Deltares

Surface-2-Storage - Final Report

enabling delta life

Surface-2-Storage - Final Report

Author(s)
Hessel Winsemius
Antonio Moreno Rodenas

Surface-2-Storage - Final Report

Client	European Space Agency
Contact	Marc Paganini
Reference	
Keywords	Earth Observations, Reservoir monitoring, Water storage, Humanitarian Response

Document control	
Version	1.0
Date	07-05-2024
Project nr.	11207650-002
Document ID	11207650-002-ZWS-0020
Pages	31
Classification	
Status	final

Author(s)		
	Hessel Winsemius	
	Antonio Moreno Rodenas	

Executive Summary

In the project Surface2Storage, we have explored and developed two different methods to derive relationships between surface area, estimated from earth observations, and water levels. Once established, these relationships can be used to operationally invert a water level from an EO observed surface area (for which we use the freely available Sentinel-2 data, in conjunction with Landsat) and integrate water level and surface to volumetric storage estimates. Not only have methods been developed, they have also been validated and applied for use cases together with 510, the digital and data initiative of the Netherlands Red Cross (hereinafter Red Cross 510). This was done in co-design with stakeholders in Lesotho and Zambia. Within the project, storage estimates were made available in the Global Water Watch web platform, for global surface water monitoring. In the platform, surface area estimates are made using freely available Sentinel-2 data combined with Landsat data, and volumes are estimated by feeding surface area into the found surface area – water level relationships. Every month, any new image overpassing a reservoir is processed into new surface area and volume estimates. In this final report, we summarize the results of the full project.

This final report (FR) with the Executive Summary (ESR) also completes the milestone MS-5 “Upon the Agency’s acceptance of all deliverable items due under the Contract and the Contractor’s fulfilment of all other contractual obligations including submission of the signed Contract Closure Documentation.”

The first developed method relies on widely available global (or local) static digital terrain maps and hydrologic derivatives of these, such as flow directions and upstream area. A geomorphological approach is used to replace the lake surface elevation (typically a constant value in global terrain datasets) with bathymetric elevation estimates, constrained by the knowledge that the lowest point is expected to lie at the dam’s bottom, and geomorphological indicators such as slope and stream direction, as suggested by earlier literature contributions from other researchers. The second method utilizes ICESat-2 lake surface elevation estimates, paired with surface area estimates at (approximately) the same moment in time. This method only resolves water level – surface area as occurred within the range of the observations but has the added benefits that it may include shoreline changes if used within recent periods, and can include estimates of noise in the found points.

Validation of the first method has been performed extensively over India using in-situ records. This provided very promising results. Over Zambia, for two reservoirs more detailed validation was possible against recent bathymetric surveys. This revealed that both methods give very promising results, with the side note that for very small reservoirs, where ICESat-2 does not provide overpass coverage, the dynamic approach (using ICESat-2) may not give enough information. For very deep reservoirs the first method is likely to also give less reliable results. Further validation for both methods is currently ongoing and focuses on time series intercomparison.

Two use case areas are investigated in the project. For Lesotho, options to use the surface water monitoring together with other indicators as a trigger for early action for droughts is being investigated. Red Cross 510 established user requirements from several interviews with the Lesotho Red Cross Society as well as other stakeholders working with surface water resources in Lesotho, including two dam management entities. Looking several months ahead in time is key for most use cases.

Therefore, skill assessments of data mechanistic models, using the monitored volumes as input have been investigated as a first step towards predictions. This showed that monitoring of surface water volumes at present day provides a strong predictor for surface water availability in the coming months, especially when combined with the Standardized Precipitation and Evaporation Index. For Zambia, several possible uses for monitoring are explored with the Water Resources Authority of Zambia (WARMA), including permitting checks and water resources planning or curtailment planning. This resulted in a presentation by one of WARMA's associates during the New York Water Week on their intended use of the Global Water Watch platform and its storage estimates resulting from this project. The engagement with these stakeholders brings the project to a mature level where end users are attracted to our data, and understanding is gained what data is needed, and how it should be presented so that a user can improve his/her/its decisions.

The methods developed have been published in a Github repository with documentation on how to install the methods and examples how to apply them. Several outreach events have been attended, including the Global Dialogue Platform (8/9 October), and the annual SADC Waternet symposium (Zanzibar, October 2023). Several blog posts on the work have been written. Finally, it is important to mention that near real-time results from this project are continuously becoming available via the web platform and API of Global Water Watch. The web page can be visited on https://globalwaterwatch.earth/. The API can be accessed through https://globalwaterwatch.earth/api/.

Contents

1 Introduction

1.1 Purpose

This document serves as the Final Report (FR) of the EO4Society project “Surface2Storage: Enhancing drought Resilience by global real-time monitoring of water volumes stored in small to medium sized reservoirs” (S2S). It provides an overview of the results of the project and achievements made in terms of EO developments and societal use of the developed methods.

1.2 Background

In an affiliated project “Global Water Watch” (completed in summer 2023), Deltares developed state-of-the-art data for near real-time reservoir monitoring using several background methods (Donchyts et al., 2016, 2022; Luijendijk et al., 2018). This is possible thanks to the plethora of freely available Sentinel-2 and Landsat imagery, which forms the backbone of the surface area estimates. However, the Global Water Watch project focused mostly on surface area time series and disclosure of these in a user-friendly platform. For many, if not most, use cases, *volumetric* estimates of the state of a reservoir are required in order to take action. Within S2S the surface area estimates are paired with globally available dynamic altimetry estimates (e.g. ICESat-2) and several existing static terrain datasets (e.g. NASA-DEM, Copernicus DEM) and terrain hydrography (Hydro-MERIT) to establish relationships between a reservoir’s surface area and its volume, so that volume in m^3 can be estimated from surface area in m^2. ICESat-2 offers lake elevation for many water bodies world-wide (Cooley et al., 2021), provided they are large enough to give sufficient overpasses to characterize different reservoir states. Static terrain data is also widely available. Combined with geomorphological laws and a common understanding of constraints in the shape, typical for a reservoir (deepest point at the dam wall) these may serve as a strong predictor for its bathymetric properties.

Volumetric reservoir information, precise and in near real-time, is not readily available, especially in transboundary river basins without data sharing agreements. This is despite the fact that such data can be of great importance to several use cases including disaster management, water allocation, permit management, and more. The S2S project therefore is a collaboration between Deltares and the Red Cross 510, where Deltares implements methods, and Red Cross 510 works with several Red Cross Societies and stakeholders within their ecosystem to work out potential uses for the data in disaster management and related stakeholder landscapes. During the project it was decided to also engage with the Water Resources Management Authority of Zambia, who are very keen to operationally use the data. Strong pillars of the project are:

- **Innovation:** we investigate two different approaches to use EO-data to derive geometrical “hypsometry” relationships. These are relationships between water levels and surface area, and (through integration over the water level) water volume. With these relationships, an observed water level or surface area, can be converted into a volume estimate.
- **Validation:** we investigate how well and under what conditions such methods work and do not work.
- **Development:** we turn the methods into publicly available, open-source, documented software that allows any researcher world-wide to use the developed methods.

- **Use:** we investigate how end users, that make decisions around surface water, may utilize the data and what this means for technical and function requirements, as well as interoperability.

1.3 Results in a nutshell

Below, we describe very succinctly what has been achieved in the project, related to the different components of the project:

Internal and external stakeholder interaction:

1. A kickoff meeting was held at the beginning of the project, and minutes of the kickoff meeting have been written and distributed.
2. Several internal meetings have been held, including several working days on software (WP1 for bathymetry algorithms, and WP2 for API developments) and meetings with Red Cross 510 and Deltares on the use cases (WP3)
3. Several meetings with ESA have been held to stay up to date.
4. Contributions have been delivered to a UN report on SDG indicators. In particular surface water data has been addressed.

Use cases:

5. Red Cross 510 has held several meetings and dialogues with stakeholders in Lesotho and Eswatini for further use case investigations early April. This meeting has been held in partnership with a second project I-CISK (EU Horizon, lead partner IHE Delft). The meetings led to further detailing of technical and user and visual requirements which may be pursued in further work and in part in this project.
6. The Water Resources Management Authority of Zambia (WARMA) has been added as a new active user to follow during this project. Engagements and user interviews have been held.
7. An online workshop was organised, with the participation of Red Cross 510, Lesotho Red Cross Society, Deltares, and various stakeholders from Lesotho, including representatives from Lesotho Meteorological Services, Department of Water Affairs, and the Water and Sewerage Company. The session involved evaluating scenarios for early actions related to drought, using new data from the Global Water Watch on water surface area and storage levels to enhance decision-making processes.

Algorithms and software:

8. The first version of the software, which includes fully working static and dynamic methods has been prepared on GitHub and delivered (deliverables SW1 and SW2). The repository is public and documented on https://github.com/global-water-watch/bathypy.
9. The API of the Global Water Watch Platform has been extended so that hypsometric relationships resulting from this project can be inserted into the database, and storage estimates retrieved as a function of monitored surface area and the hypsometric relationship.
10. Validation of the static hypsometry method has been completed, using a set of *in-situ* hypsometric points in India. Validation of both methods has been performed on detailed bathymetric surveys of two Zambian reservoirs, obtained through WARMA showing very good results.
11. Documentation in the reStructuredText language Sphinx has been prepared and will be published on a github.io pages site, including code examples for reproduction and re-use.

