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WORKING PAPER

POTENTIAL REMOTE SENSING TECHNOLOGIES TO ENHANCE THE MONITORING AND REPORTING OF WATER FLOWS

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1. Introduction and context

The interactions between humans and the hydrological cycle and how this interaction has transformed the fresh water systems have been explored by Vorosmarty et al (2013) who identified five major human pressures on fresh water resources such as increasing water withdrawals, building of large dams, increasing pollution, expansion of invasives and declining streamflow which is projected to decline well into the future, as illustrated in Figure 1.

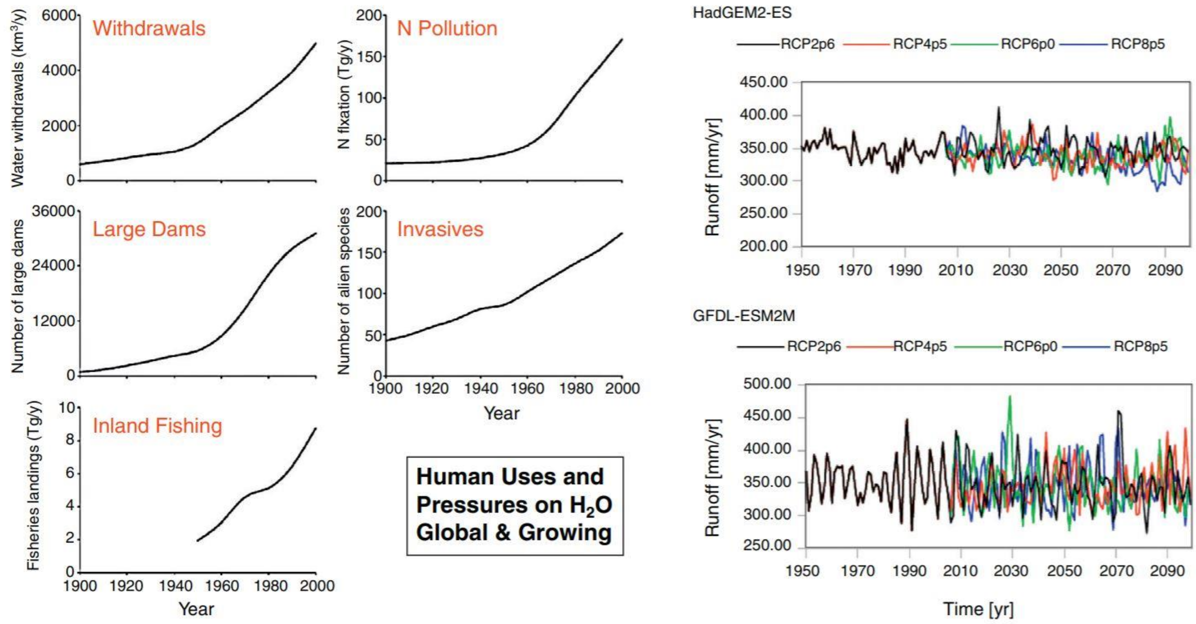

Figure 1: Five major interactions of humans with fresh water systems (source: Vorosmarty et al, 2013)

These interactions or human pressures on fresh water lead to alterations in the stocks and flows of water that change its availability in space and/or time. The key factors that affect water availability include climatic variability and change, population growth that reduces per capita water availability, contamination that reduces usable water supplies, physical overuse of a stock such as groundwater overdraft and technological factors (Vorosmarty *et al*, 2013). The impacts of these multiple driving alterations in water availability need to be continuously assessed (Montanari et al, 2013) through measurements of hydrological variables to continually assess the quantities and usability of water as a foundation for water security (Lawford *et al*, 2013). The adoption of the Sustainable Development Goals (SDGs) specifically SDG 6 has created an increased demand for extensive observations of good quality data and more dense monitoring networks especially in developing countries (Tauro *et al*, 2018). Despite being a developing country, South Africa has a long history of hydrological monitoring which dates back to the late 19^{th} century and early 20^{th} century. The aim of the hydrological monitoring is to measure precisely where and in what quantities water is stored, and how the water moves between those stores. It is from these observations that the spatial distribution of rainfall, runoff, soil moisture, evapotranspiration, etc are determined. The observation networks in South Africa also provided further evidence of a non-linear relationship between rainfall and runoff as illustrated in Figure 2 (Schulze, 2011). Schulze (2011) reasoned that the non-linearity of the runoff response to rainfall can be attributed to antecedent conditions in a catchment, with a larger proportion of rainfall being converted to runoff when a catchment is wetter or because the soil water content just prior to a rainfall event may have been high as a result of previous rainfall. With a mean annual precipitation (MAP) of approximately 500 mm, the translation of rainfall to runoff in South Africa is estimated to be approximately 10% (see Figure 2) which is low by any standards and hence the country has a natural, physical water scarcity issue.

