TECHNICAL REPORT

Current Trends in River Bathymetry using UAV-borne Technology to Inform E-flow Assessments in Southern Africa

Singh, Keanu[1*]

[1] *GroundTruth, Pietermaritzburg, South Africa*

INFO

Submitted	30 November 2023
Keywords	Environmental Flow Management, River Bathymetry, Unmanned Aerial Vehicles (UAVs), Hydraulic Modelling
Flagship	Digital Twin
Work Package	System Modeling

ABSTRACT

Freshwater, constituting a mere 2.5% of Earth's total water, is a critical resource facing escalating competition due to an anticipated global population surge to 9.7 billion by 2050. Southern Africa is characterized by uneven water distribution and quality challenges which exacerbates these issues. Environmental flow (E-flow) management is a crucial approach that quantifies water requirements for maintaining ecological integrity, aiming to balance human and environmental water needs. Including E-flows in management helps to ensure sustainability of water resources River bathymetry is a core part of E-flow assessments. This document reports on core research within a project that delves into management of E-flows in the Limpopo and neighbouring basins in Southern Africa. It covers a scientific investigation to determine optimal water quantities and qualities for river systems and to assist with their management. The report focuses particularly on the use of bathymetric surveys, specifically the need for high-resolution Digital Elevation Models (DEMs) to inform hydraulic modelling. The spatial and temporal variability of bathymetry is crucial for applications ranging from flood risk mitigation to ecosystem studies and for long-term management of E-flow implementation. While traditional Total Station Theodolite (TST) surveys provide accurate ground control points and in the past were the basis for river hydraulic studies, they are limited in scale and efficiency. In situ measurements, despite their accuracy, may lack spatial representativeness and are resource intensive. Remote sensing techniques, particularly Unmanned Aerial Vehicles (UAVs), offer an alternative for bathymetric data collection driven by their ability to access challenging areas of a river and provide high-resolution data at relatively low cost. To this end, this report focuses on direct methods for bathymetric data collection, exploring optical and acoustic approaches. The primary objective was to explore and investigate UAV-based water-penetrating surveying techniques to create high-resolution DEMs for hydraulic modelling linked to E-flow studies. A review of recent, relevant literature indicated that airborne laser bathymetry appeared preferential in the context of E-flows, compared to spectrally derived bathymetry, multimedia photogrammetry, Ground-Penetrating Radar (GPR), and Sound Navigation and Ranging (SONAR) techniques. Currently, the RIEGL VQ-840-GL green lidar sensor appears to be the forefront technology for use in E-flows UAV-borne bathymetric surveys. This research aims to contribute valuable insights into efficient and cost-effective methods for E-flow studies, addressing the growing challenges in water resource management.

1. Introduction

Approximately 2.5% of the total amount of water on the earth's surface is accounted for by freshwater, with just 1.5% of that accessible for biophysical processes (Stephens et al., 2020). Freshwater is critical for agricultural, manufacturing, and domestic purposes, with intense competition for freshwater among various sectors expected to rise with the projected increase in the world population to 9.7 billion by 2050. The equitable distribution and management of freshwater resources in Southern Africa is particularly challenging, given that freshwater resources are unevenly distributed and that there are limited good quality and quantity water resources for both human and ecological use (Sibanda et al., 2021). Climate variability further compounds issues of water distribution, quality and quantity.

**Corresponding author (keanu@groundtruth.co.za).*

Singh, K. 2023. *Current trends in River Bathymetry using UAV-borne technology to inform E-flow assessments in Southern Africa*. Colombo, Sri Lanka: International Water Management Institute (IWMI). CGIAR Initiative on Digital Innovation. 17p.

An approach to water resources management that quantifies water requirements to maintain the ecological integrity of rivers is to determine and manage the environmental flows (E-flows) of a river. An E-flows study (also known as a Reserve Determination, or E-flows assessment) is a scientific investigation and assessment of a particular river system or wetland to determine the quantity of water required to maintain the integrity of the system. In South Africa, E-flow studies are conducted in accordance with the National Water Act of 1998, which stipulates that a reserve of water (E-flow) must be maintained to protect the ecological functioning of a river system or wetland. The approach involves assessing the current state of the ecosystem with regards to water requirements of its resident flora and fauna. An E-flow study also considers the potential impacts of human activities such as water abstraction, land use changes, and pollution on the ecosystem. Findings from the study are aimed to inform management strategies to balance water requirements between human and environmental uses.

One objective of an E-flow assessment is to conduct a bathymetric survey. A bathymetric survey accurately determines the quantity of water at a site on the river by obtaining the water profile of the river channel to inform hydraulic modelling. Bathymetric surveys are done to measure water depths and map underwater features of a water body. Bathymetry of inland waterbodies plays a critical role in many hydrological and hydraulic problems and applications such as flood risk and climate mitigation, sediment transport and erosion, and ecosystem studies. High resolution bathymetry maps of inland water bodies are essential for hydraulic flow modelling and flood hazard forecasting (Conner and Tonina, 2014; Gichamo et al., 2012), predicting sediment transport and changes to the streambed morphological (Manley and Singer, 2008; Nitsche et al., 2007; Rovira et al., 2005; Snellen et al., 2011), and monitoring instream habitats (Brown and Blondel, 2009; Powers et al., 2015; Walker and Alford, 2016). Similarly, the spatial variability of bathymetry along a watercourse may require continuous or high-resolution mapping to accurately obtain river morphology and geology characteristics (Diaconu et al., 2019).

Existing approaches for bathymetric surveys range from traditional Total Station Theodolite (TST) surveys and levelling equipment to digital photogrammetry, terrestrial laser scanning, and aerial Light Detection and Ranging (LiDAR). TST surveys use electronic survey equipment and a measuring tape, level, and a rod to record the profile of the terrain by measuring distances, azimuth and elevation (Viney and Kirk, 2000). The accuracy of TST surveys has a point spacing accuracy of approximately 0.05 m within an area of 0.075m² to 0.275 m² (Vieny and Kirk, 2000) and are therefore commonly used as Ground Control Points (GCP) for remote sensing mapping (Fonstad et al., 2013; Passalacqua et al., 2015); Woodget et al., 2015). However, significant manpower, time, and subsequent financial investments are required to produce a Digital Elevation Models (DEM) using TST surveying. Additionally, TST surveys are limited to channel cross section surveys and lack the ability to produce 3D maps. This makes TST an inefficient method for providing large and continuous measurements to quantify the spatial and temporal variability due to the high cost/area covered ratio (Baneg et al., 2014; Alverez et al., 2018).

Bathymetric data collected from in situ manual measurements, such as using the TST, may not always be satisfactory in terms of spatial representativeness and temporal variability (Gholizadeh et al., 2016). Furthermore, in situ measurements require significant investments of resources which include equipment, hardware, software, and manpower (Lejot et al., 2007; Fonstad et al., 2013). As a result, remote sensing techniques have been investigated as an alternative means of bathymetric data collection. In particular, the development and growth of UAVs as remote sensing platforms, as well as advances in the miniaturization of equipement and data systems, have resulted in the increased feasibility and use of Unmanned Aerial Vehicles (UAVs) technology in environmental monitoring communities (MacVicar et al., 2009). The ability to capture data in dangerous or often inaccessible areas, high spatial and/ or temporal resolution measurements of environmental attributes, and the introduction of novel sensing technology over a variety of environments have all promoted the further use of UAVs.

Bathymetric studies can be broadly categorized into indirect methods, which are used to estimate the average depth or flow area, and direct methods, which determine the full bathymetric profile. Indirect remote sensing methods are based on estimating the average depth from satellite measurements of Water Surface Elevation (WSE) and modelled discharge (Leon et al., 2006), or estimating flow area from WSE and cross-section average flow velocities (Moramarco et al., 2019). Direct methods are able to observe subsurface topography and reconstruct the full cross-section profile in a water body. Direct methods include optical approaches such as spectrally derived and multimedia photogrammetry or acoustic approaches such as Ground Penetrating Radar (GPR) and Sound Navigation and Ranging (SONAR). The primary aim of this report is to investigate and review options around UAV-based water

penetrating surveying techniques for identifying the below water profiles of river channels to create a high-resolution DEMs for the purpose of carrying out hydraulic modelling linked to E-flow studies.
This exploration is not designed to be comprehensive; it is simply aimed at investigating existing and proven options best suited to novel application in Southern Africa.

2. Optical Sensing

Optical sensing involves actively measuring reflected energy or passively sensing reflected or scattered light using multi- or hyperspectral imaging in the visible light spectrum. Optical methods generally used for capturing airborne bathymetry of seabed and natural or human-made objects in clear and shallow water bodies with depths < 60 m. Optical techniques are not suited for data capture in water bodies > 60m due to the high absorption of light in water. The strength of airborne optical methods when compared to other methods such as SONAR are that the effective SONAR Field-of-View (FoV) reduces with decreasing water depth, whereas the swath width for airborne methods mainly depend on the flying altitude. Furthermore, shipborne SONAR requires a minimum water depth for safe operation which limits its applicability.

Spectrally Derived Bathymetry (SDB), multimedia photogrammetry, and Airborne Laser Bathymetry (ALB) are widely applied optical methods. SDB and multimedia photogrammetry are passive approaches that use backscattered solar radiation from the bottom of the water body for depth measurements, whereas ALB is an active method based on Time -of-Flight (ToF) measurements of a green laser. Figure 1 shows a schematic diagram of the three main optical methods in bathymetry studies.

2.1. Passive Approaches

Passive approaches use backscattered solar radiation from the bottom of the water body for depth measurements.