Outreach:

12 Both Deltares and Red Cross 510 actively engaged in conferences, including the WaterNet/WARFSA/GWPSA Symposiums and the Global Dialogue Platform, where they delivered presentations.
13 A side event was organized at the UN Water Week, showcasing project progress and capabilities.
14 A contribution was made to a UN report on SDG indicators, focusing on monitoring SDG 6 through surface water data.
15 Three blog posts were authored by key members of the project and distributed across various channels to stakeholders.

1.4 Outline of remainder of report

In the remainder of this report, we provide more detailed insights in the established project and its result. The descriptions are organised per Work Package.

2 WP1: Bathymetry development

The Earth Observation innovations made in this project are covered in Work Package 1. We developed two methods to estimate bathymetry and hypsometry exclusively from Earth Observation data. The methods have been implemented in python code under package name “BathyPy” and delivered as deliverables “SW1” and “SW2”. In brief the methods work as follows:

2.1 Static approach to derive hypsometry relationships

The static approach is outline in Figure 2-1 and is further described below:

1 User defines a required region of interest in the form of a polygon, that at minimum covers the surface of a reservoir. This polygon can be self-defined or derived from any database available such as the GWW reservoir polygons, HydroLakes, OpenStreetMap or Global Dam Watch.
2 Software downloads static elevation dataset (different elevation datasets are possible) with stream topology always being extracted from Hydro-MERIT. The Hydro-MERIT dataset is used as a baseline because this contains flow directions and upstream areas all over the world, guaranteeing its global applicability. Elevation data however, can be derived from other datasets, or even local datasets if these are deemed to be more accurate. Downloads are done for a bounding box around the polygon with a small buffer, which the user can also manipulate if wanted.
3 Elevation within the reservoir’s surface is masked using the dam’s elevation and flow topology.
4 With a class method, upstream and downstream edges are found at the dam’s most downstream location, and an upstream location above the elevation of the water in the main stream (selected with the upstream area layer of the topography) during the acquisition period of the terrain dataset.
5 The mainstream elevation is estimated by extending the slope in the most upstream location to the downstream elevation at the foot of the dam, assuming the slope reduces in downstream direction following a power law.
6 Smaller tributaries are filled with the same procedure as the main stream. This can be iterated several times (e.g. 3 or 4). For larger reservoirs, more iterations are recommended. The user must set this value.
7 Missing elevation is estimated with bilinear interpolation in between the shorelines and the mainstream elevation creating a full bathymetric map. An example for Mita Hills reservoir in Zambia is shown in Figure 2-2.
8 Hypsometry is extracted from the bathymetry map as water level – surface area pairs over a user selected vertical interval (e.g. 1 meter). The hypsometry can be summarised in a power law $A(h) = a(h-h_0)^b$ where A [m^2] is the water surface, h [m] is the water level, h_0 [m] is the water level where A becomes zero and a and b are coefficients. This is part of a python Hypsometry class, which allows a user to convert one variable into the other using the found relationship, store the data into .csv files or plot the relationships.

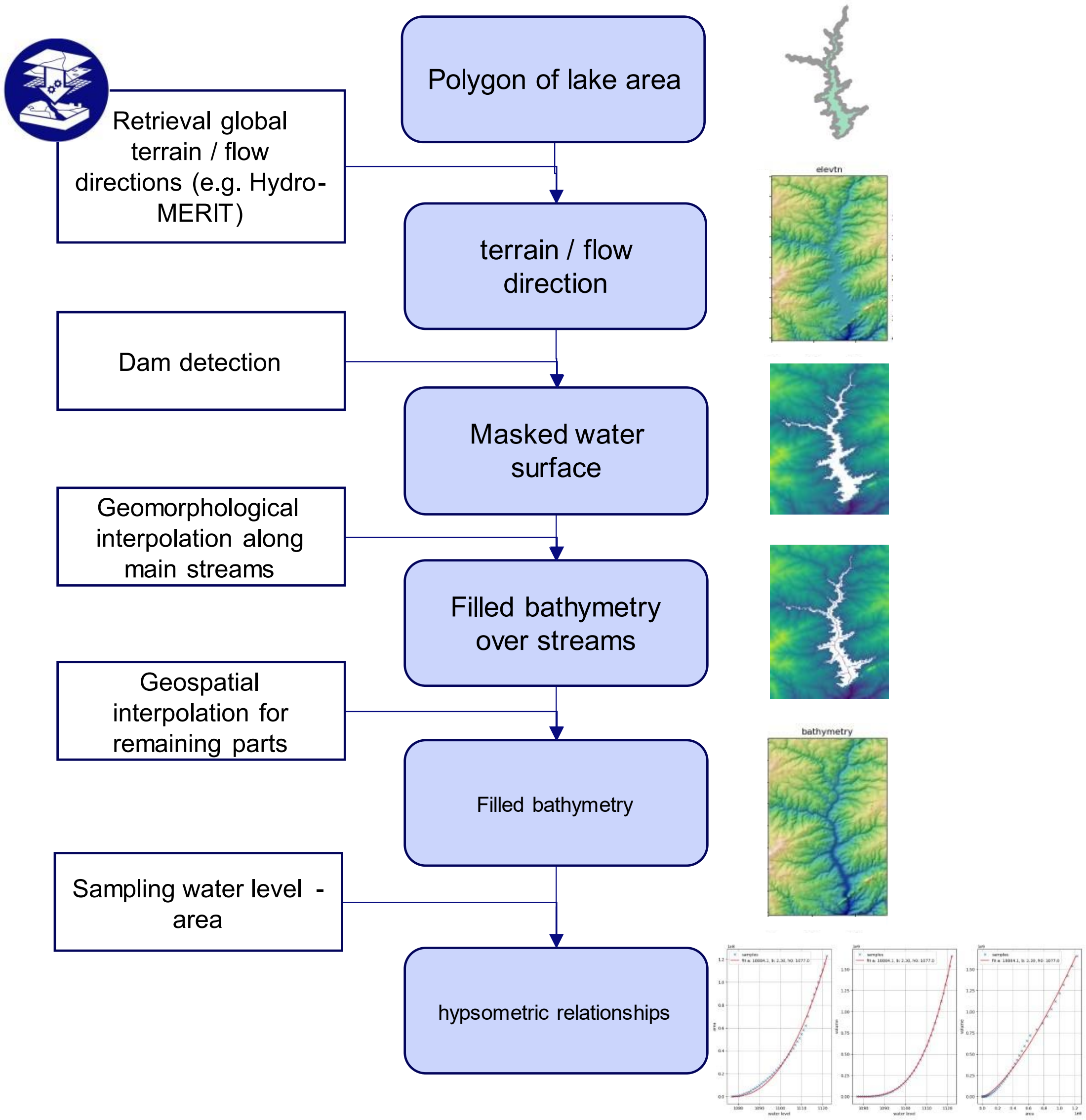

Figure 2-1 Schematic of the approach for hypsometry derivation using static terrain datasets.

Validation for a large number of reservoirs in India performed in scope of an MSc thesis work with Delft University of Technology (Klein Holkenborg, 2023) shows a good resemblance between the total volume of the reservoir and the largest reported volume from local data sources (see Figure 2-3, Figure 2-4, and Figure 2-5). The smaller filling levels show less resemblance, but this is very likely due to the local time series of Indian reservoirs having a different volumetric datum against which volumes are reported. This datum is likely not commensurate with the bottom of the reservoir, but instead commensurate with a certain minimum operating level such as the dead storage level. Total volumes are then likely reported in terms of “Live Storage”. This is the storage in the reservoir that in principle can be released and used. Anything below this level cannot be retrieved for use. The validation in Figure 2-5 particularly shows the performance for reservoirs under 3 km^3 in size. The R^2 values reach 0.78 for the 100% filled reservoirs (right-hand side of figure). This is much higher than the value of 0.68 for all reservoirs in the database. This reveals a very good performance for in particular the small to medium sized reservoirs as opposed to the (very) large reservoirs.

