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Evaluation and improvement of remote sensing-based methods for river flow management

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A B S T R A C T

Rapid advancements in technologies open up possibilities for water resource authorities to increase their ability to accurately, safely and efficiently establish river flow observation through remote and non-intrusive observation methods. Low-cost Unmanned Aerial Vehicles (UAVS) in combination with Global Navigation Satellite Systems (GNSS) can be used to collect geometrical information of the riverbed and floodplain. Such information, in combination with hydraulic modelling tools, can be used to establish physically based relationships between river flows and permanent proxy. This study proposes a framework for monitoring volatile, dangerous and difficult to access rivers using only affordable and easy to maintain new technologies. The framework consists of four main components: i) establishment of geometry using airborne photogrammetry and bathymetry; ii) physically based rating curve development through hydraulic modelling of surveyed river sections; iii) determination of non-intrusive observations with for instance simple cameras or satellite observations; and iv) evaluating the institutional and societal impacts of using new technology. To establish this framework, a number of research questions require addressing. First, the factors impacting on accuracy of geometrical information of the floodplain terrain and bathymetry need to be investigated. Second the accuracy of a physically based rating curve compared to a traditional rating curve needs to be established. Third, for rapidly changing river segments, it should be investigated if the collection of occasional snapshots of multiple proxies for flow can be used to assess the uncertainty of river flows. The study finally explores the social and institutional impact of using new technologies for remote river monitoring. If these research gaps are addressed, this may strengthen water manager's ability to observe flows and extend observation networks.

1. Introduction

The unavailability of consistent accurate river flow data is a significant impediment to understand water resources availability, and hydrological extremes. This is particularly true for remote, difficult to access, morphologically active and therefore rapidly changing rivers. The state of global river discharge monitoring has been on the decline over the past few decades. This is despite the significant importance of these data for river flow predictions (Fekete and Vörösmarty, 2002). The water resources of poorly gauged river basins may be of strategic importance yet may be challenging in terms of data collection due to reasons such as poor accessibility, strong seasonal variability, and for certain parts of the world, presence of large wild animals. Financial and physical resources are not the only challenge when it comes to data collection in areas of this nature; changes in river geometry also make it necessary to update stage discharge relationships through fieldwork more frequently than in other river systems. Remote sensing may reveal such rapid changes (Donchyts et al., 2016). These issues make it extremely important to investigate data collection methods which reduce the reliance on empirical relationships between flows and permanent flow proxy observations (typically water levels), to eliminate or reduce the need for contact with water during surveys and permanent

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observations, and finally, to reduce the costs associated with such observations. This paper sets forth research requirements that will lead to a framework for remote river flow observations, suitable for rivers that are difficult to access frequently, and difficult to equip with permanent water-borne instruments and applicable with little financial resources. We make a strong case for utilisation of Unmanned Aerial Vehicles (UAVs), which may eliminate the risk in dangerous and difficult to access places (Gustafsson and Zuna, 2017) and allow for rapid collection of geometrical data as well as calibration snapshots of flows and flow proxies in areas with limited direct accessibility to the stream. A limited amount of research has been done in concrete applications to use UAVs in rating curve development. We exemplify that the framework will work by relating these to a typical application environment, the Luangwa River, one of the major tributaries of the Zambezi basin. This river faces the typical challenges mentioned, i.e. remoteness, large seasonal variability, large morphological activity and dense wildlife activity. This study hypothesizes that advanced techniques can contribute and even improve efficient river flow monitoring. The ideal outcome is an interconnected framework which clearly presents the steps which are necessary for river monitoring in remote locations. We explain how each critical step is related to the other and how modern technologies are assimilated into the method. Section 2 describes an overview of currently practiced methods to observe flow or flow proxies using ground, contact or non-contact remote observations including satellite remote sensing. Section 3 introduces the selected illustration case, the Luangwa river. Section 4 describes our proposed flow observation framework. In Section 5, we summarize a number of research questions that need to be addressed to establish this framework. Finally, we conclude this paper in Section 6.

2. Inventory of flow observation techniques

2.1. In-situ flow observations for natural control sections

Despite the importance of discharge data for hydrological modelling, the number of monitoring stations has declined over the years (Shiklomanov et al., 2002). The traditional method by which flow is monitored has not changed for over 100 years (Costa et al., 2000). River observations consist of three general steps: surveying in the classical sense whereby corresponding sets of discharge, and water levels, or other flow dimensions such as surface area or width in the vicinity of the site are recorded. These sets comprise an empirical relationship between flows and dimensions (also known as the "rating curve"). Through installation of gauging stations on site which record the proxy dimension and continuous observations are realised.). In classical gauge sites, the dimension that is observed is typically the water level. Proxies of flow such as surface area and river width can also be recorded.