2.1.1. Spectrally derived bathymetry

In SDB, a relationship is created between the radiometric image content and the water depth (Mandlburger, 2022). Spectral methods are based on the wavelength-dependent attenuation of light in the water column (Lyzenga, 1978; Stumpf et al., 2003). Spectral methods to estimate water depth of inland waterbodies have been applied to multispectral (or hyperspectral) and RGB images from (a) satellites (Geyman and Maloof, 2019; Jagalingam et al., 2015), (b) aircrafts (Legleiter, 2012; Marcus et al., 2002) and (c) UAVs (Flener et al., 2013; Lejot et al., 2007; Rossi et al., 2020). An understanding of the interaction of solar radiation with the atmosphere, the water body, the water surface and the bottom of the water body as a function of the wavelength is necessary for spectrally derived bathymetry. Generally, two approaches are used for deriving bathymetry from the radiometric image content; a physical-based method and a regression-based approach.

Physical-based approach

The radiometric image content comprises backscatter components from atmosphere, water surface, water column, and water bottom, and with the sun as a light source, as shown schematically in Figure 2. The total radiance arriving at the sensor is as the sum of individual partial contributions (Legleiter et al., 2009), as illustrated in Equation
1. The total radiation (LT) at the sensor is the sum of the radiation reflected from the bottom of the water body (LB), the radiation backscattered from the water body or water column (LC), the signal component from reflections at the water surface (LS), and components from backscattering particles in the atmosphere (LP).

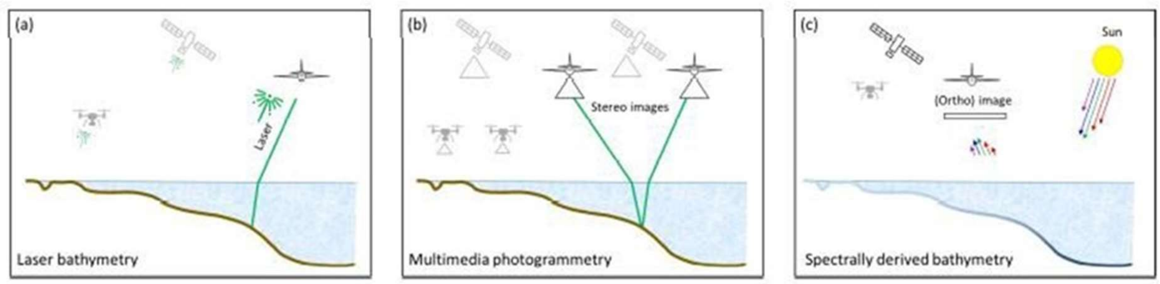

Figure 1 Schematic diagram of optical methods in hydrography; (a) airborne laser bathymetry, (b) multimedia stereo photogrammetry, (c) spectrally derived bathymetry (Mandlburger et al., 2020)

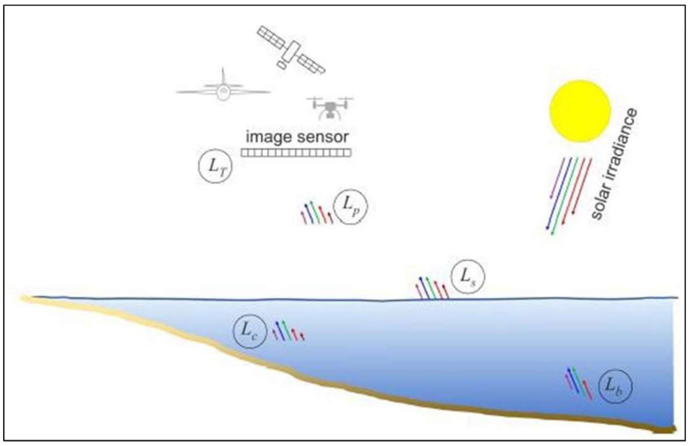

Figure 2 Schematic diagram of optical methods in hydrography; (a) airborne laser bathymetry, (b) multimedia stereo photogrammetry, (c) spectrally derived bathymetry (Mandlburger et al., 2020).

$$LT(\lambda) = LB(\lambda) + LS(\lambda) + LS(\lambda) + LP(\lambda) \qquad (1)$$

The signal absorption within the water column is significant as a result of continuous forward and backward scattering. The LB signal contribution depends on both water depth and water bed properties such as reflectance and roughness. The LC contribution is determined by the optical properties of the water column. Absorption and scattering by pure water, and turbidity caused by suspended sediment and organic matter are all contributing properties (Grobbelaar, 2009). Assuming homogenous surface and subsurface conditions, the depth can be determined from a single spectral image channel without the presence of external reference data. However, multiple radiometric bands of multispectral images are used in practice due to the signal absorption in the water column and bottom reflectance of the wavelength.

Regression-based approach

One of the disadvantages of the physical-based approach is that radiation reflected from the water body depends on the water depth and bottom reflectance, meaning both effects are interlaced. To address and overcome this limitation, Stumpf et al. (2003) introduced ratio-based calculation of two spectral bands with different wavelengths. This was found to be approximately constant and, thus, to a certain extent independent from variations of bottom reflectance. This is the premise of the regression-based approach.

Machine-learning in SDB

In addition to the well-established physics- and regression-based depth inversion methods discussed above, machine learning approaches such as artificial neural networks (Makboul et al., 2017), nearest neighbor regression (Legleiter and Harrison, 2019), random forest (Sagawa et al., 2019; Yang, Ju et al., 2022), gradient boost (Susa, 2022), multilayer perceptions (Duan et al., 2022), back propagation neural networks (Wu et al., 2022), ensemble learning (Eugenio et al., 2022) and support vector machines (Misra et al., 2018) have been successfully applied for deriving bathymetry from multispectral images.

2.1.2. Multimedia photogrammetry

Photogrammetry is the science of determining geometric properties from objects based on digital images. It is a well-established technique for acquiring a dense 3D point cloud and generating DEMs from the overlap of stereoscopic images that have been applied in a variety of fields. Photogrammetry is commonly used in, inter alia, geomorphology for floodplain analysis (Lewin et al., 1977; Mertes, 2002), identification of erosion and deposition patterns (Lapointe et al., 2000), river channel dynamics (Westaway et al., 2003), quantification of sediment transport rates (Lane, 2000), and bank erosion studies (Nikora, 1998).

Digital photogrammetry and automated evaluation methods such as Structure from Motion (SfM) (Schonberger and Frahm, 2016) and photogrammetric depth determination from stereo images, have received increased attention. SfM is a technique to provide 3D scenes using a series of temporal red-green-blue (RGB) images and georeferencing information (Condorelli et al., 2020). It provides information on the internal and external camera orientation at the time of acquiring each image by using automatic algorithms for estimating the camera's location. This results in a model that enables the determination of how individual 3D coordinates are projected on the images from the camera (Chandrashekar et al., 2018; Eltner and Sofia 2020). Digital photogrammetry faces challenges when applied to bathymetry in reservoir and river systems because of the reflection and refraction of light at the water surface. This requires consideration and correction to obtain accurate images. In optimal conditions, refraction corrections are possible if the water is clear and visible from the photographs (Dietrich, 2016).

Hybrid approaches (Slocum et al., 2020; Starek and Giessel, 2017) have been demonstrated that combine the advantages of the spectral approach, which performs better when the sediment is comparatively homogeneous (Legleiter et al., 2009; Overstreet and Legleiter, 2017), and the photogrammetry approach, which ensures higher spatial resolution and performs better if the bottom is sufficiently textured to enable feature matching(Feurer et al., 2008). In summary, spectral and photogrammetry methods are limited to waterbodies with high water clarity and can deliver results only for depths as that measured when using a Secchi Disk (SD). The measurement from a SD is an indicator of the transparency of a water column.

2.2. Active Approaches

Optical sensors can also actively measure reflected energy by simultaneously using two lasers, infrared and green wavelengths, in the light range.

2.2.1. Airborne laser bathymetry

Airborne bathymetric LiDAR systems are very specialized. Some commercial manufacturers of these systems include the Hawk Eye II (Airborne Hydrography, Sweden), the Laser Airborne Depth Sounder (Tenix LADS Corporation, Australia), and the Scanning Hydrographic Operational Airborne LiDAR System (SHOALS) (Optech, Canada) (Hilldale and Raff, 2008; Kinzel et al., 2013). These bathymetric LiDAR systems were designed to optimize the depth penetration using high power to overcome concerns related to recovery of laser pulses in deep attenuating water (Kinzel et al., 2013). Furthermore, UAV-borne topo-bathymetric LiDAR has been used for river and coastal engineering applications (Mandlburger et al., 2016; Mandlburger et al., 2020; Kinzel et al., 2021). In addition, there are novel UAV-based Green LiDAR Systems (GLS) with a high-resolution lightweight camera, Global Navigation Satellite System (GNSS) receiver, and an Inertial Measurement Unit (IMU) that can be used for river and coastal engineering applications (Mano et al., 2020; Green, 2023).

In contrast to the passive methods, laser bathymetry in general, and ALB in particular, represents an active technique for mapping shallow waters using a pulsed green laser (Philpot, 2019). Laser based bathymetric scanning systems use of two lasers in the light range: infrared and green. An infrared pulse reflects off the surface of water or land, while a green pulse penetrates the water and reflects off the bottom of a water-body or land (Quadros et al., 2008). The beams are usually not perpendicular to the terrain surface, as in the case of aerial topographic laser scanning, but forward at an angle of 15–20° to facilitate laser penetration to limit surface scattering. The water depth is determined from the difference in registration time of the beam reflected from the water surface and the beam reflected from the bottom of the water column (Mandlburger, 2022). A schematic representation of airborne laser bathymetry is shown in Figure 3.

