# OPEN PROFILE

## Final Report

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WMO Hydrological Research Agenda


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# OPEN PROFILE

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# Contents

# 1 Introduction

## 1.1 Purpose

This final report of the project Open Profile, funded in the WMO hydrological research agenda call of 2023, focusses on the outcomes of the project. In the project, a method has been developed for affordable, low complexity surveying of bathymetry of streams and reservoirs. Proof-of-concept software has been developed that interprets the collected data and derives,for alluvial streams, parameters of the stream section related to conveyance and the shape of the river section, based on geomorphological laws. Further field campaigns have mainly focused on small to medium-sized reservoirs. In this report, we summarize the developed methods of hardware and software, the experiences gained during several field campaigns of students and the consortium, lessons learned, and suggestions for future work.

## 1.2 Outline

Chapter 2 describes in brief the hardware and software components and how these are available to an end-user. Chapter 3 details our fieldwork experience and the resulting datasets created in Zambia, on Ray reservoir. Chapter 4 shows the scientific benchmarking against proven methods. Chapter 5 describes lessons learned and what is needed to bring the solution to a service level. Finally in Chapter 6 we discuss the results, what was achieved in the project and what are the shortcomings.

**For readers that wish to set up their own service, a full overview of the required hardware components and their costs is provided in Annex A.**

# 2 Hardware and software developments

## 2.1 Hardware design and developments

Requirements for hardware and software were derived from several conversations with stakeholders from WARMA including Frank Nyoni and Douglas Lubaba. The most prominent requirements are:

- The methods should use hardware that is reasonably affordable and can be replaced without too much effort.
- Not only depth must be accurate, for cross sections in smaller streams and rivers, also the position must be accurate.
- The components should be able to withstand fast flow conditions and heat.
- In-field methods should be of low complexity. Ideally a local technician can perform the survey without attendance of a client (e.g. water management authority, irrigation officer, hydropower manager) representative to supervise. The use of a smartphone is seen as a very promising direction.
- The processing in software should be straightforward. Contour lines are an important end result especially if software will be extended eventually to cases applicable to reservoirs.
- Ideally, a tie line measurement should not be required. In many cases, the banks are not easily accessible, e.g. due to vegetation, unstable banks or wildlife.

Hardware developments focused on getting "wet" bathymetry. For the dry part, we use an unmanned aerial vehicle. Typical echo sounders cost in the range of 15,000 USD. Our challenge was to build a method that fulfills the requirements above, yet at a fraction of the cost.

TU Delft and UNZA co-developed a hardware setup that fulfills the requirements. It uses a simple off-the-shelf fish finder and combines this with geographical measurements of location using a very precise Real-Time Kinematic (RTK) Global Navigation Satellite Systems (GNSS) observation method, using uBlox ZED-F9P dual frequency chipsets for the GNSS part.

*Figure 2.1: From top to bottom: GNSS antenna, GNSS chipset (ublox ZED-F9P on an ardusimple breakout board), Android smartphone and a Deeper Chirps 2+ fish finder. Cabling is for connecting the GNSS antenna to chipset and reading GNSS data on the smartphone.*

Since a couple of years, these GNSS chipsets have become highly affordable. Thanks to suppliers such as Ardusimple, highly modular break-out boards make development of new sensing projects relatively easy. The dual frequency nature allows for the use of a base station / rover combination resulting in typical horizontal accuracies of observations within a couple of centimeters. The fish finder sensor was tested to be very accurate if used in a small beam mode. We have a nice configuration that replaces smartphone GNSS positioning with the uBlox chipset's, hence providing very accurate GNSS positioning on a smartphone. This in turn is used by the fishfinder's android app to provide a very accurate position on the bathymetric estimates. The first two requirements are fulfilled with these materials. The materials are shown in Figure 2.1.

The third requirement needed an additional design. Fish finders, even though their sensor is very accurate, are not meant to be used in fast moving water or while dragging them through the water. First tests also revealed that the fish finder can lose WiFi connection with the smartphone. Imagine you want to cross a reservoir to measure bathymetry, you want to do it with some speed in order to get your data fast. Or imagine you want to measure in a stream with two meters per second flow velocities while dragging the sensor from one side to the other on a bridge. Any generally usable solution needs to stabilize the sensor. For moving fast with a boat, Deeper sells a flexible arm mount, but for deployment from a bridge and within a fast flowing stream, a rig is required.

To address these challenges, TU Delft iterated a number of times a rig design to provide stable readings and stable telemetry while using PVC plumbing under the premise that PVC and PVC glue can be acquired in most contexts. The main design requirements for the rig were that it must be easy to assemble, consist of locally available parts, should be stable in high velocity flow conditions, keep electronics dry even if the construction gets submerged.

*Figure 2.2: PVC rig design. The beam towards the center can be used to drag the device across fast flowing water from a bridge. The center cylinder keeps the android phone dry. Full documentation is provided in the hookup guide, see Section X.X.*

The resulting design is small, stable, and has a central positioning beam where a rope can be connected. This prevents the rig becoming unstable if it is operated from a higher point (e.g. a bridge) with high flow velocities. The smartphone is carried in a cylinder shaped opening with a lid. The GNSS antenna and radio are carried on top of that. The rig was tested while moving slowly through the water and while moving fast.

Next, first designs were made and tested with BSc students in Delft, The Netherlands. Hubert Samboko (UNZA) replicated the rig in Zambia and tested it on a diversion channel of the Lunsemfwa River, validating part availability, local production of the design, and stabilization of the sensor in situ. The rig is demonstrated in Figure 2.2.

Several observation trials have been carried out ranging from a very small pond near TU Delft to the "Mooie Nel", a lake near the city of Haarlem. Impressions of the results of these surveys are provided in Figure 2.3 and Figure 2.4. The surveys led to the following conclusions:

- for lakes, sailing with 20 meter contour lines is the most efficient
- a 2 meter per second sailing velocity keeps the fish finder stable enough
- having two smartphones is important: one to keep track of the surveyed locations, and one to keep an eye on the depths.

