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Remotely sensed applications in monitoring the spatio-temporal dynamics of pools and flows along non-perennial rivers: a review

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ABSTRACT

Non-perennial rivers (NPRs) account for more than 50% of the world's river network and their occurrence is expanding. Some rivers that were previously classified as perennial have evolved to be NPRs in response to climate change and socio-economic uses. There is inadequate understanding of the spatio-temporal dynamics of flows and pools along these rivers due to lack of data, as a priority of river monitoring has been placed on perennial rivers. The current understanding and methods used for monitoring NPRs are mostly derived from perennial rivers perspective. This review paper examines challenges for collecting data on these hydrological attributes of NPRs using current methods. Furthermore, this paper provides an overview of the potential and limitations of using remote sensing data for monitoring NPRs. Remote sensing data are successfully used for monitoring wetlands and lakes, but little is known about their capabilities for monitoring pools along NPRs. Remote sensing has also been successfully used to estimate discharge of large perennial rivers; however, this has not been fully explored for NPRs. Remote sensing has the potential to extract more hydrological information that currently cannot be extracted using conventional in-situ measurement methods. With advancements, remote sensing technology could become useful for managing NPRs.

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Hydrology; remote sensing; river discharge; temporary rivers; surface water inundation; water storage

Introduction

Non-perennial rivers (NPRs) also referred to as temporary rivers or ephemeral rivers are streams and rivers that cease to flow for some time during the course of the year (Skoulikidis et al., 2017; Stubbington et al., 2017). These rivers and streams can either dry out completely or parts of their length of their channel (Stubbington et al., 2017). The hydrology of NPRs differs from that of perennial rivers as they have highly variable flows illustrated by a high coefficient of variance, as a result, the flows are difficult to predict (Larned et al., 2010; De Girolamo, Gallart et al., 2015). This is worsened by their spatial variability as information cannot be easily extrapolated from one river to another. The flow of these rivers are usually rainfall event-driven, but can be groundwater-dependent,

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especially during the dry periods. During the zero flow period, the storage and quality dynamics of static pools play a critical ecological and social role (Hughes, 2009). The terms, definitions and classifications of NPRs vary from location to location (Delso et al., 2017) which can cause confusion (Arthington et al., 2014). However, there is a global consensus about their characteristics which is the zero flow and high spatial and temporal variability.

River classification distinguishes river types based on geographical, geological, climatic, or biotic boundaries (Rossouw, 2011). However, the most common way to classify non-perennial rivers is to use seasonal flow patterns and their flow characteristics. Hence, non-perennial rivers can be classified based on flow permanence into the following classes: intermittent, ephemeral and episodic (Rossouw, 2011; Buttle et al., 2012; Datry et al., 2017). There are, however, no fixed boundaries between these river classes (Datry et al., 2017). Intermittent rivers cease to flow on a seasonal basis for weeks to months. Ephemeral rivers flow for days to weeks in response to rainfall events. Episodic rivers flow for a short duration, usually hours to days after heavy rainfall events (Datry et al., 2017; Skoulikidis et al., 2017). Given that flow permanence varies from one location to another, some studies further disaggregate flow permanence into percentages whereby intermittent (semi-permanent) have no flow between 1% and 25% of the time, ephemeral rivers have no flow between 26% and 75% of the time and episodic rivers have no flow for more than 76% of the time (Arthington et al., 2014; Rossouw, 2011; Seaman et al., 2016). This disaggregation made the classification of rivers more applicable to any region. Overall, the three types of river classification (intermittent, ephemeral, and episodic) are generally accepted, even though there is an overlap in their definition (Skoulikidis et al., 2017).

Non-perennial rivers occur worldwide, especially in arid and semi-arid areas (Aridity Index of 0 and 0.5). According to the World Atlas of Desertification (WAD) (2018), arid and semi-arid regions covers at least 40% of the world's terrestrial land area and at least 28 countries in Africa are mainly classified as semi-arid and arid (Cherlet et al., 2018). The WAD 2018 data show that 73% of South Africa is classified as semi-arid and arid which may have evolved from 60% estimated by Nomquphu et al. (2007). Despite that most NPRs are found in semi-arid and arid areas, Buttle et al. (2012) indicate that NPRs/temporary rivers can also be found in humid and sub-humid areas such as in Canada, where precipitation significantly exceeds evapotranspiration.