In order to determine discharge during the surveys it is important to record the water velocity across a cross-sectional surface. There are a number of methods that can be used to do this. These include floats, dilution gauging, trajectory, current meter and Acoustic Doppler Current Profiler (ADCP) methods. The float method only provides velocity at the surface and involves placing objects on the surface of a flowing water body at several locations within the cross section for a predetermined distance and consequently calculating the surface velocity (Gordon et al., 2013). This method is only suitable for small and straight streams (Hudson, 1993). The dilution method utilises the rate of diffusion of a particular tracer to determine streamflow (Comina et al., 2014). Inaccuracies can occur as a result of insufficient mixing. The method is therefore limited to relatively small and turbulent water bodies. It is difficult and impractical to use this method in large streams with discharge which is above 2 m^3/s because a large amount of tracer is required to distinguish concentration differences properly, and full mixing may become problematic to achieve. A new study is being undertaken by Sentlinger (2019) who uses an automated salt dilution method which can be used for larger discharges. In some situations it is difficult to obtain permission to insert tracers into water bodies due to risk of contamination (Moore, 2004). In the current meter method, the velocity is determined by assuming it as proportional to the rate of rotation of a rotor in a specified amount of time (Chauhan et al., 2014). This method has relatively high accuracy and time efficiency (Survey, 2007) but requires that a sensitive instrument is brought into contact with water, compromising its use during high velocities. The trajectory method involves diversion of streamflow into a pipe so as to estimate flow (Salguero et al., 2008). This can only be used in small streams where the flow is small enough so that it can be directed through a pipe (Liu et al., 2014). Finally, an ADCP, which transmits sound into the water, determines water particle velocity by calculating the differences in the frequency of the transmitted sound and echoes (Costa et al., 2006). Similar to the current meter, the ADCP is expensive, requires trained personnel to use it and must be used in contact with water. The ADCP is best utilised in large rivers with flat terrains (Flener et al., 2015). Similar to other contact based methodologies, the ADCP may be difficult and dangerous to use especially when velocities are very high and debris is flowing through the stream's section. In fact, all above mentioned methods have limitations in applicability, especially during high flows since the surveyor and instruments need to be in contact with water during potentially dangerous conditions. . Furthermore, the empirical rating curve method, typically requires quite a large number of points to collect and prepare the relationship, and are applied under the assumption that the relationship remains stable. Table 1 shows a summary of the different methods and gives a brief outline of some of the advantages and disadvantages of each method.

When it comes to continuous observations, flow dimension observations (classically water levels) can be obtained with a pressure transducer in a stilling well or manual reading of a staff gauge. Lin et al. (2018) was able to successfully test an automated water reading mechanism using single camera images pointed on a staff gauge providing efficient non-contact water level monitoring. Heusinkveld (2014) developed an application which uses a smartphone to automatically record water levels even when it is raining or when there is dirt on the scale. Besides water levels, it may be beneficial to record proxies of water level such as surface area and river width to identify changes in discharge.

Table 1
Advantages and disadvantages of classical flow estimation methods.

Method	Advantages	Disadvantages
Float	Typically easy and quick to conduct.	Only suitable for small straight streams. Can be affected by weather conditions such as wind. Requires contact with water. Large degree of uncertainty.
Salt dilution	Capable of determining not only velocity but total discharge.	Can be affected by lack of sufficient mixing. Only applicable in small rivers.
Trajectory	Very accurate as it collects total volume	Usually more difficult to conduct due to expense of experiment. Permission to divert water required. Requires contact with water
Current meter	Easy to use. Relatively accurate.	Affected by location of measurement across the river cross section. Requires contact with water with a person in the water, or a construction.
Acoustic Doppler Current Profiler (ADCP)	Relatively accurate. Relatively fast to apply. Applicable over large streams	Relatively expensive equipment. Cannot be used for shallow river channels (less than 1m)

2.2. Satellite observation methods

Besides ground or close to ground observations to observe continuous proxies for river flow, satellites may also be used to obtain proxies in large but difficult to access sites. To our knowledge, there are currently three remote sensing methods of estimating proxies of river discharge (Dobriyal et al., 2017). These are; (i) direct radar altimeter measurements of water surface level with respect to a common datum (Alsdorf et al., 2000; Plant and Keller, 1990), (ii) determination of water width and surface elevation through identification of the point of contact between land and water surface using high resolution satellite imaging, and (iii) satellite derived water surface area proxies (Revilla-Romero et al., 2014). The first method utilised radar altimetry to derive water surface levels within acceptable accuracy standards (Bogning et al., 2018). This method is best utilised if we expect change in flow is particularly sensitive for changes in depth. The altimetry method is limited in spatial resolution by the specific overpass locations which may not coincide effectively with a user's point of interest. Altimetry is well placed to make use of the upcoming Surface Water Ocean Topography Mission (SWOT (Biancam et al., 2016),) which will present an even higher resolution and a much more robust temporal scale. The SWOT mission is designed to observe all rivers wider than 100m. The mission will observe all rivers regardless of nadir (camera/sensor looking vertically downwards) overpass. It will provide the very first discharge variations and river storage data in a globally consistent manner. The second approach can be applied using high-resolution imagery such as Sentinel-2 with spatial resolution in the order of 10m and temporal revisit time of at least 5 days. This method is however compromised by cloud cover, but can still offer many width estimates over non-clouded areas in high resolution imagery (Huang et al., 2018). A number of researchers have shown that satellite derived surface area in conjunction with appropriate ground data can be used to estimate river discharge changes (Bjerklie et al., 2005; De Groeve, 2010; Temimi et al., 2005).