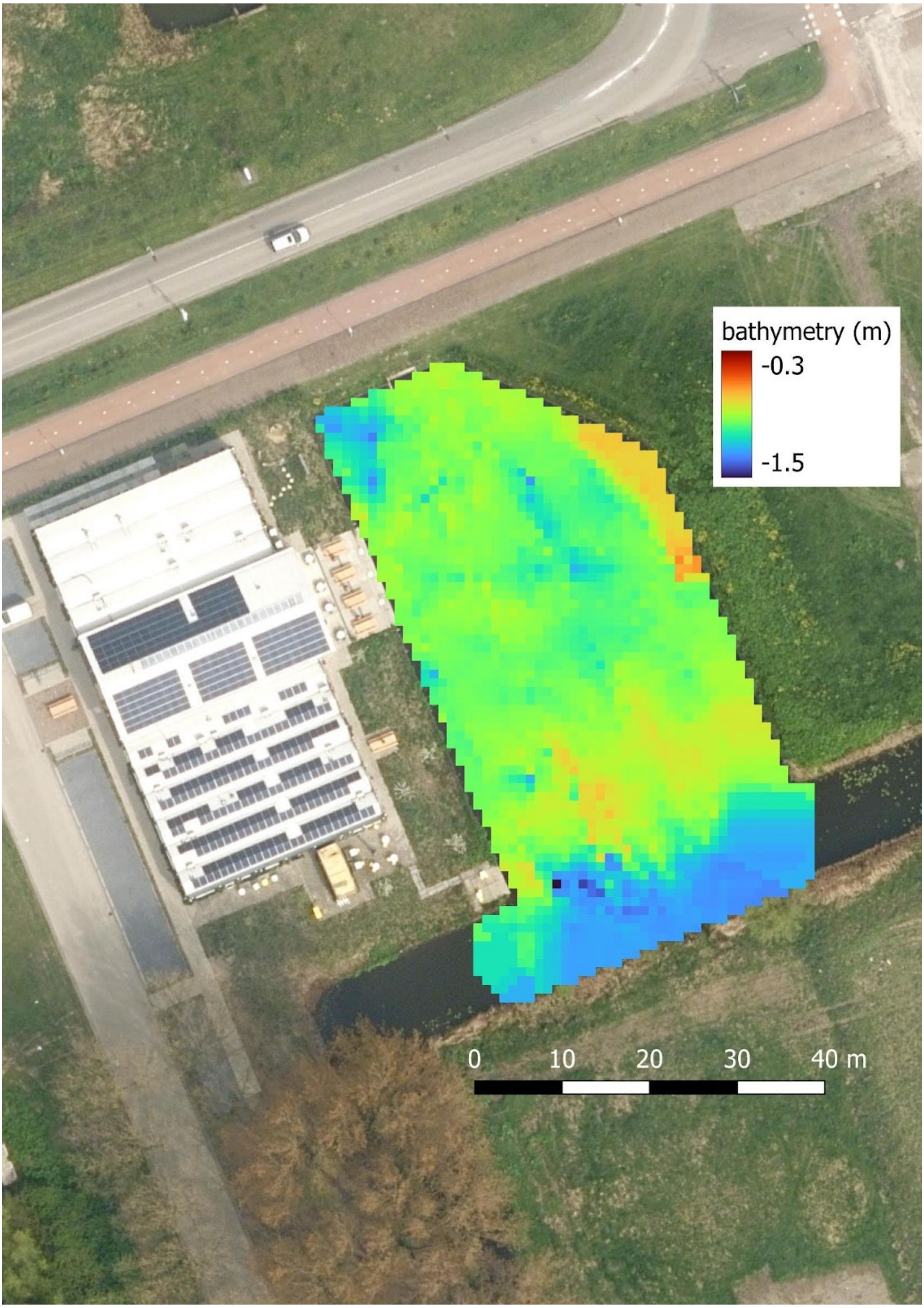

*Figure 2.3: Seamless bathymetry of a small pond near TU Delft - The Netherlands*

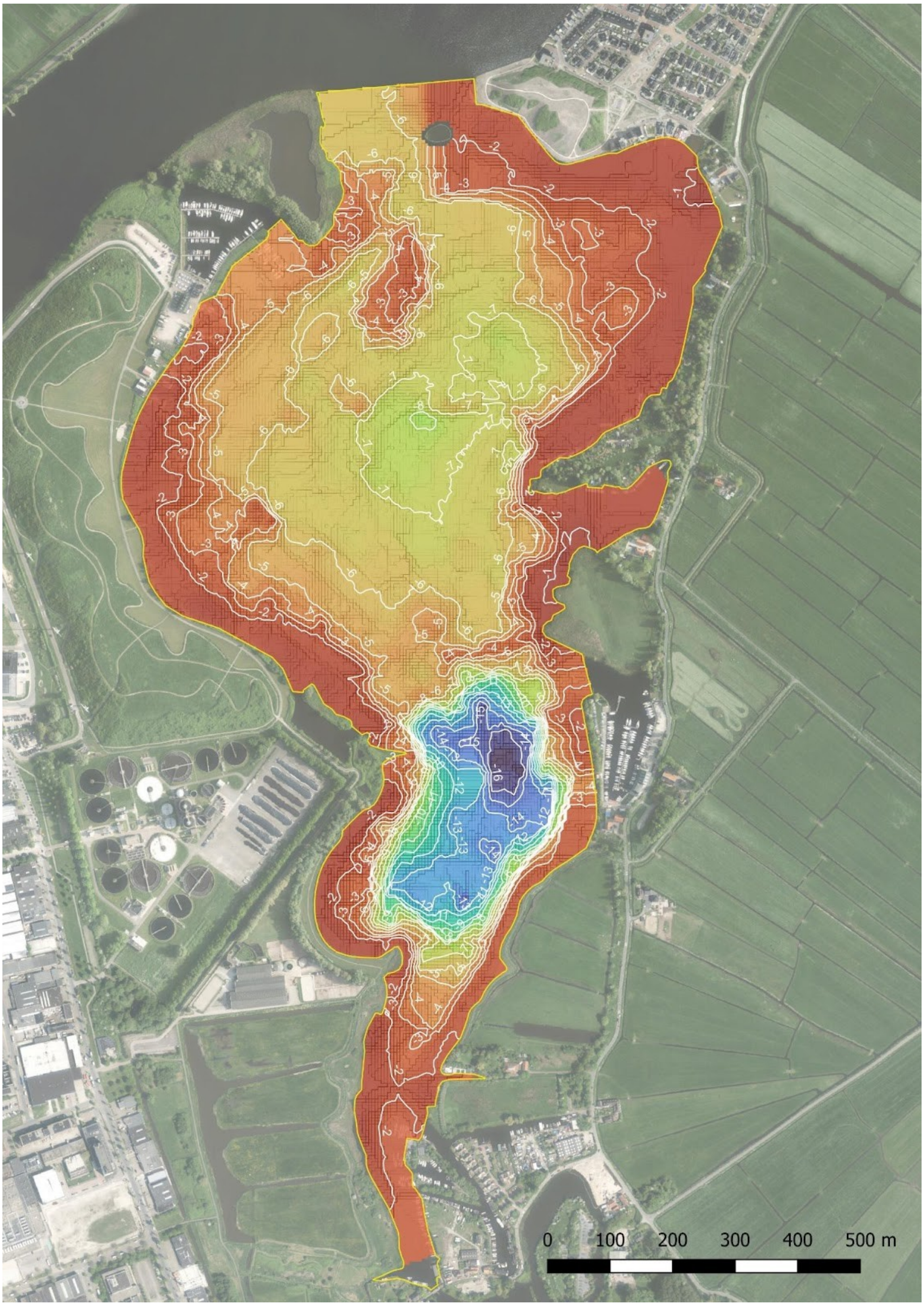


*Figure 2.4: Bathymetry of "Mooie Nel", about 1 km2, surveyed in 5 hours, by sailing following centric contours starting at the outside, moving inside with intervals of about 20 meters.*

Price points of the required hardware (base GNSS station, rover materials, fish finder, cabling and PVC materials) is about 1,500 USD. In addition, the parts are easy to replace if they at some point fail. A typical RTK enabled echo sounder costs in the order of 15,000 USD (excluding a GNSS base station!). With a factor 10 difference in pricing, and easy access to spare parts, we consider our rig design and hardware set up to be very promising for further use anywhere in the world.

## 2.2 Hardware guide

We have prepared a hardware guide that allows one to set up a rig and configure and measure with this set up. The hardware guide can be found on https://docs.google.com/presentation/d/1-20GT_kJZRlo2iy9VqDYBEpLsxQkqFnX/edit?usp=drive_link&ouid=101076572895054203395&rtpof=true&sd=true. It contains explanations of the required components and how to configure them step-by-step. It also describes the required PVC parts to make a floating rig. All configurations can be done on an Android smartphone and with the U-center application! This makes the hardware simple to use as long as instructions are carefully followed.

## 2.3 Software design and developments

In terms of software, we decided to focus on two cases:

- Understanding of bathymetric properties of alluvial streams from a modest set of samples
- Integration of dry (from UAVs) and wet (from the fish finder rig) bathymetry.

### 2.3.1 ORProfile

As it is expected that a river survey offers the most complex situation in terms of interpretation of the data, we decided to develop several methods that can interpret a relatively sparse wet bathymetry survey into a better understanding of the stream's conveyance. We have provisionally called the software "OpenRiverProfile" abbreviated to ORProfile. The software in principle does the following:

1. Read data from one or several surveys, using the above-mentioned CHIRPS fish finder. The data format can be directly read and interpreted

2. Create a curvilinear mesh that follows as closely as possible the dry/wet interface (e.g. based on a GNSS survey of the wet/dry interface). By following a convention in the order of the provided splines for the curvilinear grid, the grid "knows" what upstream and downstream is.

3. Create a bathymetry, by providing a set of 5 parameters:

- $A$ [$m^2$]: the wetted surface (assumed constant over the entire longitudinal reach).

- $c$ [-]: dimensionless constant defining how the largest depth over a cross-section relates to the grid width at any given location. This is the typical Lacey law, i.e. that there is a depth / width ratio, dependent on the sediment types (fine sediments: depth/width is small, coarse sediments: depth/width is large)
- $\alpha$ [m]: the amplitude of the offset from the center of the deepest point. This parameter measures the scale of the meanders.
- $L$ [m]: the length scale (wave length) of the offset of deepest point sinus.
- $\kappa$ [rad]: the phase of the deepest point sinus.