Importance of non-perennial rivers

Despite the increase in the number of non-perennial rivers caused by climate change and anthropogenic activities such as water abstraction and land-use change (Skoulikidis et al., 2017), in some regions, NPRs are the only source of freshwater. Ecological research has revealed that they are critical in terms of supporting life on earth. In fact, NPRs may be more vital than perennial rivers, as they can support both aquatic and terrestrial species by alternating between dry and wet habitats (Snelder et al., 2013).

Pools are one of the most distinguishing characteristics of NPRs when the flow has ceased (Datry et al., 2017; Hughes, 2005). These pools are important water sources in rural areas as they often provide water for vegetable gardening, livestock, and wildlife, and therefore support the tourism sector and people's livelihoods (Amede et al., 2011;

Naidoo et al., 2020; Zamxaka et al., 2004). Pools also act as habitats, feeding and spawning grounds for various aquatic species (Makwinja et al., 2014). There is a significant species-volume relationship in pools, as larger pools tend to have higher species richness and abundance (Bonada et al., 2020). Species richness also depends on the physical-chemical properties of the pools. Several studies have shown that pools are sources of water during droughts to the surrounding communities, while some studies show that pools attenuate floods (Liu & Zhang, 2017) as they store floodwater (Datry et al., 2017). In some locations, pools are also zones of groundwater and surface water interactions (discharge and recharge zones) as most pools in arid and semi-arid areas are groundwater-dependent (Bestland et al., 2017).

Challenges of non-perennial rivers

The spatial and temporal dynamics of flows and pools along non-perennial rivers are poorly understood due to limited studies aimed at understanding spatial distribution, the frequency of occurrence, persistence, and pool storage in catchments (Snelder et al., 2013). The impacts of land uses on flows, water storage in pools, and physicochemical aspects of waterlogging along NPRs are not fully understood, which constrains implementation of appropriate management approaches (Leigh et al., 2019; Seaman et al., 2016; Skoulikidis et al., 2017). The lack of adequate data due to limited routine monitoring of the quantity and quality of water, including ecological status has contributed to the current limited understanding of these systems. Monitoring of NPRs is not prioritized as they are perceived by NPRs to be less valuable compared to perennial rivers (Rodríguez-Lozano et al., 2020). This has resulted in a lack of political will to monitor or fund research on NPRs (Skoulikidis et al., 2017).

Monitoring of various elements of non-perennial river systems is necessary to overcome the knowledge gaps. However, monitoring of NPR systems is a challenging task as compared to perennial rivers due to their high variability and complex behaviour (Day et al., 2019). Extrapolation of data from data-rich to data-poor areas is problematic for NPRs due to the high variability of elements making up these rivers systems. For instance, a pool along the same river reach may function differently to a neighbouring one, e,g composition and diversity of aquatic species, dependency on groundwater. As a result, extrapolation of data may be inaccurate and hence not recommended for NPRs (Seaman et al., 2016). Most studies have been conducted along specific river reaches and extrapolating the results to other parts of the river is highly problematic. There is a need for studies that consider the river and capture the spatial and temporal variability of NPRs. Understanding the factors that explain patterns will be beneficial for the development and implementation of appropriate management approaches. This paper discusses the methods used to monitor the spatial and temporal dynamics of flows and pools along non-perennial rivers, and provides an overview of the potential of using satellite remote-sensing methods to monitor these river systems.

Monitoring of non-perennial rivers

The importance of non-perennial rivers and the hydrological aspects that are important and need to be monitored are highlighted in the previous section. This section reviews the methods that are used to monitor the hydrological states, and estimates the volume of pools along non-perennial rivers. Wetland and lake research is also included as pools can be monitored in the same way. Thereafter, monitoring of the spatial and temporal variations of flows in NPRs is reviewed. The section concludes with general remarks on the use of remote sensing in monitoring both flows and pools along NPRs.

Monitoring the presence of surface water along non-perennial rivers

Flow measurements at one point do not provide information about the spatial distribution of flows, pools, and dry riverbeds (hydrological phases/states), which is important for the non-perennial river system. Turner and Richter (2011) stated that the expansion and contraction in the length of wet reaches can cause variations in water quality, the composition of aquatic and riparian communities, and meta-population dynamics. Data that adequately represent the spatial variation of these characteristics. Gallart et al. (2016) added that mapping of wet and dry areas provides important information for the selection of correct sampling sites and the method to determine the ecological status. Mapping of the spatial distribution of flows provides information about the flow contributing areas. Such information will assist in explaining and predicting flows along non-perennial rivers.