2.2.2. The principle of the green laser operation

A laser is a device that emits electromagnetic radiation in the visible, ultraviolet (UV), or infrared range using the phenomenon of forced emission (Mandlburger, 2022). It consists of three elements, which are: (a) an external pumping system, (b) an excited active medium, and (c) an optical resonator. Usually, the most important feature of lasers is the wavelength of the laser radiation and its power. Lasers can be divided into low power lasers (1 to 6 mW), medium power lasers (6 to 500 mW), and high-power lasers (500 mW). The frequently used lasers include CO_2 lasers (gas lasers), solid crystal neodymium-YAG lasers, and the doubled-frequency neodymium-YAG lasers (Szafarczyk and Tos, 2023).

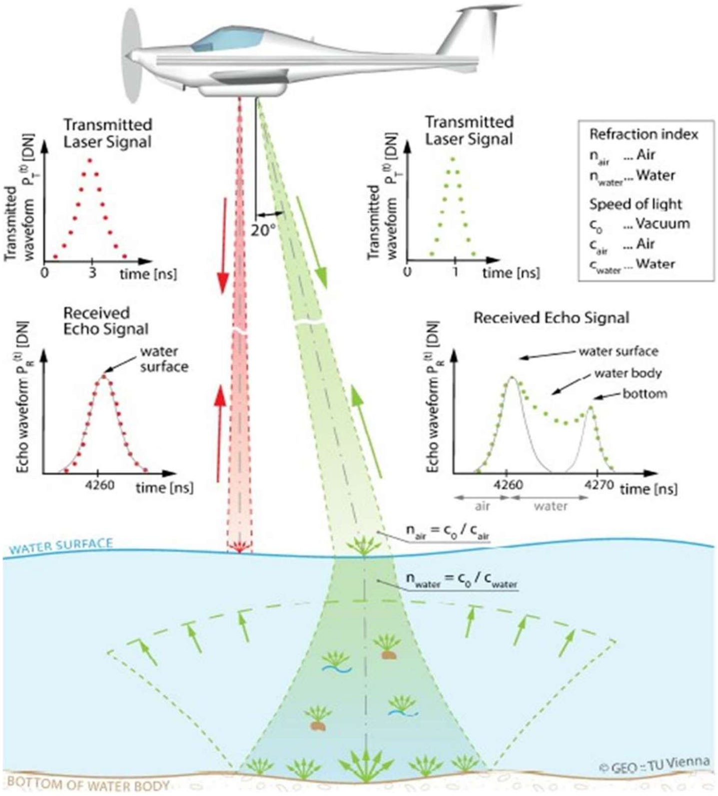

Figure 3. Schematic representation of airborne laser bathymetry using a green water-penetrating laser to detect the water surface and bottom and an additional infrared laser to detect only the air-water interface (Mandlburget et al., 2020).

The energy directed to the active medium by a pumping mechanism causes the emission of energy in the form of radiation. The active medium is located between mirrors that make up an optical resonator. One of these mirrors is a unidirectional mirror (Szafarczyk and Tos, 2023). The radiation of the active medium is amplified by the resonator, however, only a limited quantity of radiation can leave the optical resonator through the unidirectional mirror. This radiation in the form of a beam is laser radiation (Szafarczyk and Tos, 2023). Light particles excited by electricity emit energy in the form of light. Laser radiation has four essential properties: coherence, monochromatic, strong beam concentration, and enormous power (Szafarczyk and Tos, 2023). The green laser is the neodymium-yag (Nd: YAG) laser and the name green comes from the colour of the laser beam which. The laser is characterized by a wavelength of 532 nm and is characterized by high precision. The laser's performance reduces in low temperatures and requires a frequent charging of batteries (Szafarczyk and Tos, 2023).

The penetration of light through water depends on its transparency. As such, the penetration depths are expressed in relation to the Secchi disc depth as opposed to meters (Idris et al., 2022). The Secchi disc is a white, matte circle-shaped plate with a standardized diameter and white and black checkered colour pattern. The transparency of the water is defined by the depth to which the disc is still visible once lowered into the water. Penetration of bathymetric laser systems is in the range of 1–3x the Secchi depth (Idris et al., 2022).

2.2.3. Bathymetric examples using laser technology

Many of the instruments used for ALB are relatively newer in practice and as such, there are not many scientific articles focused on these systems (Mandlburger et al., 2020). Fugro, RIEGL, and Atmospheric and Space Technology Research Associates LiDAR Technologies (ASTRALiTe) are examples of companies that recently developed ALB sensors targeted at UAVs (Quadros and Keysers, 2018). These ALBs are classified as either lightweight (15kg) and ultra-lightweight (5kg) (Quadros and Keysers, 2018).

The RIEGL VQ-840-G and Fugro RAMMS (Rapid Airborne Multibeam Mapping System) sensors are both lightweight and swath capable (Quadros and Keysers, 2018). Furthermore, the RIEGL VQ-840-G can be used with larger UAV platforms for both coastline and shallow-water waterway mapping (1.5 x Secchi depth). The Fugro RAMMS ALB sensor uses push broom technology. Therefore, it can be mounted on fixed-wing UAVs with greater depth penetration of up to 3 x Secchi depth (Quadros and Keysers, 2018). The ASTRALiTe is an ultralight topographic-bathymetric (topo-bathy) LiDAR sensor, and it is swath capable.

The University of Colorado (CU) developed a novel bathymetric LiDAR technology and signal processing technique that uses the polarization state of the reflected laser pulse to distinguish between returns from the water surface and from the bottom of a river (Mitchell et al., 2010; Mitchell and Thayer, 2014). Subsequently, an exclusive license of this LiDAR technology was established between CU and ASTRALiTe (Kinzel et al., 2021). ASTRALiTe developed a lightweight topo-bathymetric LiDAR called EDGE (< 5 kg) that can be deployed using a small UAS. Kinzel et al. (2021) assessed the performance of a compact USA-deployable topo- bathymetric LiDAR using the ASTRALiTe EDGE system. They found that under ideal conditions, depths up to 9.3 m could be detected by the LiDAR and consistent bed returns were observed for river depths between 4.4 and 5.5 m.

Mandlburger et al. (2016) evaluated the RIEGL BathyCopter that uses short laser pulses in the green spectrum. The study found that the 3D points obtained using the RIEGL BathyCopter can be used to obtain riverbed geometry, grain roughness, waster surface and depth information which is useful for many hydrodynamic models. Mandlburger et al. (2020) assessed the performance and accuracy of the RIEGL VQ-840-G (12 kg), which is a fully integrated airborne laser scanner used for topographic and bathymetric surveying. The study found that the RIEGL VQ-840-G is suitable for mapping river channel bathymetry with the advantage that the sensor parameters can be adjusted.

Mano et al. (2020) studied the measurement accuracy and measurement characteristics of the TDOT GREEN LiDAR sensor. The study found that the point cloud obtained using the sensor could be used to gather data about the riverbed topography accurately. Islam et al. (2022) also used the TDOT GREEN sensor to obtain river topo-bathymetry and vegetation attributes of a river basin in Japan. Results from the TDOT GREEN sensor were comparable to corresponding high resolution aerial images.

Wang et al. (2022) evaluated the Mapper 4000U for shallow water bathymetry. The Mapper4000U is described as a lightweight (4.4 kg), compact topo-bathymetric LiDAR system. The system has a dual-wavelength laser and can measure shallow waters in small areas. The Mapper 4000U is a miniature version of the SIOM Mapper5000 that has been designed for manned aerial platforms (Xing et al., 2019). Wang et al. (2022) found that the Mapper 4000U, coupled with a position and orientation system, can be used to simultaneously obtain land, water surface, and water bottom point clouds with a maximum detectable Secchi depth of 1.7–1.9 m.

As an additional example of the performance of bathymetric LiDAR sensors, Awadallah et al., (2022) used three bathymetric LiDAR sensors, CZMIL (Coastal Zone Mapping and Imaging LiDAR) Supernova, Riegl VQ880-G, and Riegl VQ840-G with different acquisition approaches in mapping the Lærdal River bathymetry in Norway. The performance was evaluated based on comparing the sensors against a multibeam echosounder (MBES) (Norbit Winghead i77h, a terrestrial laser scanner (TLS) (Leica ScanStation P50), and by an intercomparison between the individual sensors. The study shows that all the LiDAR instruments provide high-quality representations of the river geometry and create a solid foundation for planning, modelling, or other work in rivers where detailed bathymetry is needed. Costa et al. (2009) also evaluated the performance of the Laser Airborne Depth Sounder (LADS) Mk II Airborne System in providing benthic habitat maps compared to ship-based multibeam (MBES) SONAR at the western coast of Puerto Rico. In terms of the overall cost and mapping capabilities, the bathymetric LiDAR works as an efficient alternative to the MBES in mapping and monitoring shallow water coral reef ecosystems at less than 50 m deep.

2.2.4. Summary of sensors

A summary of the active sensing approaches with examples is provided below:

- Green LiDAR
    - Wavelength: A green LiDAR sensor operating in the green spectrum (around 532 nanometers) is often preferred for bathymetry. Green light provides better penetration in water compared to other wavelengths, allowing for accurate depth measurements.
    - Examples: Optech CZMIL Nova, RIEGL VQ-820-G, Velodyne VLP-16 Green.
- Hybrid or Dual-Wavelength LiDAR
    - Wavelength: Some LiDAR systems use both green and infrared wavelengths to improve the accuracy of bathymetric measurements. The green wavelength is used for water penetration, while the infrared wavelength is employed for topographic mapping.
    - Examples: RIEGL VQ-840-G, Leica Chiroptera 4X/5X.
- Airborne Topographic LiDAR (with water penetrating capability)
    - Wavelength: Traditional airborne topographic LiDAR sensors, which typically operate in the near-infrared spectrum (around 1064 nanometers), can also be suitable for bathymetry if they have water penetrating capability. These sensors use an additional green channel or technology to enhance water penetration.
    - Examples: Leica ALS80, Teledyne Optech Titan, RIEGL VQ-880-G.