4. Apply an optimization to fit the aforementioned parameters. This optimization function typically is quite well capable of fitting *A*, *c* and $\alpha$. Our first experiences demonstrated that L and $\kappa$ are optimized less well, likely because these are smaller scale features and can also be significantly influenced by features on the banks or upstream in the water such as closeby bridges and roads.

The method can easily be applied by modifying a script or a Jupyter notebook. A full example with a complete dataset for Bamboi bridge (Ghana) is included in the repository. With this Jupyter notebook, a user can go through all steps and re-implement them with their own data. The software can be found on https://github.com/localdevices/ORProfile. More details and a much broader description of the background and theory of the code can be found in the README of the software and the Jupyter notebooks that are available along with the code.

### 2.3.2 DEM blender

The seamless merging of terrain datasets requires a method that takes care of information on the overlaps between the two datasets. In particular at the edge of lakes and reservoirs, this requires a careful approach to come up with a seamless dataset. DEM blender was released to manage this. A user can provide a folder with several terrain models stored a GeoTIFF files. On their edges with overlap, the terrain models are merged by using euclidean distances to the edge to weigh both terrain model's values.

# 3 Fieldwork Zambia

Demonstration fieldwork was conducted for the Water Resources Management Authority of Zambia (WARMA). In close consultation with the Operations Manager of WARMA, Mr. Douglas Lubaba, the Ray reservoir was chosen. This reservoir at normal conditions is about 2.5 km2 in size. The water is primarily used for irrigation.

The objectives of this fieldwork were:

- Establish the technical viability of the measurement approach. This was done by a cross-comparison with depth observations collected with an ADCP.
- Establish the level of effort required to survey significant portions of a reservoir.
- Engage with end-user WARMA to assess if they see value in a locally provided service using our methods.

Combined, these three objectives provide insight into the viability for uptake by end-users directly, or entrepreneurs that provide services to end-users.

## 3.1 End-user engagement

We engaged with WARMA to identify if they are a logical end-user. From our discussions, we can summarize the following:

- Affordable low complexity methods are very much appreciated by WARMA.
- A large issue with WARMA is the relatively low number of available staff for surveying. Hence a logical approach to implementation with WARMA is to offer bathymetry surveying as a service, delivered by a local entrepreneur. This requires an affordable approach in terms of used materials, so that the threshold for a local entrepreneur to start providing this is relatively low.
- Surveys are needed and necessary for checking for surface water storage permits. Sometimes impoundments are made or modified to store more water than allowed under the provided permit.
- Surveying for sediment accumulation is important in case reservoirs lose capacity.
- The issue is also timely because of the current (3rd quarter 2024) ongoing crippling drought.

## 3.2 Fieldwork instrumentation

During the fieldwork, the following data were collected:

- Deeper Chirps 2+ (as mentioned in the hardware) and GNSS combined survey points over the entire reservoir.
- Drone surveys using a Parrot Anafi and a DJI Phantom 4 Pro (about 50/50%) over a significant portion of the dry part of the reservoir with 70% overlap in both directions, and flown at maximum allowed altitude.
- ADCP soundings using a Teledyne RD Instruments  - RiverRay ADCP.
- A water line around the reservoir with GNSS base/rover set up. This was done by walking along the shoreline with the rover, whilst keeping the antenna in a hat.

For the surveys on the reservoir, a boat was made available by WARMA, and operated by coxswain Mr. Chris Ntobolo.

### 3.2.1 GNSS station and surveying

The GNSS Base station was set up on the dam wall with the receiver antenna on the top of a Toyota Landcruiser (see Figure 3.1), using an LR radio for transmitting correction messages to the rover station using Real Time Kinematics (RTK). For surveying further away and for the waterline, the base station was also moved several times using a tripod (see Figure 3.2). The entire set up, and components are shown in Figure 2.1.

*Figure 3.1: Base station on vehicle*

*Figure 3.2: Base station on tripod*

### 3.2.2 Fish finder surveying

The mobile materials used for the fish finder survey are shown in Figure 2.1. Figure 3.3 shows how the mobile rig was carried on the boat. The right-hand side shows that a Deeper chirps clamp was used to keep the fish finder stable (costs: about 50 USD). Figure 3.4 demonstrates the side-by-side survey with ADCP. Only the bottom-tracking data of the ADCP was used for further analysis.

*Figure 3.3: GNSS and fish finder set up on boat*

*Figure 3.4: ADCP instrumentation side-by-side with fish finder set up for validation*

### 3.2.3 Drone operations

Drone operations were conducted using a fleet consisting of two consumer grade RGB camera drones. The two UAVs were the Parrot ANAFI DJI Phantom 4 quadcopter. Table 3.1 gives a brief outline of the drone specifications. Note that other consumer drones can also do this work, as long as they support autonomous flight planning and execution.

*Table 3.1: Specifications of drone materials used*

| Specification | Parrot Anafi | DJI Phantom 4 |
|---|---|---|
| Weight: | 386g | 1380 g |
| Transmission system: | Wi-Fi | Radio |
| Max transmission range: | 4km | 5km |
| Battery type: | Lipo (2 cells) | LiPo 4S |
| Battery life: | 25 min | 28 min |
| Wide Resolution: | 21MP | 12.4MP |

To map the dry bathymetry, flight plans were created using two main Android App flight applications: Pix4D Capture and DroneDeploy's 'Flight' app. The flight plans are used to let the drone fly and capture imagery entirely autonomously. The pilot only has to keep the drone in direct line of sight for security reasons. Due to intermittent and sometimes unavailable internet connections, both mobile applications had to be used interchangeably. A total of 1,375 images were collected across an area of approximately 9 $km^2$ (perimeter - 17 km). The flight path followed a typical grid pattern, with the camera tilted slightly off nadir (angle >5°). The drone's average speed was maintained at 10 m/s, and the altitude was kept at the highest permissible height according to local regulations (440 feet = 120 meters). In some instances, new flight paths had to be created onsite to ensure there were no gaps in the data. The aim was to map the entirety of the reservoir up to the spillway level. The campaign was completed in approximately 7 days due to the limited availability of drone batteries. The remoteness of the site made recharging the available batteries tedious and time-consuming. Additionally, a significant amount of time was spent trekking through wide areas of land to maintain a constant visual line of sight (CAA Regulation) and to conserve battery life. Typically, the drone is able to fly maps while moving from location to location, ensuring a continuous field of view (Figure 3.5). An overview of the photos obtained through all drone flights is provided in Figure 3.6.