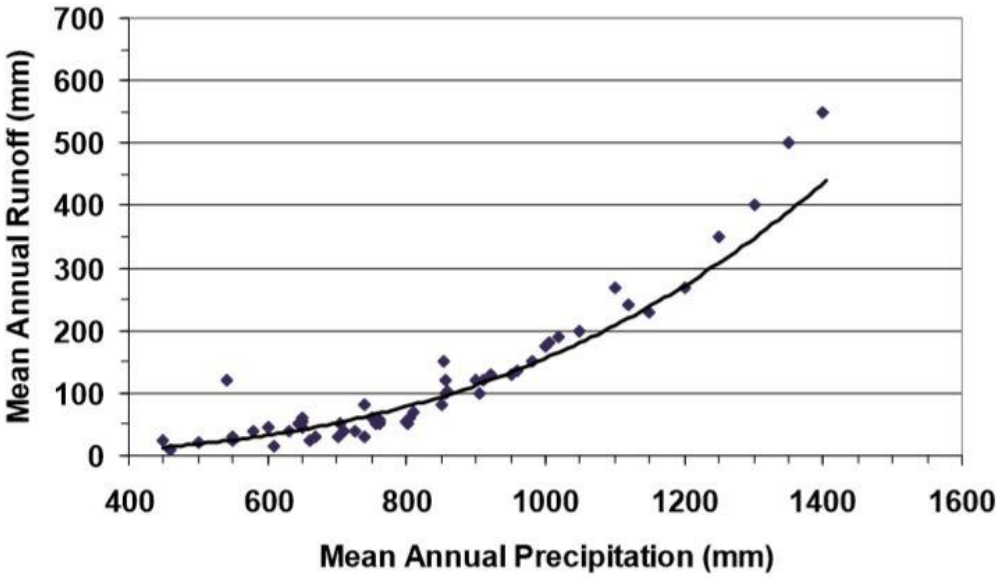

Figure 2: The non-linear rainfall- runoff relationship for selected streamflow gauging points in the summer rainfall region of South Africa (after van Biljon, Cornelius and Moore, 1987 quoted in Schulze, 2011).

There are two primary sources of hydrological data that are required in the assessment, evaluation and management of water resources, and these include rainfall and streamflow data (Dent, 1994). The existing standard methods of rainfall and streamflow measurements consists mainly of rain gauges and weirs and flumes, respectively. However, the *in situ* observation networks for these fluxes tend to be limited due to a lack of technical and institutional capacity and a lack of investment in maintaining and sustaining these observation networks. This is especially true for developing countries 'where not only data are scarce but where pressure on water resources is often already very high and increasing' (Zogheib et al, 2018). Furthermore, technologies to measure these fluxes have evolved over the last few decades but the uptake for these technologies has been slow in developing countries.

Therefore, the objective of this paper is to highlight the challenges with the current hydrological monitoring network and to explore the potential use of innovative technologies to supplement the steadily declining *in situ* observations in South Africa.

