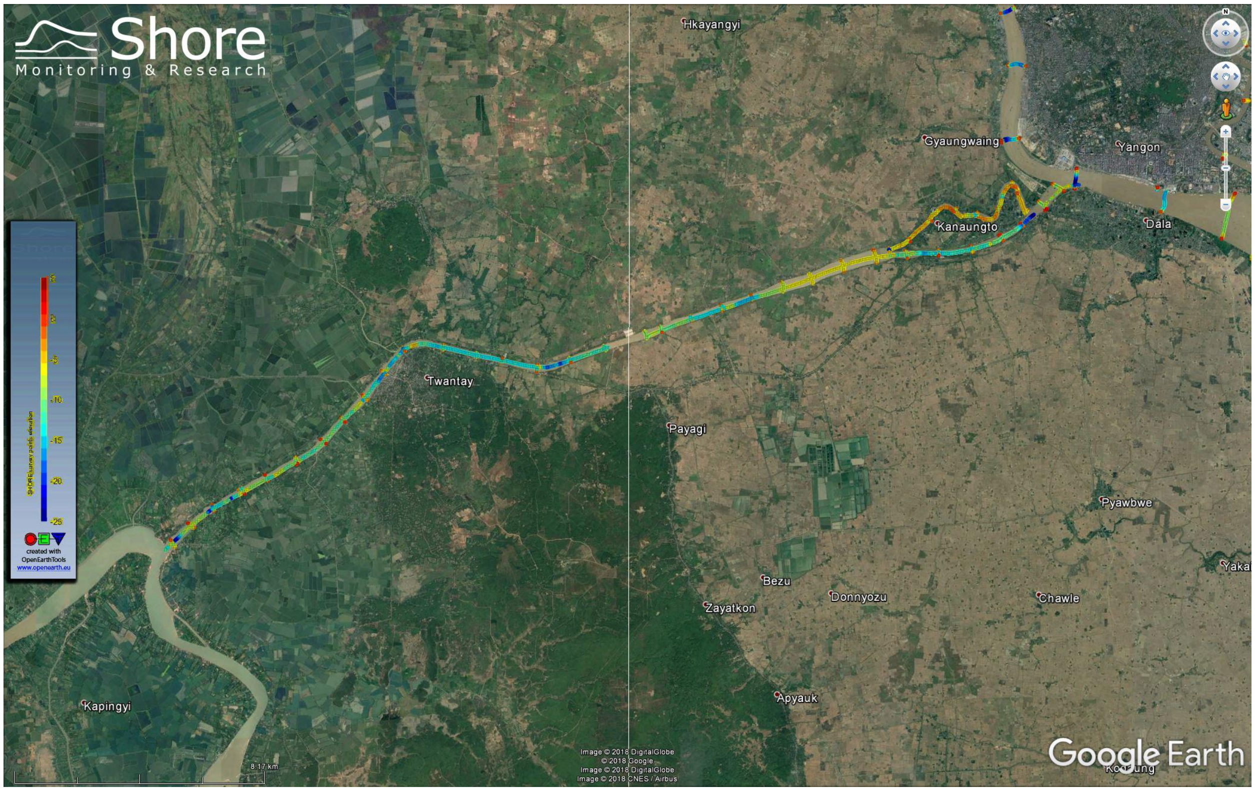

Figure 6.8: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Nyaungdon area

Figure 6.9: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Mezali area

Figure 6.10: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Hlaing River

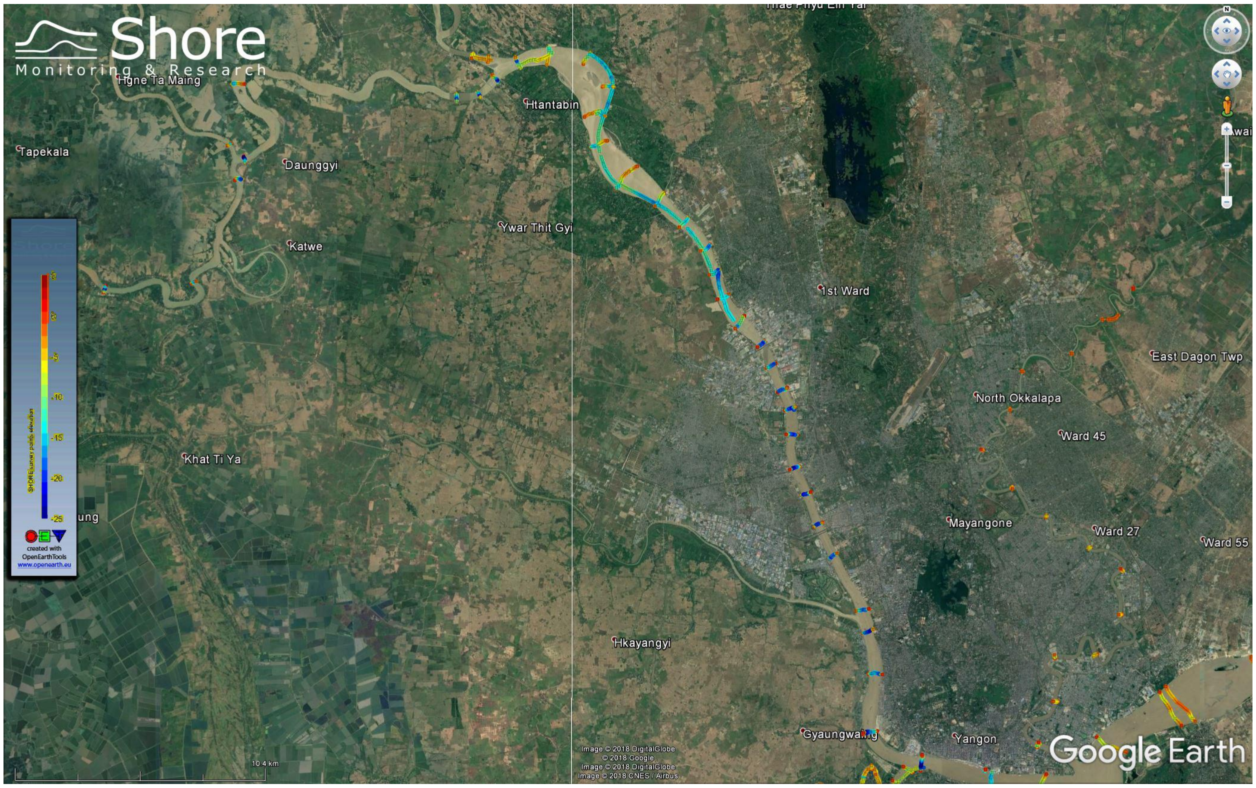

Figure 6.11: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Hle Seik

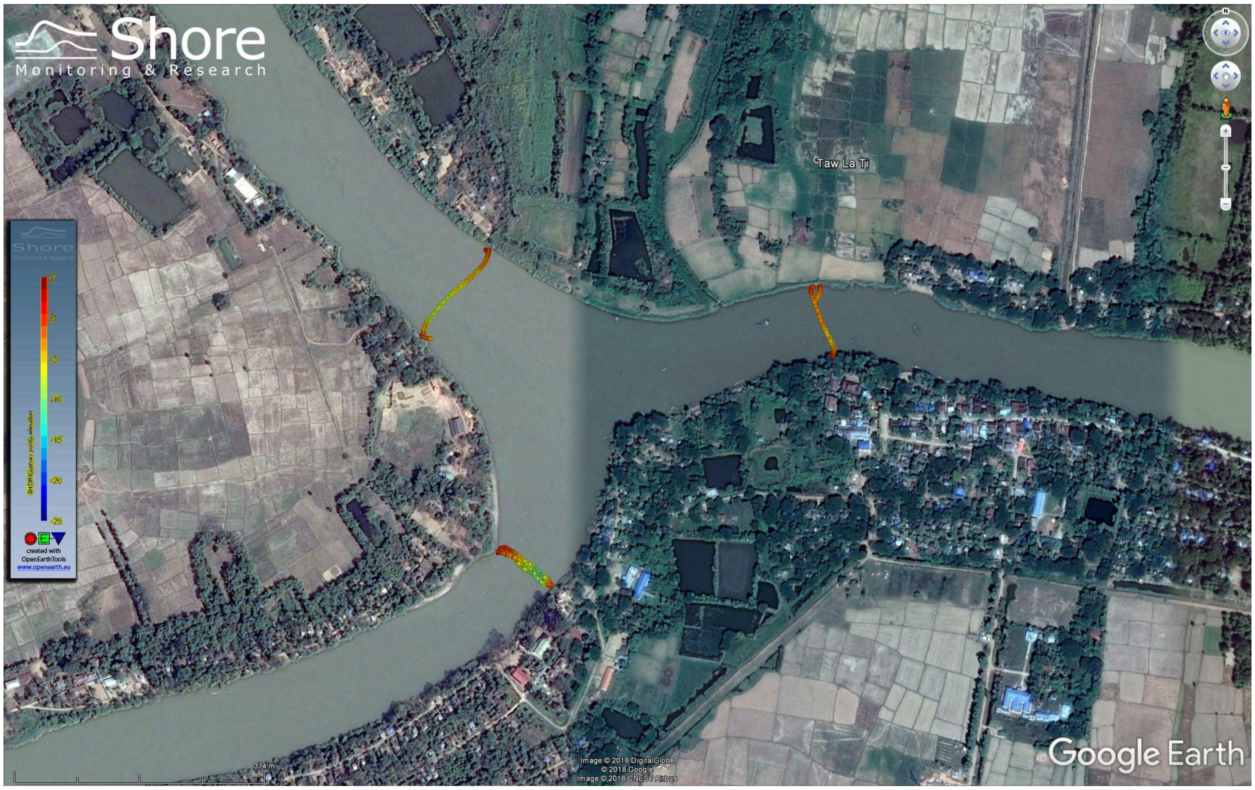

Figure 6.12: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

Overview Estuary

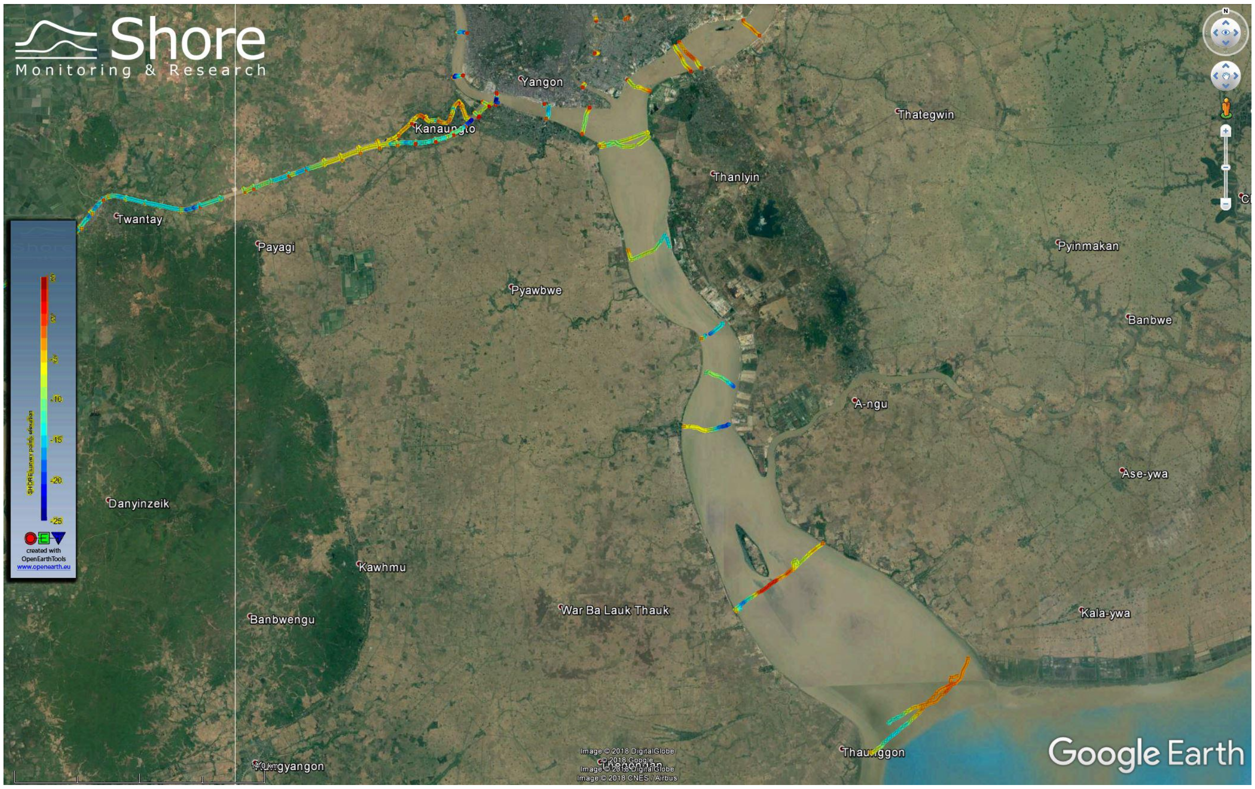

Figure 6.13: Surveyed cross-sections. Colours correspond to elevation in EGM08 (m). White line indicates UTM boundary 46-47N