*Figure 3.5: Drone operations*

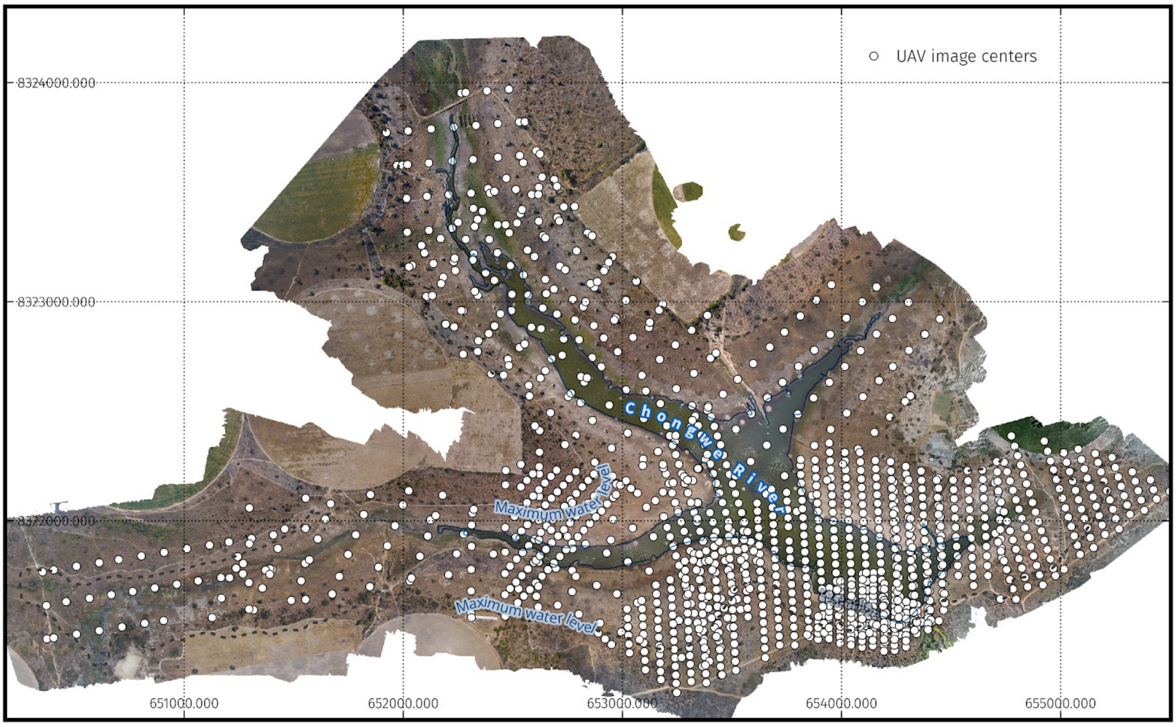


*Figure 3.6: Map of camera positions of all photos used in OpenDroneMap*

## 3.3 Fieldwork data

In summary, the data collection resulted in the following datasets:

- Bathymetry points up to a minimum depth of about 0.6 m (the fish finder can measure shallower water, but the boat was too deep for this). A total of 35,106 points were collected at a spacing of roughly 1.5 meters.
- The location of the shoreline, by walking along the shoreline with a GNSS antenna tied up in a hat. This is used to have a zero-meter boundary for interpolation of the bathymetry points, and align the RGB-drone terrain data.
- 1,375 Raw RGB photos covering the dry parts of the reservoir. The photos are used in OpenDroneMap's WebODM to establish a dry-bed terrain dataset through photogrammetry. Due to limited time for ground control, we post-processed the dry bed bathymetry data using an innovative merging through use of much coarser satellite terrain data MERIT Hydro and field data. We recommend for future applications to use an RTK enabled drone, in combination with the base station.

We describe the data and the treatment and merging procedures in the subsequent subsections.

### 3.3.1 Bathymetry and waterline data

The waterline dataset was entirely connected in QGIS and subsequently used as samples of zero-meter water depth in order to establish a complete result. The zero-meter samples were combined with the bathymetry points collected with the fish finder and interpolated to a 2m resolution grid. The resulting wet bathymetry map is shown in Figure 3.7. The procedure is very straightforward and can easily be replicated by a person with some knowledge in QGIS.

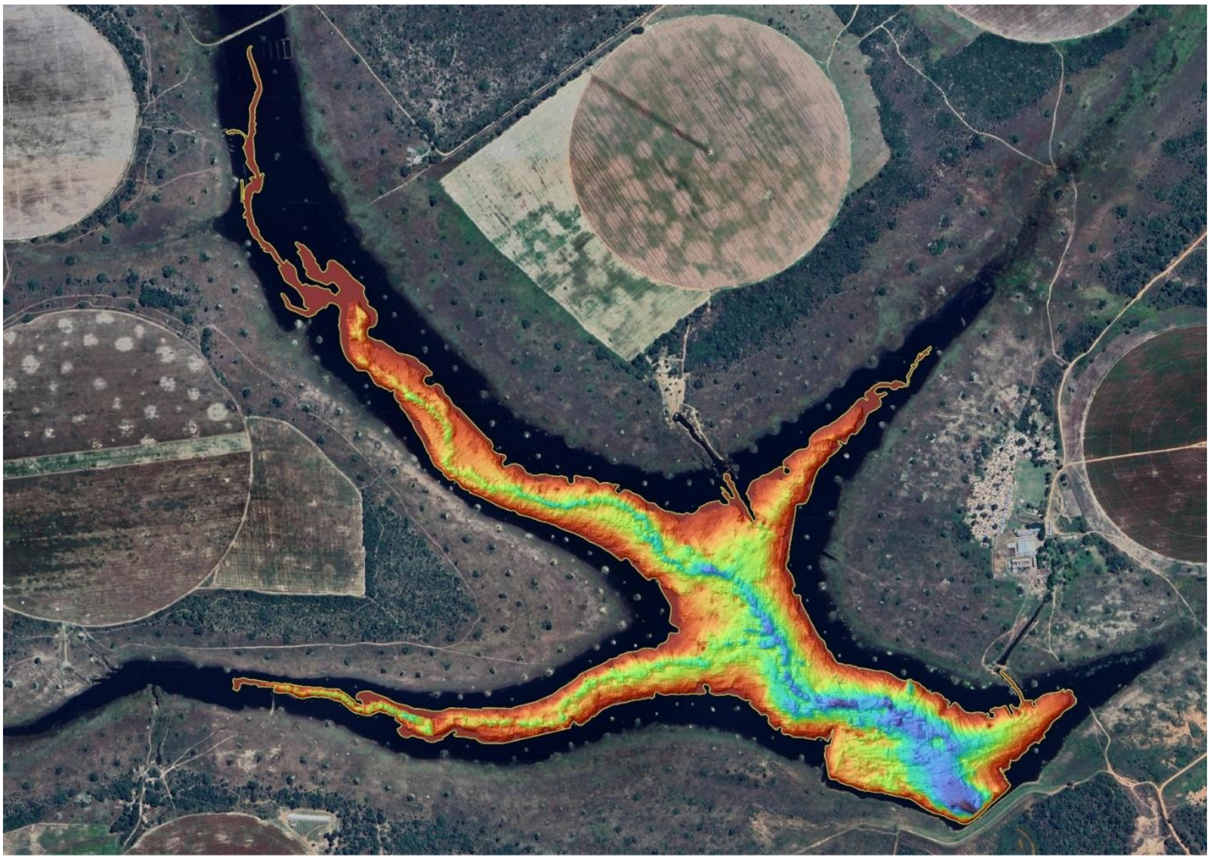

*Figure 3.7: Hill shade view of bathymetry raster (2m) resulting from waterline and fish finder survey.*

### 3.3.2 UAV point cloud and merging

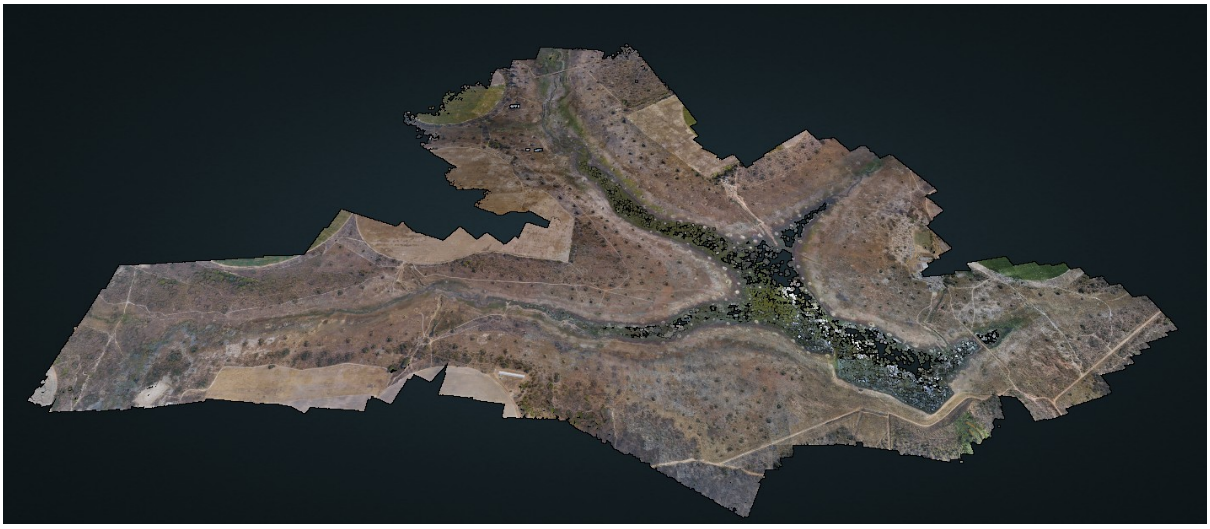

*Figure 3.8: 3-dimensional point cloud from WebODM processing.*

The UAV point cloud (see Figure 3.8) was filtered out from the wet part (photogrammetry cannot resolve on open water) and the remaining points interpolated and combined with the wet bathymetry. For seamless bathymetry merged from the wet and dry data, two characteristics are required: *accurate* and *consistent* wet and dry bathymetry. To make this easier, in future surveys, we recommend deploying with either an RTK drone or ground control points to ensure accurate landscape shape for dry bathymetry, particularly for reservoirs of this size that require multiple days of flights. As we were not flying an RTK drone, we had biases in our dry bathymetry which needed corrected prior to conflating and merging with wet bathymetry. As these errors were low frequency errors associated with drone elevation errors and inconsistencies between days, we derived corrections from larger global scale data.