One of the most used methods for capturing the spatial and temporal variability of river flows involve establishing river flow gauging stations at several locations. There are various methods used to determine the hydrological phases (e.g Sefton et al., 2019). This is rather expensive if the aim is to capture the variability along all important parts of the river. The involvement of communities residing alongside NPRs in collecting data through citizen science programmes provide an opportunity to overcome the constraints arising from reliance on data collected at river gauging stations with limited spatial coverage (e.g, Gallart et al., 2016; Walker et al., 2016). A major challenge in depending on local communities is the variable quality data collected (Walker et al., 2016; Weeser et al., 2018). These initiatives tend to be successful if members of the local community collecting and providing data perceive a benefit from improved understanding and management of their rivers including NPRs (Walker et al., 2016).

The most common method is to use sensors that collect data continuously, this includes water level, temperature, and conductivity sensors. The hydrological phases are thereafter derived through analyses of these data. However, this is laborious and costly to instal and maintain, hence there is a decline in the number of operating flow stations worldwide (Samboko et al., 2020). Zimmer et al. (2020) also argued that the zero flows can be misinterpreted due to frozen surface water, flow reversals, instrumental errors, and naturally driven upstream source losses or bypass flow. Furthermore, monitoring taking place at a small set of geographic points at frequent time intervals require extensive interpolation to characterize catchment scale conditions, which may also not effectively communicate the essential spatial details of the complex hydrological system.

Assendelft and Ilja van Meerveld (2019) used low-cost multiple sensors (electrical resistance, temperature, flow sensor, float switch sensor), the combination of this could distinguish and time hydrological states accurately (<10% error). However, like gauges these sensors can only be placed at points, limiting their spatial coverage. Furthermore, the instruments are exposed to vandalism, and may not be suitable for larger NPRs. Of recent, time-lapse imagery is also being used to monitor the presence of surface water but suffers from the same limitations as sensors and gauges, in addition, the quality of the images can be affected by the surrounding environment such as fog and sunlight (Kaplan et al., 2020). On the basis that physical and biological indicators respond to hydrology, Fritz et al. (2020) proposed that physical and biological indicators can be used to predict the hydrological phases. For instance, the reduction in the extent and variety of aquatic habitat available indicates contraction of surface connected habitats to isolated pools to drying river beds and subsurfaces.

Hydrological modelling can also be used to derive hydrological phases, but often does not include assessing the presence of pools, making no separation between dry rivers and isolated pools. For instance, Jaeger et al. (2019) used the probability of streamflow permanence model (PROSPER) to determine wet-dry parts of the river, but the model was limited by the spatial extent of gauges. Yu et al. (2018) also simulated the spatial and temporal dynamics of dry/wet segments of a river using statistical predictive models. Models are mainly used in estimating the magnitude of flows and the required training data.

The increasing availability of satellite imagery with both spatial and temporal resolution that capture features of NPRs offers an opportunity for monitoring these systems. Remote sensing data can be used to detect whether a river or reach are flowing or has pools or dry riverbed. Walker et al. (2019) could determine the presence of flow in sandy NPRs by applying NDWI to Sentinel-2 images. The study concluded that knowing the presence/absence of flow can assist the surrounding communities that rely on sandy aquifers for water as this can provide information about the recharge occurrence and therefore provide information about the water available in sand. Allen et al. (2020) also found that there was no significant difference between the flow frequency distribution from multiple gauges and the flow frequency obtained from Landsat images. Seaton et al. (2020) mapped pools along non-perennial rivers and Gallart et al. (2016) could also successfully determine river hydrological state using aerial photography.

The combination of the above-mentioned remote sensing approaches indicates that the hydrological phases along a river or reach can be determined using remote sensing with more ease as compared to other methods. There are, however, some challenges in using remote sensing data such as rivers too narrow to be detected by some sensors, and cloud covers for optical remote sensing (Fritz et al., 2020). Improvements are being made to overcome these challenges. For instance, SAR data is being used to overcome the cloud cover and images from commercial satellites have very fine resolution with sub-metre spatial resolution and 3 days revisit time, such as Worldview 1–4, GeoEye-1 and Quickbird (Niroumand-Jadidi & Vitti, 2017).