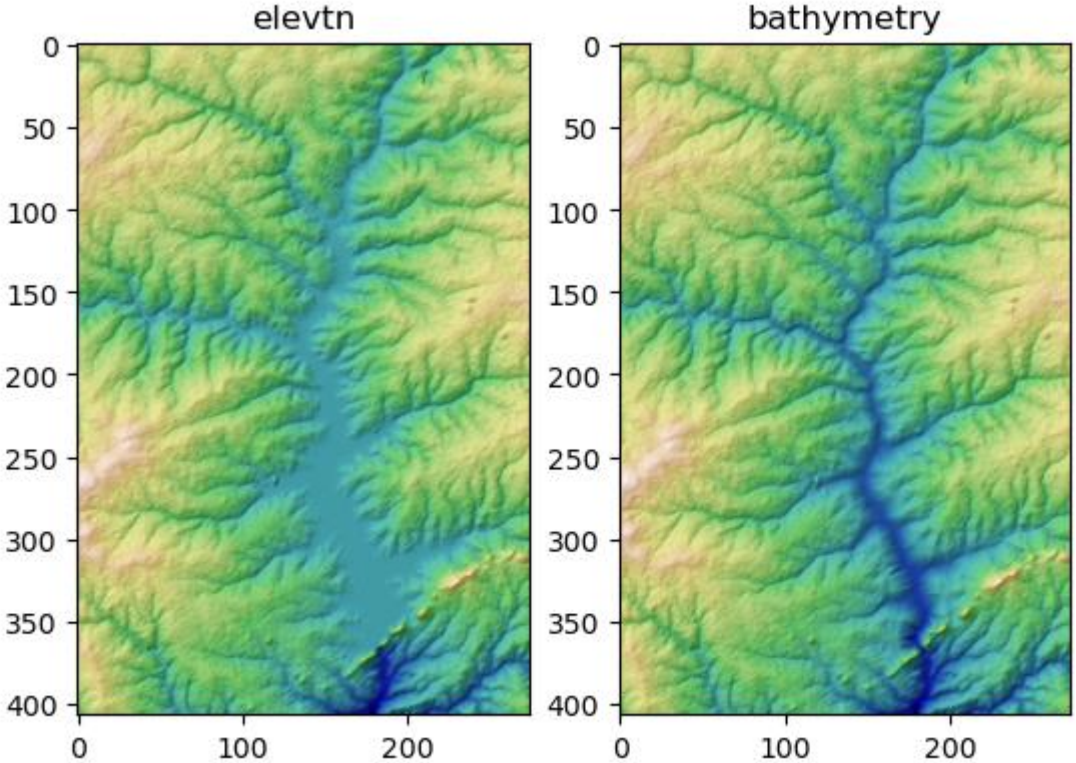

Figure 2-2 Mita Hills bathymetry derivation (from draft Sphinx documentation). Left: original elevation, right: interpolated elevation from software procedure.

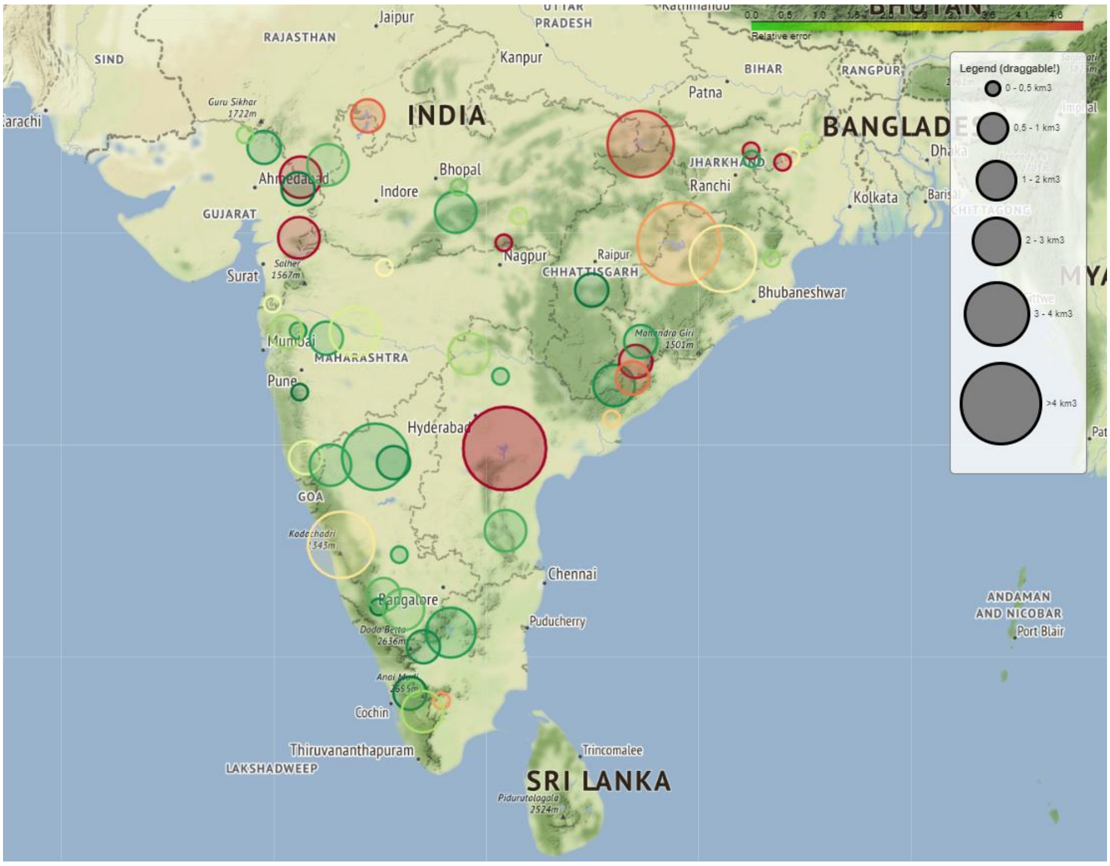

Figure 2-3 Spatial overview of validation results over India. Size of circles represent volumetric size of reservoirs. Color represents the relative bias in volume estimation

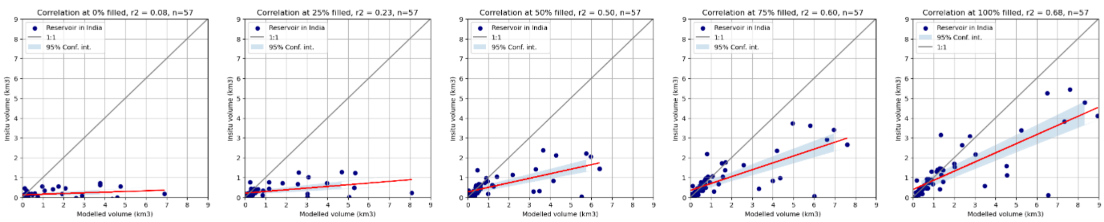

Figure 2-4 performance of volumes, with different levels of filling. From left to right: 0%, 25%, 50%, 75% and 100% filling levels.

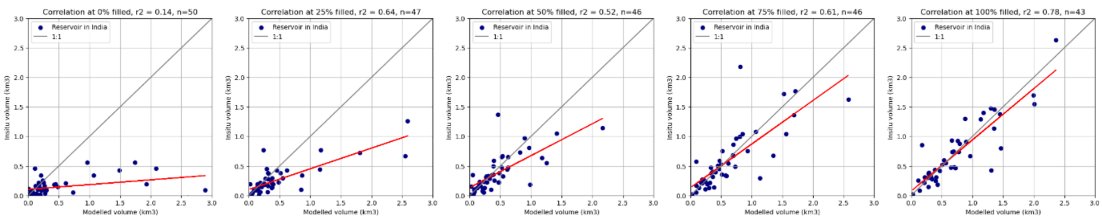

Figure 2-5 Same as Figure 2-4 but only reservoirs of maximum 3km3 in volumetric capacity.

2.2 Dynamic approach to hypsometry derivation

This method relies on dynamic data and requires a connection with the Google Earth Engine (GEE) platform. Within the processing, ICESat-2 data will be retrieved from the ICESat-2 API, and uploaded to GEE and used in conjunction with the surface area estimates from the GWW algorithms, which also run in GEE. The code performs the following:

1. Establish available ICESat-2 tracks for a given reservoir, dictated by a polygon (both ATL03 and ATL08 are possible to use).
2. For the dates of the ICESat-2 tracks, estimate surface area from Sentinel-2 and/or Landsat using Global Water Watch back-end code.
3. Pair all water levels and surface areas.
4. Return pairs as hypsometry points.