We used MERIT Hydro as a global standard for hydrologically adjusted elevations, prior to combination with wet bathymetry, we employed a technique to adjust our dry bed bathymetry to match the low frequency component of MERIT Hydro data. To do so, we took the following steps:

1. Resampled MERIT Hydro to 180m resolution using Lanczos resampling via the GDAL library
2. Resampled dry bed data to 180m resolution using Lanczos
3. Calculated the difference between MERIT Hydro and dry bed elevations
4. Resampled the difference to the dry bed elevation resolution (1 meter) using Lanczos
5. Added the resampled distance to the dry bed bathymetry in order to apply the differences as a correction.

This resulted in a more accurate representation of the terrain as exemplified by the flow directions. Figure 3.9 show these before the correction, and Figure 3.10 shows this after the correction. The procedure is schematized in Figure 3.11.

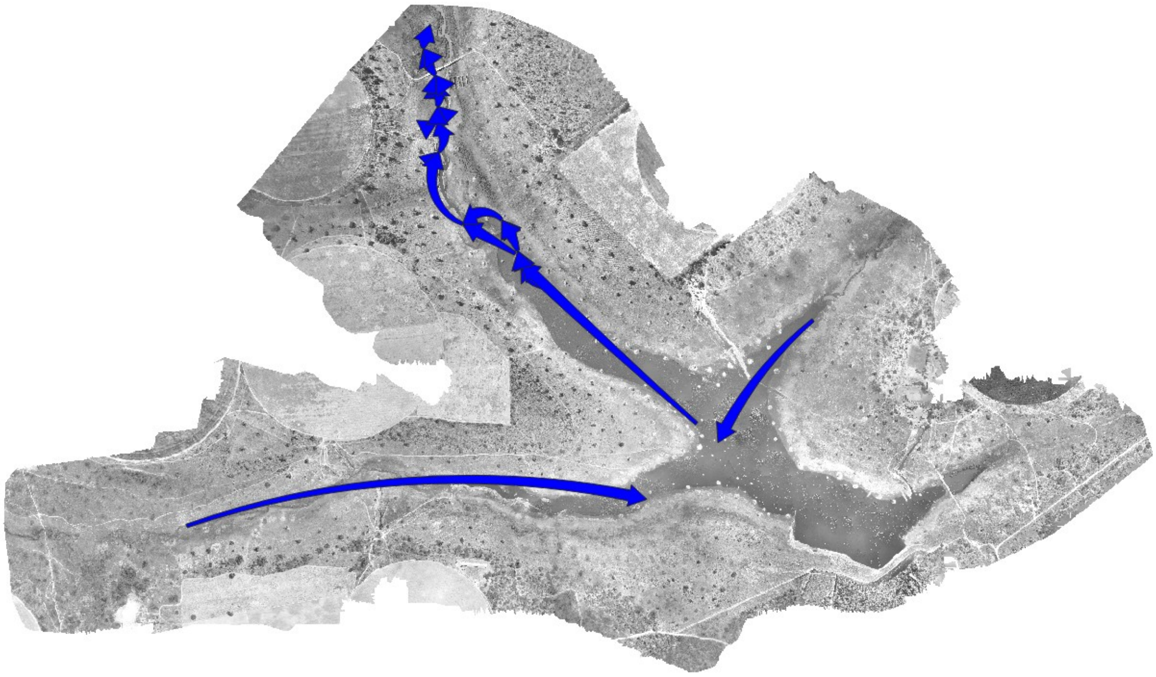

*Figure 3.9: Generalized flow direction prior to correction with MERIT data*

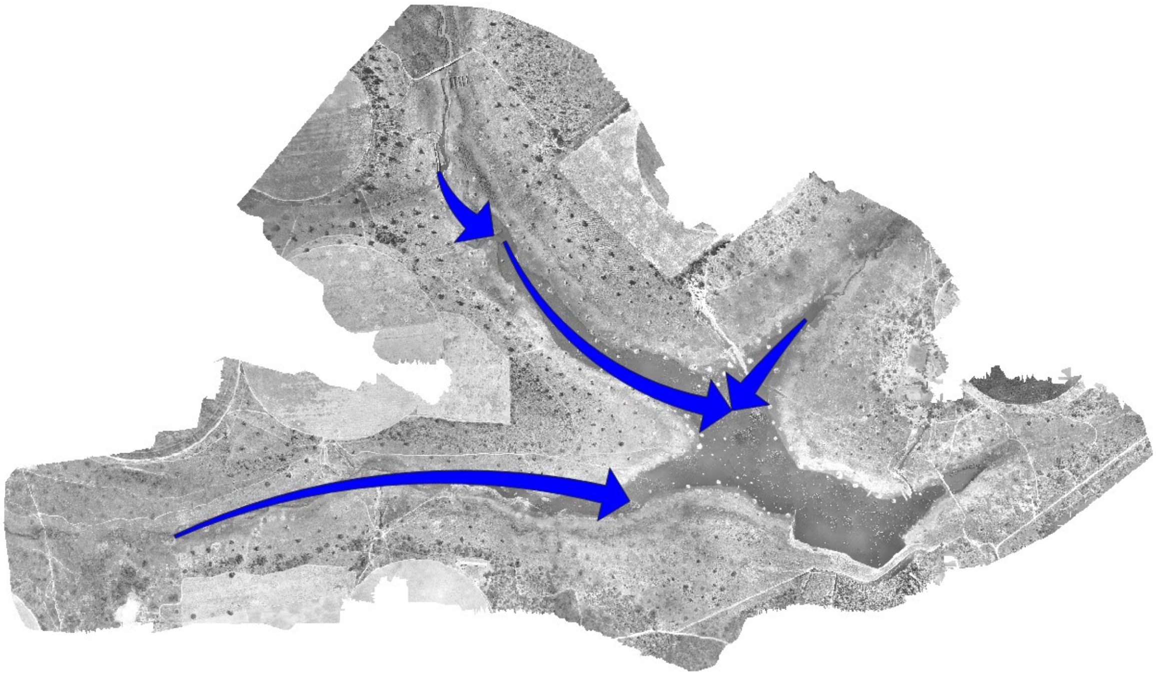

*Figure 3.10: Generalized flow direction after correction with MERIT data*

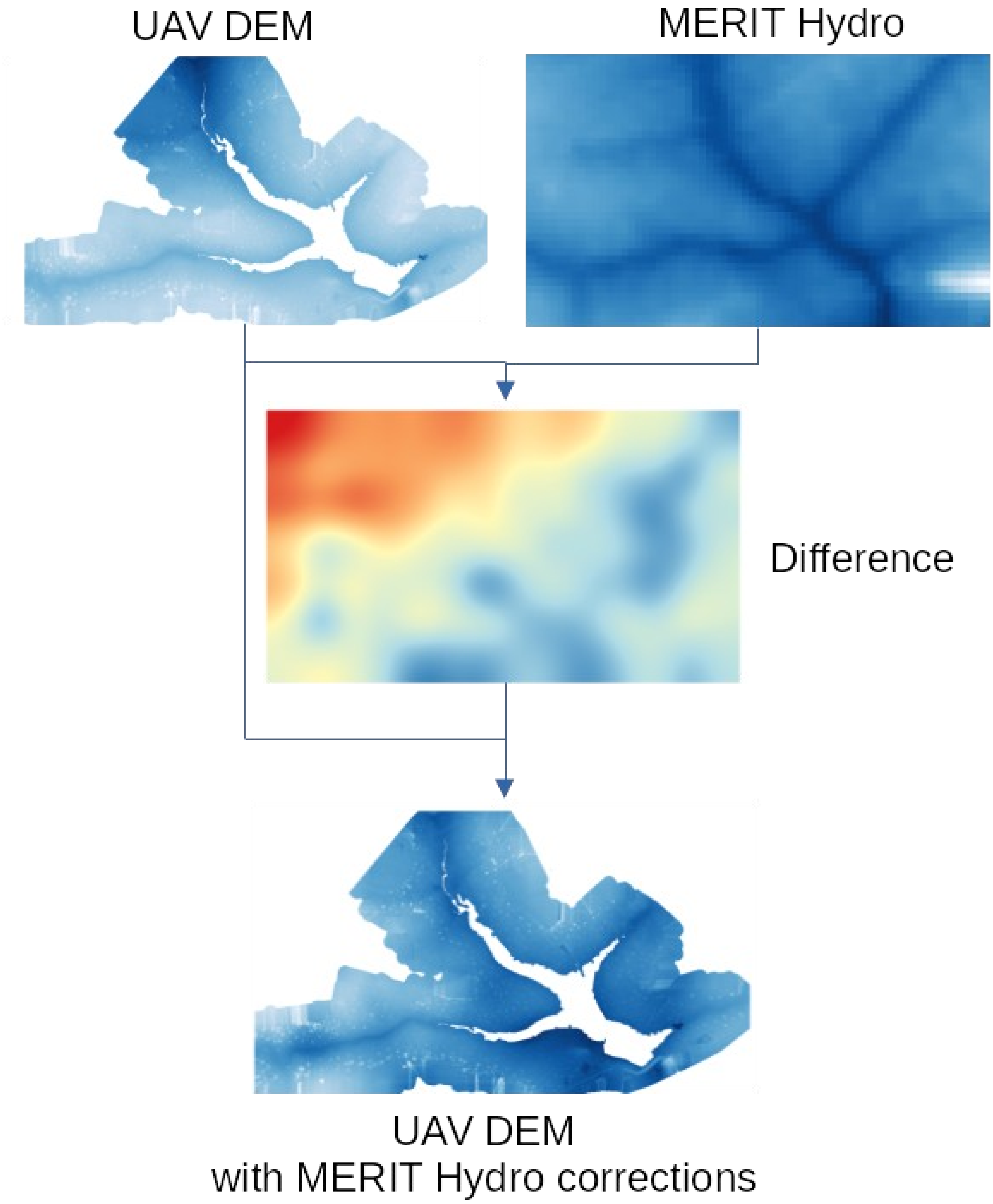


*Figure 3.11: Schema of dry and wet bathymetry alignment procedure*

The final result of the merging process is displayed in Figure 3.12.

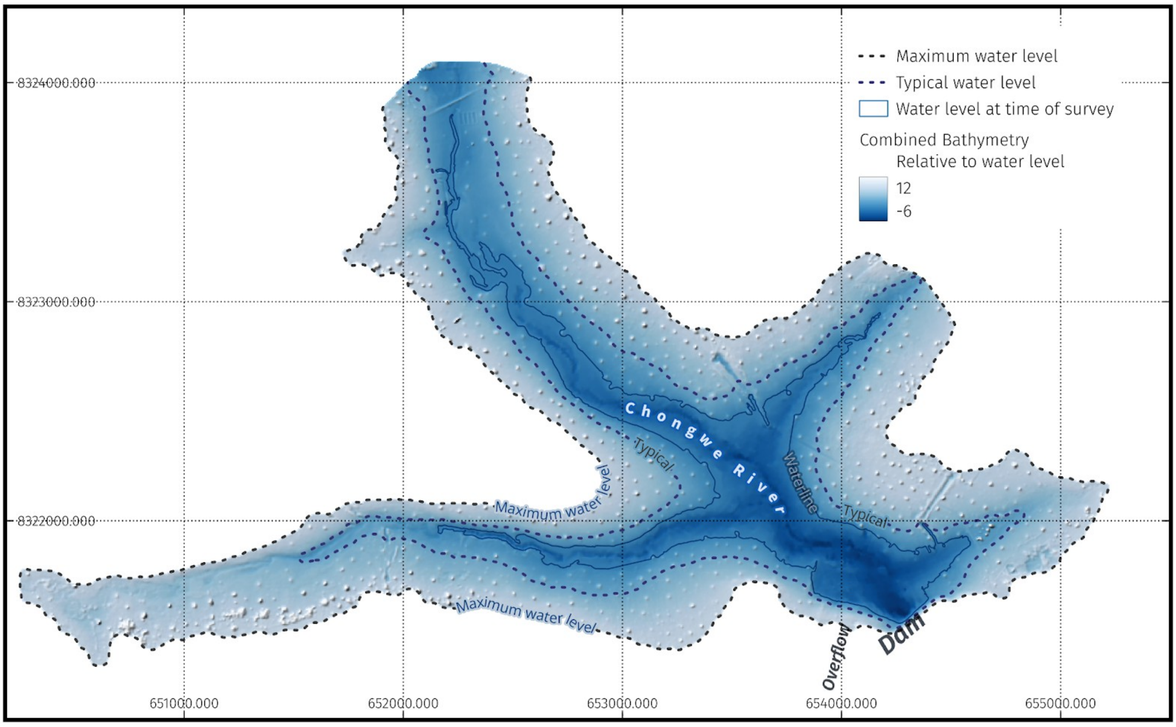