7 Discharge measurements and drifter trajectories

7.1 Objectives

The objectives of the discharge and drifter measurements are to deliver high quality spatial current pattern data as well as discharge data, to gain insight in the hydrodynamic properties of the Ayeyarwady river and delta system. The measurements are performed to capture the river discharge near Pyay and tidally influenced river bifurcations near Nyaungdon and Hle Seik. River discharge in combination with measured water levels during the discharge data acquisition can be used to extend or verify existing rating curves of the Ayeyarwady river and calibration of the numerical models. GPS-tracked drifters are deployed to map and analyse spatial current patterns at the two bifurcations.

7.2 Methodology

A Sontek M9 ADCP (Acoustic Doppler Current Profiler) was used to perform the measurements (Fig. 7.1, Tab. 7.1). This device uses bottom-tracking technology to determine the vessels location and speed along the sailed transect. The obtained velocity is subsequently used to correct for the measured water current velocities. These corrections of the velocity data are done real time, such that a first quality assessment of the discharge is allowed during the acquisition procedure. Edge, bottom and top discharge estimates are extrapolated from the measured discharge, this is done to correct for flow across areas of the river that cannot directly be measured by the ADCP. Moreover, all discharge measurements are corrected for the speed of sound using a YSI Castaway CTD. The depth-averaged sound speed profile was sampled once every lap (three transects). Discharges are given in m^3/s.

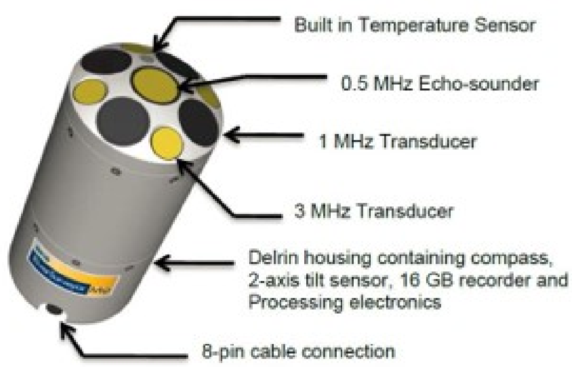

Figure 7.1: Sontek M9 ADCP used for discharge measurements.

Table 7.1: Sontek River Surveyor M9 accuracy, based on the manufacturer's declaration.

Instrument:	Brand and type:	Accuracy:	Resolution:
ADCP	Sontek RiverSurveyor M9	$+/-$ 0.25% of measured velocity; 0.2cm/s	0.001 m/s

GPS drifters consist of smartphones with a tracking app installed, providing 1 Hz location and velocity data. Smartphones were installed in locally acquired plastic barrels, that use concrete (for ballast) and pvc pipes to keep the smartphone above the waterlevel. Construction was performed with inhabitants of Nyaungdon (Fig. 7.2).

Figure 7.2: GPS drifters constructed with inhabitants of Nyaungdon

7.3 Results and deliverables

7.3.1 Pyay

Results for Pyay are presented by a single value for the discharge, averaged over the number of transects sailed and the standard deviation between the measurements (Tab. 7.2).

Table 7.2: Pyay discharge measurement results

Average Discharge:	No. of transects:	Standard Deviation:
6943.4 m^3/s	6	56.7 m^3/s

Results for the 13 hours discharge measurements at Nyaungdon and Hle Seik are presented by means of a google earth image in which measurement transects and positive flow direction are indicated, as well as a graph showing discharge per (hourly) measurement per transect over time.

Deliverables for the discharge measurements are ascii .txt files per branche, with time series of the measured discharge per transect in UTC +00.00 hrs time and m^3/s:

- DischargeTimeSeries_Nyaungdon_East_UTC+00.00.txt
- DischargeTimeSeries_Nyaungdon_North_UTC+00.00.txt
- DischargeTimeSeries_Nyaungdon_South_UTC+00.00.txt
- DischargeTimeSeries_HleSeik_North(main)_UTC+00.00.txt
- DischargeTimeSeries_HleSeik_East_UTC+00.00.txt
- DischargeTimeSeries_HleSeik_West_UTC+00.00.txt

Drifter results are presented by means of google earth images with floated trajectories of the drifters, of which the colour indicates the velocity of the drifter at that location. Although drifters were deployed over approximately 11 hours, only a few results are presented in the report. Data files contain all floated trajectories.

Deliverables for the GPS drifter measurements are ascii .txt files per drifter, with time series of the measured location (x/easting and y/northing in m) and velocity (m/s) in UTM 46 N (Nyuangdon) an 47 N (Hle Seik) projection. Times are in UTC +00.00 hrs.

- Drifter(1-10)VelocityTimeSeries_Nyaungdon_UTC+00.00.txt
- Drifter(1-10)VelocityTimeSeries_HleSeik_UTC+00.00.txt

7.3.2 Nyaungdon

The discharge measurements show tidal influence in the discharge, be it only via the eastern channel (Fig. 7.3, red line). On average the discharge is approximately 6000 m^3/s, of which 5000 m^3/s continues into the southern branche and 1000 m^3/s flows into the eastern branche: the Pan Hlaing River. No flow reversal was measured, only water level variations. This observation suggests upstream propagation of a long (tidal) wave against the river currents.

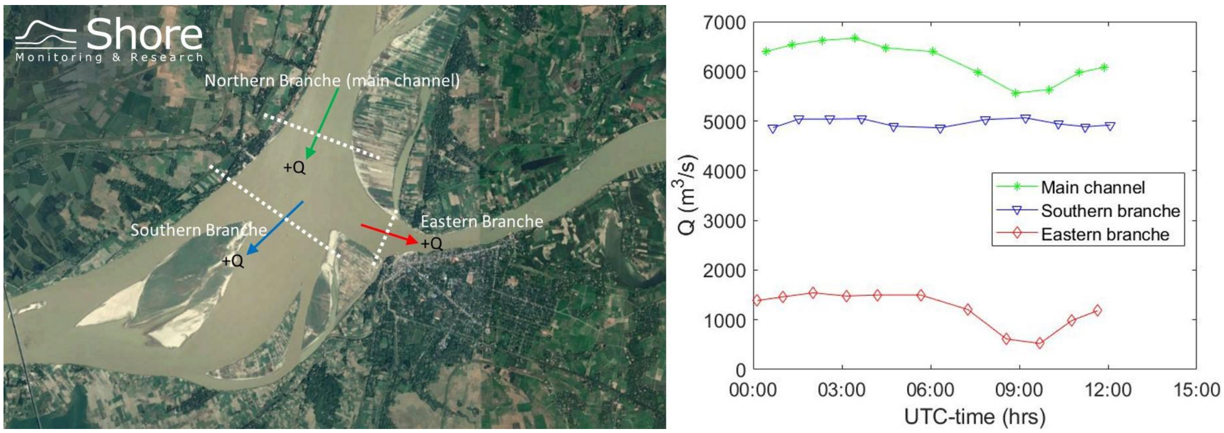

Figure 7.3: Nyaungdon, overview of transect locations, flow direction and corresponding Q sign. The right panel indicates the measured discharge for each transect over the tidal cycle.

Measurements with GPS drifters add extra information on the spatial current pattern and velocities. This is very well illustrated by figures 7.4 and 7.5, which show velocity in space. Plotted in Google Earth background they reveal for instance the large influence of the groins (constructed on the eastbank of the Ayeyarwady north of the bifurcation) on the current velocity in the outer bend just west of the town of Nyaungdon, where current velocities reach 1.5 m/s easily during the low water period (Fig. 7.4) and erosion is severe.

During the high water period, no flow reversal was measured, though significantly lower flow velocities (Fig. 7.5). Also, at this time, the majority of the drifters floated along the eastern part of the Ayeyarwady, over the groins and southward through the eastern channel south of the bifurcation (instead of on the west side, at low tide).

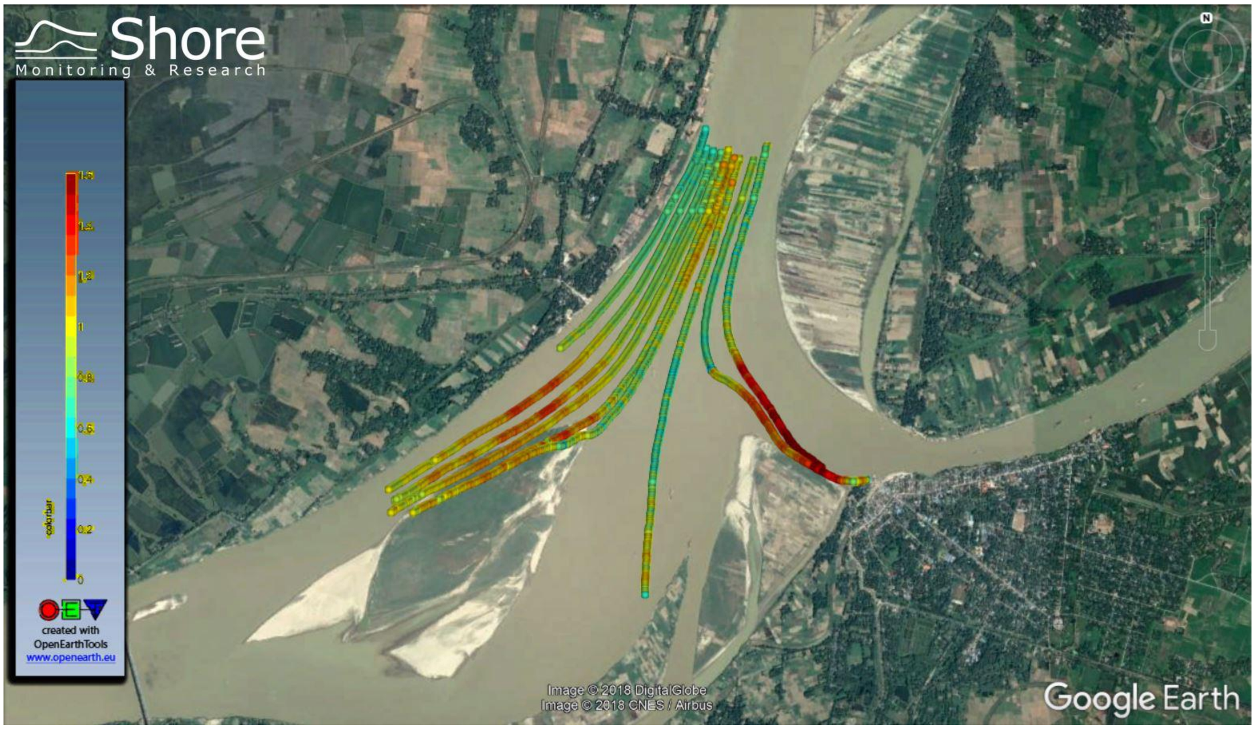

Figure 7.4: Current velocities around low tide, measured with gps drifters. Colours of trajectories correspond to velocity in m/s. Colourbar shows velocities between 0 and 1.6 m/s.