The third approach makes use of the relationship between the surface area of a water body as viewed from satellites and flow. Bjerklie et al. (2005) showed that empirical relationships between discharge and water surface area can be established. This can be done by establishing water surface and maximum channel width from orthophotos coupled with slope estimates derived from topographic maps so as to determine discharge. If discharge is particularly sensitive for changes in the floodplain inundation extent, this implies that these two can be used interchangeably when it comes to monitoring flows (Zimba et al., 2018). This is the case to a greater extent in wide relatively flat terrain places like wetlands and floodplains. All methods require some form of a relationship between the observed satellite signal, and the in-situ flow. The relationship which is calibrated using ground data works best when the surface area co-varies most strongly with discharge. Satellite passive microwave sensors can be very useful due to their reduced impact from cloud cover in estimating river discharge and temporal revisit times (Brakenridge et al., 2007). Van Dijk et al. (2016) showed a strong correlation using a combination of optical, and microwave sensor inundation extent proxies (i.e. not actual surface areas) to determine river discharge of many rivers worldwide.

All these non-contact satellite-based monitoring methods have some disadvantages. Remote sensing is susceptible to the high reflective nature of trees in the visible and infrared section of the spectrum which can affect accurate estimation of water body surface area and width (Ward et al., 2013). Satellite based remote sensing however only show river variability (and either vertically or horizontally, not both simultaneously) and not river flow itself, always requiring in-situ information to achieve a flow estimate. A further limitation is the temporal resolution of most satellite data which typically has an inverse relationship with the spatial resolution. This means in the instances where relatively high resolution is required, there will be the limitation of having less observations per unit time. Remote sensing methods ultimately, cannot estimate discharge directly yet (Costa et al., 2000). Ground observations are required to make the translation into flow estimates.

2.3. The role of aerial photos and videos in river monitoring

UAVs and smartphones are much closer to the ground than satellites and therefore present an opportunity for non-contact monitoring at a much higher spatial resolution and at any time convenient to the user. This can help in taking efficient snapshots of flow and flow dimensions in areas that are typically difficult to access, and help translating remote sensing proxy observations into actual flow estimates (Bandini et al., 2017). Compared to other velocity estimation methods, a normal RGB camera UAV is priced at approximately 10% of a typical ADCP. UAVs but also ordinary cameras on smartphones can be used to record movies. In combination with Large Scale Particle Image Velocimetry (LSPIV) software and simple surveys, these can be turned into surface flow estimates (Tauro et al., 2016a, 2016b). LSPIV is made up of five main components: flow visualization, illumination, image recording, orthorectification and image processing (Muste et al., 2010). Despite needing validation due to the indirect nature of the method, LSPIV gives accurate readings in comparison other methods (Hauet et al., 2008). LSPIV methods (Beat et al., 2014; Kim, 2006) have been developed to estimate water flow by focusing only on natural tracers, such as foam, ripples generated by turbulence and differences in water colour created by sediments or suspended solids. These new methods overcome the requirement for manual addition of tracers onto the water surface (Gustafsson and Zuna, 2017). The open source LSPIV software Fudaa-LSPIV provides a user-friendly method of surface velocity estimation. The method is based on the LSPIV technique and the output includes surface velocity and combined with cross-section surveys, also river discharge using assumptions on the vertical velocity distribution (Jodeau et al., 2017).Topography and bathymetry of a river bed and floodplain can be constructed using photos acquired with an UAV using the process of photogrammetry. .

3. Study area

In this section, we describe a site in the Luangwa Basin, Zambia which exemplifies a typical location on which UAVs and other new technologies can be used to establish a flow observation site and data collection process. In addition to this, the site was also chosen due to the positive working relationship with the Water Management Authority of Zambia (WARMA). WARMA has nearby gauging stations which we can use as benchmark for results of our proposed framework.

The basin has a catchment area of approximately 160,000 km^2 (The World Bank, 2010). The Luangwa River originates in the Mafinga Hills in the North-Eastern part of Zambia and is approximately 850 km in length flowing from the South-West. The river drains into the Zambezi River, shaping a broad valley along its course. The river basin is pristine and the valley is well-known for its abundant wildlife (WARMA, 2016).

Strategic locations for research are Luangwa Bridge, Mfuwe and Mulopwe village, as these are in close proximity to WARMA stations where results of our framework can be benchmarked. The site is relatively uniform in sediment type and channel form with easy access to the floodplain to observe Ground Control Points (GCP).

To exemplify the potential use of new observation sites, we refer to two use cases. The Luangwa's confluence into the Zambezi, is closely upstream of Lake Cahora Bassa, one of the largest hydropower schemes in Southern Africa. Rapid variations in inflows make it difficult to manage Cahora Bassa. Furthermore, near the outlet of this river (south of Luangwa bridge in Fig. 2), a large flood-prone area is located, making the river relevant to monitor upstream. For these reasons it may prove useful to predict flows several days ahead in time near the outlet for humanitarian aid (Zambia Red Cross, personal communication) or for prediction of inflow variability (Cahora Bassa, personal communication). To this end, monitoring upstream flows is highly important, because a river gauge location in the upstream area (for instance Mfuwe, see Fig. 1) may provide significant skill for such forecasts. Fig. 3, shows the Luangwa River at Mfuwe (see Fig. 2) in the dry season. The complex nature of the river is depicted by the branching of the river into different channels. The river channel shown in the figure primarily flows on the left-hand side of the river, however, it could easily be on the right or in the middle in the next season. This makes it difficult to setup permanent gauging infrastructure. Furthermore, extreme floods have repeatedly caused observation sites to get seriously damaged. The floods of 2019 washed away the stilling well and pressure transducers (Hulsman, personal communication). This makes it an ideal and relevant location to test the usability of UAV based flow estimation in difficult to access places.