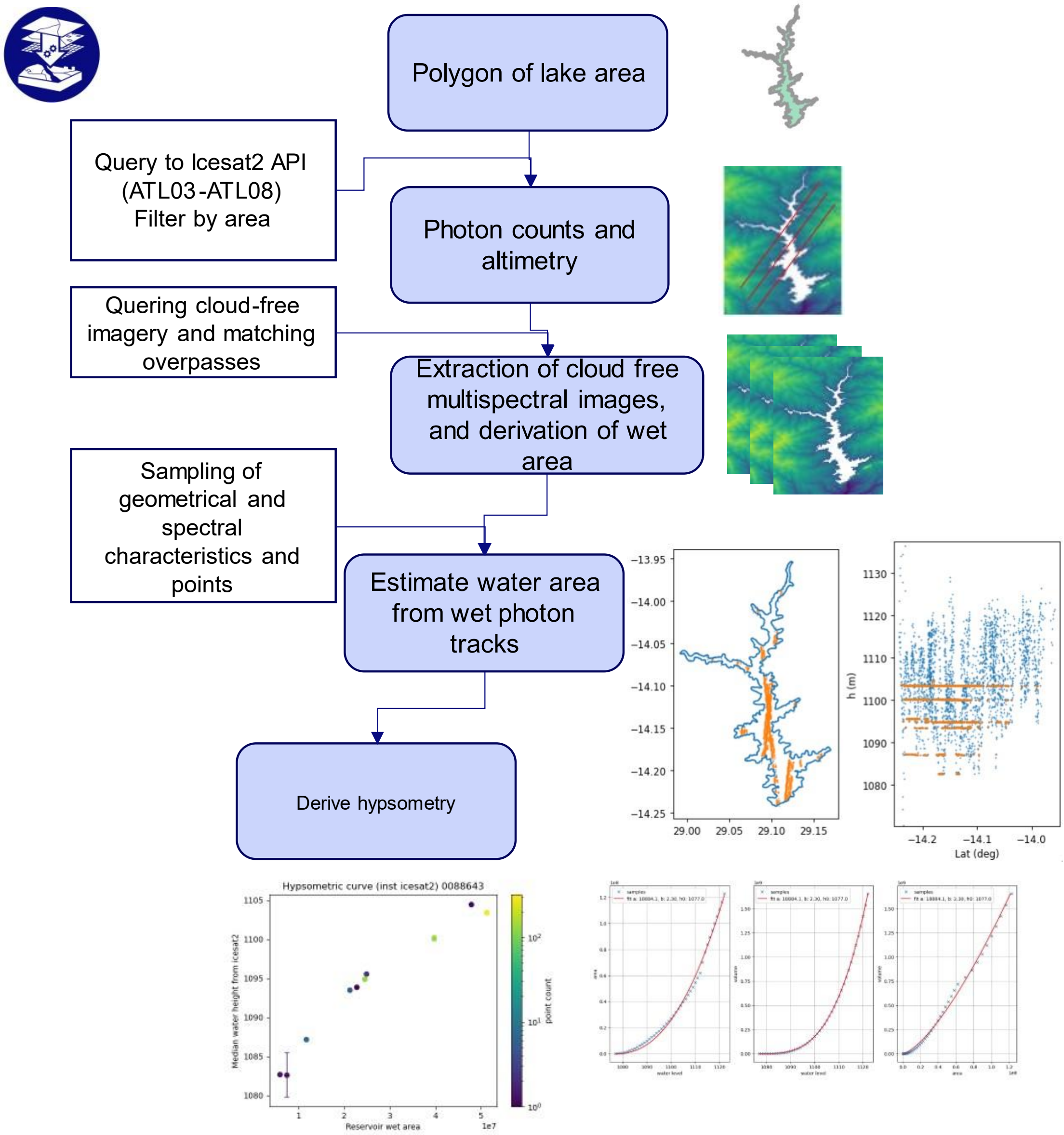

Figure 2-6 Schematic of the approach for hypsometry derivation using dynamic (ICESat-2) elevation tracks.

From here, the points can be combined into a hypsometry relationship encapsulated in a python “Hypsometry” object, derived from the above-mentioned Hypsometry class (see item 8 in Paragraph 2.1), entirely equivalent in form as defined by the static elevation datasets. As mentioned before, this class then allows a user to extract specific points in the relationship or store the relationship into a .csv file.

In Figure 2-7, one example of our validation is shown, for Mita Hills reservoir in Eastern province – Zambia (Lunsemfwa basin). The in-situ data was kindly shared by the Water Resources Authority of Zambia, with whom we are working together within this project. We have performed a direct validation against a total of 5 reservoirs for which water level / surface area relationships were available from bathymetric surveys. These include 3 reservoirs in Spain and two reservoirs in Zambia (among which Mita Hills) and have been reported in the memo as part of SW1 and SW2.

This method works best (as opposed to the static method) for medium and large reservoirs as here there is a higher probability of having matched overpasses. Given the amount of parameters in a hypsometric relationship (3), at least 3, but ideally more overpasses must be available. Typically, reservoirs from our validation datasets yield 3 to 8 valid overpasses. The added advantage of the method is that it provides reliable, and (with recent overpasses) also up-to-date hypsometry points, and that it provides a more direct estimation of a hypsometry sample than the static method. The reflectance from the different photon echoes can also be used to construct an uncertainty estimate for each hypsometry point. Disadvantages are that with very large reservoirs, inhomogeneities in the water surface may occur, e.g. due to wind setup. In these cases, the water level measured during an overpass may not be entirely commensurate with the water level over the entire lake, as this may vary from place to place. Furthermore this method only yields a limited set of hypsometry points, while the static method resolves for the full bathymetry.

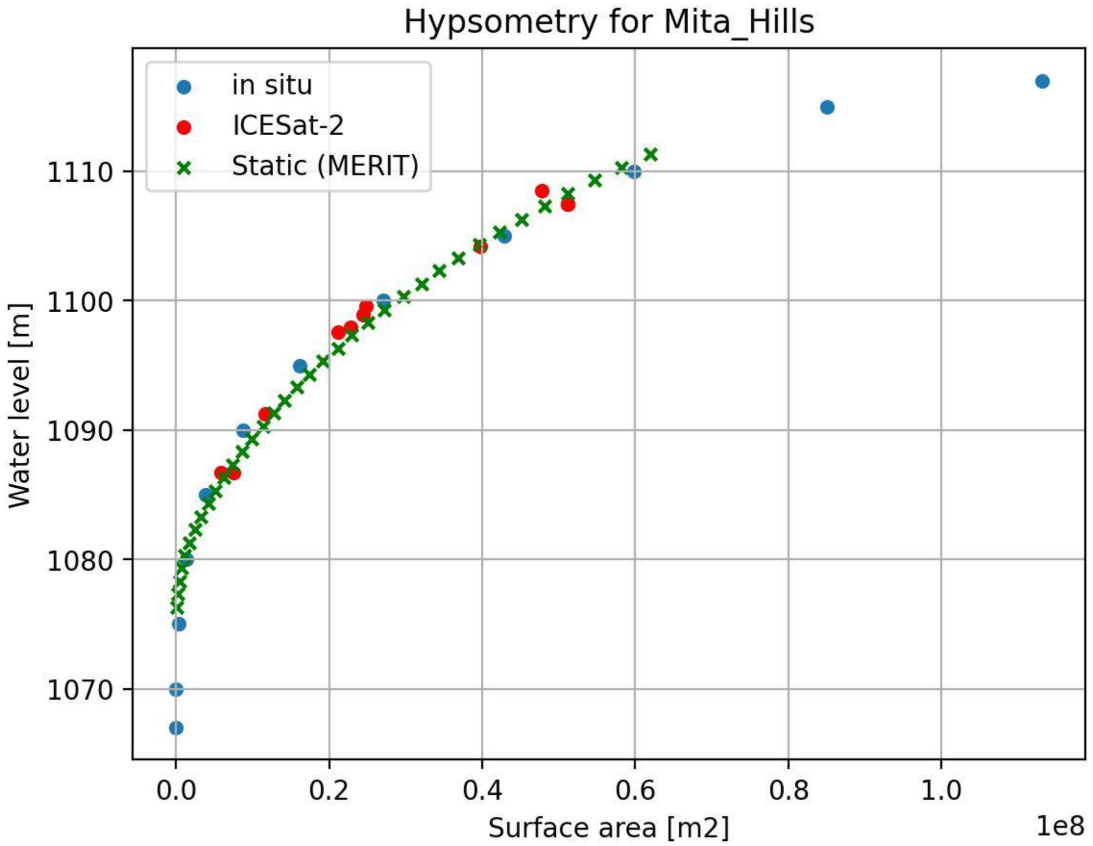

Figure 2-7 Dynamic (Red points) and static (green crosses) hypsometric relationship for Mita Hills dam - Zambia, compared against locally measured hypsometry (blue dots).

2.3 Discussion of methods

Static method

The application of the static method over reservoirs where in-situ records were available provided a benchmark for how well the method works and what the possible reasons for successful or less successful results are. Klein Holkenborg (2023) discusses this in her thesis work and below we provide an overview of the reasons:

- If the user supplies a very inaccurate polygon for the approximate reservoir surface area that misses the part containing the dam wall, the dam wall will not be accurately detected. This is not an algorithmic problem but may occur relatively frequently if polygons are used without any supervision from an online source. E.g. even the Global Water Watch polygon database is in some countries not very accurate.
- Wrong detection of dam wall: the method can in principle automatically detect the dam wall in the stream network by looking at the slope. In some cases where the background slopes are large this automated detection is not correct. After the thesis work, several improvements have been made to ensure that dam detection is as accurate as possible. Most of these issues are therefore now resolved. Only in cases where the slope is not a clear descriptor for the location of the dam wall (e.g. with relatively shallow dams), the automatic detection may still fail.
- The method searches for flat areas in the topography. In case the reservoir was not yet built during the acquisition of the static terrain dataset, flat areas are not found. However, in this case, a user may manually supply the location and height of the dam wall and skip all the bathymetry infilling steps to get bathymetry as the elevation already describes the bathymetry.
- In some cases, the stream network is not properly connected (mostly in relatively flat areas) and part of the stream network that encompasses the reservoir is missed. This results in an underestimation of the reservoir area and volume with given water level.
- Very large dams and reservoirs will likely result in large errors, in particular in the absolute volume estimates. This is because the bathymetry will be very deep and a lot of bathymetry must be interpreted with very little constraints of the dam wall location and shorelines locations. We have seen that performance deteriorates quite severely with reservoirs above 3km3, but it should be noted that large reservoirs that are not very deep and that have a lot of shoreline compared to surface area may still provide good results. This needs to be further investigated.
- Cascading reservoirs within the same polygon are not detected by the algorithm as it assumes that there is only one reservoir in the area of interest.
- The algorithm assumes no sedimentation. In fact, it assumes that the depth at the dam wall is equal to the depth measured just downstream of the dam wall. This may lead to overestimation of the present-day capacity in dams that are very prone to sedimentation and do not have a facility to remove sediments. To overcome this, a combination of the proposed algorithms with a limited local survey of strategically chosen points over the reservoir may help. Optimizations of the parameters of the bathymetry model may then be performed on the collected limited survey data.