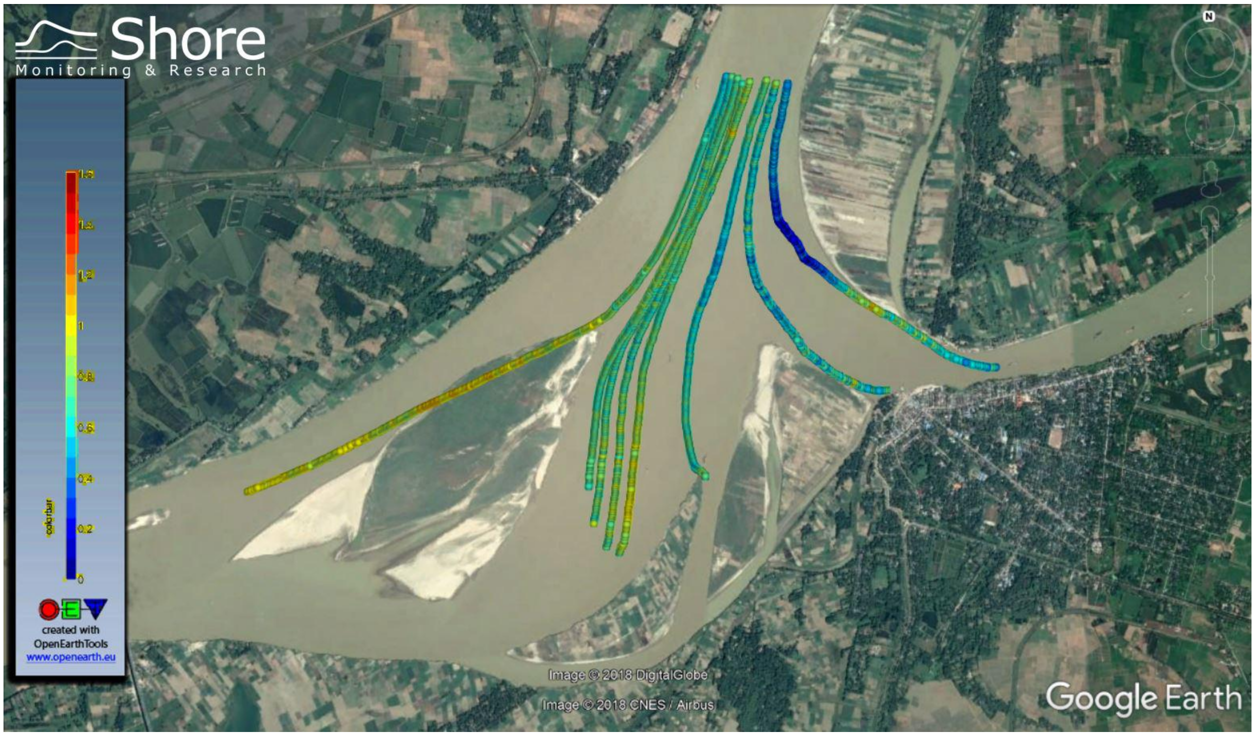

Figure 7.5: Current velocities around high tide, measured with gps drifters. Colours of trajectories correspond to velocity in m/s. Colourbar shows velocities between 0 and 1.6 m/s.

7.3.3 Hle Seik

The discharge measurements show more tidal influence in the discharge than Nyaungdon, including flow reversal. Measurements also show that the tidal influence (i.e. flow reversal) in the eastern branche occurs sooner than in the western branche. Overall, the discharges are a lot smaller than at Nyaungdon, obviously. Given the total northward 'discharge' (incoming tidal current) of approximately 400 m^3/s to 500 m^3/s in the northern branche, it is believed that the river discharge of the northern branche (ultimately originating near Mon Yo as a tributary of the Ayeyarwady) is very small m^3/s this time a year. Water level measurements at this location still need to be retrieved from an installed water level logger, to further analyse the river hydrodynamics.

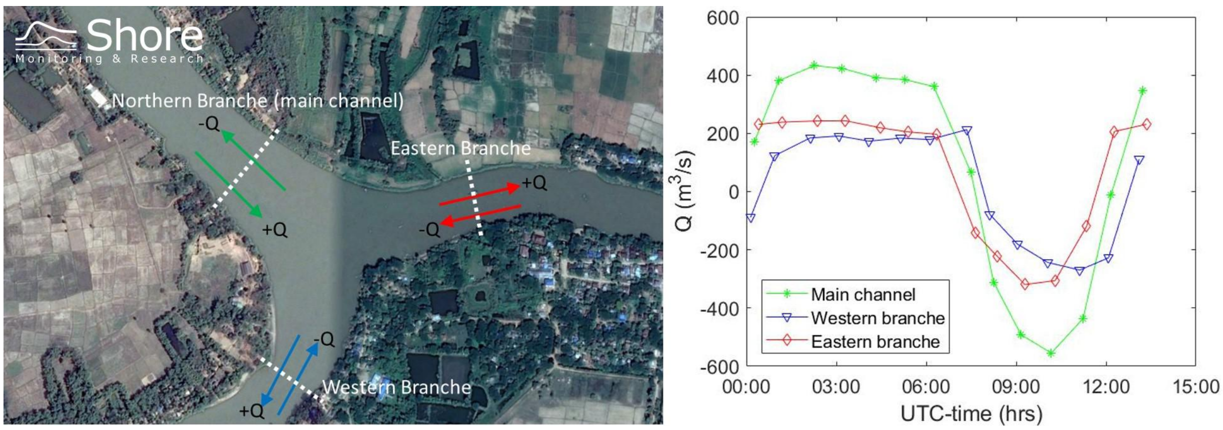

Figure 7.6: Hle Seik overview of transect locations, flow direction and corresponding Q sign. The right panel indicates the measured discharge for each transect over the tidal cycle.

Measurements with GPS drifters also nicely show flow reversal. Figure 7.7 shows drifter trajectories with velocities to the south (ebb currents and river discharge) and figure 7.8 shows trajectories with velocities to the north (flood currents). Note the larger tidal induced flow velocities in the eastern branche (+/- 0.6 m/s) compared to the western branche (+/- 0.4 m/s) 7.7. These observations are in line with the discharge measurements, which revealed that the tidal wave reaches Hle Seik sooner via the eastern branche compared to the western branche.

figure 7.8 reveal spatial flow patterns during ebb. Note how drifters where forced to the outer bend of the channel, this can be partly explained by the light (1.5 m/s) northern wind during the survey day. Flow velocities lay around 0.6 m/s.

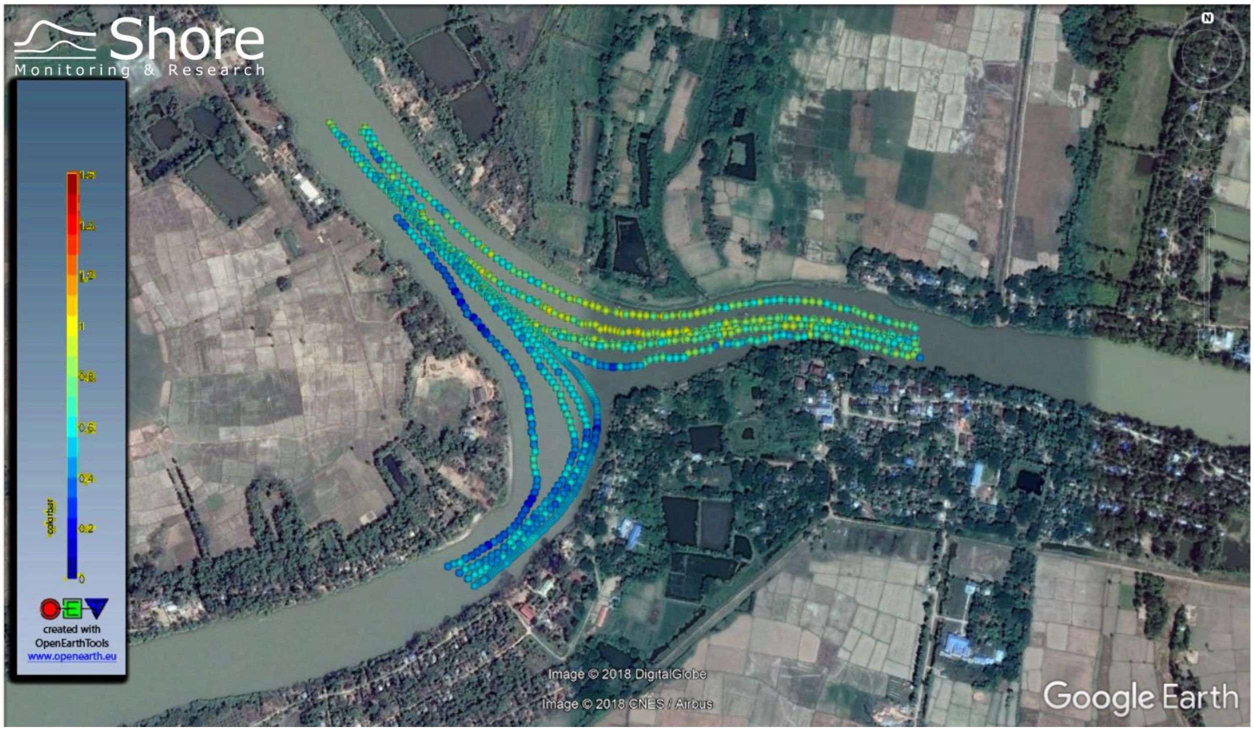

Figure 7.7: Current velocities around rising tide, measured with gps drifters. Colours of trajectories correspond to velocity in m/s. Colourbar shows velocities between 0 and 1.6 m/s.

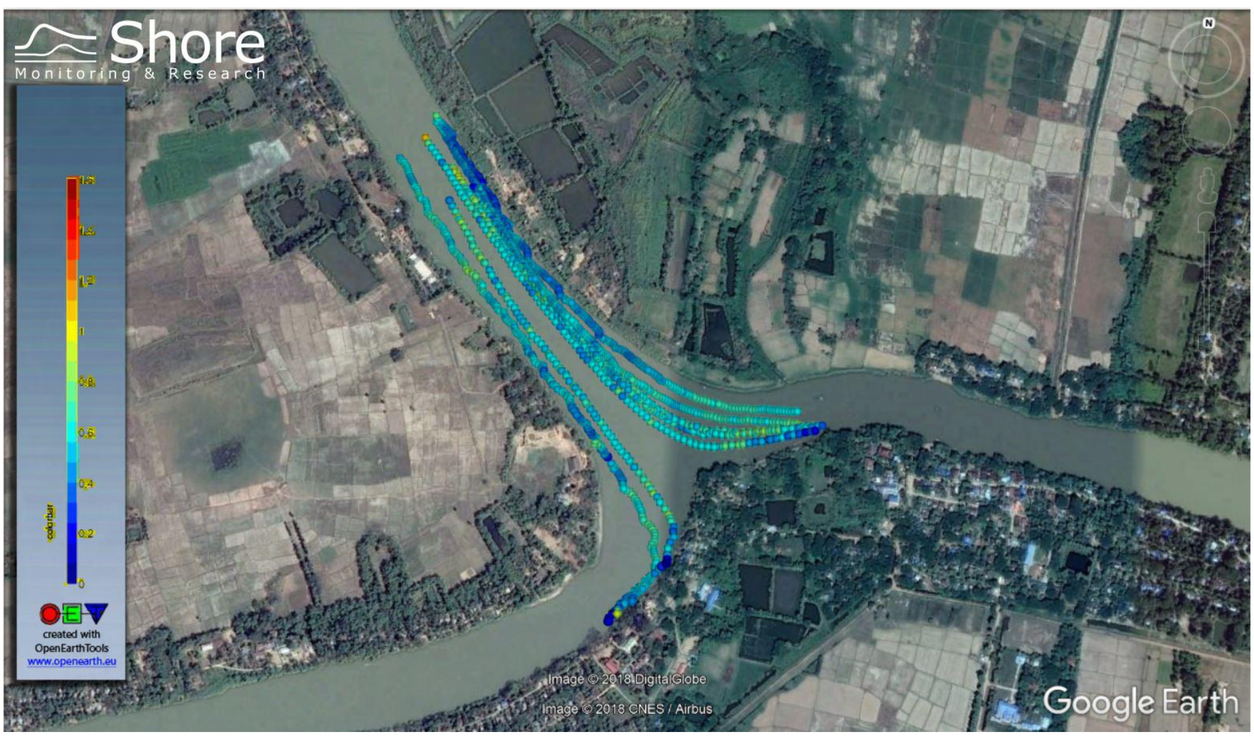

Figure 7.8: Current velocities around falling tide, measured with gps drifters. Colours of trajectories correspond to velocity in m/s. Colourbar shows velocities between 0 and 1.6 m/s.