Estimation of surface water storage (volume) in pools along NPRs

Lakes, wetlands and other water bodies are important in the terrestrial water system. Information on the inundated area and water volume is essential for effective management of competing functions and uses such as flood control, drought mitigation, irrigation, etc. (Cai et al., 2016). Estimating the volume of water in irregularly shaped water bodies is a challenge. Various approaches have been developed to estimate the volume of water bodies. Generally, water volume is expressed as a product of the water-occupied area and the height of the water from the bottom of the water body. The differences in the methods are mainly in the way the area is derived.

In situ methods for estimating the volume of water require shore topography and bathymetry data which are often difficult to acquire due to the high costs for labour and equipment (Lu et al., 2013). The areal extent of a water body can be determined from remote sensing data since water strongly absorbs the near-infrared range of the spectrum, which enables distinguishing land from water through image analysis and classification. Estimates of the inundated area are used to determine the volume of water using volume–area relationships (e.g Cai et al., 2016; Lu et al., 2013). There are limited studies done on estimating the volume of water in pools along NPRs. Seaton et al. (2020) successfully mapped surface areas of selected pools along NPRs using remote sensing, but did not estimate the volume of water in these pools. Hence, some of the studies used here are derived from wetland and lake research as pools volume can be estimated in the same way.

One of the approaches to estimate volume is to use a combination of satellite-derived data and field-observed measurements. For instance, Lu et al. (2013) used in-situ water-level measurements and satellite-derived surface areas to estimate the volume of a lake over a 40 year period. The underwater geometry was constructed using a triangulated irregular network (TIN) volume model. The NDVI and MNDWI were applied to Landsat MSS/TM/ETM+ and HJ-1A/B to derive the inundated surface areas. The estimated volume was consistent with the one derived from the fitted equation of the lake that is 366 km^2 in size.

The Moderate Resolution Imaging Spectroradiometer (MODIS) imagery was used to determine the volume of water stored in 128 lakes and 108 reservoirs between 2000 and 2014 in the Yangtze River Basin, China (Cai et al., 2016). The MODIS derived surface area was validated using Landsat 8 Operational Land Imager (30 m). Storage capacity is highly correlated with surface area at a regional and global scale, thus storage was calculated as:

$$S = a * A^b \tag{1}$$

where S is the storage, A is the area and, a and b are constants. Cai et al. (2016) highlighted a few sources of error including the issue of mixed pixels which can either be classified as water or non-water, the presence of clouds reducing the number of observations, etc. However, Smith and Pavelsky (2008) demonstrated that assuming a linear relationship between the surface area and the water level is reasonable for many water bodies, and also concluded that the use of both water level and surface area can yield better results compared to estimates from surface area only.

Radio Detection and Ranging (RADAR) provides information often unavailable from the optical sensors, limitation of cloud and vegetation and has also been successfully used for flood extent mapping. RADAR can be a solution for weather-vegetation induced errors, as it can penetrate clouds and is able to operate day and night (Huang et al., 2018; Ritchie & Das, 2015; Smith, 1997). Synthetic Aperture Radar (SAR) can detect water under vegetation as long as it is not dense. Huang et al. (2018) have shown the potential of RADAR using Sentinel-1 SAR data in detecting water surfaces. Besides having these advantages, SAR data have not been employed as much as optical sensors, due to the limited availability of the data as there are fewer SAR satellites and often have longer revisit time.

Another approach is to derive a rating curve between satellite altimetry data and field observed storage (e.g Zhang et al., 2006). The use of altimetry has also been limited to large water bodies due to the narrow swaths, low spatial resolution, small footprint size and complex terrain around some of the small water bodies (Alsdorf et al., 2007; Gao et al., 2012; Magome et al., 2003). Alsdorf et al. (2007) and Politi et al. (2016) further argued that altimetry is not very useful as too many inland water bodies are missing as it only captures specific water bodies that fall into the satellite's track. In addition, the temporal resolution of altimetry is generally poor (10 days to 35 days) (Hirpa et al., 2013). However, Smith and Pavelsky (2008) suggested that volume can be estimated by combining satellite-derived surface area, altimetry and in situ measured water levels (e.g Gao et al., 2012; Getirana et al., 2018). Gao et al. (2012) highlighted that errors in this approach can be committed from altimetry data, surface area, the relationship and the reported configuration.