Fig. 2. Site Mfuwe - Luangwa River. Photo taken on November 6, 2018.

4. Framework

In this section, we propose a framework, which combines all the elements necessary for river flow monitoring from surveying to the ultimate goal of non-intrusive monitoring with limited field assessment using novel and low-cost methods. Fig. 3 presents the framework. We propose that remote river flow observations entail the following 5 major steps:

Step 1 which is node 1 defines requirements and possible benefits of site characteristics for our workflow. The site has to be a suitable compromise among some of the following aspects:

- The site should be relatively uniform in sediment type and channel form with accessibility to the floodplain to observe Ground Control Points (GCP).
- The site must be reasonably far from flow impediments like bridges to avoid backwater effects (similar to classical site selection requirements)
- A reasonable amount of accessibility to the permanent stream is necessary in order to conduct bathymetry cross-section observations or snapshot flow proxy observations.
- The stretch must be reasonably long enough to make slope estimates

Beneficiary characteristics include:

- A site may be selected where an altimetry satellite overpass is available so that altimetry heights can be used as flow proxy
- A site may be selected where the flow is particularly sensitive to increases in inundation surface areas, such as wetlands or floodplains. In this case satellite surface area, width or surface area proxies (see Section 2.2) can be used as permanent observation instead of water level instruments.

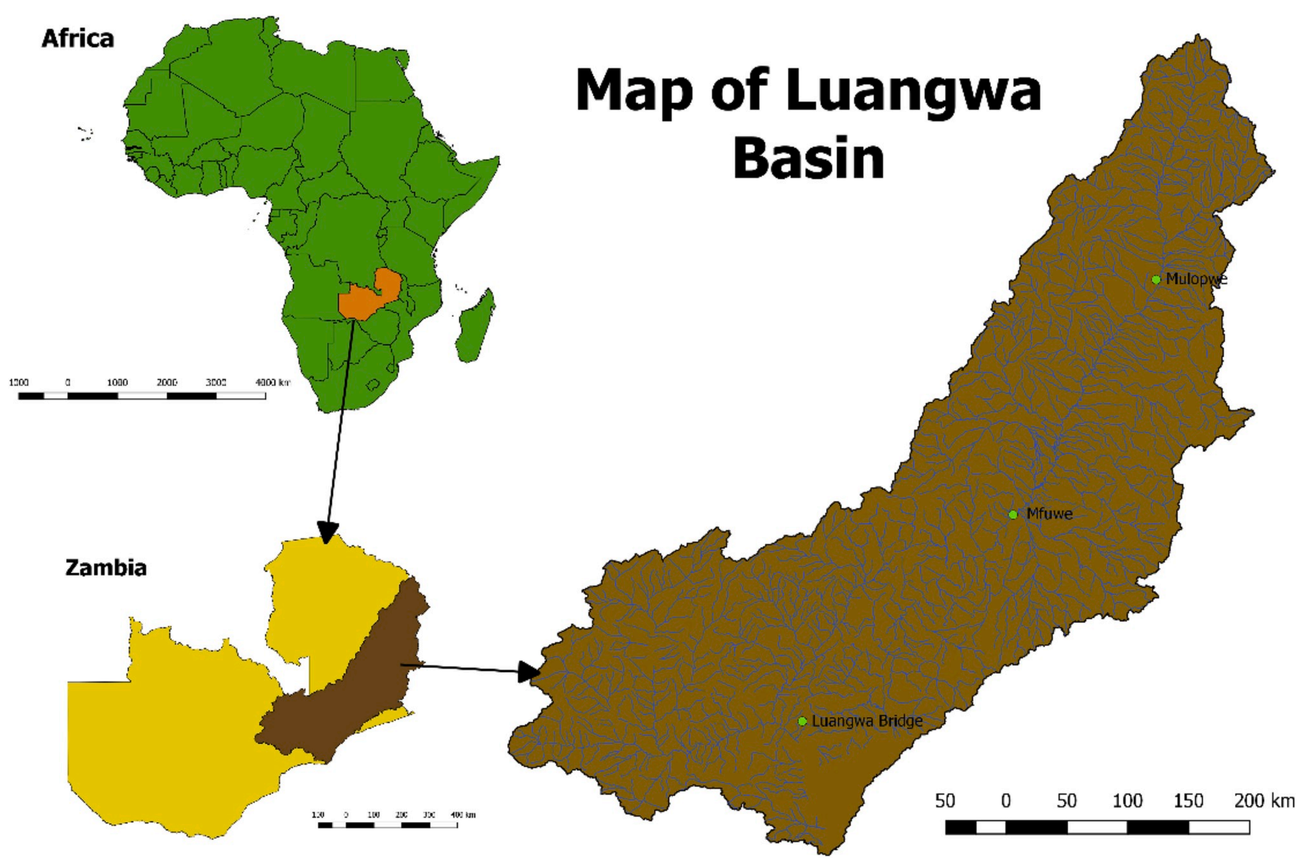

Fig. 1. Map of Luangwa basin.