8 Conclusion & Recommendations

This integral survey and data assessment campaign focused on acquiring new data, transforming existing data and installing equipment for continuous real time data in the Greater Yangon area, for a more profound understanding and future hydrodynamic modelling of the water system, by:

A Investigating the presence of and/or creating new GPS benchmarks, including assessment of local measurement methodologies by DWIR, DMH and IWUMD.
B Verification of available water level measurement time series
C Installation water level and salinity loggers
D Survey of strategic stretches to transform available bathymetric data
E Survey of 52 bathymetric cross-sections
F Measuring river discharges together with spatial current flow patterns

Results were presented in this report and its Appendices and data can be downloaded from www.shorewaterdata.com. Final remarks and recommendations are presented here below.

Online data portal: shorewaterdata.com
All measurement results from this and previous RVO projects executed by SHORE or shared with SHORE, are stored in SHORE's proprietary data portal www.shorewaterdata.com (Fig. 8.1). RVO decides on which parties can download the data, by requesting a username and password from SHORE.

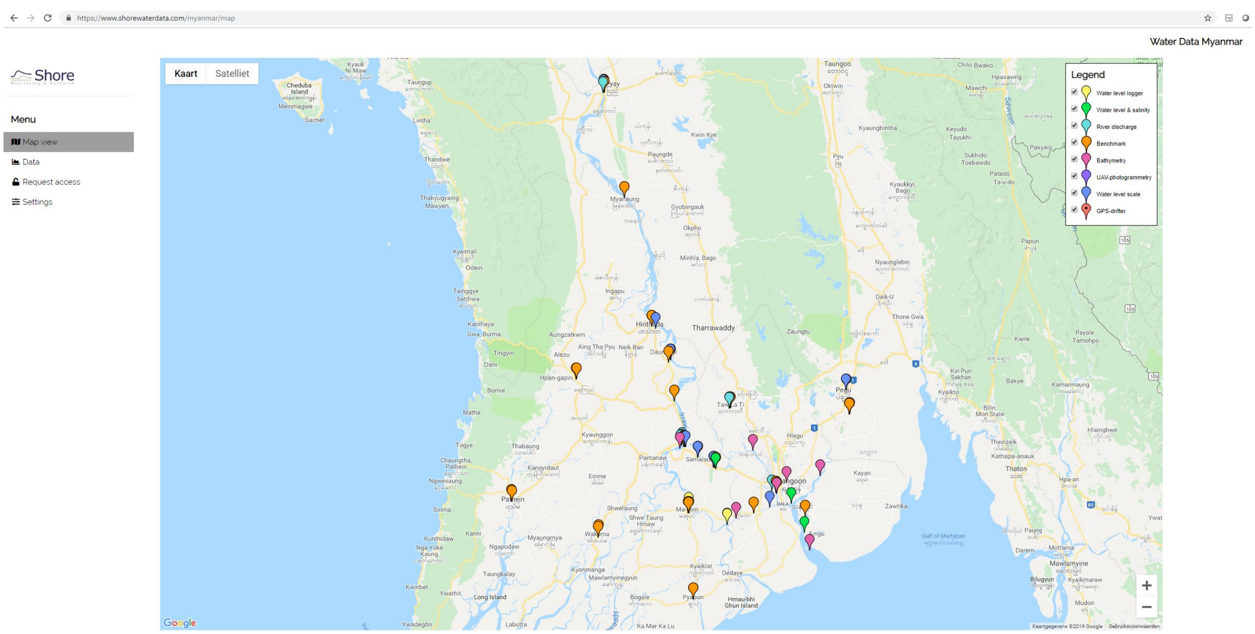

Figure 8.1: Screenshot of shorewaterdata.com online portal for data download

A manual on how to use the data portal is deliverd to RVO and subsequently emailed to approved users of the data portal. There are a few items that need specific attention

Existing bathymetry data of DWIR
While it is known that DWIR has quite extensive survey results of the bathymetry of the Twante Canal

and various parts of the Ayeryawaddy and Hlaing River, this data was not shared with SHORE, to transform it to useful data for modelling. Attempts by SHORE, RVO and the Dutch Embassy have not resulted in data sharing by DWIR. It is recommended to keep asking DWIR for this data, since it can be used to assess sedimentation rates.

Existing water level data of DMH, IWUMD and DWIR

DMH, IWUMD and to a lesser extent also DWIR, measure water levels in Myanmar. DMH has the most professional infrastructure and network in which daily meaurements are performed and archived. However, none of the organisations has shared data with SHORE and/or RVO. Therefore, historic timeseries were not transformed into useful water level timeseries for modelling efforts. However, the scales/gauges and methodology was assessed and reported in this document. If timeseries are shared in the future, they can be transformed with the results from this study.

Besides the manual gauge stations, many radar gauges on bridges were encountered during the survey, which all log the water level automatically. DMH uses these measurements for water level and flood risk warnings. RVO is encouraged to seek DMH's approval to use this data for future modelling.

Elephant Point water level logger

Water level time series on the seaward end of the Yangon estuary can provide valuable information on water level variations on a scale of years due to monsoons and cyclones. Flooding due to high river discharges is one thread for this region, however, flooding due to high sea levels are also very important for water safety in the Greater Yangon area.

No fixed structures to attached water level loggers to, are presented on the seaward end of the estuary. Therefore private jetties further inland were targetted. The most seaward suitable jetty at which permission could be obtained to install a permanent water level logger on is the IBTT jetty, as presented in this report. Although it is the most seaward water level information at this point, the need for a water level logger near Elephant Point or at sea remains.

An option could be the MPA navigation tower located about 20km south of the estuary. It is a concrete structure on which a sensor could be established. RVO is encouraged to seek MPA's permission to install a water level loggers sensor that transmits real time data.

Wet season high river discharges

This survey campaign was planned to be performed at the end of the wet season, when heavy rains are no longer present, but river discharges and water levels are still high. When SHORE was commissioned, water levels and river discharges had already decreased substantially. Since modelling activities are already in progress, SHORE recommends to assess the necessity for discharge and water level measurements in the dry and wet season with the Consultants that are involved with the modelling tasks and plan survey campaigns accordingly.

Repairs on existing water level loggers Mezali and KIP

During the wet season of 2017-2018 the loggers at Mezali (in the Pan Hlaing River and the canalised part south east of the new sluice) that were installed in 2017, were partly damaged. The logger at KIP jetty (Yangon) was also damaged, due to a boating accident. The logger was saved by KIP personnel. SHORE repaired the KIP logger and this time included a modem for real time data transmittance.

Appendix A Details of benchmarks

A.1 SHORE benchmarks

A.1.1 Benchmark Pyay SHORE rooftop

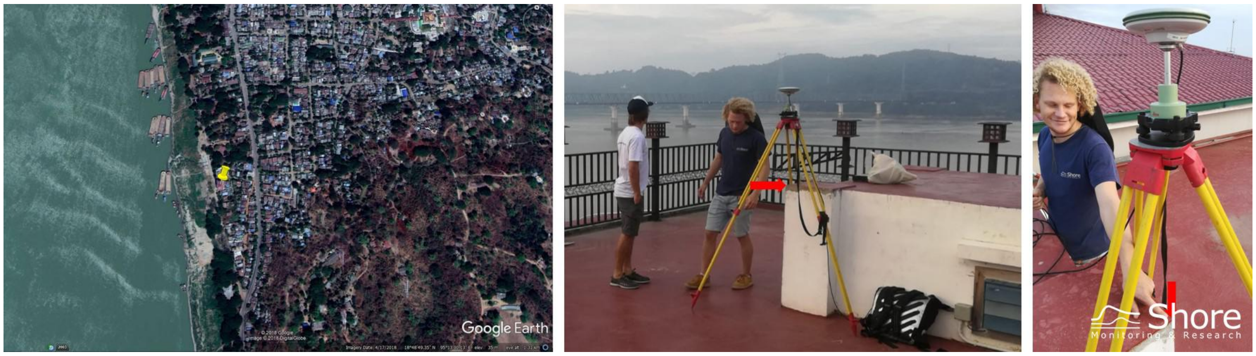

Figure A.1: Geographic location of benchmark Pyay SHORE rooftop (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel). Benchmark is a corner of an existing structure and indicated with the red arrow.

The final coordinates are presented in Tab. A.1 below:

Table A.1: Coordinates benchmark Pyay SHORE rooftop

Point ID:	X/Easting (m)	Y/Northing (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Pyay SHORE Rooftop	733454,531	2081649,459	46N	4,700	55,029

A.1.2 Benchmark Myanaung SHORE

Figure A.2: Geographic location of benchmark Myanaung SHORE rooftop (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.2 below:

Table A.2: Coordinates benchmark Myanaung

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Myanaung SHORE	745302,174	2023951,100	46 N	-28,011	22,370

A.1.3 Benchmark Hinthada SHORE Pagoda

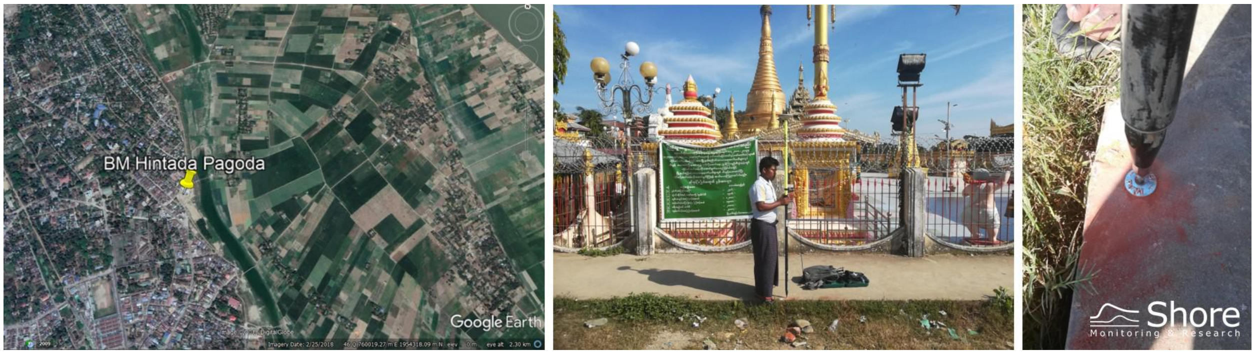

Figure A.3: Geographic location of benchmark Hinthada SHORE Pagoda (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.3 below:

Table A.3: Coordinates benchmark Hinthada SHORE Pagoda

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Hinthada SHORE Pagoda	761219,694	1953476,779	46 N	-33,948	16,265