Some approaches are fully remote sensing based with no required field measured inputs. Avisse et al. (2017) used Landsat imagery and DEM to obtain information about water storage. Whereby Landsat imagery is used to estimate surface area and DEM is used to derive underwater topography of the water body. The obtained storage was compared to the observed storage from a close-by lake, and there was a good agreement ($R = 0.84$). However, this method has DEM-induced errors such as determining the elevation/geometry in reservoirs that were significantly covered with water when the data used to derive the DEM was captured.

The combination of remote sensing derived from inundated surface area and water level from satellite altimetry can be used to estimate water body storage as both surface area and water depth which are required for volume estimation are known. For instance, Busker et al. (2019) used water surface area obtained from the JSC global surface water dataset which is derived from L1T Landsat 5, 7 and 8. The satellite-derived altimetry was obtained from the Database for Hydrological Time Series over Inland Waters (DAHITI) which combines altimeter data from different satellites. The water levels were strongly related ($R < 0.8$) to the surface area. However, there was a weak relationship for the smaller lakes. Muala et al. (2014) and Getirana et al. (2018) used the same approach and also found that there was a strong relationship ($R^2 = 0.94$) between estimated and observed volume. The use of both altimetry and surface area is accepted to be advanced by the launch of the SWOT mission in 2021 as both surface area and water level are obtained from one satellite.

A major problem in monitoring water bodies using remote sensing is that small water bodies such as less than 1000 m^2 are not identifiable in most images. However, Avisse et al. (2017) could produce accurate results for reservoirs smaller than 0.5 km^2 using data from Sentinel-2 and Landsat 8. Sharma et al. (1989) could detect water bodies that are smaller than 0.9 ha using Landsat TM. Avisse et al. (2017) suggested combining Sentinel-2 and Landsat 8 data could yield better results for small reservoirs, while also reducing the revisit time and thus enabling near real-time monitoring.

However, like any other methods, the remote-sensing derived water body storage methods have limitations and disadvantages. The use of inaccurate satellite-derived data can be carried into the estimated storage; the inaccuracies can be sensor or algorithm related. The nearly constant surface area can result in weak relationships used to estimate the volume or rating curves (e.g Area-Volume, Height-Volume, Height–Area relationships) (Alsdorf et al., 2007; Magome et al., 2003). The water storage will be biased if the characteristics at capacity are not accurate. The storage capacity might change, due to sedimentation over time. However, it is rare for sedimentation to be the major cause of errors.

The launch of the Surface Water and Ocean Topography (SWOT) satellite, which will have both altimetry and optical sensors for the surface area measurement will improve the accuracy of remote sensing derived volume, and further advance the application of remote sensing in water resource management (Getirana & Peters-Lidard, 2013). Fusing data from Synthetic Aperture Radar, and the optical remote sensing data can be an advancement in the application of remote sensing as it can improve the spatial, temporal and spectral information. However, there are few SAR-based products at sub-hectare (100 m) level. Smith (1997) and Bioresita et al. (2018) argued that interpretation of RADAR images is not as straightforward as optical images; in addition, the wind-induced waves or emergent vegetation can roughen the surface of open water bodies, making it difficult to distinguish water from other land cover types. Therefore, the ideal situation will be smooth and open water bodies. There are also developments in using satellite gravimetry (e.g GRACE) to estimate water storage changes (e.g Hwang et al., 2011) will also aid in improving the accuracy of remote sensing.

Monitoring spatial and temporal variation of flow rate in NPRs

The conventional methods of measuring flows that are used for perennial rivers are also used in non-perennial rivers whereby discharge is a product of the average velocity and the cross-sectional area. Using continuous water level measurements from instruments such as pressure transducers, continuous discharges can be obtained from predetermined stage–discharge relationships (rating curves). This relationship is verified or calibrated periodically to determine whether the relationship has changed which is often caused by channel geometry and/or channel roughness. To avoid frequent changes in the geometry and channel roughness, weir or flumes are constructed to stabilize the cross-section. However, this still requires calibration occasionally. Dobriyal et al. (2016) state that weirs are suitable for long-term monitoring of small hill streams. Other once-off or experimental methods include particle image velocity, float and dilution methods (Dobriyal et al., 2016). However, in developing countries, the financial cost associated with the methods (installation, maintenance) becomes a constraint; consequently, a low-cost method is often used such as manual reading of water levels from a staff gauge and thereafter use rating curve to derive discharge. Errors associated with conventional methods include gauge reading, stage sensor, water surface to sensor, hydraulic induced and recorders errors (World Meteorological Organization, 2010). The non-contact measurement methods, in particular, remote sensing poses the potential for providing the required information.