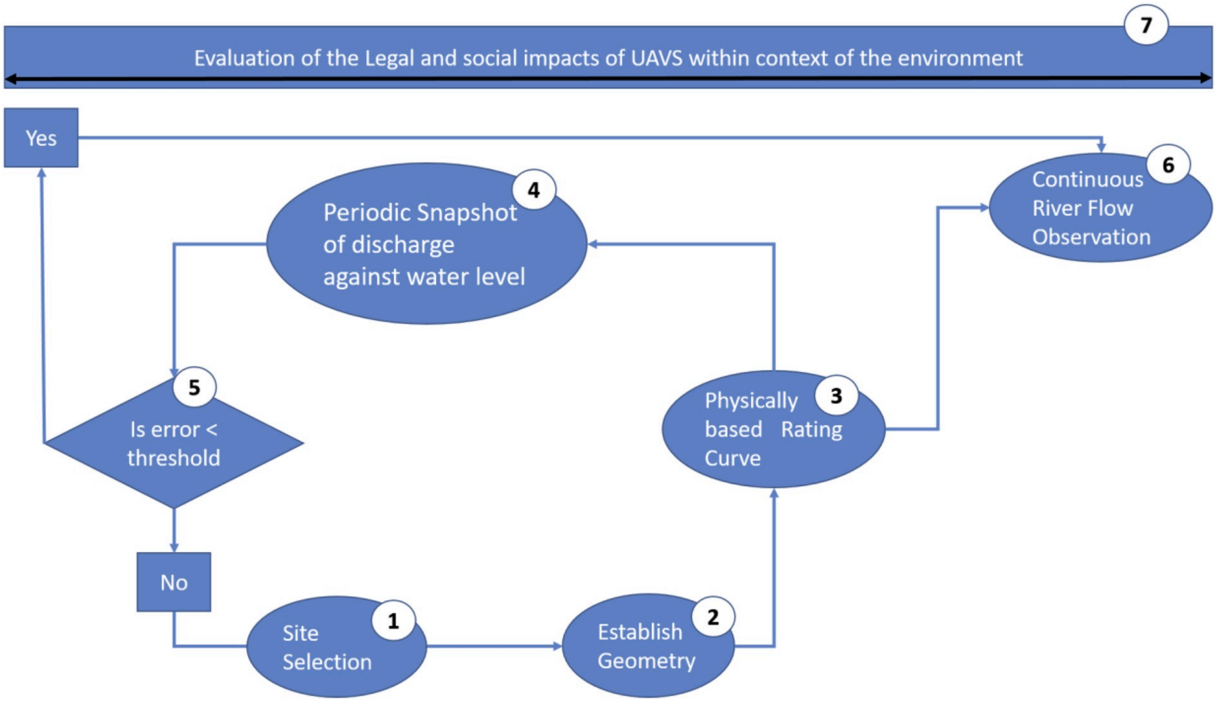

Fig. 3. River monitoring framework.

It should be noted that site selection may also depend on the use case for the flow observations. Whether satellite proxies can be used strongly depends on this. For instance, for the forecasting use cases defined above, altimetry is not likely to provide sufficient coverage in time (once every 10–35 days approximately), as the likelihood of missing flood events is high. Other proxies such as surface area (from particularly passive microwave remote sensing) may be sufficient as these can be provided on a daily basis. For long-term water resources analysis, altimetry may prove a useful continuous observation as well. It should also be noted that the channel does not necessarily have to be entirely straight or uniform in shape as our rating relationship (further described in step 3) may also rely on a 2D or 3D physically based model.

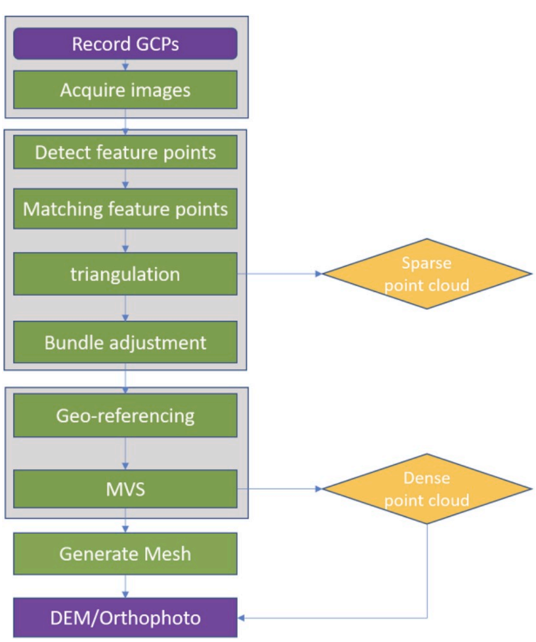

Fig. 4. Photogrammetry process adapted from Balogh and Kiss (2014)

Step 2 which is the node 2 on the framework diagram involves, after site selection, establishment of geometry of the dry riverbed, floodplain and the wetted perimeter. In this step, a UAV, or other airborne platform such as kites, or balloons, is used to determine the geometry of a river reach using photogrammetry (see Section 2.4) in combination with sufficient sampling of Ground Control Points using a GNSS survey. For seasonal rivers, this is preferably done in the end of the dry season to maximise the visible area. An example of a point cloud captured in the dry season at Mfuwe is shown in Fig. 5. This survey took only one day with a team of 2 persons to complete. UAVs should be employed with optimal flight conditions, using optimal settings and flight paths. These conditions and settings may be specific for the purpose of surveying a riverbed and therefore require investigation. The technique that is used to generate the geometry from UAV images is called photogrammetry. Photogrammetry makes use of these overlapping images to identify common points or objects on different images (Schenk and Quarter, 2005). There exists a line of sight between the location of the camera and the point of interest. The (x, y, z) coordinates are determined by the intersection of these lines of sight. Fig. 4 shows the Photogrammetric Process (Balogh and Kiss, 2014). Photogrammetry has been used by many different researchers to monitor rivers by establishing elevation models of river channels (Bird et al., 2010; Chandler et al., 2002; Lane, 2000; Westoby et al., 2012). Most of the monitoring has been for the