A.1.4 Benchmark Hinthada SHORE Baseballfield

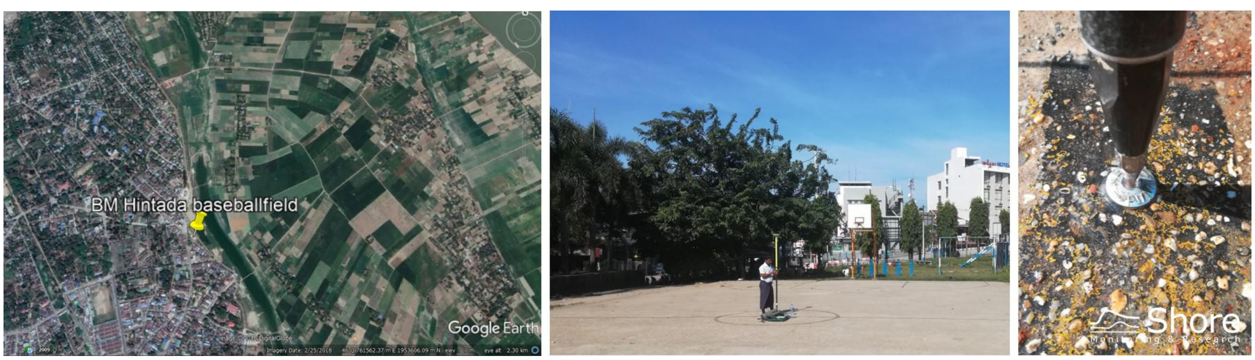

Figure A.4: Geographic location of benchmark Hinthada SHORE Baseballfield (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.4 below:

Table A.4: Coordinates benchmark Hinthada baseball field

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Hinthada SHORE Baseballfield	761296,591	1953304,933	46 N	-35,292	14,917

A.1.5 Benchmark Hinthada SHORE Rooftop

Figure A.5: Geographic location of benchmark Hinthada SHORE Rooftop (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.5 below:

Table A.5: Coordinates benchmark Hinthada SHORE Rooftop

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Hinthada SHORE rooftop	761239,497	1953377,981	46 N	-19,423	30,789

A.1.6 Benchmark Danubyu SHORE

Figure A.6: Geographic location of benchmark Danubyu SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.6 below:

Table A.6: Coordinates benchmark Danubyu

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Danubyu SHORE	774332,124	1912334,984	46 N	-42,148	7,499

A.1.7 Benchmark Ngathaingchaung SHORE rooftop

Figure A.7: Geographic location of benchmark Ngathainchaung SHORE rooftop (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel). Benchmark is a corner of an existing structure and indicated with the red arrow.

The final coordinates are presented in Tab. A.7 below:

Table A.7: Coordinates benchmark Ngathaingchaung SHORE rooftop

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Ngathaingchaung SHORE rooftop	719531,297	1923904,490	46 N	-32,294	18,850

A.1.8 Benchmark Pathein SHORE Rooftop

Figure A.8: Geographic location of benchmark Pathein SHORE Rooftop(left panel). GNSS setup over benchmark (right panel). Benchmark is a corner of an existing structure and indicate with the red arrow.

The final coordinates are presented in Tab. A.8 below:

Table A.8: Coordinates benchmark Pathein SHORE Rooftop

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Pathein SHORE Rooftop	684699,332	1855693,838	46 N	-21,558	30,152

A.1.9 Benchmark Pathein SHORE Boulevard

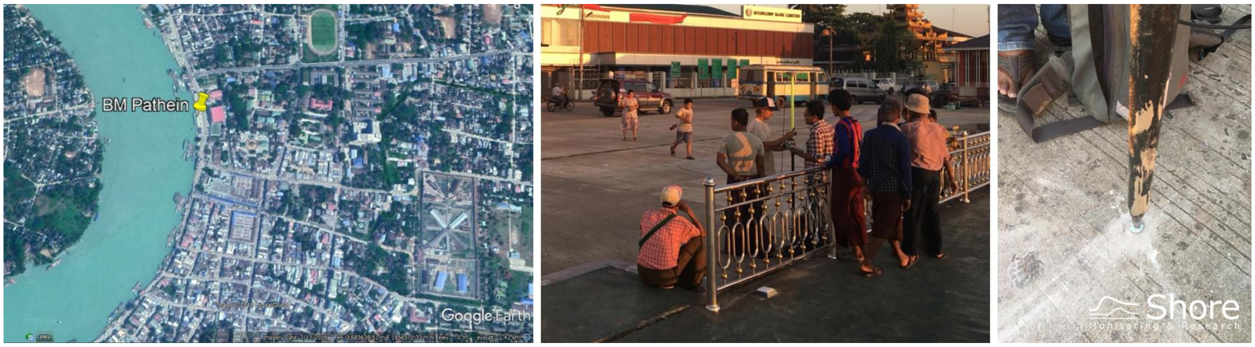

Figure A.9: Geographic location of benchmark Pathein SHORE Boulevard(left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.9 below:

Table A.9: Coordinates benchmark Pathein SHORE Boulevard

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Pathein SHORE Boulevard	684424,975	1856285,516	46 N	-48,707	3,026

A.1.10 Benchmark Nyaungdon S2 SHORE

Figure A.10: Geographic location of benchmark Nyaungdon S2 SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel). The benchmark is marked by a bolt indicated by the red arrow in the right panel

The final coordinates are presented in Tab. A.10 below:

Table A.10: Coordinates benchmark Nyaungdon

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Nyaungdon S2 SHORE	780290,321	1887049,442	46 N	-39,061	10,186

A.1.11 Benchmark Wakema SHORE

Figure A.11: Geographic location of benchmark Wakema SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.11 below:

Table A.11: Coordinates benchmark Wakema SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Wakema SHORE	733114,599	1837271,834	46 N	-47,132	2,871

A.1.12 Benchmark Pyapon SHORE Rooftop

Figure A.12: Geographic location of benchmark Pyapon SHORE Roof(left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel). The benchmark is located in the left corner of a concrete column, where a piece of reinforcement steel sticks out (indicated with red arrow, right panel)

The final coordinates are presented in Tab. A.12 below:

Table A.12: Coordinates benchmark Pyapon SHORE Rooftop

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Pyapon SHORE Rooftop	786530,477	1803140,936	46 N	-27,180	21,064

A.1.13 Benchmark KIP

Figure A.13: Geographic location of benchmark KIP SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.13 below:

Table A.13: Coordinates benchmark KIP SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark KIP SHORE	192814,462	1861778,068	47 N	-41,731	5,507

A.1.14 Benchmark Mezali S1 SHORE

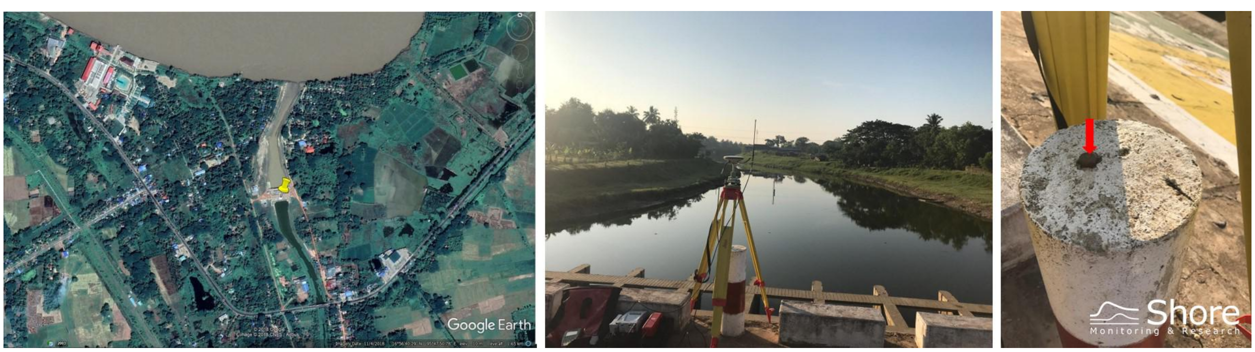

Figure A.14: Geographic location of benchmark Mezali S1 SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel). The benchmark is located on top of a concrete pillar and is indicated with the red arrow in the right panel

The final coordinates are presented in Tab. A.14 below:

Table A.14: Coordinates benchmark Mezali S1 SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Mezali S1 SHORE	797998,027	1875476,852	46 N	-40,043	8,473

A.1.15 Benchmark Tawa SHORE

Figure A.15: Geographic location of benchmark Tawa SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.15 below:

Table A.15: Coordinates benchmark Tawa SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Tawa SHORE	233660,689	1905111,120	47 N	-39,407	6,690

A.1.16 Benchmark MMU SHORE

Figure A.16: Geographic location of benchmark MMU SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel). After the photo of the right panel was taken, a bolt was put in the hole indicated by the red arrow in the right panel.

The final coordinates are presented in Tab. A.16 below:

Table A.16: Coordinates benchmark MMU SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark MMU SHORE	208452,562	1848790,373	47 N	-42,091	4,723

A.1.17 Benchmark Hle Seik SHORE

Figure A.17: Geographic location of benchmark Hle Seik SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.17 below:

Table A.17: Coordinates benchmark Hle Seik SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Hle Seik SHORE	805706,205	1908966,845	46 N	-40,765	7,446

A.1.18 Benchmark Twantay SHORE

Figure A.18: Geographic location of benchmark Twantay SHORE (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.18 below:

Table A.18: Coordinates benchmark Twantay SHORE

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Twantay SHORE	819529,391	1851116,962	46 N	-42,119	5,385

A.2 Existing benchmarks

A.2.1 Benchmark Pyay DMH Office

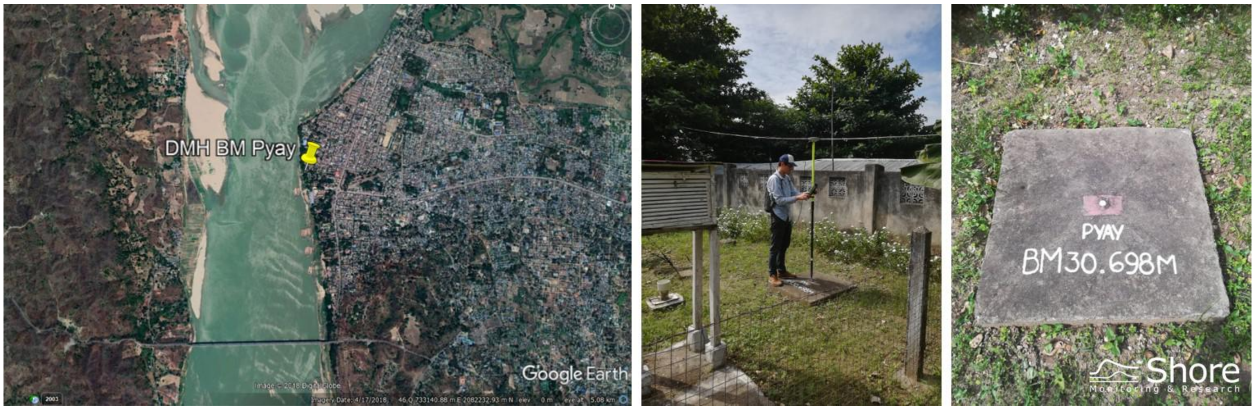

Figure A.19: Geographic location of benchmark Pyay DMH Office (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.19 below:

Table A.19: Coordinates of Pyay DMH Office

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Pyay DMH Office	733184,386	2082512,244	46 N	-18,904	31,427

A.2.2 Benchmark Pyay DMH Control

Figure A.20: Geographic location of benchmark Pyay DMH Control (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.20 below:

Table A.20: Coordinates of Pyay DMH Control

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Pyay DMH Control	733191,287	2082770,333	46 N	-13,151	37,178