Dynamic approach

Our current experience with the dynamic approach is:

- It is usable with reservoirs with a significantly large size above several km^2 in surface area.
- It only provides reasonable relationships for the water levels and surface areas within the range of the observations. Anything below the lowest water level recorded is not available.

- It also provides error bands on the basis of the variability in water level over the track and hence it is easier to identify the uncertainty in the relationship as well.

Combination of static and dynamic approach
It is worthwhile to note, that the dynamic and static methods can likely be combined in cases where both methods yield enough results, i.e. enough bathymetry points to warrant a reasonably valid estimate of the bathymetry in a significant portion of the domain of water levels and surface areas. This raises the question how to combine the best of both methods into one comprehensive hypsometric relationship. We see this as a case-by-case decision, as in some cases there are enough points available in both methods, and in others not. Within our code base, we have provided an example notebook that provides guidance how to optimally use both methods together. We summarize this approach in further detail below.

In combining both approaches it may be assumed that the estimates from method 2 (dynamic) are more accurate, whilst the estimates from method 1 are more complete (i.e. these provide hypsometric points over the entire range of the reservoir). Hence if points from method 2 are available within the same data range, these may be prioritized over the points given by method 1. This is because of two reasons: first method 2 relies on more direct observations of surface area and water level; second, method 2, when using more recent observations, may include information on shoreline sedimentation in the bathymetry, hence making the hypsometric relationship more up to date. Method 1 only relies on data of the survey period of the static elevation product under consideration, which could be relatively old. For instance, the Hydro-MERIT data we have used relies on Shuttle Radar Topography Mission data from the year 2000.

A further important point of attention when combining both, is that the water level for both distinct methods, is measured against a different datum. Based on the aforementioned observations, we can explore two strategies to combine both datasets. 1) we assume that we can make the water levels equivalent by adding an offset, such that the difference in surface areas belonging to both methods in the overlapping region is minimized. Note that by doing this, we assume that the water levels are not biased against each other and only different by random white noise. 2) we compute the water level datum difference by comparing the local offset between the ellipsoid or geoid used for the two different elevation data sets (ICESat-2 versus static terrain datasets). This assumes that the local ellipsoid/geoid difference for each reservoir considered is accurate, and that there are no other systematic offsets between the two elevation data sources. Both possibilities are yet to be explored in the remainder of this project.

For Mita Hills reservoir in Zambia, we have the results as shown in Figure 2-8 for the two methods. Different from Figure 2-7, we have not corrected any offset based on the in-situ data, but rather make a direct intercomparison.

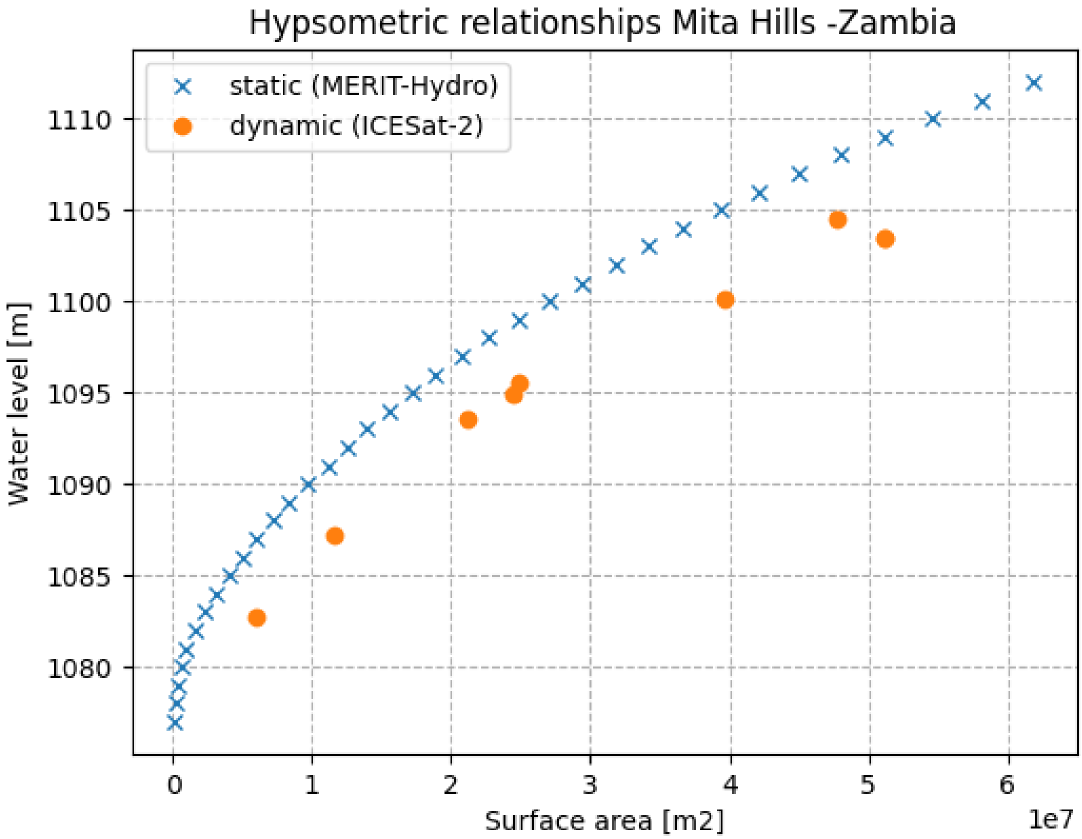

Figure 2-8 Hypsometry points for method 1 (static) and method 2 (dynamic)

It can clearly be seen that the points have some kind of offset with respect to each other. Reasons for the offset may be as follows: 1. The elevation of the ICESat-2 altimetry points is related to the WGS84 ellipsoid according to the NASA documentation. However, the elevation of MERIT-Hydro is related to the EGM96 geoid. This creates offsets between the two that are not constant in place and work over the y-axis. 2. Our Global Water Watch surface area calculations, used to form elevation - surface area pairs, are perhaps overestimating surface area causing an offset on the x-axis. 3. There is other bias in either one of the methods causing some sort of offset.

To resolve this mismatch, we need to make some assumptions in order to decide how to combine the two sets of points. We here assume the following: 1. Most of the bias is in the water level, hence we assume that differences in estimated surface area between the two methods are negligible. 2. A constant offset in water level may be assumed. This follows from the fact that the datums used for the static MERIT-Hydro and dynamic ICESat-2 are different. 3. As mentioned above, at lower bathymetric levels (compared to the highest on record) the dynamic hypsometric points are more trustworthy as these are based on actual observations, while the static hypsometry has to entirely rely on geomorphological assumptions.

In the example, we use a user-defined overlap between the two series to decide on the offset. To implement these assumptions, we do the following:

First, we select a overlapping part of the points where we assume both methods give good estimates. This is likely in the upper part of the graph. Hence, we select points that are above 50% of the range between lowest and highest surface area according to the static bathymetry points. Through piece-wise interpolation, we estimate the surface area at points measured with method 1, through the relationship found for method 2.

The mean of the differences of the interpolated surface area estimates and the actual estimates from method 1 itself are assumed to be our offset and used to datum-correct one series against the other. The result is shown in Figure 2-9.

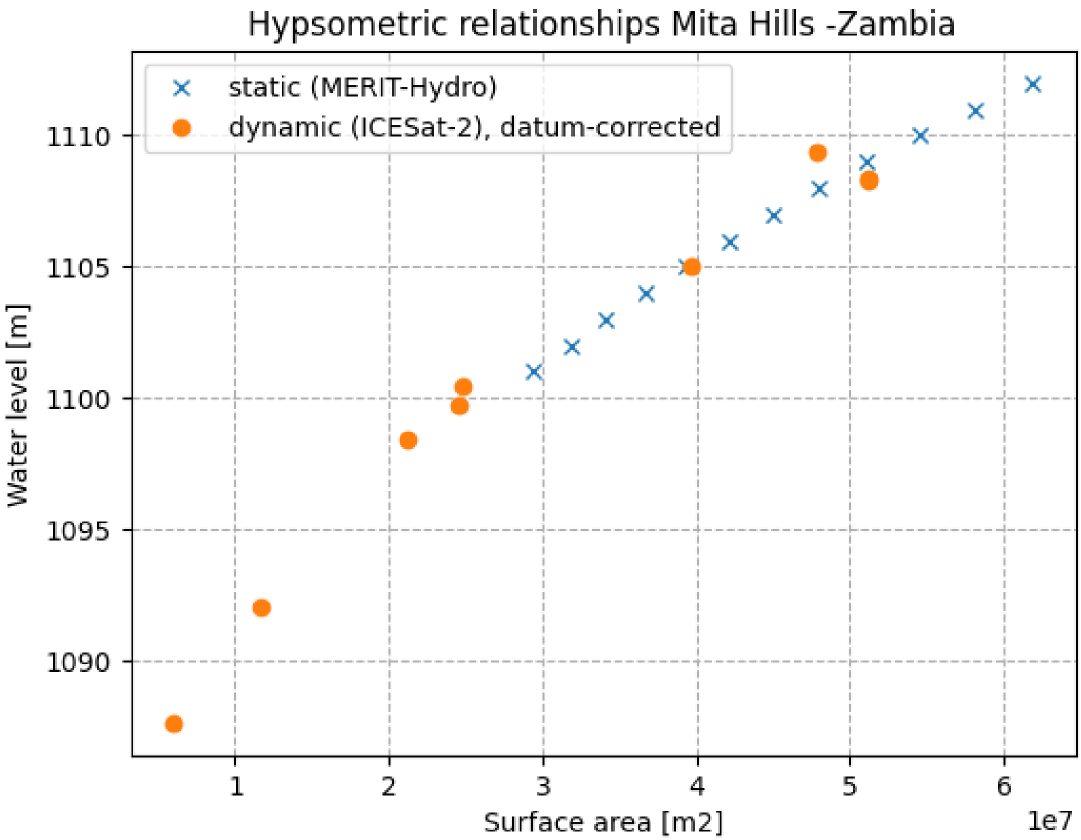

Figure 2-9 corrected hypsometry points.