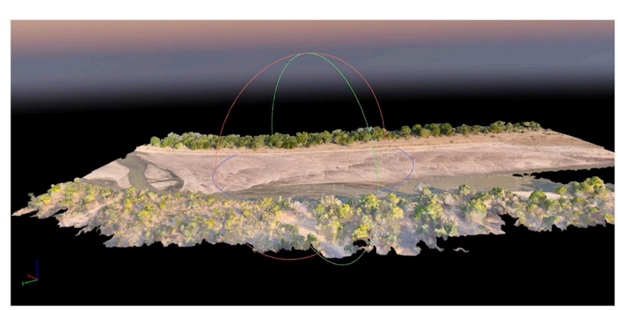

Fig. 5. Point cloud of the Luangwa River at Mfuwe.

purpose of assessing the hydromorphology of rivers. For instance, Woodget (2017) used photogrammetry to assess river habitat and the hydromorphology, whilst Cucchiaro (2018) applied photogrammetry to assess the geomorphic effects of debris flow. To our knowledge very little research has been conducted using photogrammetry to explicitly determine flows through hydraulic relationships. There are many different types of photogrammetry software available. The most well-known include Agisoft Photoscan (Metashape) (Jebur et al., 2018), Pix4D (Burns and Delparte, 2017) and the relatively recent package, OpenDroneMap (Burdziakowski, 2017). Of these three, ODM is the only photogrammetry package that is open source and free. For low-resource environments, it is of interest to determine if the output from this freely available software is similar to other relatively expensive commercial packages provided by Pix4D and Agisoft.

Areas which are constantly covered by the water may be compensated for, through use of simple methods such as point profile measurements using e.g. a rod with distance markers, or a Real-Time Kinematics GNSS equipment, attached to a long rod. The wet and dry geometry information needs to be combined into a complete and seamless terrain and bathymetry geometry. Validation of this method may be performed using real time kinematic GNSS surveys in the dry season and ADCP bathymetric surveys for under water spatial observations. In line with the aim to improve the quality of geometrical data, it can be argued that the high spatial resolution data collected from tools such as UAVs is an improvement on in situ surveys, but at specific locations, where GNSS survey point are taken, we can perform validation against these points as independent estimates of position and elevation. We will do this by leaving out several points from the DTM reconstruction process and keep these available as independent validation data.

Step 3 is a combination of node 3, and 4 and 5 on the framework diagram and involves establishment of rating curves between flows, and proxies for flow such as classical water levels, surface velocities, width or surface area, or a combination of these. To establish this relationship, we propose to utilize hydraulic simulations. There are 3 main methods of generating a physically based hydraulic simulation model, these are 1D (i.e. one-dimensional), 1D-2D (one-dimensional over the main flow direction, 2-dimensional in the floodplain) and 3D. Which of these 3 is to be used, depends on which proxy variable the user wishes to use to calibrate or validate the modelled relationship. For instance, if a user can collect total discharge (e.g. through an ADCP) along with water levels, and the river section is uniform enough (i.e. lateral transport is negligible) then a 1D model may be sufficient because a 1D hydraulic model can represent both water levels and integrated cross-sectional flow (Liu et al., 2014). If the channel section is more complex and/or the user cannot collect integrated flow but only surface velocities (for instance through LSPIV, see Section 2.3) or other surface proxies then a 3D model may be required, as a 3D model can represent more complex geometries, as well as surface variables such as velocity. Let us here assume a straight uniform section with moderately changing flow conditions so that steady-state conditions can be assumed. We also assume that the user can establish snapshot observations of cross-section integrated discharge and water levels at the same time. Under these conditions a simple 1D Manning's equation can be utilised to establish a physically based rating curve. It is simple and produces reliable results under the assumption that flow is steady and uniform (Herschy, 2009). The formula can be separated into two parts, roughness/slope constants and the conveyance. The conveyance part is attributed fully to the geometry of the river, i.e. it is in this case independent of roughness. This allows us to use a combination of UAV imagery and wetted profiles to establish a complete geometry in order to determine the conveyance. Manning's equation can be expressed as follows:

$$Q = n^{-1}\sqrt{i}\ AR^{2/3}$$

where:

Q = Discharge in m^3/s
n = Bed roughness[$s/m^{1/3}$]
i hydraulic slope [-]
A = Cross-sectional area in m^2
R = Hydraulic Radius in [m]

An estimation of slope can be established using the head drop in a saturated water hose or using GNSS equipment. The roughness may be estimated from a table which presents values of roughness against qualitative descriptions of those environments (Wu and Wang, 1999).

In more complex environments the flow may not be steady or uniform, for instance when the direction of flow on the floodplain is highly unpredictable. Also, a user may want to rely on surface flow velocities to simulate cross-sectional discharge. These conditions require a 3D model application to simulate flow predictions in the x, y, and z directions, allowing for assimilation of surface velocities. The digital elevation and bathymetry model becomes critical in this application. Given that a low-cost drone can provide this information, a 3D model may be implemented in this case.