A.2.3 Benchmark Zalun DMH Office

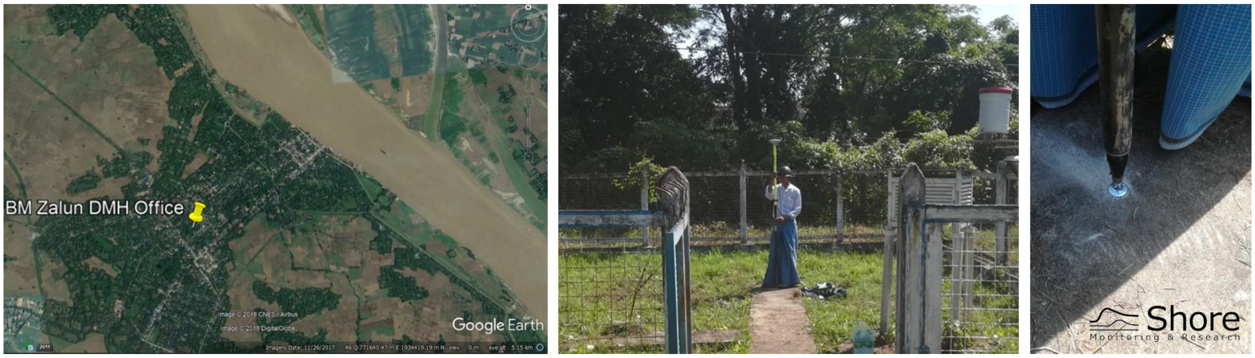

Figure A.21: Geographic location of benchmark Zalun DMH Office (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.21 below:

Table A.21: Coordinates Zalun DMH Office (office location)

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Zalun DMH Office	770965,951	1933885,911	46 N	-40,674	9,154

A.2.4 Benchmark Zalun WaterLevel scale

Figure A.22: Geographic location of benchmark (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.22 below:

Table A.22: Coordinates existing DMH benchmark Zalun WaterLevel scale

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Zalun WaterLevel scale	772125,373	1934888,107	46 N	-37,912	11,877

A.2.5 Benchmark Zalun DWIR

Figure A.23: Geographic location of benchmark (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.23 below:

Table A.23: Coordinates Zalun DWIR

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Zalun DWIR	772088,238	1934969,961	46 N	-37,921	11,870

A.2.6 Benchmark Ngathaingchaung DMH

Existing DMH benchmark

Figure A.24: Geographic location of benchmark Ngathaingchaung DMH (left panel). GNSS setup over benchmark (center panel) and detail of benchmark right panel).

The final coordinates are presented in Tab. A.24 below:

Table A.24: Coordinates benchmark Ngathaingchaung DMH

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark DMH Ngathaingchaung DMH	719851,560	1923781,601	46 N	-44,485	6,652

A.2.7 Benchmark Nyaungdon DWIR

Existing benchmark of DWIR

Figure A.25: Geographic location of benchmark Nyaungdon DWIR (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.25 below:

Table A.25: Coordinates existing DWIR benchmark Nyaungdon

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark DWIR Nyaungdon	780258,102	1887023,799	46 N	-39,548	9,700

A.2.8 Benchmark Maubin DMH1

Figure A.26: Geographic location of benchmark Maubin DMH1 (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.26 below:

Table A.26: Coordinates existing benchmark Maubin DMH1

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Maubin DMH1	783316,666	1850795,539	46 N	-43,094	5,725 9

A.2.9 Benchmark Maubin DMH2

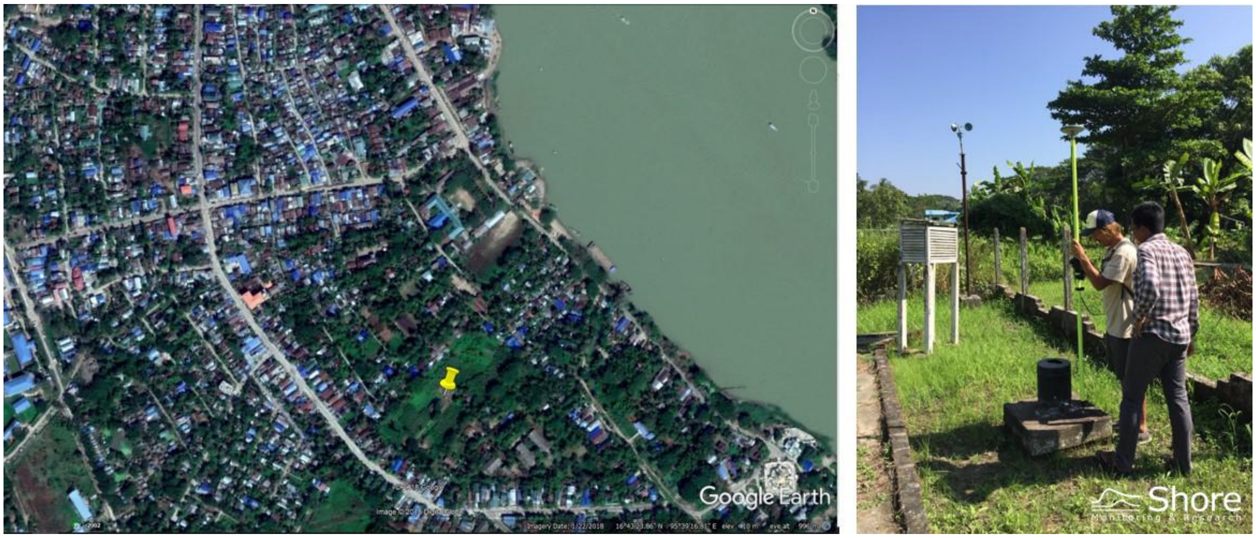

Figure A.27: Geographic location of benchmark Maubin DMH2 (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.27 below:

Table A.27: Coordinates existing benchmark Maubin DMH2

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Maubin DMH2	783104,755	1850659,482	46 N	-44,792	4,032

A.2.10 Benchmark Samalauk IWUMD

Existing benchmark of ID

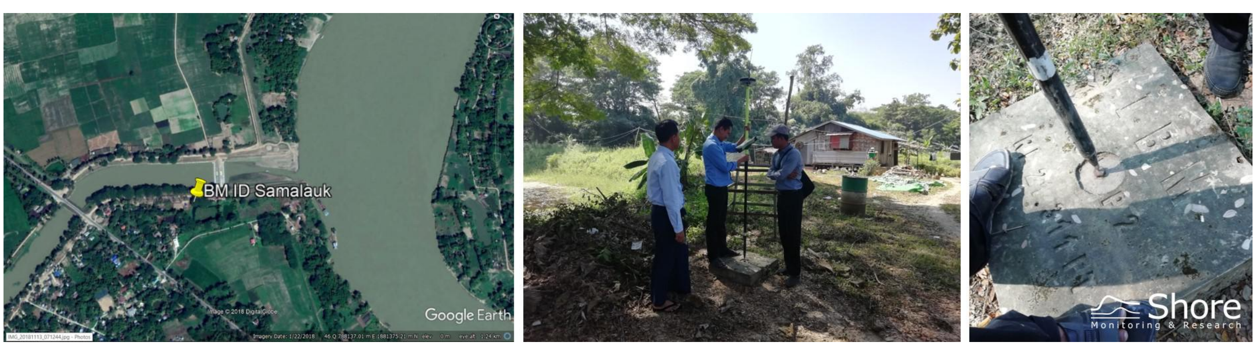

Figure A.28: Geographic location of benchmark SAMALAUK IWUMD (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.28 below:

Table A.28: Coordinates existing benchmark Samalauk IWUMD

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Samalauk IWUMD	788009,747	1881300,226	46 N	-41,028	7,909

A.2.11 Benchmark Mezali IWUMD North Sluice

Figure A.29: Geographic location of benchmark Mezali IWUMD North Sluice (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.29 below:

Table A.29: Coordinates Mezali IWUMD North Sluice

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Mezali IWUMD North Sluice	796961,851	1876084,275	46 N	-40,456	8,105

A.2.12 Benchmark Tawa IWUMD1

Figure A.30: Geographic location of benchmark Tawa IWUMD1 (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.30 below:

Table A.30: Coordinates Tawa IWUMD1

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Tawa IWUMD1	233644,969	1905122,616	47 N	-39,556	6,542

A.2.13 Benchmark Tawa IWUMD2

Figure A.31: Geographic location of benchmark Tawa IWUMD2 (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.31 below:

Table A.31: Coordinates Tawa IWUMD2

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Tawa IWUMD2	233913,969	1905136,058	47 N	-37,848	8,241

A.2.14 Benchmark Bago DMH

Figure A.32: Geographic location of benchmark Bago DMH (left panel). GNSS setup over benchmark (center panel) and detail of benchmark (right panel).

The final coordinates are presented in Tab. A.32 below:

Table A.32: Coordinates Bago DMH

Point ID:	X (m)	Y (m)	UTM Zone	Z (m) WGS84	Z (m) EGM08
Benchmark Bago DMH	232193,001	1918241,142	47 N	-35,210	10,843

Appendix B Historic Water Level Scales

B.1 Water Level Scale DMH Bago

Figure B.1: Water level scale Bago. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.2 Water Level Scale IWUMD Tawa inside Sluice

Figure B.2: Water level scale Tawa inside Sluice. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.3 Water Level Scale IWUMD Tawa outside Sluice

Figure B.3: Water level scale Tawa outside Sluice. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.4 Water Level Scale IWUMD Tawa Bago River

Figure B.4: Water level scale Tawa Bago River. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.5 Water Level Scale DWIR Twantay 3.5Mile

Figure B.5: Water level scale Twantay 3.5 mile. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.6 Water Level Scale IWUMD Samalauk inside

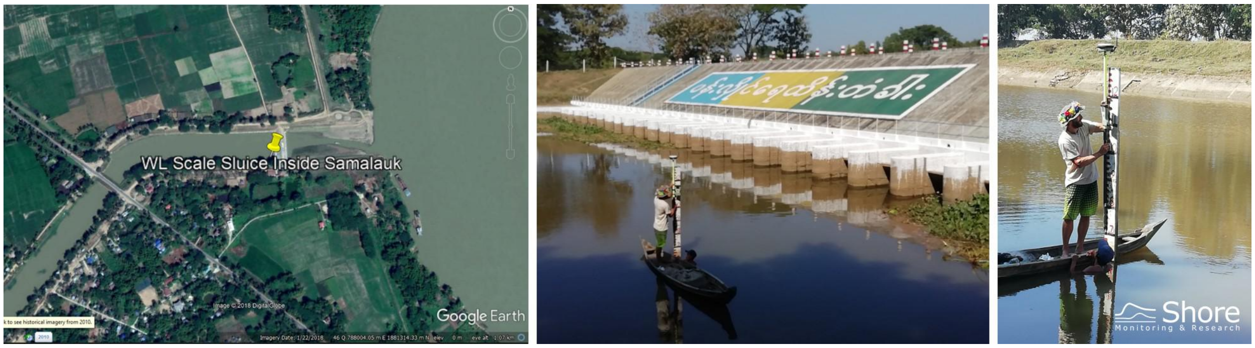

Figure B.6: Water level scale Samalauk inside. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.7 Water Level Scale IWUMD Samalauk outside

Figure B.7: Water level scale Samalauk outside. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.8 Water Level Scale IWUMD Mezali North sluice Low Level

Figure B.8: Water level scale Mezali North Sluice Low Level. Top left panel: Geographic location. Bottom left panel: Overview of location. Bottom right panel: Close up of measuring reference point. Top right panel: Detail of measuring offset

B.9 Water Level Scale IWUMD Mezali North sluice High Level

Figure B.9: Water level scale Mezali North sluice High Level. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

B.10 Water Level Scale IWUMD Nyaungdon

Figure B.10: Water level scale Nyaungdon. Left panel: Geographic location. Right panel: Close up of measuring reference point

B.11 Water Level Scale DWIR Twantay 21 Mile

Figure B.11

B.12 Water Level Scale DMH Maubin

Figure B.12: Water level scale Maubin. Top left panel: Geographic location. Bottom left panel: Schematic of measuring location and example of a written log. Right panel: Overview of location