Remote sensing is widely applied in hydrology, however, it is still considered new in the estimation of river discharge. The general principle is to use the information that can be derived from satellite imagery (width and depth) as a proxy to discharge. Some methods require field measured variables; some methods do not, and thus solely based on remote sensing. The general trend is to move towards estimates that are solely based on remote sensing without any ground-measured variables. However, the biggest challenge is that velocity cannot be directly obtained through satellite remote sensing methods.

River discharge can be estimated using the relationship between ground-measured discharge and satellite-derived inundation area. This assumes that there is a relationship between discharge and inundated area. This relationship is described using rating curves. These rating curves can thereafter be used to solely estimate discharges from remote sensing data. As in estimating storage/volume, this is also affected by the determination of the inundated area. Smith (1997) states that it is difficult to extrapolate the relationship to other rivers; however, it can be used in ungauged catchments. However, Smith and Pavelsky (2008) demonstrated that satellite-derived width-discharge rating curves and hydraulic geometry (b exponents) converge around the stable value ($b = 0.48$) which indicates that the method is transferable to different locations. This approach is only successful when field-observed data are available for calibration as they fail to indicate the dynamic topography of the river (Alsdorf et al., 2007; Pan et al., 2016). Some studies show that topographic information such as slope can be derived from a Digital Elevation Model (DEM) (Pan et al., 2016). Other studies argue that DEM is limited as it can be too coarse, hence problematic for small water bodies. This can therefore be addressed by either using high-resolution DEM or in situ elevation measurements.

Orbital sensors, such as passive microwave sensors do not suffer from clouds and vegetation interference and allow the separation between non-water and water pixels, hence they can be used in the same way as optical remote sensing data. Brakenridge et al. (2007) used passive microwave data to estimate discharges in the United States. Advanced Microwave Scanning Radiometer (AMSR-E) at 36.5 GHz was resampled to produce daily estimates. The study concluded that AMSR-E can provide useful international measurements of daily river discharge even if only mean monthly discharge data are available for calibration. Ahmad and Kim (2019) used Sentinel-1 SAR data and discharge were estimated accurately, but they could not estimate discharge in small rivers with a channel width of less than 20 m. Hirpa et al. (2013) also concluded that this method can be useful in data-scarce regions. The errors may be due to misclassification and rating curve-related issues.

Another common approach is to use satellite altimetry data to estimate discharge (e.g Zakharova et al., 2006; Bogning et al., 2018). Similar to the above approach, discharges are estimated from rating curves developed from satellite altimetry and field measured discharge (Equation 2).

$$Q = a.(H - z)^b \tag{2}$$

Where Q is the discharge, a and b are coefficients, H is the height of water and z is the zero flow height.

The errors are relatively small when applied to large water bodies such as the Amazon River, Ob River, Chari River, Lake Chad, Ogooue River (Getirana & Peters-Lidard, 2013). There have been few studies where this approach was applied to small water bodies and non-perennial rivers. As stated, the measurements (satellite altimetry) miss many small water bodies. Therefore, it is not ideal to use it for non-perennial rivers as they are often small (<100 m in width). Several studies have attempted to estimate discharges using the water balance approach whereby water body storage, evaporation and precipitation are estimated using remotely-sensed data and water inflows from models. The results vary, for example, Muala et al. (2014) obtained acceptable results in Roseires reservoirs, Sudan, although they obtained high error for lakes in Egypt. Swenson and Wahr (2009) also used the same approach for Lake Victoria and concluded that remote sensing data are unable to estimate the outflow from the lake with acceptable accuracy. The error may be induced by the number of inputs required for this approach (e.g rainfall, evaporation). These inputs have their errors which are carried into the discharge estimates.