*Figure 3.12: Merged wet and dry bathymetry, with maximum water level, typical water level, and water level at time of survey shown over bathymetry relative to water height at time of survey. Hillshade overlaid in order to show subtle details in the bathymetry dataset.*

## 3.3.3 Hypsometric relationship

We have also produced a typical final product that customers will ask for: a stage-area and stage-volume relationship (a.k.a. hypsometric relationship). This can easily be derived with simple GIS operations. The relationship can be used to better understand (changes in) the reservoir's capacity, or enable a simple way to measure the current volume, with only a gauge plate. Below, we show the resulting stage - area and stage - volume relationships. Note that the spatial accuracy of the GNSS equipment also reveals the location of the original channel and other details. This can e.g. work for mapping of sedimentation if surveys are performed at a more regular basis. The relationships are shown in Figure 3.13.

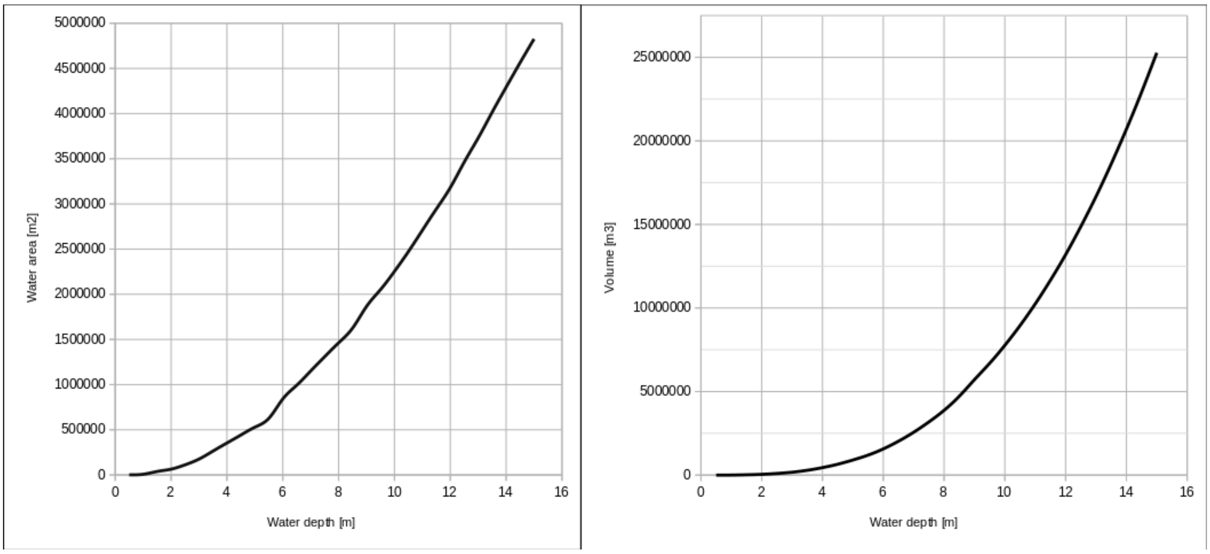


*Figure 3.13: Left: depth - area relationship, right: depth - volume relationship*

# 4 Hypothesis, quality and effectiveness

Within 7 days a large dataset was acquired with a phenomenal level of detail. For the WMO hydrological research agenda, it is crucial to assess our original hypotheses, i.e. that:

- data can be collected and turned into a usable product with high accuracy, comparable with professional survey-grade equipment for a much lower price using locally maintainable devices.
- The level of effort of data collection is satisfactory and leads to a competitive data service option.