The combination of slope and roughness may be calibrated based upon field work snapshots, assimilated to the hydraulic model. This is done by collecting water level and discharge data or non-intrusive surface flow velocities within low, medium, high water regimes and comparing this snapshot data against the established hydraulic model to determine consistency and thus validity of the rating curve. When snapshots show that the observed flows or flow proxies cannot be matched against the observed water levels, widths or surface areas, apparently the geometry changed such, that a new geometry observation is required. The accuracy of this physically based method to establish a rating curve should be investigated. Whether surface flow velocity estimates (e.g. through LSPIV) provide sufficient and certain enough information to calibrate the hydraulic relationships also requires investigation. For instance, the location of the illustration site (see Section 3) is in close proximity to already established Water Resources Authority of Zambia (WARMA) gauging stations. This allows us to compare the rating curves generated from the physically based rating curve developed here, with rating curves used by WARMA. Validation can be performed by generating a 95% confidence interval of the WARMA curve to establish if the physically based rating that has been modelled lies within limits in the range of the observations available. We will also investigate if the physically based rating curve is closer to existing rating points when only using relatively recently surveyed points as another form of validation. Our hypothesis is that in rapidly changing rivers, this will be true because the recent geometry is represented in the physically based rating curve.

Step 4 is represented by node 6 on the framework diagram. Continuous observation of one or more of the proxies for river flow is needed, either through a permanent instrument or satellite observations (dependent on the size and flow regime of the river). In order to be fully remote, a process of determining a permanent instrument such as a fixed camera or determining the most appropriate satellite-based monitoring method is required. If indeed a permanent instrument is to be used, we need to determine the location, orientation, data transmission method and applicability in the particular environment. In the case of satellite-based monitoring, a transfer model between the satellite view and what is visible on the ground is required. The decision to use altimetry or water surface proxies (e.g. from microwave remote sensing or optical methods) will be motivated by the expectation of a strong or weak relationship between changes in discharge against flow elevation (in the case of altimetry) or flow width (in the case of surface proxies). A combination of the two methods may be applied where a relationship is uncertain. This is to provide a proxy whereby the outputs of both methods should be within reasonable variation of each other. SWOT may provide key insights into the sensitivity of river flow to surface water level variations and surface extent variations. As SWOT observes both surface water level and extent at the same time, it may be used to translate other altimetry or surface extent methods into a continuous signal. The long-term observations of proxies of flow can be validated against in–situ observations. For instance the surface area observed from satellite data can be cross checked against ground surveys or UAV surface area calculations.

Step 5 is represented by node 7 on the framework diagram. It is comprehensive analysis of the social and legal implication of using UAVs or other airborne methods is needed. As it stands there are significantly different rules and regulations when it comes to utilisation of UAVs in different countries, and technologies also require different human resources. The reliance on UAVs of this workflow make it important to determine how legal and social issues may impact on the framework's success. It becomes important so as to be able to confidently advice water managers and water authorities who intend on implementing this suggested framework. To address this questionnaires and interviews should be conducted with users of the technology as well as related stakeholders (e.g. in Zambia, among others the Civil Aviation Authority, Wildlife Authority) to establish these social and legal implications, and conclude what is required for successful application of the framework.

Taking an all-inclusive look at the framework suggested, it is necessary to validate the hypothesis itself ("advanced techniques can contribute and even improve efficient river flow monitoring"). We will do this by conducting a pilot study and testing the hypothesis to establish the distribution of the responses which we obtain from the questionnaires and interviews and evaluating how this data deviates from the anticipated results.

5. Discussion

Through our literature research, we demonstrated that pieces of the puzzle have been laid that can be used to establish this framework. We identify that there are 4 general sets of specific research areas in need of analysis to be able to successfully implement remote river monitoring conclusively. These are related to the establishment of geometrical uncertainty, physically based rating curves, move from integrated direct, to non-contact proxies for determining flows, and finally, societal and institutional impacts of new technologies including UAVs. Here we identify the research questions in each area that require investigation in order to establish the framework for remote river observations presented in Section 3.