More recently, there have been attempts to measure discharges with no field measured variables. This is achieved by combining remotely sensed stage and width of the flow. The combination of orbital/optical-sensed (e.g NIR) and altimetry data is used to improve the temporal and/or spatial information or even accuracy. Sichangi et al. (2016) used MODIS and altimetry data to optimize unknown parameters of the modified Manning's equation. Huang et al. (2018) and Bjerklie et al. (2018) also merged stage-discharge and width-discharge equations, and the results demonstrated that the use of both altimetry and infrared data improves discharge estimation. However, due to the spatial properties of the altimetry data, both studies were done in large perennial rivers (channel width >100 m). Discharge can also be solely derived from remotely sensed data by including the channel geometry such as width and depth. This is done using a characteristic scaling law referred to as At-Many station Hydraulic Geometry (AMHG), which eliminates half of the parameters, required by traditional hydraulic geometry, and can estimate from only repeated surface widths (Gleason & Smith, 2014; Gleason & Wang, 2015). However, the uncertainty in this method is high and still requires prior knowledge about the river. The method has mostly been tested in large perennial rivers and also performed poorly in a river with temporary flows due to the high variability of discharge (Gleason & Smith, 2014; Sichangi et al., 2016).

Every technique and sensor have its limitations and advantages. For the area-discharge methods, the main errors may be high when small changes of a few metres in river width are not easily detected by remote sensing, and they produce significant changes in discharge. Due to the high availability of optical remote sensing and advancement in ways to obtain surface area of water body, which makes it user-friendly, the area/width to discharge method has been commonly used and has shown to be more accurate compared to other methods. The stage-discharge method has also shown good accuracy but is not commonly used because satellite altimetry has poor temporal and spatial resolutions, hence it has been mostly applied to large rivers. However, the combination of data from different sensors can yield better estimates and further improves temporal resolutions estimates.

General remarks on the use of remote sensing in monitoring NPRs

The use of remote sensing data for estimating hydrological information offers an opportunity to obtain information in areas with inadequate coverage by in-situ measurements (Bjerklie et al., 2005). It is possible to use remote sensing to map wet-dry parts of the river system. This implies that remote sensing may provide information about the spatial and temporal distributions of the pools. Factors and processes can be explained using the physiographic characteristics of the catchment. Remote sensing also has the potential to estimate river flows. This implies that the amount of contribution by each stream into the river can be estimated, thereafter identifying the major source areas. Since NPRs have become more important in water resource management issues owing to the conversion of perennial rivers to NPRs, there is a need to monitor these temporary rivers. The identification of source areas may assist in determining the streams that need to be monitored for hydro-modification impacts (Beck, 2017). Furthermore, this will inform monitoring programmes in identifying the best methods and tools for the task. Turner and Richter (2011) state that remote sensing may even be capable of providing information that cannot be directly feasible when using models and flow data such as the mapping of the hydrological state/phase (wet-dry mapping) of the river system. There are platforms that provide mapped surface water globally (e.g https://global-surface-water.appspot.com/#features; https://land.copernicus.eu/global/products/wb), and this could provide ready-made useful information about NPRs for any end-user.

Remote sensing is continuously improving in terms of spatial and temporal resolution, and in the ways the obtained information is processed and analysed (algorithms) to overcome some of the weaknesses. However, the use of remote sensing has been limited to large (width of more than 400 m) wetlands and perennial rivers. There have been few studies focusing on pools and flow spatial and temporal dynamics (occurrence and changes in storage) in NPRs. Whereas, the potential of using remote sensing to obtain this information has not been fully investigated in NPRs. Given such potential, this will contribute towards understanding the spatial and temporal dynamics of NPRs and in supporting the management of these rivers especially in data-scarce regions like South Africa and the rest of Africa. There is a need to test the ability of remote sensing in obtaining this useful information from NPRs.

Strengths and limitations of methods used for monitoring non-perennial rivers

The applicability of common methods used to monitor NPRs are summarized in (Table 1). The following were considered: the ability to determine the hydrological state of the river; the ability to estimate flow magnitudes and pool sizes; considering the spatial and temporal dynamics of these and the accuracy at which this can be monitored. Experimental/once-off methods such as float and dilution methods were excluded as

Table 1. Summary of the strengths and weaknesses of commonly used methods.