We here present whether these hypotheses are just or need to be falsified.

## 4.1 Accuracy with affordability

First of all, we show below the comparison of the ADCP bottom track and the fish finder observations for surveys performed at Ray reservoir. On 27 August about 10AM local time, a one-hour survey was performed with both the fish finder and the ADCP recording. The ADCP is not equipped with a GNSS sensor. Hence matching of the records was done based on the time stamps.

Figure 4.1 shows a time series comparison side-by-side with a scatter plot of the two observation datasets.

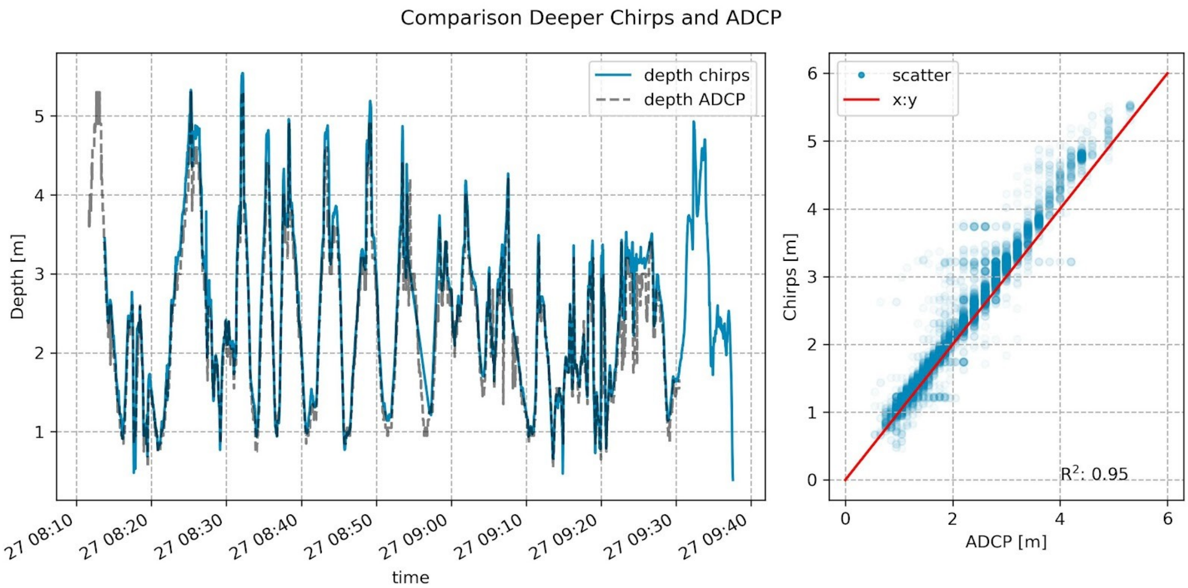


*Figure 4.1: Time series and scatter plot of simultaneous depth recordings by ADCP and Chirps fish finder estimates.*

The dataset collected with the Deeper Chirps 2+ and GNSS, i.e. depth and positions, were matched to the time stamps of the ADCP dataset to be able to make a difference plot in space. In Figure 4.2, these differences are displayed.


*Figure 4.2: Absolute differences between Chirps and ADCP, measured in space.*

The results demonstrate that the two platforms give a remarkably good fit. The largest differences between the two datasets appear in deeper water, where differences of about 0.2 meters are experienced. We believe that this is due to the fact that the ADCP bottom tracker only has a vertical resolution of 0.2 meters and that the software only adds a 0.2 meter interval once a full 0.2 interval has been observed.

## 4.2 Level of effort

From our comparison we can conclude that the fish finder combined with the GNSS is perfectly able to replace a typical 15,000 USD single beam echo sounder. With a base station and (X)LR radios and a clamp for attaching the fish finder to a boat, the total cost of the solution (without any spare parts) is about 1,350 USD. If a spare fish finder and GNSS set (in case of unforeseen failure or loss of equipment) would be included, this would double the amount. For drone data collection, more costs will have to be made. We describe this further onwards.

Our second test was to find out if the data collection process is viable within a reasonable amount of time. From our experience we can conclude the following for a lake of about 2 km2:

- Collection of bathymetric data with sufficient density: 2 full days of data collection by two persons.
- Collection of GNSS tie line: 1.5 days for two persons. This includes moving the base station to several locations for a good line of sight. Alternatively, offline Post-Processing Kinematics can be considered for future data collection as well.
- Collection of drone imagery: 2 days for two persons. This includes moving the drone flight location to several locations for a good visual line of sight. This is an estimate, as we required more time due to the fact that we had problems with our first drone, and too few batteries with the second drone.

Naturally the data collection process can be accelerated by teaming with a larger group. We do notice that the larger the team, the larger the importance of careful communication and planning within the group, especially if the base station is shared between the group acquiring the water line and the group acquiring the bathymetry data. They then have to focus on the same parts of the reservoir simultaneously.

Summarizing, with a team of 4 persons, **less than a week** is required to assemble all required data for a reservoir of the size of about 1.5$km^2$ (wet part). This makes the data collection highly feasible, especially if conducted with locally skilled people. Our team took more time than needed because we collected a denser sampling than strictly needed, we lost a drone, and had insufficient batteries for the drone. Ensuring that there are enough batteries is essential!

# 5 Bringing the solution to a service level

From the experience with the hardware solutions (combination of drone, GNSS and fish finder) and the performed full scale fieldwork experience we can draw lessons on what is required to bring our solution to a service level that can be independently run locally by a surveying entrepreneur.

## 5.1 From data to end product

The data collection approach results in several pieces of a puzzle that must be combined into a typically needed end-user product. Typical products with use cases are:

- 2D Bathymetric map of the entire reservoir up to spillway level → identify shallow areas, direct dredging activities.
- Level – area and (integrating) level – volume relationships → identify the total volume stored at a single moment as well as the maximum storage capacity, e.g. to check if permitted water storage is obeyed.

The pieces of the puzzle that are available after a survey are:

- A terrain reconstruction (with orthophoto) of the reservoir's dry area. If a simple drone solution (i.e. no RTK and no use of ground control points) is used, this dataset may still contain large-scale errors, and requires work to 3D-coregister with the zero-meter tieline as described before. Typically as a raster GeoTIFF file.
- A set of bathymetry points over the wet part. Typically as a vector Point Shapefile or Geopackage file
- A water tieline as vector Linestring file

For river stretches, a software approach to data integration was established that combines these (see Section 2.3.1). However for reservoirs such an approach is still lacking as the project was too small to facilitate this. The approach to integrate the data was currently still done in separate steps, which can be summarized as follows:

- Combine the zero-meter tieline with the bathymetry points into a gridded bathymetry. This can be easily done in QGIS
- Horizontally coregister the tieline with the drone-based terrain and orthophoto. Here this was done using the approach with Hydro-MERIT. We do not have a programmed solution for this, and recommend using RTK enabled drone data in forthcoming applications.
- Resample drone-based terrain to a joint final desired grid resolution and extent and combine final corrected drone-based terrain with bathymetry to get a seamless. bathymetry. This leads to the desired 2D bathymetric map. This step is done with the developed DEM blender.

- Derive h – A / h – V relationships from the integrated bathymetric map.

The steps are currently programmed in Python and can be easily replicated in a QGIS plugin and we highly recommend outsourcing the development of such a plugin to a company that is specialized in developing these such as Lutra consulting or Kartoza.