2.2.5. Advantages and limitations of using LiDAR bathymetry

Until the use of LiDAR bathymetry, surveyed data of coastal zones and the profile of water reservoirs had to be combined from various sources such as manual surveys and boat-based SONAR, in which the data were not uniform. This resulted in discrepancies in the data, due to various coordinate systems across data inputs, unique and disjunct characteristics of a given device/sensor, and changes in morphology due to the temporal variability from the data captured from the different devices (Bandini et al., 2013).

Bathymetric LiDAR has various advantages over these preceding traditional methods:

- Bathymetric LiDAR is a cost-effective solution for mapping the environment over large land and coastal zones (Szafarczyk and Tos, 2023).
- The high resolution and accuracy of the data obtained make the LiDAR bathymetry technology an excellent tool for mapping, planning, maintaining, and managing national water bodies and coastal regions (Szafarczyk and Tos, 2023).
- Reduced payload, measurement in non-navigable areas, and high resolution and accuracy (differences of up to 8cm and correlations of up to 0.97) (Yoshida et al., 2019).

The main limitations of the commercial bathymetric LiDAR systems are (a) their cost, (b) difficulties in mapping river regions with riffles and outlets of weir basins, (c) auto-classification errors in vegetated regions (Bandini et al., 2013; Awadallah et al., 2022), and (d), interference from suspended sediments in the water column.

3. Acoustic Sensing

Acoustic sensors typically rely on active sensing by emitting acoustic waves and measuring the reflected, scattered, and absorbed energy. Examples of acoustic sensing are GPR and SONAR in which water depths measured by GPR and SONAR are subtracted from WSE's to compute bathymetry.

3.1. Ground-penetrating radar

GPR is typically used on terrestrial landscapes to detect subsurface features such as buried utilities, bedrock, or archaeological artifacts. GPR can also be used in bathymetric studies to map seafloor or riverbed profiles. The basic principle of GPR is to send electromagnetic waves into the ground and measure the reflections that bounce back. GPR data can also be combined with other bathymetric data, such as SONAR, to provide a more complete subsurface measurement.

In bathymetric applications, GPR systems can be mounted on a boat and emits electromagnetic waves that penetrate the seafloor or riverbed. The time taken for the reflections to return is measured and is then used to estimate the depth of the seafloor or riverbed. The use of boat-mounted GPR has been successfully used to monitor bathymetry in lakes (Kidmose et al., 2013; Swain, 2018) and rivers (Sambuelli et al., 2009). The high electric conductivity and high relative dielectric permittivity of water make GPR-based bathymetry monitoring of liquid freshwater more challenging than monitoring of ice or snow.

As an example, Bandini et al., 2013 used the GPR antenna Gekko-80 with RTS1600 data processing unit with a DJI Matrice 600 UAV. The drone was equipped with a radar altimeter (UgCS, SPH Engineering, Latvia) to enables flight at constant and low altitude in automatic flight missions. Drone-borne GPR showed accuracy similar to water-coupled GPR, and the GPR measurements were benchmarked against traditional SONAR measurements, showing that GPR measurements significantly outperform SONAR measurements in waterbodies with medium or high density of aquatic vegetation. An example of a Guden 13859 radargram from this study is shown in Figure 4.

The limitations of drone-borne GPR are (a) restrictive minimum depth requirement (typically 0.8–1.1 m for drone-borne GPR, while 0.3–0.4 m for water-coupled GPR (Bandini et al., 2013) which implied poor results close to streambanks, , and (b) requirement to fly the GPR antenna fixed at altitudes of approx. 0.5 m above the water surface (Bandini et al., 2013).

3.2. Sound Navigation and Ranging

SONAR works in bathymetric surveys by emitting sound waves into the water column and measures the time taken for the waves to bounce back from the seafloor or riverbed. The speed of sound in water is influenced by factors such as temperature, salinity, and density. The measured time is used to calculate the distance between the SONAR transducer and the seafloor or riverbed. Measured depths can then be used to produce a bathymetric map. To obtain accurate results, the position and attitude of the system are necessary, so GNSS and IMU are used.

In rivers, single beam or multi-beam SONAR on- board manned or unmanned vessels are used (Bio et al.,

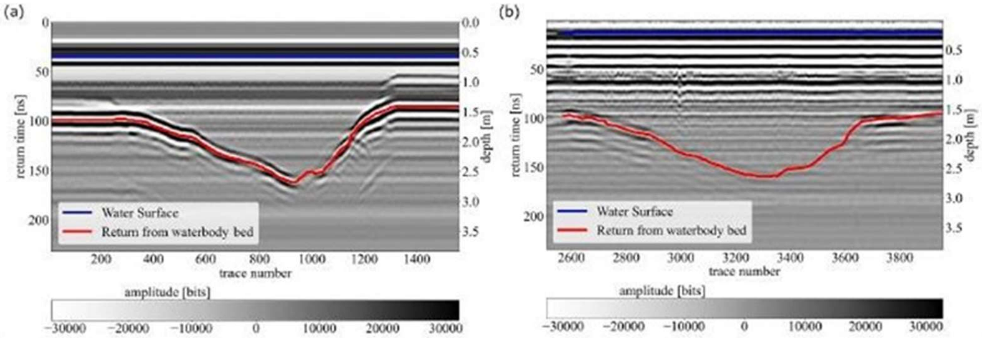

Figure 4 Guden 13859 radargram is shown in (a) water-coupled and (b) drone-based (Bandini et al., 2013).

2020; Halmai et al., 2020; Leyland et al., 2017; Specht et al., 2020; Stateczny et al., 2019; Young et al., 2017). A single beam SONAR measures the bathymetry using a single beam that produces measured depths. It performs well in generating seafloor profiles and is used to assist navigation in real time. A multi-beam SONAR measures the bathymetry using an array of beams and supplies an larger swath of measured depths perpendicular to the vessel. The application of multibeam technology for bathymetry requires significant further investment in technologies and may inappropriate for all water body spatial scales. However, single- beam surveying remains a low-cost and effective mapping technique (Dinehart, 2002), and has been used to identify bedform movement in fluvial systems, such as the Jamuna, Mississippi and San Joaquin Rivers (Diehart, 2002; Ashworth et al., 2000).

SONAR systems have the following limitations:

- Challenges in measuring very shallow depths due to surface clutter and multipath effects (Albright Blomberg et al., 2013) at commonly used frequencies (less than 1 MHz).
- The accuracy of SONAR significantly degrades in vegetated rivers (Helminen et al., 2019). This is attributed to the high level of reflection of sound waves from the vegetation which can result in depth measurements within vegetation canopy (Sabol, 2002).
- Deployment of boats can be complicated in remote areas and is limited to navigable water or, especially for unmanned vessels, locations with dense floating aquatic vegetation.

To alleviate the issues of SONAR deployment in remote areas or non-navigable rivers, researchers (Alvarez et al., 2018; Bandini et al., 2018) and recently companies (e.g., UgGS-SPH Engineering (Latvia) and Thurn group (UK)) have developed SONAR systems tethered to an Unmanned Aerial System (UAS). However, the tethered SONAR has to remain in contact with water throughout the survey, which complicates automatic pilot flights and reduces the possibility to perform beyond visual line of sight flights. An example of a tethered system, the Bathy -drone system which uses a Lowrance Elite ti7 SONAR sensor attached to a DJI M600 drone (Diaz et al., 2022), is shown in Figure 5.

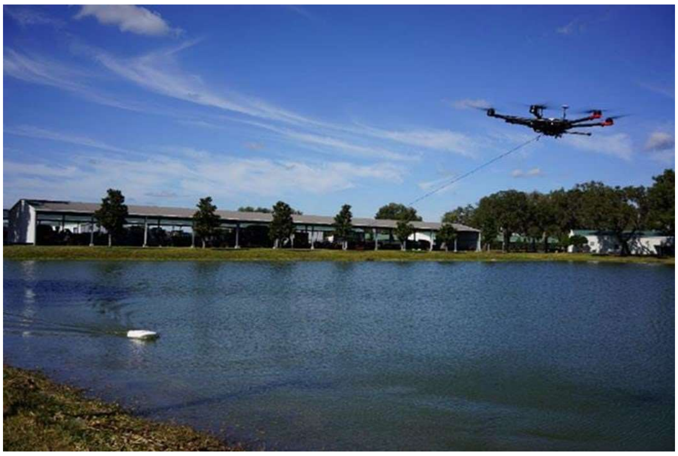

Figure 5 Tethered Bathymetry system which uses a Lowrance Elite ti7 SONAR sensor attached to a DJI M600 drone (Diaz et al., 2022).

As a further example, Bandini et al., 2018 integrated two types of UAS sampling techniques, as shown in Figure 6. The first coupled a small UAS (sUAS) to a low-cost, single beam echosounder attached to a boat towed by a DJI Phantom 3 Pro for surveying submerged topography in deeper water within the range of accuracy. The second uses SfM photogrammetry to cover shallower water areas no detected by the echosounder where the bed is visible from the sUAS. The final product was an interpolated raster layer. The resultant water depths ranged from 0 to 5.11 m, with the minimum depths detected from 0 to 0.05 m as shown in Figure 7.

4. Summary of Sensing Technologies

This report investigated (a) optical sensors, which actively measure reflected energy or passively sense reflected or scattered light using hyper- or multispectral imaging strictly in the visible light spectrum, and (b) acoustic sensors, which actively sense by emitting acoustic waves and measuring the reflected, scattered, and absorbed energy.