B.13 Water Level Scale DMH Zalun

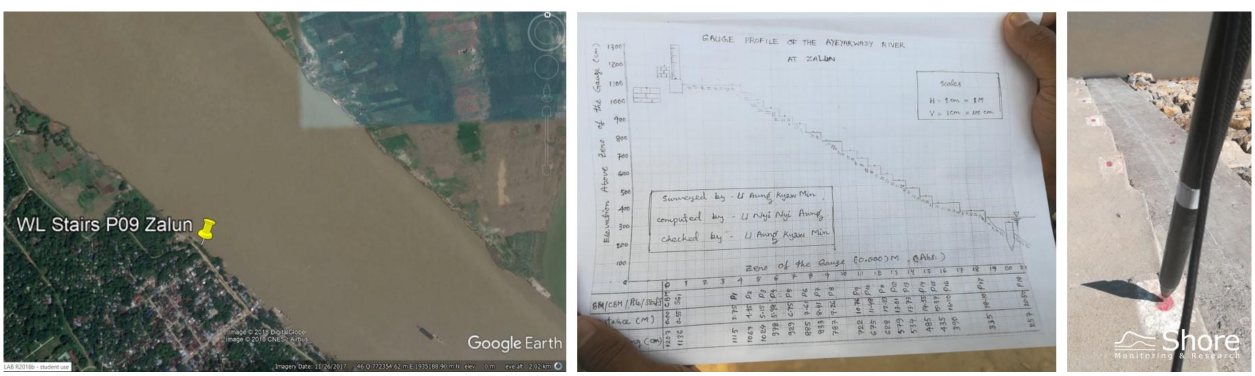

Figure B.13: Water level scale Zalun. Left panel: Geographic location. Center panel: Schematic of measuring location. Right panel: Close up of measuring reference point

B.14 Water Level Scale DMH Hinthada

Figure B.14: Water level scale Hinthada. Top left panel: Geographic location. Bottom left panel: Example of written log. Bottom right panel: Overview of measuring location. Right panel: Close up of measuring reference point

B.15 Water Level Scale DMH Pyay

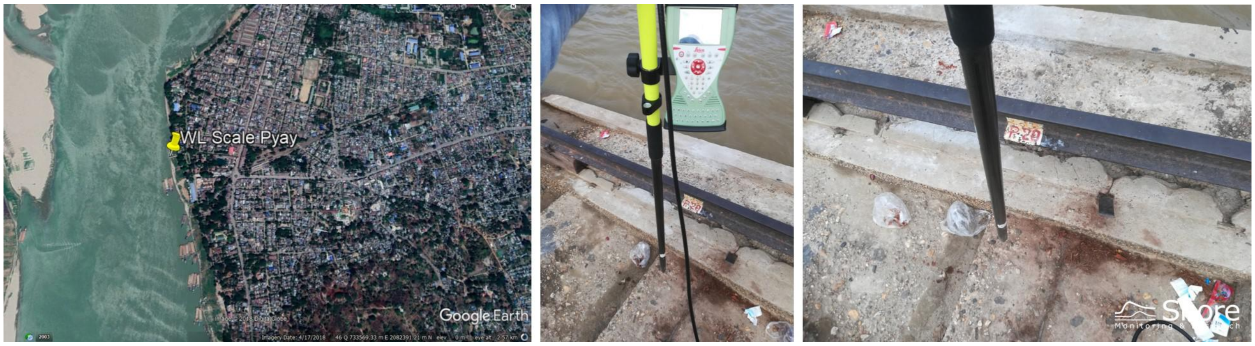

Figure B.15: Water level scale Pyay. Left panel: Geographic location. Center panel: Overview of location. Right panel: Close up of measuring reference point

Appendix C Details new Water Level Loggers

C.1 Water level logger Elephant Point

Figure C.1: Installation of Water level logger Elephant point. Left panel: location of CTD. Center panel: Location of Modem. Right panel: location of GNSS Reference Point.

C.2 Water level logger Monkey Point

Figure C.2: Installation of Water level logger Monkey point. Left panel: location of CTD. Center panel: Location of Modem. Right panel: location of GNSS Reference Point.

C.3 Water level logger Nyaungdon

Figure C.3: Installation of Water level logger Nyaungdon point. Left panel: location of CTD. Center panel: Location of Modem. Right panel: location of GNSS Reference Point.

C.4 Water level logger Tawa

Figure C.4: Installation of Water level logger Tawa. Left panel: location of CTD. Center panel: Location of Modem. Right panel: location of GNSS Reference Point.

C.5 Water level logger Hle Seik

Figure C.5: Installation of Water level logger Hle Seik. Left panel: location of CTD and reference point.Right panel: overview of location

Appendix D Bathymetric Survey System

D.1 Introduction

The bathymetric survey system is a combination of multiple instruments that together form a modular survey kit that can be used on a variety of vessels. The modular character of the system increases the flexibility as the type of vessel can be selected based on specific local conditions and is not restricted to fixed setups. In this introduction the survey system with corresponding instruments is introduced based on deployment on a vessel (Fig. D.1).

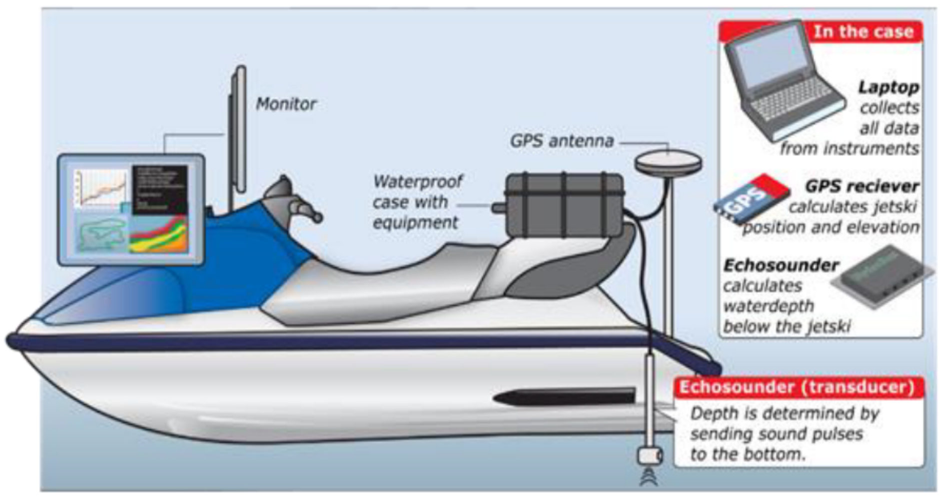

Figure D.1: The instrument setup for a bathymetric survey. Example of deployment on a vessel

The water depth under the vessel is measured with a Hydrobox Single Beam Echo Sounder (SBES, frequency 10 Hz). The SBES sends sound pulses towards the bottom which reflect and are received back by the SBES sounder. From the time between sending and receiving a pulse and the speed of sound through water, the water depth under the echo sounder can be determined.

The speed of sound through water varies based on differences in water temperature and salinity. Therefore, CTD-measurements are performed multiple times during a survey to collect the necessary information. Locations of CTD-measurements are carefully selected, based on expected spatial gradients in the speed of sound among the surveyed area.

The survey system is equipped with a motion sensor to log movement (pitch / roll) of the vessel. The logged movements are used to correct/reject the depth measurements for pitch and roll.

A dual frequency (L1/L2) RTK GPS and GLONASS (GNSS) receiver with real time radio/GPRS/3G connection with a GNSS base station or reference network is used. Its antenna is placed in one vertical axis with the SBES transducer of which the offset is measured carefully before deployment of the survey system on a 'new' vessel. The GNSS receiver logs the X,Y,Z position of the vessel at 2 Hz. RTK technique is used to obtain centimeter positional accuracy.

The latency between the instruments is calculated from the correlation between the time series of the vessel's GNSS elevation and the sounding depths below the vessel. The presence of waves results in vertical movement (heave) in the vessel elevation, which is reflected in an equal variation in the depth measured below the vessel. The time shift to correlate maxima of both signals is the resulting latency, with which the sounding depths are corrected.

The final measurement of the elevation of the bed level is then obtained from the elevation of the GNSS (z_{GNSS}) subtracted with the vertical offset between the GNSS antenna and SBES (z_{offset}) and the depth measured by the SBES (d):

$$z_{bedlevel} = z_{GNSS} - z_{offset} - d \tag{D.1}$$

The above is illustrated in Figure D.2 below.

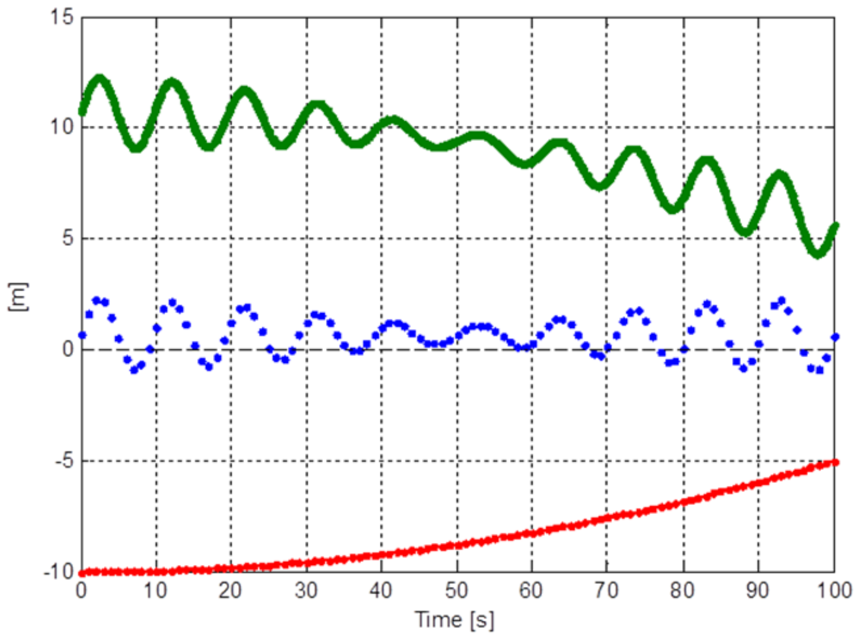

Figure D.2: Calculation of the bed level. The green line shows the 10 Hz measurements of depth under the SBES. The blue points correspond to the 2 Hz RTK-GPS elevation of the vessel *at the bottom of the SBES* ($z_{GNSS} - z_{offset}$). The resulting bottom level (2 Hz) is obtained by subtracting both signals and is shown in red.

Details of the instruments of the survey system are summarized in Table D.1 below:

Table D.1: Overview of used instruments and corresponding accuracy. The accuracy is based on the manufacturer's declaration

Instrument:	**Brand and type:**	**Accuracy:**
SBES	Syqwest Hydrobox 210kHz	± 0.01 m +/- 1% depth
RTK-GNSS	Septentrio AsteRx	± 1 cm + 1 mm/km
Speed of sound sensor	YSI Castaway CTD	± 0.15m/s
Motion sensor	SBG Ellipse 2 E	Roll/Pitch 0.1°

The survey system is completed with a wireless monitor kit and waterproof case containing hardware and a rugged laptop are used to collect and display the survey data real-time. The monitor shows the operator all data needed for a safe, accurate and effective survey: real-time sensor status, speed, position, depth, GNSS statistics, survey tracks, sailed tracks, background drawings etc.

D.2 Details motion correction and latency

D.2.1 Motion correction (heave, pitch and roll)

D.2.1.1 Heave

The heave motion of the vessel is not compensated for with a heave compensator due to the high accuracy of the GNSS positioning. A heave sensor will record (and compensate for) the changes in vertical positioning of the vessel, which is done in the bathymetric surveys by using the elevation data from the GNSS. The vertical accuracy of the GNSS is smaller than 3 cm due to the close proximity of the GNSS base station that was used to compute the positions.

As the GNSS antenna and the transducer are in one fixed vertical line, no separate compensation is needed for the dynamic draft of the vessel as function of the vessel speed.