We can now use the combination of corrected samples to create a new hypsometric relationship in which both methods are used. The result of this new relationship is shown in Figure 2-10.

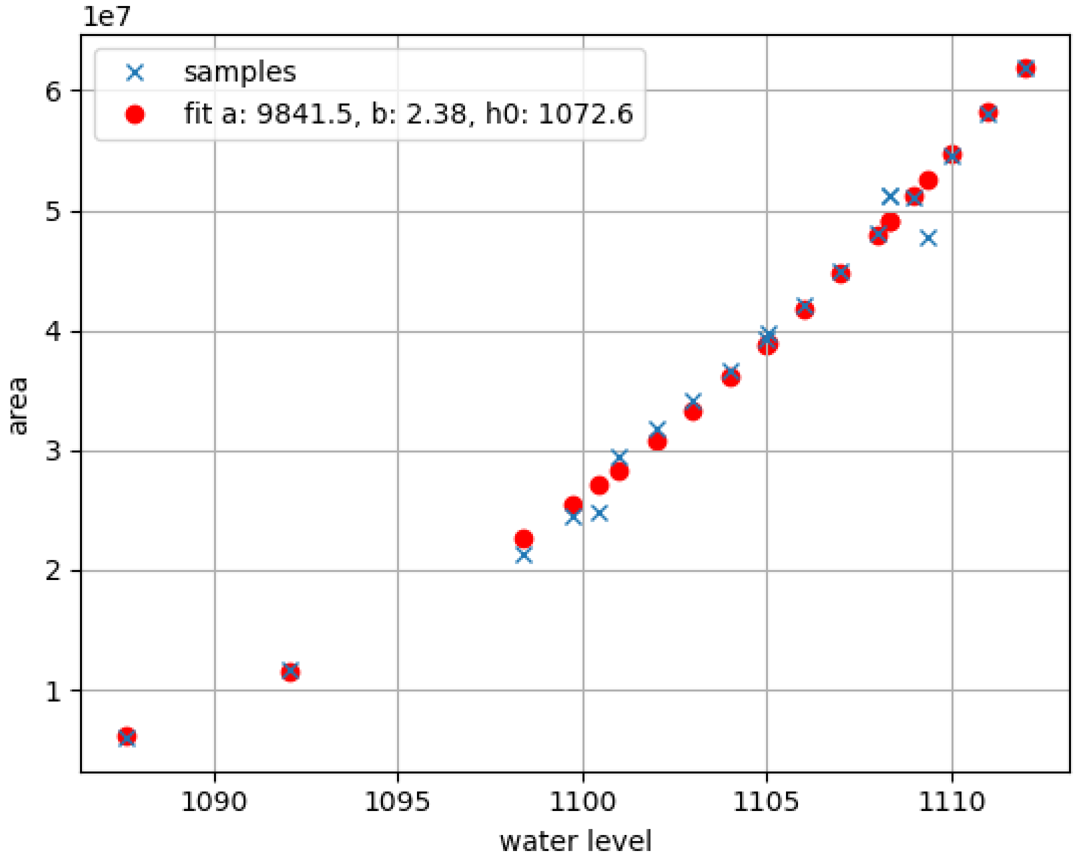

Figure 2-10 Hypsometric relationship (red) found through fitting of both static and dynamic points

3 WP2: API development

The Global Water Watch API had to be extended to also serve storage estimates as a function of the hypsometric relationship. This extension has been programmed as part of the S2S project (funded by ESA). This has been implemented in the following way:

- Tables have been added to the database, which, per record, store the parameters of a relationship between water level and surface area. This can typically be described by a power relationship, i.e. $A = c(h - h_0)^b$. To accommodate possible future wishes to incorporate other relationship shapes, we have made the relationship generic, allowing for other possible relationship forms in the future (e.g. piecewise linear or polynomial).
- Several functions were developed to use the hypsometry relationship to estimate surface area or volume (i.e. the integral of the above equation) from a surface area estimate. To accommodate possible future uses of altimetric records as input to the platform, on top of the existing surface area estimates, we have also made functions that do the inverse operations.
- Several API end points were made to use the above-mentioned tables and function to output water level or storage as a time series.
- Unit tests were written for all and a first hypsometry curve for the Mita Hills reservoir (Zambia) was uploaded and used for practical tests of the API end point.
- After testing, hypsometry was derived and uploaded for reservoirs in Spain, South-Africa, India and the United States, where validation data was available.

Within the GWW project, also front-end developments were made that provide volumetric estimates within the GWW front end.

With this extension the API is ready for operational use. Several hundreds of hypsometric relationships have already been uploaded to the platform, and now provide volumetric estimates for the considered reservoirs. An example is shown below for Theewaterskloofdam near Cape Town – South Africa. A user can interactively request these results on https://globalwaterwatch.earth/

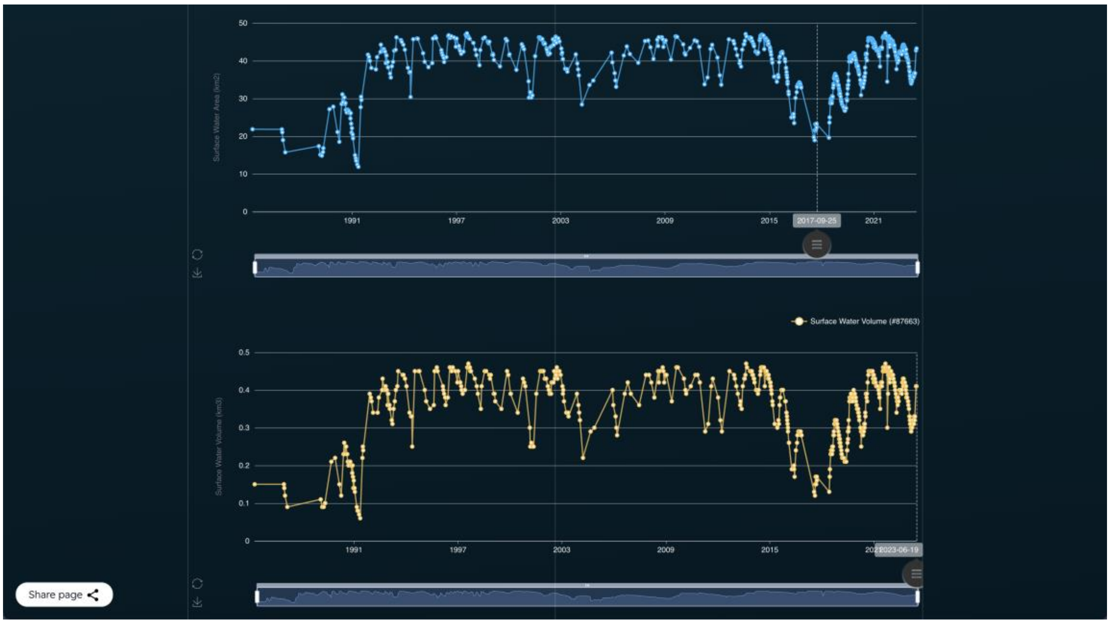

Figure 3-1 surface area (blue) and volumetric time series(yellow) for Theewaterskloofdam - South Africa (source: globalwaterwatch.earth).

4 WP3: Use case development

Red Cross 510 has ongoing projects in Lesotho related to anticipatory actions for drought. The Lesotho Red Cross Society recently launched its Early Action Protocol for drought. The S2S project has been aligned with these ongoing projects to find out the possible uses of the data in real-world application related to humanitarian response and other uses surrounding that. Several stakeholder meetings were held with the aim of getting a better understanding about how the S2S results and GWW platform can support decision making in humanitarian response and preparedness practices. In the first section, we describe the use cases and requirements from stakeholders in Lesotho and Eswatini. A specific requirement is to be able to assess how water availability may alter in the forthcoming months. Therefore, in the second section we provide a more in-depth analysis of the predictive skills provided by the data. Finally, in the third section, we present additional use cases and requirements following from these from the Water Resources Management Authority of Zambia (WARMA).