Optical sensors can be categorized as either being passive, whereby backscattered solar radiation from the bottom of the water body is used for depth measurements, or active, in which reflected energy is actively measured by simultaneously using of two lasers in the light range (i.e., infrared and green wavelengths). Passive approaches include spectral and

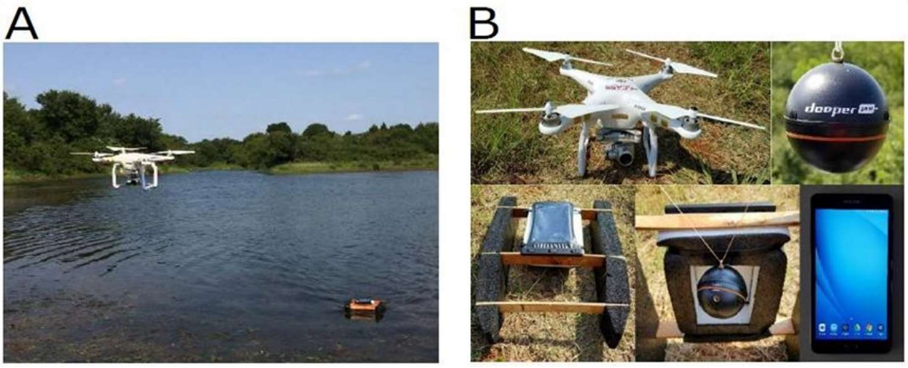

Figure 6 Small UAS-echosounder system. (A) shows the DJI Phantom 3 Pro UAV propelling a mini-boat carrying the single-beam echosounder. (B) shows the DJI Phantom 3 Pro UAV, Deeper Smart SONAR Pro+ wireless SONAR, designed boat and an Android tablet (Diaz et al., 2022).

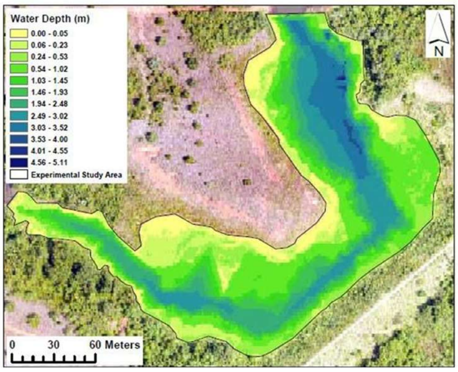

Figure 7 Water depths as determined using small UAS-echosounder system (Bandini et al., 2018).

multimedia photogrammetry. These approaches perform well in environments with homogenous sediments (such as coastal environments) and with surface bottoms that are sufficiently textured (such as large boulders or rocks). However, passive approaches are limited to waterbodies with high water clarity. Green LiDAR is an active approach that provides a cost-effective solution for large land and coastal zones and offers payloads compatible with many commercial UAV's. This also allows for measurements in often difficult to reach areas and provides high resolution and accuracy. The main limitations of the commercial LiDAR systems are (a) their cost depending on the project budget, (b) mapping regions in river with riffles and outlets of weir basins, (c) auto-classification errors in vegetated regions, and (d) interference from high suspended solid loads.

Acoustic sensors typically rely on active sensing by emitting acoustic waves and measuring the reflected, scattered, and absorbed energy. Water depth observations, retrieved by GPR and SONAR, are subtracted from the WSE to compute bathymetry.

GPR is typically used on land and can also be used in bathymetric studies to map the seafloor or riverbed. The basic principle of GPR is to send electromagnetic waves into the ground and measure the reflections that bounce back. SONAR works similarly in bathymetric surveys whereby sound waves are emitted into the water column and the time taken for the waves to bounce back from the seafloor or riverbed is measured and corelated to a depth.

Bathymetry-based GPR performs well when compared to in situ bathymetry measurements. Furthermore, the application of airborne GPR has showed accuracy similar to water-coupled GPR. GPR measurements were also shown to significantly outperform SONAR measurements in waterbodies with medium or high density of aquatic vegetation. The limitations of airborne GPR are (a) more restrictive minimum depth requirement (typically 0.8–1.1 m, which have implied poor results close to streambanks, making it not applicable in narrow and very shallow rivers), and (b) requirement to fly the GPR antenna at altitudes of approximately 0.5 m above the water surface throughout.

SONAR systems can be broadly categorized into single-beam and multi-beam systems with single-beam surveys being more cost effective. SONAR systems performs poorly in measuring very shallow depths due to surface clutter and multipath effects. SONAR's accuracy significantly degrades in vegetated rivers which is attributed to the high level of reflection of sound waves from the vegetation. The application of SONAR on boats can be complicated in remote areas and is limited to navigable water or, especially for unmanned vessels, locations without dense floating aquatic vegetation.

The objective of this exploration was to identify a robust approach that performs well in all environments, perform repeatable measurements, and can conduct surveys in remote / difficult to access river reaches. Based on a review of the current trends in the literature, green laser (i.e., LiDAR) appears to be best suited to further study and implementation in Southern African systems.

5. Green LiDAR Sensors and Platforms

The first measurement system allowing for the simultaneous measurement of the topography of the area and the depth of a water reservoir was introduced in 2001 (Quadros, 2013). Various new sensors have been developed to measure both topography and shallow water bathymetry from an airplane or drone. Currently, available drones equipped with a bathymetric LiDAR allow the measurement of up to 40,000 points per second on a deep bathymetric channel and up to 140,000 points per second on a shallow bathymetric channel (Mandlburger, 2022). Current bathymetric measurement platforms include surface ships, underwater platforms, aircraft, and satellites.

5.1. Satellite-borne sensors

SDB conducted through multispectral satellite image processing has been used for ocean mapping. It provides bathymetry using physics-based models at a coarser spatial resolution compared to conventional acoustic surveying (Mandlburger, 2022). High-resolution satellite sensors, such as the DigitalGlobe's WorldView-2 and -3, Sentinel-2A/B and Quick Bird (Said et al., 2017) have been shown to be cost- and time- effective solutions for shallow water bathymetry (Doxani et al., 2012; Jawak et al., 2015; Caballero et al., 2020).

5.2. UAV-borne sensors

Traditionally, bathymetric laser scanners could only be operated from manned platforms such as aircraft, helicopters, or gyrocopters due to weight prerequisites. With ongoing sensor research and development of uncrewed aerial platforms, more compact and integrated laser scanners are being integrated on both fixed-wing and multi-rotor UAVs. Drones are typically operated at low flying altitude of about 50–120 m above ground level and with moderate flying velocity of 4–10 m.s-1, entailing a significantly smaller laser footprint size, as well as a higher point density. Therefore, drones allow a higher spatial resolution compared to operation from crewed airborne platforms at higher altitudes. Furthermore, due to the shorter measurement range, more signal strength is available for penetrating a water body.

Figure 8 The ASRTALiTe EDGE airborne laser sensor mounted to a DJI M600 UAV.

ASTRALite EDGE

The ASTRALiTe EDGE, as shown in Figure 8, is a LiDAR sensor that can perform topographic and bathymetric surveys. The sensor is able to detect underwater objects, survey underwater infrastructure, and measure shallow water depths. The system consists of an IMU with GNSS, onboard computer, and battery pack. The sensor uses a 30-mW laser and is typically operated from a flying altitude of approx. 20 m above ground level. The small weight of approx. 5 kg allows for the integration on many commercially available multi-rotor UAV platforms such as the DJI M600 UAV. The sensor has an precision / accuracy of 5-10 mm and a depth penetration of 0-5 m and >1.5 SD.

The performance of the ASRTALiTe EDGE sensor has been evaluated in the study by Kinzel et al. (2021). The study reported that the correspondence of LiDAR depths varies between 0.60 to 0.97 against RTK measurements and 0.72 against the MBES measurements. Moreover, the study showed that the sensor maps deeper in gravel-bedded rivers, compared to sand-bedded rivers which have lower suspended sediment concentration. Kinzel and Legleiter (2019) also evaluated the performance of the ASRTALiTe EDGE sensor and showed the sensors applicability in measuring water profiles in waterbodies up to 1.2 m deep, with a strong correlation between sensor measurements and in situ manual measurements at shallow depths ($R^2 = 0.95$) and a lower correlation in deeper regions ($R^2 = 0.61$).

The limitations of the sensor include: (a) a limited areal coverage measurements performance due to a maximum flight altitude of 20 m above ground level (as an example, a nominal height of 4 m above the water surface resulted in only a 2 m swath (Kinzel and Legleiter, 2019)), (b) a moderate performance in bathymetry of between 1 and 2 SD's, and (c) poor performance in distinguishing between water surface and profile bottom returns in water depths less than 0.15 m (Kinzel and Legleiter, 2019).

RAMMS

The RAMMS (Mitchell, 2019; Ventura, 2020) is a topographic and bathymetric laser scanner with a depth penetration of 3 SD. The sensor uses a push broom technique. The measurement resembles the principle of multibeam echo sounding with a single ping and multiple transducers. The system weighs 14 kg and is designed for integration on light aircraft, helicopters and on UAV platforms. The system has been designed for large scale coastal bathymetric mapping projects (areas greater than 10 000 km²).

Limitations of the system include, (a) large payload necessitating the need for an aircraft or advanced UAS such as the Schiebel CAMCOPTER S-100 as compared to a commercial drone, (b) the system generates large datasets, which restricts free cloud based sharing and requires shipping of physical hard drives, and (c) the systems performance is reduced in regions of deeper water, rapids and poor water clarity.

The Teledyne Optech CZMIL

The Teledyne Optech CZMIL, as shown in Figure 9, is an airborne multi-sensor used for topographic and bathymetric surveys (Wozencraft, 2010; Ramnath et al., 2015; Feygels et al., 2017). The laser has been used in coastal applications due to the high laser energy per pulse characteristic (Wozencraft, 2010; Ramnath et al., 2015). Laser energy and the point density are negatively correlated and as such the system comes at a point density cost due the high laser penetration. (Quadros, 2013).