1. Which geometrical properties are important for flow estimation and how do uncertainties in these propagate into uncertainty of flows? This question requires experiments that identify what factors affect the quality of measurements of these properties. The factors are camera angles, flight height, light intensity, flight speed, and orientation with respect to the river channel, GCP formation and spread in the reach. Several flights with different combinations over a typical river and floodplain section must be performed to investigate the impact of these factors. There have been attempts to review UAV acquisition systems, orientation and regulation, (Colomina and Molina, 2014). There is need to go further and scrutinise hydrodynamic characteristics that need to be tested. These are, besides the overall terrain accuracy, the slope in the direction of flow and the shape of the cross-sectional area. Such experiments allow us to understand the best practices when it comes to photogrammetry with UAVs over river valleys, and will serve as a guideline for deployment.
2. How accurately can we establish rating curves by combining the generated geometry information with physically based hydraulic modelling? We anticipate that a hydraulic model, using the established geometry can translate continuously observed proxies for flow, including water levels, widths or surface water extents, into actual flows, by feeding such a model with boundary conditions of upstream flows across a wide range, and assess the resulting used proxy at surveyed cross-section locations. We will assess if this can be achieved with a 1-dimensional integrated model, which simulates integrated discharge estimates and uses water levels as continuously observed proxy. The model requires calibration against observed snap shots (during low, medium and high water) from e.g. ADCP observations. We can then assess how uncertainties in the geometry propagate into uncertainties in flow estimation.
3. How accurately can we determine discharge using non-contact observation methods? Non-contact observations would alleviate the need to expose surveyors to dangerous, inaccessible river reaches and reduce the need for costly and sensitive equipment. Which seasonality factors may affect the output of measurement? To address this, we need to investigate if a hydraulic relationship can be calibrated based on non-contact surface observations only. This will allow us to replace the rather expensive and sometimes difficult to deploy ADCP or other intrusive observation methods, by a non-contact method such as LSPIV. It requires the use of a distributed 3-dimensional model (instead of 1-dimensional integrated) because surface flow velocities at specific locations in the vertical and horizontal must be evaluated and data on the surface assimilated. To this end, experiments can be conducted that only utilize the ADCP surface observations instead of the entire profile, and instead of an upstream boundary condition, assimilate these into a 3D model. Furthermore we can take advantage of the theoretical simulator proposed by Hauet et al. (2008). Finally, the impact of using less direct observations such as LSPIV-based surface flow (see Section 2.3) on the rating curve, compared to traditional integrated flow estimates, must be investigated. . The factors which may affect LSPIV results such as light reflection, tracer size and waves can be tested under varying conditions and using different tracer materials in time and space. Addressing question 2 and 3 requires taking snapshots using different observation methods at several moments during the season, traditional methods as benchmark, alternative observation such as LSPIV as test bed. The resulting rating curve can be evaluated against classical empirical rating curve points.
4. A final research questions relates to the socio-economical context: what skills and qualifications are needed by water authorities to adequately and effectively apply remote discharge observations. This concerns particularly the use of new technologies such as UAVs There seems to be resistance to use UAVs in most countries for many reasons which are mostly concerning security. What is the best strategy for water management institutions to induce a policy change to be granted permission to use UAVs in a manner which satisfies all parties involved? In what way can we make sure that water managers who are not familiar with new techniques can access training and what aspect of the institution must be amended to maximise adoption? What does the legal statute say about utilisation of UAV in these sensitive areas such as protected national parks? This also involves public opinion, co-design of use case development and appropriate licensing with aviation authorities, and social acceptance. The aim is to be able to fully advice all potential users of the implications. This part is fundamental in the sense that all the gains of the use of UAV remote river rating will not effectuate if certain aspects of the law, institutional requirements and social norms are not taken into consideration.

6. Conclusions (and recommendations)

There is indeed a need to design a framework specifically for monitoring flow in difficult environments such as our illustrative example, the Luangwa River in Zambia. The main principle is to utilize hydraulic simulation of relationships between discharge and proxies for discharge based upon physics of momentum and mass balance, constrained by the observation location's geometry and roughness. This would allow for assimilation of any permanent observation of flow proxies into these hydraulic simulations, not just the classically observed water levels. This principle would also reduce the requirements for using a straight, uniform channel section as observation location. Although pieces of the puzzle are laid out in the scientific domain, there remain at least four main areas which we have identified as key to development of a holistic monitoring method and understanding its capabilities and accuracy. The first is in the area of mapping of the geometry of a river and its floodplains. We see low-cost UAVs as high potential, but there is no known (defined) flight method for surveying water bodies using UAVs. The unknown variables which can significantly affect the geometrical output, range from flight characteristics (application, altitude, speed, camera angle, light intensity, direction) to processing software settings. The second area of research emanates from the requirement to establish relationships (rating curves) between some continuously observed proxy for river flow and river flow itself. We propose that this is done through development of models which allow for non-contact or even space-based monitoring with occasional snapshots of both discharge and discharge proxies to validate if the geometry underlying the relationship is still accurate. The third aspect is in the snapshot observations. There is a knowledge gap how to assimilate non-contact surface flow observations (instead of integrated flow observation) such as LSPIV or satellite derived observations into the defined relationship, and how uncertainties in these observations propagate into uncertainties of flow estimates. In the case of large and extremely volatile rivers such as the Luangwa, non-contact observations may be easier to collect than contact observations. Advancements in affordable technologies allow for comparison of the available methods which best suits small budget water authorities. The fourth aspect concerns the context and environment of the user, for instance water authorities. To adopt this new framework, we require an evaluation of the social, legal and institutional implications of utilisation of new technology, in particular UAVs.

If we are able to tackle the 4 mentioned research areas, this opens doors to a new hydrological understanding of previously ungauged catchments through low-cost, high accuracy monitoring. It allows for optimal utilisation of the upcoming SWOT satellite mission as well as other satellite missions, but also low-cost readily available sensors such as cameras on smartphones, so as to ultimately monitor flows from space or locally without requiring contact with the water. We recommend that the research community addresses these gaps within the forthcoming years.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

H.T. Samboko: Writing - original draft, Writing - review & editing, Data curation, Investigation. **I. Abas:** Investigation. **W.M.J. Luxemburg:** Writing - review & editing. **H.H.G. Savenije:** Resources, Supervision, Conceptualization, Funding acquisition. **H. Makurira:** Writing - review & editing. **K. Banda:** Writing - review & editing. **H.C. Winsemius:** Resources, Writing - review & editing, Conceptualization, Project administration, Supervision.

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Appendix A. Supplementary data

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