4.1 Cases Lesotho and Eswatini

Use cases for the S2S data in Lesotho have been identified together with relevant stakeholders such as the Lesotho Red Cross Society, Ministry of Water, Disaster Management Authority, Lesotho Meteorological Services, Water and Sewerage Company, and dam operators. It was discussed how the stakeholders collect and analyse reservoir information, how they use the information to inform communities about drought or flood and what data gaps they have. As a result, the following opportunities for the model have been highlighted by the stakeholders:

- Monitoring the storage levels of the reservoir and send an alert to dam operators when certain thresholds are reached. In the environmental release plan of the reservoir, thresholds for water shortages are set. When a water storage level below the threshold is observed, a warning could be sent (e.g., on WhatsApp or SMS) to the users for them to act timely.
- Using the satellite imagery to identify erosion prone or dry areas surrounding the reservoir. Areas without vegetation are perceived as more erosion prone. By having an overview of these areas, soil conservation measures can be taken to minimize soil run-off in the reservoir. This functionality in the meantime has been added to the GWW platform.
- Expanding the model with a functionality to measure sedimentation to be able to calculate the storage capacity of the reservoir in a more accurate way.
- Comparing water levels monitored by the GWW to critical benchmarks such as dead storage and full supply levels, particularly during the rainy season.
- Using storage information as a proxy for drought and incorporate it in the current drought trigger model. This might be further investigated by making use of the prediction methodology explained in the remainder of this section.
- Calibrating the estimations of the model with local data collected by dam operators. This is important to gain trust in the data before using it in decision-making.

Moreover, the stakeholders flagged out the following challenges that might arise when using the model:

- Communities in Lesotho mostly rely on *other water* sources such as boreholes and wetlands. Water from reservoirs is mainly used to serve the urban population or is transferred to South Africa under a water treaty. Therefore, in this specific case, the model is less suitable for monitoring the situation in rural areas.

- It was noticed that users had some difficulties with the interface of the Global Water Watch platform. Functionalities such as the timeline and imagery comparison were difficult to understand. Moreover, outlier values are visible in the timeline which is perceived confusing by several stakeholders. The GWW platform has in the meantime already been improved: Timelines are now very clearly indicated and an explanation of the functionality added to the web view with reservoir details.

During a recent workshop organised by Red Cross 510 together with various stakeholders in country, an idea emerged for future projects: establishing a specialized platform capable of accessing GWW data through its existing API, merging it with local data, and producing supplementary operational indicators. Red Cross 510 aims to partner with Lesotho Red Cross Society to explore this idea further for potential future development initiatives.

Additionally, a correlation analysis was performed, aimed to explore the potential link between meteorological indicators of drought and water storage data from the Global Water Watch for Lesotho's reservoirs. Using the Standardized Precipitation-Evapotranspiration Index (SPEI), commonly utilized in drought analysis, data for reservoirs including Katse, Metolong, Maqalika, Mohale, and Muela Dams were examined. Surprisingly, no significant correlation was found between precipitation and water surface areas. This could be attributed to several factors, including delayed reservoir response to precipitation, limitations in the resolution of SPEI data, active reservoir management, and the recent completion of Metolong Dam. The absence of a direct relationship emphasizes the necessity of incorporating reservoir information alongside traditional meteorological indicators for a more comprehensive approach to drought preparedness strategies.

4.2 Investigation of predictability of reservoir storage

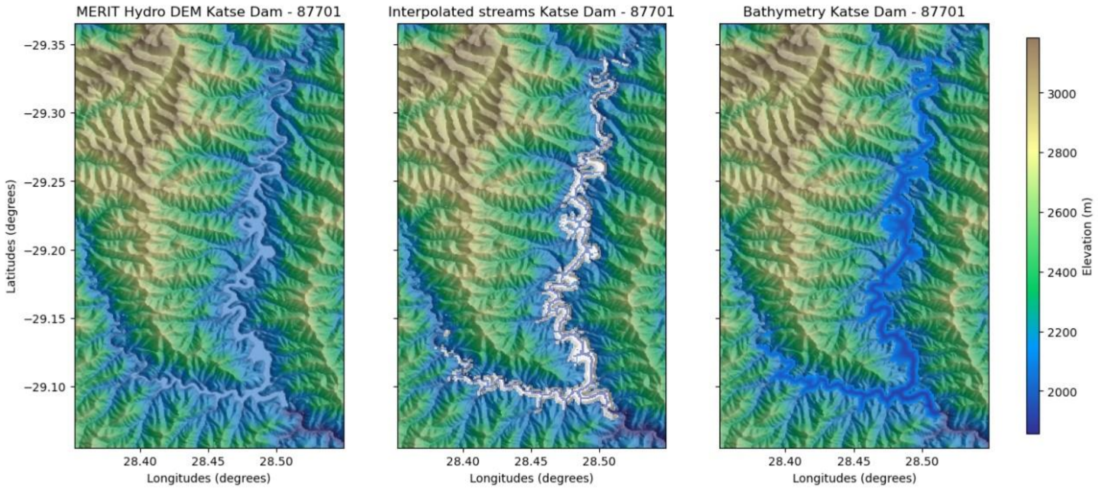

Figure 4-1. Bathymetry estimated with static geomorphological method for Katse dam in Lesotho. Left: original elevation, middle: elevation with reservoir surface masked (shown as white), right: interpreted elevation using the "static" method.

The static hypsometry method, based on geomorphological methods, after validation in India and Zambia, has been applied on Katse dam in Lesotho and Hawane reservoir in Eswatini. As part of an MSc study (Klein Holkenborg, 2023) first simple prediction models have been established that can predict upcoming storage in the reservoirs several months ahead in time as a function of its present day monitored storage and possible other co-variables.

Several trials have been performed with several co-variables including:

- The present day and previous month's storage in the reservoir. The earlier months were also included to be able to let the model use the trend in storage as additional predictive strength.
- Precipitation in the upstream contributing catchment in the months before the moment of prediction, assuming that low amounts of precipitation may result in a lower amount of runoff also in the forthcoming months as a result of drier soils.
- The Standardized Precipitation and Evaporation Index (SPEI) in the entire surrounding area, assuming that low values in SPEI concur with a combination of low precipitation and higher evaporative demand of plants, leading to a higher use of surface water resources by agriculture.

Simple multiple (auto)-regression models were derived with one regression relationship for each t0 (i.e. time of prediction) and each lead time, up to 6 months ahead in time. Figure 4-2 and Figure 4-3 show the skill in predicting if forthcoming storage will be at least 1 (for Hawane) or 0.5 (for Katse) standard deviations below normal conditions using the Heidke skill score.

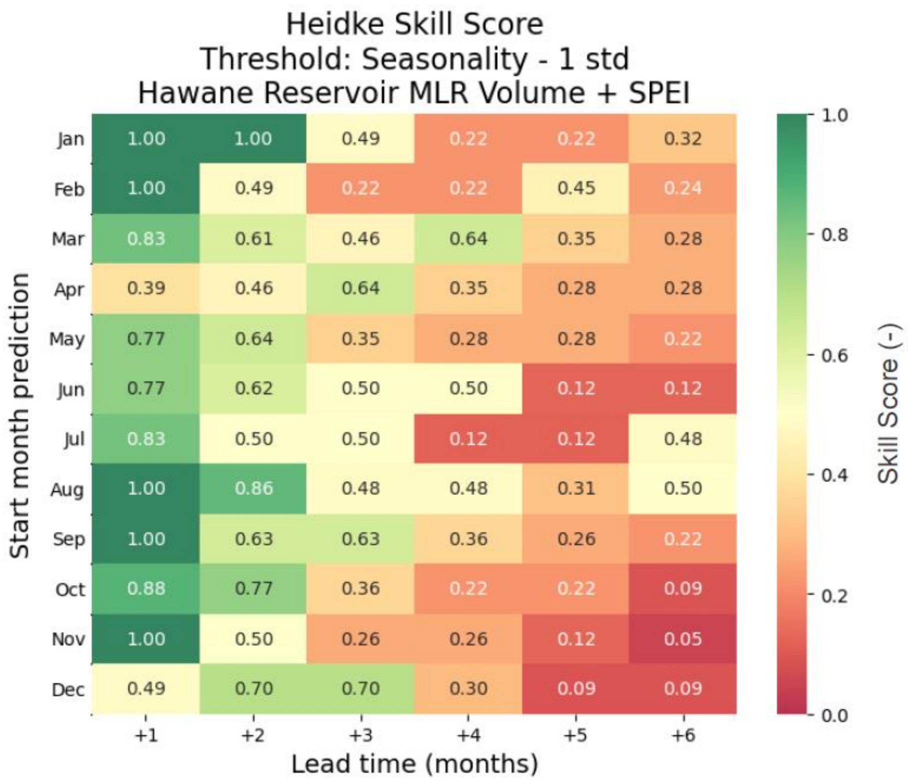

Figure 4-2 Heidke skill score for predicting under 1 climatological standard deviation below normal for Hawane reservoir, Eswatini.