Figure 9 The Teledyne Optech CZMIL airborne laser scanner.

The RIEGL VQ-840-G

The RIEGL VQ-840-G, as shown in Figure 10, is a complete airborne laser scanner for both topographic and bathymetric surveying. The instrument can be equipped with a factory calibrated IMU/GNSS system and with an industrial camera. The VQ- 840-G LiDAR has a total volume of 20.52 L and weighs 12 kg. The system can be installed on various platforms including UAVs. The laser scanner comprises a frequency-doubled infrared laser, emitting pulses with about 1.5 ns duration at a wavelength of 532 nm and at a PRR of 50–200 kHz (Mandlburger et al., 2020).

The VQ-840-G utilizes a Palmer scanner generating an elliptical scan pattern on the ground. The scan speed can be set between 10–100 lines.s-1 to generate an even point distribution in the center of the swath. A higher point density is produced towards the edge of the swath where the consecutive lines overlap.

For drone-based bathymetric LiDAR sensors, the performance of the Riegl VQ840-G has been evaluated by Mandlburger et al. (2020). These authors showed a close performance to the Riegl VQ880-G, which has been applied for bathymetric surveys of up to 9m deep. In comparison, the performance of the ASTRALite EDGE and CZMIL sensors have both been found to be vulnerable to missing the river bottom at those locations and in some cases reported the water surface as the river bottom (Mandlburger et al., 2020).

Figure 10 The RIEGL VQ-840-G airborne laser scanner.

RIEGL – VQ-840-GL

The RIEGL VQ-840-GL, as shown in Figure 11, is a newer (2022) airborne laser scanner by RIEGL that combines topographic and bathymetric surveying. The LiDAR system has an updated design that reduces weight to less than 10 kg. The scanner uses a visible green laser beam to measure underwater topography and can penetrate water to measure submerged targets. The sensor can be complemented with an IMU for subsequent estimation of the instrument's location and orientation. A high-resolution digital camera can also be integrated.

Figure 11 The RIEGL VQ-840-GL airborne laser scanner.

6. Synthesis

The primary purpose of an E-flow study is to determine the amount of water required to maintain the ecological integrity of a water-dependent ecosystem, thereby protecting the function of that system. Traditionally, in situ measurements have been used to inform E-flows assessments. However, such measurements do not always provide adequate spatial representativeness, and information may not be readily available to stakeholders or policy makers. This has led to the exploration of remotely sensed data collection techniques. In this context, this report aimed to investigate options around UAV-based water penetrating surveying techniques for identifying the below water profiles of river channels to create a high-resolution DEM for the purpose of carrying out hydraulic modelling linked to E-flow studies. Airborne laser bathymetry techniques appear favourable compared to spectrally derived bathymetry, multimedia photogrammetry, GPR and SONAR techniques. A non-exhaustive list of the best current LiDAR sensors was reviewed, with several options highlighted that seem best suited to further study and implementation in a Southern African context.

References

Acharya BS, Bhandari M, Bandini F, Pizarro A, Perks M, Joshi DR, Wang S, Dogwiler T, Ray RL, Kharel G and Sharma, S. 2021. Unmanned aerial vehicles in hydrology and water management: Applications, challenges, and perspectives. Water Resources Research 57: 1-33.

Albright Blomberg AE, Austeng A, Hansen RE, and Synnes, SAV. 2013. Improving SONAR performance in shallow water using adaptive beamforming. IEEE Journal or Oceanic Engineering 38 (2): 297- 307.

Alvarez LV, Moreno HA, Segales AR, Pham TG, Pillar-Little EA, and Chilson PB. 2018. Merging Unmanned Aerial Systems (UAS) Imagery and Echo Soundings with an Adaptive Sampling Technique for Bathymetric Surveys. Journal of Remote Sensing 10: 1362-1386.

ARGANS. 2022. Satellite Derived Bathymetry: Measuring Water Depth from Space & Drafting Nautical Charts. [Internet]. Available from: https://sdb.argans.co.uk. [Accessed 26 April 2023].

Ashworth PJ, Best JL, Roden JE, Bristow CS, and Klaassen GJ. 2000. Morphological evolution and dynamics of a large, sand braid-bar, Jamuna River, Bangladesh. Sedimentology 47: 533–555.

Awadallah MOM, Malmquist C, Stickler M, and Alfredsen K. 2022. Quantitative Evaluation of Bathymetric LiDAR Sensors and Acquisition Approaches in Lærdal River in Norway. Remote Sensing 15: 263-284.

Bagheri O, Ghodsian M, and Saadatseresht M. 2015. Reach scale application of UAV+SfM method in shallow rivers hyperspatial bathymetry. The International Archive of Photogrammetry. Remote Sensing and Spatial Information Sciences 40(1): 77–81.

Bandini F, Olesen D, Jakobsen, J, Kittel CMM, Wang S, Garcia M, and Bauer-Gottwein P. 2018. Technical note: Bathymetry observations of inland water bodies using a tethered single-beam SONAR controlled by an unmanned aerial vehicle. Hydrology and Earth System Sciences 22: 4165– 4181.

Bangen SG, Wheaton JM, Bouwes N, Bouwes B, and Jordan CA. 2014. Methodological intercomparison of topographic survey techniques for characterizing wadeable streams and rivers. Geomorphology 206: 343–361.

Bio A, Gonçalves JA, Magalhaes A, Pinheiro J, and Bastos L. 2020. Combining low-cost SONAR and high- precision global navigation satellite system for shallow water bathymetry. Estuaries and Coasts 1:1-12.

Brasington J, Langham J, and Rumsby B. 2003. Methodological sensitivity of morphometric estimates of coarse fluvial sediment transport. Geomorphology. 53(4): 299-316.

Bronkhorst S, Pengelly C, and Seyler H. Water. 2017. Market Intelligence Report. Greencape: Cape Town, South Africa.

Brown, CJ and Blondel P. 2009. Developments in the application of multibeam SONAR backscatter for seafloor habitat mapping, Applied Acoustics 70, 1242–1247.

Caballero I and Stumpf RP. 2020. Towards Routine Mapping of Shallow Bathymetry in Environments with Variable Turbidity: Contribution of Sentinel-2A/B Satellites Mission. Remote Sensing 12 (3), 451-474.

Chandrashekar A, Papadakis J, Willis A, and Gantert J. 2018. Structure -from-Motion and RGBD Depth Fusion. In Proceedings of the IEEE South East conference, St. Petersburg, FL, USA.

Clapuyt F, Vanacker V, and Van Oost K. 2016. Reproducibility of UAV-based earth topography reconstructions based on Structure-from-Motion algorithms. Geomorphology 260: 4–15.

Condorelli F, Rinaudo F, Salvadore F, and Tagliaventi SA. 2020. Match-moving Method Combining AI and SFM Algorithms in Historical Film Footage. International Archives Photogrammetry of the Remote Sensing and Spatial Information Sciences: 813–820.

Conner JT and Tonina D. 2014. Effect of cross-section interpolated bathymetry on 2D hydrodynamic model results in a large river. Earth Surface Processes and Landforms 39: 463–475.

Cook A, and Merwade V. 2009. Effect of topographic data, geometric configuration and modeling approach on flood inundation mapping. Journal of Hydrology 377, 131–142.

Costa BM and Battista TA, and Pittman SJ. 2009. Comparative evaluation of airborne LiDAR and ship- based multibeam SONAR bathymetry and intensity for mapping coral reef ecosystems. Remote Sensing and the Environment 113: 1082–1100.

Diaconu DC, Bretcan P, Peptenatu D, Tanislav D and Mailat E. 2019. The importance of the number of points, transect location and interpolation techniques in the analysis of bathymetric measurements. Journal of Hydrology 570: 774-785.

Diaz AL, Ortega AE, Tingle H, Pulido A, Cordero O, Nelson M, Cocoves NE, Shin J, Carthy RR, Wilkinson BE and Peter G. 2022. The Bathy-Drone: An Autonomous Uncrewed Drone-Tethered SONAR System. Drones 6: 294-316.

Dietrich JT, 2016. Bathymetric Structure from Motion: Extracting shallow stream bathymetry from multi-view stereo photogrammetry. Earth Surface Processes and Landforms 42: 355 –364.

Dinehart RL. 2002. Bedform movement recorded by sequential single-beam surveys in tidal rivers. Journal of Hydrology 258: 25–39.

Doxani G, Papadopoulou M, Lafazani P, Pikridas C and Tsakiri-Strati M. 2012. Shallow-water bathymetry over variable bottom types using multispectral worldview-2 image. International Archives Photogrammetry of the Remote Sensing and Spatial Information Sciences 39: 159– 164.

Duan Z, Chu S, Cheng L, Ji C, Li M and Shen W. (2022). Satellite-derived bathymetry using Landsat-8 and Sentinel-2A images: assessment of atmospheric correction algorithms and depth derivation models in shallow waters. Optics Express 30(3): 3238–3261.

Eltner A and Sofia G. 2020. Structure from Motion Photogrammetric Technique. Earth Surface Process 23: 1–24.

Eugenio F, Marcell J, Mederos-Barrera A and Marqués F. 2022. High- resolution satellite bathymetry mapping: Regression and machine learning-based approaches. IEEE Transactions on Geoscience and Remote Sensing 60, 1–14.

Feurer D, Bailly JS, Puech C, Le Coarer Y and Viau AA. 2008. Very-high-resolution mapping of river- immersed topography by remote sensing. Progress in Physical Geography 32: 403–419.

Feygels V, Ramnath V, Marthouse R, Aitken J, Smith B, Clark N, Renz E, Duong H, Wozencraft J, Reisser J and Kopilevich Y. 2017. CZMIL as a rapid environmental disaster response tool. In OCEANS 2017-Aberdeen: 1-7.