Method	Strength	Limitation/weaknesses	Examples
In-situ river gauging	-Availability of continuous data capturing temporal variability of flows -Capable of producing data with accuracy	-Limited spatial coverage -Exposed to vandalism -Presence/size of pools often omitted	Delso et al. (2017); Tramblay et al. (2021); Zimmer et al. (2020)
Hydrological Modelling	- Improves understanding of main hydrological processes -Can be used for predictive purposes	-Considerable uncertainty of parameter values -Input data required to adequately represent spatial variability mostly unavailable	De Girolamo, Lo Porto et al. (2015); Daliakopoulos and Tsanis (2016): Jaeger et al. (2019); Yu et al., (2019)
Unmanned Aerial Vehicles	-Appropriate spatial coverage -High-resolution imagery -Hydrological phases can be determined -Flow and pools can be estimated	-Flying conditions needs to be met -Costly to purchase and operate -Laborious (operator needs to be close to the site)	Allen et al. (2020); Samboko et al. (2020)
Optical remote sensing	-Appropriate spatial coverage -Hydrological phases can be determined -Flow and pools volume can be estimated -Images available at no to low cost	-Observation limited by cloud cover, night-time condition -Flow and pool volume are inferred from inundation of water	Walker et al. (2019); Kebede et al. (2020); Seaton et al. (2020);
Orbital-microwave remote sensing	-Appropriate spatial coverage -Hydrological phases can be determined -Flow and pools can be estimated -Images available at no to low cost -All-weather/all-time capabilities	-Flow and pool volume are inferred from inundation of water -Images can be difficult to interpret as compared to optical remote sensing (Separation between water and non-water features)	Bioresita et al. (2018); Zhang et al. (2020); Ahmad and Kim (2019), Mengen et al. (2020)

they are meant to measure flow and cannot be used to determine the occurrence of flow or volume of pools. Overall, *in-situ* monitoring through gauging stations provides acceptable accuracy but is constrained by financial, institutional, political, and spatial factors. Remote sensing has the potential to fill this gap and provide more insights. Hydrological modelling has also been shown to have advancement in terms of simulating flow (e.g Jaeger et al., 2019) and surface water extent (Yu et al., 2019) but the drawback is that it requires input data which may not be available for many non-perennial rivers (Table 1). However, it is worth noting that combining these methods can improve the determination of spatial and temporal variations of flows and the availability of water in pools along NPRs.

Possible future research directions and recommendation

Much of what is known about the NPRs is based on studies done in Australia, the USA, Spain, Portugal, and France (Datry et al., 2017). Inadequate work has been done in Africa which is the continent where most NPRs occur and will further be the most impacted by the decrease in rainfall due to climate change (United Nations Environment Programme, 2020). This uneven distribution of knowledge can result in bias in understanding the NPRs systems. Much of the understanding of the pools and flow dynamics is also based on ecological perspectives and not often from hydrology and from a multidisciplinary perspective. Currently, there is a need to develop ways of monitoring these systems. Based on the challenges of NPRs, which some are highlighted in this review, the future research direction can be derived as follows: future research should seek to bring an understanding of these river systems which means innovative ways to monitor the river system with a great understanding of the information needed to effectively manage these rivers, for instance, the use of remote sensing techniques as highlighted by this study. Innovative methods need to be evaluated, and their strengths and weaknesses outlined. Beyond monitoring the changes in these rivers, there is also a need to establish the factors that drive the variation of these systems. This includes factors that affect the spatial and temporal dynamics of both flows and pools such as precipitation, evaporation, soil properties and geology.

Conclusion

This study reviews existing literature on the monitoring of flows and pools along non-perennial rivers. NPRs are becoming increasingly significant at both local and global scales as there are more NPRs than perennial rivers in the world. The extent and magnitude of NPRs are likely to increase at a high rate due to climate change and socio-economic uses. There is, therefore, a need to understand their spatial and temporal dynamics. This includes the comprehension of the effects of climatic conditions, topography, land use/cover type, underlying geology/bed material on the distribution of flows and pools which may not be well understood. The significance of each of these factors may differ from one location to another as NPRs are highly variable. The inadequate understanding of NPRs is caused by a lack of monitoring of these systems. Conventional monitoring methods are laborious, costly, and may not be adequate to derive some of the information that is important for NPRs. Therefore, a need for the development of tailor-made methods for NPRs. Satellite remote sensing has the potential to extract some information that may not be feasible to obtain with the current methods; hence, the need to fully explore the potential of remote sensing. Remote sensing still has its shortcomings such as misclassification and spatial resolution limitations, but these are being improved through the launch of new and advanced satellites with new and advanced technology. The way in which the data are analysed is also advancing.

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