D.2.1.2 Pitch and roll

Two sources of vertical error can be distinguished when the vessel pitches or rolls. Firstly there is a small change in the vertical distance of the GNSS antenna to the transducer (dz in Fig. D.3). As the distance between these instruments is small, this effect is limited.

The second source of error is due to the angle of the transducer. The transducer of the SBES transmits 210kHz pulses in a cone-like beam of which the central lobe has a beam angle of 8 degrees. Within this cone the bottom is recognized as reflection point of the signal. Under conditions with small rotation angles, the smallest distance within this beam (d in Fig. D.3) corresponds to the actual depth and no compensation is needed for the roll of the vessel. For large angles of roll (Fig. D.3, right panel), the smallest distance within the cone, d, deviates from the actual depth d.

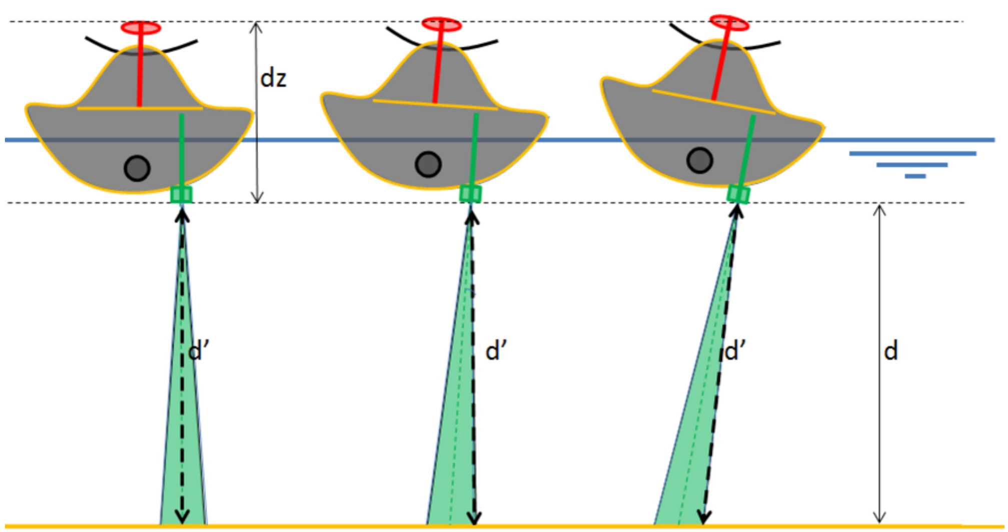

Figure D.3: Schematic of the vessel with GNSS and SBES for different angles of roll. From left to right: upright position, small angles of roll (within the SBES beam angle) and large angles of roll

The rotational motions of the vessel are logged by a motion sensor. When the logged rotational motions result in the situation shown in the right panel of Fig. D.3, the corresponding depth measurements are rejected.

D.2.2 Latency correction

The heave motion is on the timescale of individual waves and is used to resolve the relative latency of the GNSS device with respect to the echo sounder. Hereto, small fragments of both time series are analysed. If these fragments are inspected closely, a small shift between the peaks in both signals can be observed due to the latency (Fig D.4). The timing of the echosounder signal is slightly adjusted by increments of 0.1 s, after which the correlation between the GNSS elevation and shifted echosounder signal is calculated as:

$$R_{x(t_0)y(t_0+\tau)} = \frac{\overline{xy}(t_0;\tau)}{[\overline{x^2(t_0)y^2(t_0+\tau)}]^{0.5}} \tag{D.2}$$

Where R_{xy} represents the correlation function, $x(t)$ is the elevation signal of the GNSS and $y(t+\tau)$ is the signal of the echosounder (shifted by time offset τ). The time shift that gives the largest value of the correlation function, i.e. the best alignment of both signals, is taken as the value for the relative latency between both instruments (Fig. D.4, right panel).

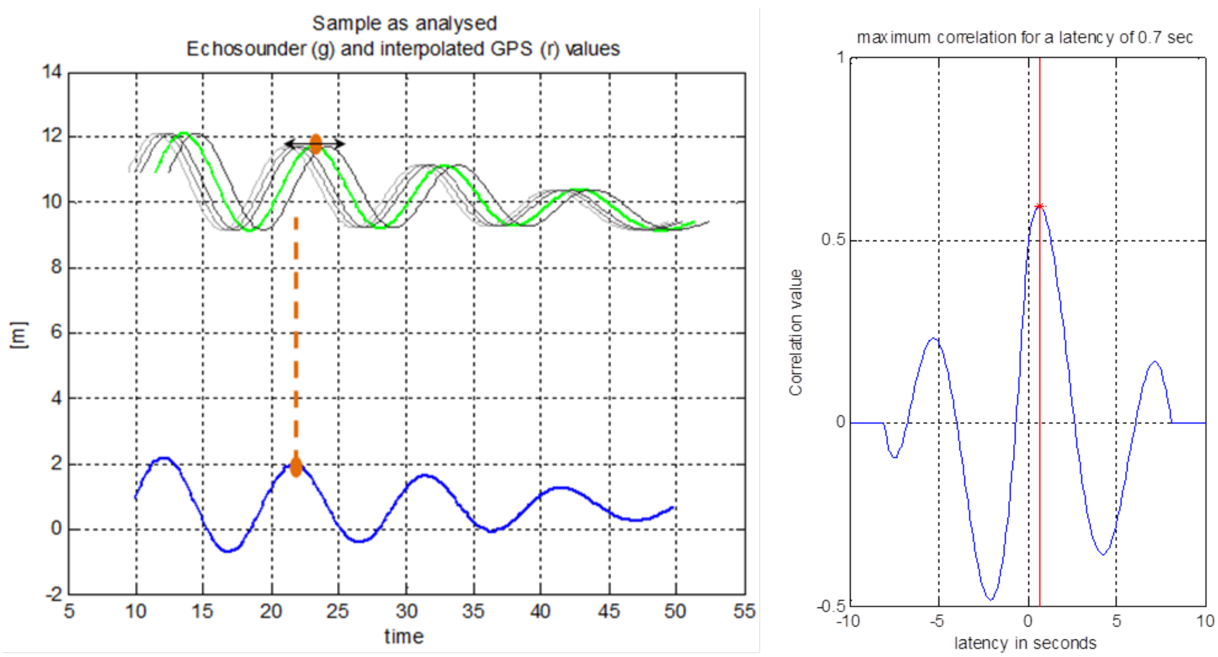

Figure D.4: Left panel: The calculation of the latency. The timing of the echo sounder signal (green) is adjusted slightly (light gray realisations) to obtain the best alignment with the GNSS elevation signal (in blue). Right panel: The correlation function of the GNSS elevation signal and the echosounder signal as function of different time lags (latency). Maximum correlation in this example is found for a latency of 0.7 s.

The latency value is checked for several subsets of the entire survey, but is generally not varying as it is mostly determined by the hardware configuration. Nevertheless, the latency test is done for each of the recordings, as part of the standard quality control.

D.3 Quality control

D.3.1 Control of SBES signal

The measured SBES signal is checked on outliers and other sources of noise. If present, outliers and noise are removed from the signal.

D.3.2 Control of quality GNSS-signal

The GNSS signal is checked on the availability of a RTK solution. Points that are aqcuired without a RTK fix are removed from the dataset.

D.3.3 Crossing analysis

The crossings of the cross-shore and alongshore survey tracks are analyzed, with the purpose to show the accuracy/robustness of the survey method. The analysis is based on the bottom level elevation of the survey points of the alongshore and cross shore tracks in the vicinity of the crossing location.

The methodology contains the following steps:

1. Identification of the locations of crossings between alongshore and cross-shore tracks.
2. Listing of all survey points in an area of 10 by 10 meter centered around the crossing. This area is chosen to be rather small (10x 10 m) to minimize large variations in bottom level within the area investigated. Taking a larger area will result in larger standard deviations, which are not the result of the accuracy of the survey system, but resulting from the actual gradients in the bed level, even on mildly sloping beaches.
3. Calculating the statistics of the points per crossing. Three main statistics are calculated:

   A The number of points n in the 10x10 meter area around the crossing
   B The mean bed level μ at the crossing obtained by using $\mu = \Sigma z_i/n$
   C The standard deviation σ in bed level values at each crossing, obtained using $\sigma^2 = \Sigma(z_i\mu)^2/(n-1)$

The methodology is illustrated using an arbitrary crossing from a bathymetric survey in Ghana performed in 2015 (Fig. D.5). The crossing contains data of two cross shore tracks (one from the beach to intermediate water depth, and one from intermediate water to deep water) and the alongshore track.

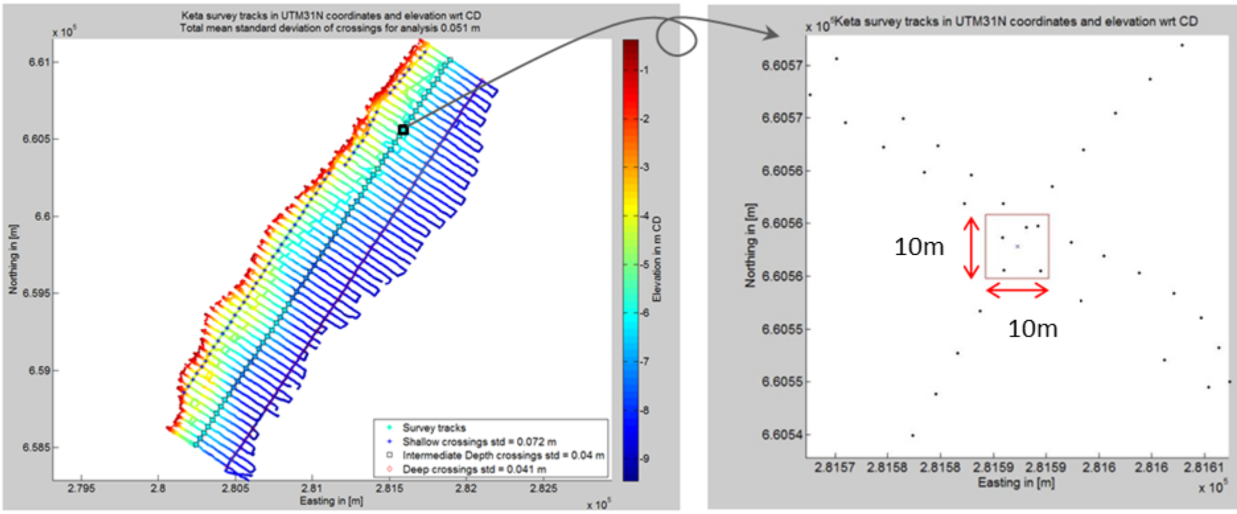

Figure D.5: Left: Survey tracks with crossings of alongshore and cross shore survey tracks. Right: Detailed view of crossing of an alongshore and cross shore track in intermediate water. Red square indicates the 10x10m area surrounding the crossing that has been investigated, black dots are the individual bed level measurements.

The survey point data in the vicinity (10x10m area) of the crossing are given in Tab. D.2. The mean water depth at the evaluated location is -5.84 m and the 5 points have a standard deviation of 3 cm.

Table D.2: Example crossings analysis values

Point nr.	Elevation bed in point in CD
1	-5.8302 m
2	-5.8124 m
3	-5.8901 m
4	-5.8444 m
5	-5.8251 m
	Mean μ = -5.8405 m, Standard deviation σ = 0.0300 m

Next, the results of all crossings are averaged per alongshore track to obtain bulk values per depth zone. The following results were obtained for the example survey (Tab. D.3).

Table D.3: Example crossings analysis values per depth zone

Alongshore transect	Number of crossings	Average bed level at crossings	Average standard deviation of bed level in survey points at crossings
Near the beach	51	-4.09 m CD	0.072 m
At intermediate water depth	61	-6.53 m CD	0.040 m
Near deep water boundary of survey	59	-8.19 m CD	0.041 m