Flener C, Vaaja M, Jaakkola A, Krooks A, Kaartinen H, Kukko A, and Alho P. 2013. Seamless mapping of river channels at high resolution using mobile LiDAR and UAV-photography. Remote Sensing 5(12): 6382-6407.

Förstner W. and Wrobel BP. 2016. Photogrammetric Computer Vision: Statistics, Geometry, Orientation and Reconstruction, Springer International Publishing, Cham, Switzerland.

Fonstad MA, Dietrich JT, Courville BC, Jensen JL and Carbonneau PE. 2013. Topographic structure from motion: A new development in photogrammetric measurement. Earth Surface Processes and Landforms 38: 421–430.

Geyman EC and Maloof AC. 2019. A simple method for extracting water depth from multispectral satellite imagery in regions of variable bottom type. Earth and Space Science 6(3): 527-537.

Gholizadeh MH, Melesse AM, and Reddi L. 2016. A comprehensive review on water quality parameters estimation using remote sensing techniques. Sensors 16(8): 1298-1311.

Gichamo TZ, Popescu I, Jonoski A, and Solomatine D. 2012. River cross-section extraction from the ASTER global DEM for flood modelling. Environmental Modelling and Software 31: 37–46.

Green, T. 2023. Product website and spec sheet of TDOT GREEN. [Internet]. Available from: https://amuse-oneself.com/en/service/tdotgreen.

Grobbelaar J. 2009. Turbidity. GE Likens, ed., Encyclopedia of Inland Waters. Academic Press, Oxford: 699–704

Halmai Á, Gradwohl-Valkay A, Czigány S, Ficsor J, Liptay ZÁ, Kiss K, Lóczy D and Pirkhoffer E. 2020. Applicability of a recreational -grade interferometric SONAR for the bathymetric survey and monitoring of the Drava River. ISPRS International Journal of Geo-Information 9(3), 149-165.

Helminen J, Linnansaari T, Bruce M, Dolson-Edge R, and Curry RA. 2019. Accuracy and precision of low- cost echosounder and automated data processing software for habitat mapping in a large river. Diversity 11(7): 116-142.

Hilldale, RC and Raff, D. 2008. Assessing the ability of airborne LiDAR to map river bathymetry. Earth Surface Processes and Landforms 33 (5): 773-783.

Idris MS, Siang HL, Amin RM, and Sidik MJ. 2022. Two-decade dynamics of MODIS-derived Secchi depth in Peninsula Malaysia waters. Journal of Marine Systems 236, 103799.

Islam MT, Yoshida K, Nishiyama S, Sakai K, and Tsuda T. 2022. Characterizing vegetated rivers using novel unmanned aerial vehicle-borne topo-bathymetric green lidar: Seasonal applications and challenges. River Research and Application 38: 44–58.

Jagalingam P, Akshaya BJ and Hegde AV. 2015. Bathymetry mapping using Landsat 8 satellite imagery. Procedia Engineering 116: 560-566.

Jawak SD, Vadlamani SS and Luis AJ. 2015. A synoptic review on deriving bathymetry information using remote sensing technologies: models, methods and comparisons. Advances in Remote Sensing, 4(02), 147.

Kidmose J, Nilsson B, Engesgaard P, Frandsen M, Karan S, Landkildehus F, Søndergaard M and Jeppesen E. 2013. Focused groundwater discharge of phosphorus to a eutrophic seepage lake (Lake Væng, Denmark): implications for lake ecological state and restoration. Hydrogeology Journal 21(8): 1787-1801

Kinzel PJ and Legleiter CJ. 2019. sUAS-Based Remote Sensing of River Discharge Using Thermal Particle Image Velocimetry and Bathymetric Lidar. Remote Sensing 11: 2317-2412.

Kinzel PJ, Legleiter CJ, and Grams PE. 2021. Field evaluation of a compact, polarizing topo-bathymetric lidar across a range of river conditions. River Research and Application 37, 531–543.

Kinzel, PJ, Legleiter, CJ and Nelson, JM. 2013. Mapping river bathymetry with a small footprint green LiDAR: applications and challenges 1. JAWRA Journal of the American Water Resources Association 49 (1): 183-204.

Lane SN. 2000. The measurement of river channel morphology using digital photogrammetry. Photogrammetric Record 16(96): 937–961.

Lapointe MF, Secretan Y, Driscoll SN, Bergeron N, and Leclerc M. 2000. Response of the Ha! Ha! River to the flood of July 1996 in the Saguenay region of Quebec: Large-scale avulsion in a glaciated valley. Water Resources Research 34: 2383–2392.

Legleiter CJ, Roberts DA and Lawrence RL. 2009. Spectrally based remote sensing of river bathymetry. Earth Surface Processes and Landforms 34, 1039–1059.

Legleiter CJ and Fonstad MA. 2012. An introduction to the physical basis for deriving river information by optical remote sensing. Fluvial Remote Sensing for Science and Management: 43-69.

Legleiter CJ and Harrison LR. 2019. Remote Sensing of River Bathymetry: Evaluating a Range of Sensors, Platforms, and Algorithms on the Upper Sacramento River, California, USA. Water Resources Research 55(3): 2142–2169.

Lejot J, Delacourt C, Piégay, H, Fournier T, Trémélo ML, and Allemand P. 2007. Very high spatial resolution imagery for channel bathymetry and topography from an unmanned mapping controlled platform. Earth Surface Processes and Landforms 32: 1705–1725.

Leon JG, Calmant S, Seyler F, Bonnet MP, Cauhop´e M, Frappart F, Filizola N, Fraizy P. 2006. Rating curves and estimation of average water depth at the upper Negro River based on satellite altimeter data and modelled discharges. Journal of hydrology 328 (3):481-496.

Leyland J, Hackney CR, Darby SE, Parsons DR, Best JL, Nicholas AP, Aalto R, Lague D. 2017. Extreme flood-driven fluvial bank erosion and sediment loads: direct process measurements using integrated Mobile Laser Scanning (MLS) and hydro-acoustic techniques. Earth Surface Processes and Landforms 42(2): 334- 346.

Lewin J, and Weir MJC. 1977. Morphology and recent history of the lower Spey. Scott. Geography Magazine 93:45–51.

Lyzenga DR. 1978. Passive remote sensing techniques for mapping water depth and bottom features. Applied Optics 17(3): 379–383.

Lyzenga DR, Malinas NP and Tanis FJ. 2006. Multispectral bathymetry using a simple physically based algorithm. IEEE Transactions on Geoscience and Remote Sensing 44(8): 2251–2259.

MacVicar B, Piegay H, Henderson A, Comiti F, Oberlin C, and Pecorari E. 2009. Quantifying the temporal dynamics of wood in large rivers: Field trials of wood surveying, dating, tracking, and monitoring techniques. Earth Surface Processes and Landforms 34: 2031–2046.

Makboul O, Negm A, Mesbah S and Mohasseb M. 2017. Performance assessment of ANN in estimating remotely sensed extracted bathymetry. Case study: Eastern harbor of Alexandria. Procedia Engineering 181: 912-919.

Mandlburger, G, Pfennigbauer, M, Schwarz, R, Flöry, S and Nussbaumer, L. 2020. Concept and performance evaluation of a novel UAV-borne topo- bathymetric LiDAR sensor. Remote Sensing 12 (6): 986.

Mandlburger G. 2022. A Review of Active and Passive Optical Methods in Hydrography. The International Hydrographic Review 28: 8-52.

Mandlburger, G, Pfennigbauer, M, Wieser, M, Riegl, U and Pfeifer, N. 2016. Evaluation of a novel UAV- borne topo-bathymetric laser profiler. The International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences 41:933-939.

Manley PL and Singer JK. 2008. Assessment of sedimentation processes determined from side-scan SONAR surveys in the Buffalo River, New York, USA. Environmental Geology 55: 1587 –1599.

Mano, K, Sakai, K, Tachibana, K, Sakita, K and Nishiyama, S. 2020. The Measurement Accuracy and Measurement Characteristics of Green Lidar Drone. International Archives of the Photogrammetry, Remote Sensing & Spatial Information Sciences.

Marcus WA, Marston RA, Colvard CR, Gray RD. 2002. Mapping the spatial and temporal distributions of woody debris in streams of the Greater Yellowstone Ecosystem, USA. Geomorphology. 44 (4): 323-335.

Mertes LA. 2002. Remote sensing of riverine landscapes. Freshwater biology 47(4): 799-816.

Mishra V, Avtar R, Prathiba AP, Mishra PK, Tiwari A, Sharma SK, Singh CH, Yadav BC ,Kamal and Jain K. 2023. Uncrewed Aerial Systems in Water Resource Management and Monitoring: A

Review of Sensors, Applications, Software, and Issues. Hindawi: Advances in Civil Engineering 1: 1-28.

Misra A, Vojinovic Z, Ramakrishnan B, Luijendijk A and Ranasinghe R. (2018). Shallow water bathymetry mapping using Support Vector Machine (SVM) technique and multispectral imagery. International Journal of Remote Sensing 39(13). 4431–4450.

Mitchell SE, Thayer, JP and Hayman, M. 2010. Polarization lidar for shallow water depth measurement. Applied optics 49 (36): 6995-7000.

Mitchell, SE and Thayer, JP. 2014. Ranging through shallow semitransparent media with polarization lidar. Journal of Atmospheric and Oceanic Technology 31 (3): 681-697.

Mitchell T. 2019. From PILLS To RAMMS. 20th Annual JALBTCX Airborne Coastal Mapping and Charting Technical Workshop.

Moramarco T, Barbetta S, Bjerklie DM, Fulton JW and Tarpanelli A. 2019. River bathymetry estimate and discharge assessment from remote sensing. Water Resources Research 55(8): 6692-6711.