## 5.2 Total investment costs for an entrepreneur

In Annex A we estimate the initial investments required to build a service by a local company that includes surveying abilities with all equipment used within our case study for Ray reservoir. The sheet with costs is estimated based on approximate market prices. Also in the sheet, redundancy is taken into account, i.e. spare equipment is included.

This demonstrates that in order to start a service, in terms of materials, an entrepreneur requires a 12,000 USD investment. This excludes costs for e.g. laptop computers that might be needed. All processing can be done with open-source software (QGIS, WebOpenDroneMap and where needed Python scripting for data preparation and post processing) and hence the costs for licenses is **zero!** The amount for materials can easily be covered under a reasonably sized Terms of Reference (TOR) for multiple water bodies, e.g. by WARMA or by the World Bank. It is important that such a TOR allows for transfer of materials to the consultant after the job is done so that the entrepreneur can keep delivering services.

The expected personnel and incidental material costs for a single survey are estimated in Annex B. Here it is assumed that local personnel has BSc level education and is supervised by a enterprise director at PhD Level. These are estimated costs for conducting a single survey. The assumption is that each survey takes 7 days to complete. The exact amount of time required is significantly dependent on the reservoir size. Note that with an RTK drone and more batteries, likely the survey time will also reduce compared to the required time during the survey done in this project.

# 6 Discussion

## 6.1 Set up of an affordable off-the-shelf echo sounding solution

With the combination of a Deeper Chirps fish finder, 2 ardusimple GNSS sets (base and rover + XLR radios), and small PVC materials it is feasible to build an echo sounder solution that costs only a fraction of a professional grade echo sounder (typically costing in the order of 15,000 USD), whilst maintaining a similar level of accuracy.

Thanks to the GNSS solution, the set up can even be used to provide very precisely positioned bathymetry or cross-sections for small streams, where the precision is very important. In this case, the PVC floater design helps to ensure that the location of the GNSS antenna is as close as possible to the location of the echo sounder.

Using a simple floater PVC construction, with a beam in the middle for stability, the echo sounder can easily be used on a stream with velocities up to about 2 meters per second. The PVC floater design allows any user to re-implement this solution locally.

## 6.2 Shortcomings of the echo sounding method

- The sonar needs a minimum of 20-30 cm depth. Also shallow areas are difficult to pass with the boat. In practice (see Chapter 3 for the Ray reservoir survey) we did not measure depths smaller than 60 cm. A lighter boat is recommended for a more broad uptake. We recommend a small polyester boat with a light 2-stroke engine (e.g. 2.5 – 5 horse power maximum). Polyester (unlike rubber) is strong enough to withstand small obstructions such as underwater branches or rocks if moving slow enough. A light boat will enable a faster and more easy deployment, also at locations where the accessibility to water is more difficult.
- We here present a solution to a *single-beam* echo sounder. This limits the surveying capacity as many transects are needed for a good coverage. Even though these are individually proven to be very accurate, the sampling over the entire reservoir remains limited. In cases where strong bathymetric variability occurs, and where it is important to map this variability, this shortcoming limits the applicability of our methods to small reservoirs (up to 5 $km^2$). Larger reservoirs would make the method unpractical as the survey will take a long time. We are considering to investigate options for an affordable multi-beam echo sounding solution in follow-up projects to reduce the required overpasses significantly. This will require an array of sensors, mounted perpendicular to the direction of the boat, and aimed in several different directions combined with roll-pitch-yaw estimation. The currently used fishfinder is not suitable for this purpose, because it returns echoes of

the nearest point only. Further research is needed, ideally started in a lab, to identify what sensors and in what set up would provide a good multi-beam set up. Software that combines the roll-pitch-yaw with the echoes is needed to estimate where (in relation to the boat's position and orientation) echoes come from.

- For surveying on a broad water surface, it is quite difficult to maintain a good view on the location and direction of a transect while using the echo sounder. To make this easier, it would be good to make a bathymetry planner, i. e. an application that generates a shapefile of lines that should be followed for a survey in a typical direction and orientation. This is very similar to what a flight planner does for a drone. The shapefile could be uploaded into the GNSS app SW Maps prior to performing the survey so that a surveyor can accurately follow the lines without becoming confused. SW Maps already has a feature to add a shapefile as a background layer for a project.
- The software ORProfile, currently works with script interfacing. The user therefore has to utilize the API directly with Python code. For a more common use, it may be considered to implement a simple interface, e.g. as a QGIS plugin. All data is already geographically tagged with projection codes, and therefore such an implementation is quite feasible without seriously changing the code base and API. We highly recommend to also extend the code so that it can be used for reservoirs.

## 6.3 Combination with affordable drone

- For a future survey, we strongly recommend using and RTK-enabled drone, or alternatively, measure several ground control points. As there already is a base station available, this is relatively simple to establish.
- Similar to ORProfile, a method to combine the different maps into one for reservoirs would be good to have. We have made steps with DEM Blender, but the large-scale landscape deviations may be good to encapsulate in a more automated routine.
- For large scale surveys, a campaign will require several days of data collection using different drones and under different lighting conditions. Larger reservoirs produce large image datasets which may require expensive compute. Within the limits of this project, we did not encounter this problem, but we can expect that with larger projects, a solution will be required. OpenDroneMao has a so-called “split-merge” functionality which can be used to split up the dataset in smaller more manageable chunks, however, for this particular survey we recommend the following:

1. The full complement of images is split into manageable chunks depending on the user's available computing power. For instance, if a project produces *x* images. The images may be split into *n* sub projects of *y* images each.
2. The first subproject is processed and a point cloud is produced. This (pointcloud) submodel is downloaded and renamed to ‘align.tif’.
3. The images within the second sub project are subsequently processed together with align.tif to produce another point cloud submodel.
4. The process is repeated until all submodels have been processed.

This guarantees that all submodels are perfectly aligned despite being flown under different conditions and at different times.

# Annex A: Investment costs

The investment costs below are estimated with day prices from typical platforms such as Amazon, or estimated costs from our experience.

| Item | Unit cost | nr | Total cost |
|---|---|---|---|
| Tripod | $150.00 | 1 | $150.00 |
| fish finder | $400.00 | 2 | $800.00 |
| fish finder clamp | $70.00 | 1 | $70.00 |
| GNSS sets + XLR radio | $853.00 | 2 | $1,706.00 |
| 20Ah power banks | $20.00 | 2 | $40.00 |
| Android phone | $150.00 | 2 | $300.00 |
| Rubber boat | $2,500.00 | 1 | $2,500.00 |
| 2.5Pk engine | $1,000.00 | 1 | $1,000.00 |
| Drone DJI Mavic 3 | $2,000.00 | 2 | $4,000.00 |
| Extra batteries | $165.00 | 5 | $825.00 |
| Small generator (on petrol) | $150.00 | 1 | $150.00 |
| SD card | $20.00 | 1 | $20.00 |
| Landing pad | $10.00 | 1 | $10.00 |
| Several cables+spares (USB-C, OTG) | $100.00 | 1 | $100.00 |
| | | | |
| **Total costs** | | | **$11,671.00** |

# Annex B: Personnel and incidental materials costs for a single survey

| Item | Description | Unit cost | Unit | nr | Total cost |
|---|---|---|---|---|---|
| Labour | Chief fieldwork manager/ UAV Licence holder | $428.00 | days | 7 | $2,996.00 |
| | Coxswain/ Boat Licence holder | $214.00 | days | 7 | $1,498.00 |
| | GNSS (Recorder (on the boat) | $72.00 | days | 7 | $504.00 |
| | Fishfinder operator( on the boat) | $72.00 | days | 7 | $504.00 |
| | UAV assistant (e.g. GCP placement) | $72.00 | days | 7 | $504.00 |
| Transport | Fuel | $1.20 | liter | 100 | $120.00 |
| | Vehicle hire | $170.00 | days | 9 | $1,530.00 |
| | Trailer hire | $90.00 | days | 7 | $630.00 |
| Boat | Boat Fuel/oil | $1.20 | liter | 40 | $48.00 |
| | Boat hire | $90.00 | days | 7 | $630.00 |
| Accommodation | 6 nights * 5 Persons | $30.00 | Person-days | 30 | $900.00 |
| **Total costs** | | | | | **$9,864.00** |

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