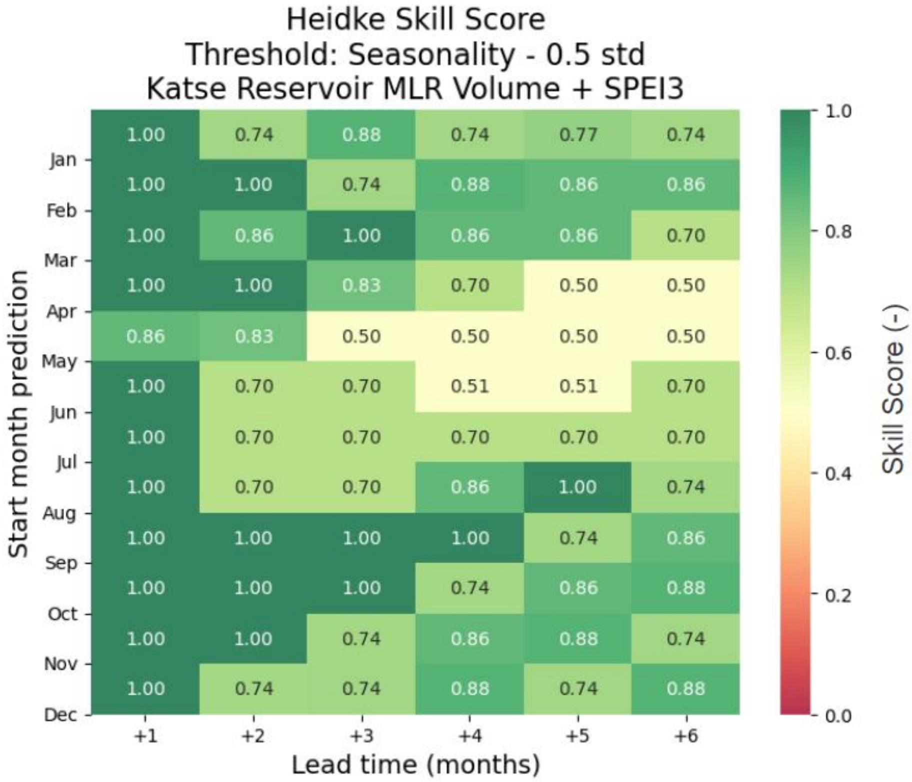

Figure 4-3 Heidke skill score for predicting under 0.5 climatological standard deviation below normal for Katse reservoir, Lesotho.

The figures demonstrate that in both cases, the storage estimates may provide a lot of skill. Especially Katse, being the larger reservoir with about 3 years of inflow worth of storage, the storage estimates provide significant memory for predictions ahead in time. Interesting further investigations into predictability may go into combination of the storage estimates with more physics-based models and using seasonal ensemble forecasts.

4.3 WARMA

Over the course of the project, many interactions took place between Deltares and the Water Resources Management Authority of Zambia (WARMA), which led to several possible uses of the data for WARMA. In summary these are:

1. Regulation of water permits and structures requires monitoring at seasonal time scale.
2. Regulation of water use requires monitoring at weekly time scale.
3. Decisions on curtailments require a transparent communication.
4. Several cases for which visuals of the situation in and around the reservoir are needed, including visualization of locations of concentration of water hyacinth and algae growth, and appearing new irrigation schemes around reservoirs.

Besides these use cases, WARMA also kindly offered us validation records in the form of recently acquired bathymetric surveys and time series, which we also used to investigate the performance of our methods (see also Chapter 2). WARMA presented during the New York Water Week during our session with great success. WARMA is co-authoring a blog on our project.

5 WP4: Outreach and communication

Within this project, we have performed a significant amount of outreach activities. We have organized these in the following subsections.

5.1 Participation at conferences

- Attendance to the 23rd WaterNet/WARFSA/GWPSA Symposium in Rustenburg (19-21 October 2022). This conference gave us the opportunity to showcase our methods to translate surface area into storage. We focused on first results of our ICESat-2 dynamic altimetry method and used recent in-situ bathymetric surveys to demonstrate how well the method works.
- A side-event was organized during the UN Water Week (hosted by ABinBEV) co-convened with Global Water Watch (22-24 March 2023). The current status of the GWW tool was presented, and first impressions of what we can do (thanks to the S2S project) with storage were shown. The Water Authority of Zambia (WARMA, Frank Nyoni) also presented during this event, and outlined no less than 6 different use cases, for which 4 require storage estimates.
- Attendance to the 11th Global Dialogue Platform in Berlin (10-12 October 2023). We were selected for a poster presentation at the conference. Bouke Peter Ottow (service coordinator for Anticipatory Action at Red Cross 510), together with Sebongile Hlubi (forecast based financing project manager at Lesotho Red Cross Society) led the presentation and collected feedback from humanitarian actors.
- Attendance to the 24th WaterNet/WARFSA/GWPSA Symposium in Zanzibar (25-27 October 2023). This conference brings together researchers and practitioners in the field of Integrated Water Resources Management. The platform was presented in an oral presentation with a specific focus on use cases.

5.2 Contribution to UN report

We provided contributions to a UN report on SDG indicators, co-authored by ESA. In particular possible sources for surface water data to monitor SDG indicators within SDG 6 have been addressed by the team.

5.3 Blog posts

The following activities are planned in the coming months:

- Blog post by Frank Nyoni (WARMA). This blog post will be posted on the Global Water Watch web page.
- Blog post by Emie Klein Holkenborg (510) for Deltares. This blog has been posted on the Global Water Watch web page.
- Blog post by Sarah Breker, Emie Klein Holkenborg, Daniele Castellana for Red Cross 510. This was disseminated in several channels within the Red Cross Red Crescent movement and externally.

6 Conclusions

6.1 Conclusions

Scientific developments

On our scientific developments we may conclude the following:

- We have developed two very distinct methods to estimate bathymetric information for reservoirs.
- Both methods work entirely independent of ground-truth information and require only little guidance from a user.
- Both methods are available open-source for anyone to use and are properly documented.
- Where available, we have conducted validation on locally acquired bathymetry (through methods such as echo sounding) and on existing timeseries of water levels and volumes. Validation led to the conclusion that the methods work satisfactorily.

Use case developments

We have investigated several use cases, most prominently on drought early action in Lesotho, and less prominently, use cases related to water management in Eswatini and Zambia. From these we can conclude the following:

- To accommodate that users can request storage from reservoirs (i.e. in m^3) we have implemented hypsometric relationships for several hundreds of reservoirs for which validation data was available, in the global reservoir monitoring tool “Global Water Watch”, which was developed in tandem with this EO4Society project.
- Many use cases related to water management can already be fulfilled with the current online Global Water Watch tool, provided that a validated hypsometric relationship for the required reservoirs is in place. This is certainly not yet the case for all reservoirs in our database.
- Many users requested contextual information such as the state of the surroundings of the reservoir, but also the reservoir state in relation to certain locally used datums such as the dead storage and full supply levels. Where contextualized information could be provided in a general form, we have implemented the requested features. Features that require highly localized information (in particular the datums) are not implemented, as these cannot be generalized. Instead, we recommend that these are implemented through dedicated monitoring platforms, using the GWW API.
- A particular requested feature, namely forecasting of storage throughout the dry season, was investigated through a dedicated MSc thesis work (Klein Holkenborg 2023). This demonstrated promising results on predictability for a limited set of investigated reservoirs. The methods require further investigation and may be considered for later implementations.

6.2 Recommendations

Sediment accretion

Many stakeholders requested the development of monitoring capabilities of siltation problems in reservoirs. Siltation is a well-known issue in many reservoirs world-wide and usually is monitored by performing periodic bathymetry surveys with echo sounding. This is a time consuming and costly task.

Currently, our geomorphological approach to bathymetry estimation relies entirely on EO-data. As a result, siltation on the reservoir bottom cannot be traced. We highly recommend investigating if a sparse sampling of local bathymetric survey points can be combined with our geomorphological bathymetry estimation approach. Sampling may for instance be concentrated close to the dam wall and close to larger original tributary locations, which are likely the most sensitive locations for sediment accretion, and the most uncertain locations to estimate using our current methodology.

Predictions
We also highly recommend to further investigate approaches to predict surface water scarcity ahead in time at seasonal time scales. This information is highly needed for many use cases In the humanitarian sector (this project), but also for broader water and agricultural management planning, hydropower planning, energy market predictions and likely more. So far we have focussed on stand-alone reservoirs using simple data-based models for predictions. With the ongoing research in large-scale hydrology at Deltares, it will become feasible to explore predictability using more physics-based approaches, and predictions for more complicated situations, e.g. with multiple reservoirs with upstream and downstream influences. Obvious research directions are integrated model development with optimization of the operation rules, and data assimilation for operational forecasts.

Filling in more reservoirs
Currently, we have implemented storage estimation for only several hundreds of reservoirs whilst there are tens of thousands of reservoirs being monitored in Global Water Watch. Extending our storage estimation world-wide would require several things among which:

- a more accurate reservoir shape (polygon) for each reservoir. The current database contains many polygons that are not accurate and hence this leads to a poor representation of the reservoir bathymetry.
- extended methods to detect where a dam body is located. Here we encourage investigations using AI to automatically detect the location of dam bodies, which we have already successfully implemented over Angola for a World Bank project. We expect that especially where the dam body is not very high compared to the surrounding terrain differences, or where the reservoir is small, this will strongly improve results of our bathymetry estimation approaches.
- A more automated approach to validate or even sanity check the results. This is currently done with a visual check, which is ideally automated.

In summary, the research has led to two viable methods to estimate bathymetric properties of reservoirs, with first uptake in the GWW platform and investigation of use cases in Lesotho and Zambia. New research questions have appeared which we will tackle in future work.

6.3 Acknowledgement

Finally, we would like to acknowledge the ESA EO4Society program for funding this research. Thanks to this grant, we have been able to pioneer in the field of EO-based bathymetry mapping, and have been able to lay grounds for both further research in the area of improving EO-methods to also map out sedimentation, as well as early warning improvements using the long memory that storage may provide in hydrological prediction systems.

A particular thanks goes to our project officer Marc Paganini for his guidance, and strong enthusiasm for our project.

Deltares is an independent institute for applied research in the field of water and subsurface. Throughout the world, we work on smart solutions for people, environment and society.

Deltares