Nikora VI, Goring DG, and Biggs BJF. 1998. On gravel-bed roughness characterization. Water Resources Research 34, 517–527

Nitsche FO, Ryan WBF, Carbotte SM, Bell RE, Slagle A, Bertinado C, Flood R, Kenna T and McHugh C. 2007. Regional patterns and local variations of sediment distribution in the Hudson River Estuary. Estuarine, Coastal and Shelf Science 71, 259–277.

Overstreet BT and Legleiter CJ. 2017. Removing sun glint from optical remote sensing images of shallow rivers. Earth Surface Processes and Landforms 42, 318–333.

Passalacqua P, Belmont P, Staley DM, Simley JD, Arrowsmith JR, Bode CA, Crosby C, DeLong SB, Glenn NF, Kelly SA and Lague D. 2015. Analyzing high resolution topography for advancing the understanding of mass and energy transfer through landscapes: A review. Earth Science Reviews 148: 174–193.

Philpot W, ed. 2019. Airborne Laser Hydrography II, Cornell University Library (eCommons), Coernell.

Powers J, Brewer SK, Long JM, and Campbell T. 2015. Evaluating the use of side-scan SONAR for detecting freshwater mussel beds in turbid river environments, Hydrobiologia 743: 127–137.

Quadros N. 2013. Unlocking the Characteristics of Bathymetric LiDAR Sensors. LiDAR Magazine 3: 62– 67.

Quadros ND, Collier PA and Fraser CS. 2008. Integration of Bathymetric and topographic LiDAR: A preliminary investigation. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XXXVII.B8: 1299–1304.

Quadros, N and Keysers, J. 2018. Emerging Trends in Bathymetric Lidar Technology. [Internet]. Available from: https://www.hydro-international.com/content/article/emerging-trends-in- bathymetric-lidar-technology.

Ramnath V, Feygels V, Kalluri H, and Smith B. 2015. CZMIL (Coastal Zone Mapping and Imaging Lidar) bathymetric performance indiverse littoral zones. In Proceedings of the OCEANS 2015—MTS/IEEE Washington, Washington, DC, USA, 19–22.

Rossi L, Mammi I and Pelliccia F. 2020. UAV-derived multispectral bathymetry. Remote Sensing 12(23): 3897-3917.

Rovira A, Batalla RJ and Sala M. 2005. Fluvial sediment budget of a Mediterranean river: The lower Tordera (Catalan Coastal Ranges, NE Spain). Catena 60: 19–42.

Sabol B and Johnson S. 2002. Hydrographic surveying in dense aquatic vegetation: Digital signal processing for improved bottom tracking. Hydro International 6(5): 7-9.

Said M, Mahmud M and Hasan M. 2017. Satellite-derived bathymetry: Accuracy assessment on depths derivation algorithm for shallow water area. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Vol. XLII-4.W5: 159-164.

Sagawa T, Yamashita Y, Okumura T and Yamanokuchi T. 2019. Satellite Derived Bathymetry Using Machine Learning and Multi-Temporal Satellite Images. Remote Sensing 11(10): 1155-1160.

Sambuelli L, Calzoni C and Pesenti M. 2009. Waterborne GPR survey for estimating bottom-sediment variability: A survey on the Po River, Turin. Italy. Geophysics 74:4: 95-102.

Sandwell DT, Müller RD, Smith WHF, Garcia E and Francis R. 2014. New global marine gravity model from Cryosat-2 and Jason-1 reveals buried tectonic structure. Science 346 (6205): 65–67.

Schäppi B, Perona P, Schneider P and Burlando P. 2010. Integrating river cross section measurements with digital terrain models for improved flow modelling applications, Computers & Geosciences 36(6). 707–716.

Slocum RK, Parrish CE and Simpson CH. 2020. Combined geometric-radiometric and neural network approach to shallow bathymetric mapping with UAS imagery. ISPRS Journal of Photogrammetry and Remote Sensing 169: 351-363.

Snellen M, Siemes K and Simons DG. 2011. Model-based sediment classification using single-beam echosounder signals. The Journal of the Acoustical Society of America 129 (5): 2878-2888.

Specht C, Lewicka O, Specht M, Dąbrowski P and Burdziakowski P. 2020. Methodology for carrying out measurements of the tombolo geomorphic landform using unmanned aerial and surface vehicles near Sopot Pier, Poland. Journal of Marine Science and Engineering 8(6): 384-401.

Starek MJ and Giessel J. 2017. Fusion of uas-based structure-from-motion and optical inversion for seamless topo-bathymetric mapping. In IEEE international geoscience and remote sensing symposium (IGARSS): 2999-3002.

Stateczny A, Błaszczak-Bak W, Sobieraj-Złobinska´ A, Motyl W and Wisniewska M. 2019. Methodology for processing of 3D multibeam SONAR big data for comparative navigation. Remote Sensing 11(19): 2245-2268.

Stephens GL, Slingo JM, Rignot E, Reager JT, Hakuba MZ, Durack PJ, Worden J and Rocca R. 2020. Earth's water reservoirs in a changing climate. Proceedings of the Royal Society. 476: 2236-2255.

Strayer DL, Malcom HM, Bell RE, Carbotte SM and Nitsche FO. 2006. Using geophysical information to define benthic habitats in a large river. Freshwater Biology 51(1): 25-38.

Stumpf RP, Holderied K and Sinclair M. 2003. Determination of water depth with high resolution satellite imagery over variable bottom types. Limnology and Oceanography 48: 547–556.

Susa T. 2022. Satellite derived bathymetry with Sentinel-2 imagery: Comparing traditional techniques with advanced methods and machine learning ensemble models. Marine Geodesy 45(5): 435–461.

Swain AK. 2018. Bathymetry of Schirmacher lakes as a tool for geomorphological evolution studies. Geological Society. 461(1): 77-93.

Szafarczyk A and Tos C. 2023. The Use of Green Laser in LiDAR Bathymetry: State of the Art and Recent Advancements. Sensors 23: 292-319.

Tamminga A, Hugenholtz C, Eaton B and Lapointe M. 2015. Hyperspatial remote sensing of channel reach morphology and hydraulic fish habitat using an unmanned aerial vehicle (UAV): A first assessment in the context of river research and management. River Research and Applications 31(3): 379-391.

Ventura D. 2020. Coastal zone mapping with the world's first airborne multibeam bathymetric LiDAR mapping system. Hydrographische Nachrichten. Vol. 115, Deutsche Hydrographische Gesellschaft e.V: 48–53.

Viney IT and Kirk GR. 2000, Trimble Navigation Ltd. Remote control and viewing for a total station. U.S. Patent 6,034,722.

Von Bormann T and Gulati M. 2014. The Food Energy Water Nexus: Understanding South Africa's Most urgent sustainability challenge. WWF-SA, South Africa.

Walker DJ and Alford JB. 2016. Mapping Lake sturgeon spawning habitat in the upper Tennessee River using side-scan SONAR. North American Journal of Fisheries Management 36(5): 1097-1105.

Wang D, Xing S, He Y, Yu J, Xu Q and Li P., 2022. Evaluation of a New Lightweight UAV-Borne Topo-Bathymetric LiDAR for Shallow Water Bathymetry and Object Detection. Sensors, 22(4): 1379-1399.

Westaway RM, Lane SN and Hicks DM. 2003. Remote survey of large-scale braided, gravel-bed rivers using digital photogrammetry and image analysis. International Journal of Remote Sensing 24: 795–815.

Westoby MJ, Brasington J, Glasser NF, Hambrey MJ and Reynolds JM. 2012. Structure-from-Motion Photogrammetry: A Low-cost, Effective Tool for Geoscience Applications. Geomorphology 179: 300–314.

Winterbottom SJ and Gilvear DJ. 1997. Quantification of channel bed morphology in gravel-bed rivers using airborne multispectral imagery and aerial photography. Regulated Rivers: Research & Management: An International Journal Devoted to River Research and Management 13(6): 489-499.

Woodget AS, Carbonneau PE, Visser F and Maddock IP. 2015. Quantifying submerged fluvial topography using hyperspatial resolution UAS imagery and structure from motion photogrammetry: Submerged fluvial topography from UAS imagery and SfM. Earth Surface Processes and Landforms 40: 47– 64

Wozencraft JM. 2010. Requirements for the coastal zone mapping and imaging LIDAR (CZMIL). In Algorithms and Technologies for Multispectral, Hyperspectral, and Ultraspectral Imagery XVI (7695): 219-225.

Wu Z, Mao Z, Shen W, Yuan D, Zhang X and Huang H. 2022. Satellite -derived bathymetry based on machine learning models and an updated quasi-analytical algorithm approach. Optics Express 30 (10): 16773–16793.

Xing S, Wang D, Xu Q, Lin Y, Li P, Jiao L, Zhang X and Liu CA. 2019. Depth-adaptive waveform decomposition method for airborne LiDAR bathymetry. Sensors 19: 5065

Yang H, Ju J, Guo H, Qiao B, Nie B and Zhu L. 2022. Bathymetric Inversion and Mapping of Two Shallow Lakes Using Sentinel-2 Imagery and Bathymetry Data in the Central Tibetan Plateau. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 15: 4279–4296.

Yoshida K, Maeno S, Ogawa S, Mano K, and Nigo S. 2019. Estimation of distributed flow resistance in vegetated rivers using airborne topo-bathymetric LiDAR and its application to risk management tasks for Asahi River flooding. Journal of Flood Risk Management 13: 1-17.

Young S, Peschel J, Penny G, Thompson S and Srinivasan V. 2017. Robot-assisted measurement for hydrologic understanding in data sparse regions. Water 9(7): 494:507.