2. Challenges with hydrological monitoring in South Africa

The continuous assessment of water resources is essential for water resource management, and two of the key hydrological fluxes that must be measured for this purpose are rainfall and streamflow. Worldwide, there has been a decline in hydrological networks (Muller *et al*., 2015; Stewart *et al*., 2015). For example, Lorenz and Kunstmann (2012) observed that operational rain gauge networks throughout the world are decreasing, and that the extent of research rainfall gauge networks worldwide are limited (Sunilkumar *et al.*, 2016). The declining observation networks is acute in developing countries, and Hughes (2008) attributes the many challenges in the collection and maintenance of rainfall and streamflow data to the socio-economic and political history of southern Africa where data collection was not regarded as a priority. However, adequate and operational hydrological networks are required to provide information that informs decisions in water resource management and to provide accurate and timely warning for droughts and floods (Sene and Farquharson, 1998). For example, a recent study by the WRC (Abiodun *et al*, 2018) which characterised drought trends in southern Africa from 1950 to the present showed that there has been an increase in the intensity, area coverage and frequency of droughts and that the projected all-dry drought patterns (dry conditions) would become more frequent while all-wet drought patterns (wet conditions) would become less frequent over the entire southern Africa as illustrated in Figure 3. Climate change projections by Christensen *et al*. (2007) and confirmed by Engelbrecht *et al*. (2009) suggest that the mean annual rainfall will decrease and evapotranspiration will increase across much of subtropical southern Africa. This has huge implications for water resources and thus more detailed hydrological monitoring will be required to inform decision-making and informed responses to the reduction in water availability.

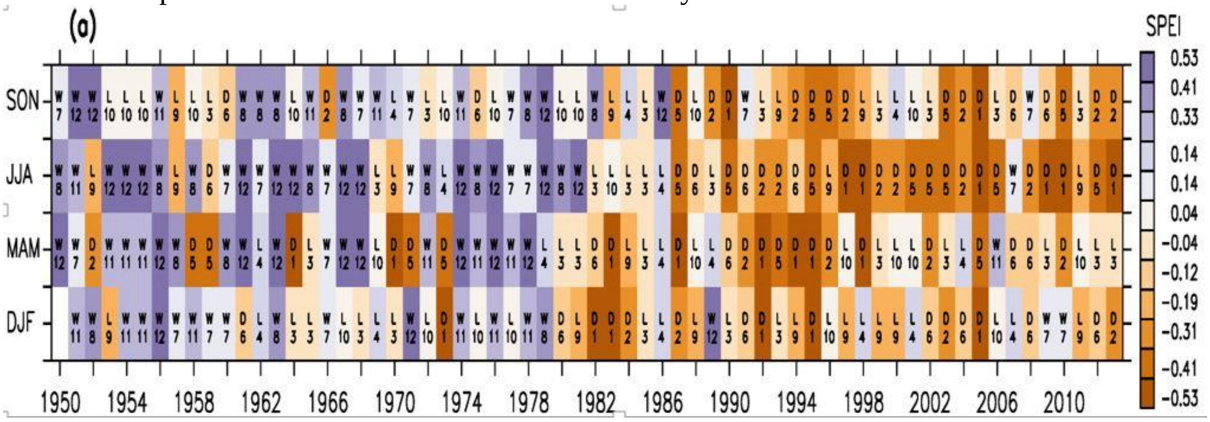

Figure 3: Drought patterns in southern Africa from 1950 to present (Abiodun et al, 2018).

Furthermore, the decline in observation networks has been accompanied by the decline in the quality of the data measured from the limited hydrological networks. The current challenges with rainfall and streamflow collection networks in South Africa are briefly highlighted below.

2.1 Rainfall network

Rainfall is the key input parameter in hydrological modelling for water resources assessment and management. Rain gauge density and data length are two important considerations when analysing rainfall data for water resource management. Mishra (2013) found that the level of accuracy in rainfall measurement is highly dependent on the density of the rain gauge stations. Rainfall events vary spatially and temporally within a catchment and a dense rain gauge network may be able to better capture rainfall characteristics (Krajewski et al., 2003; St-Hilaire et al 2013). A denser rainfall network improves the simulated total streamflow (St-Hilaire *et al.*, 2003), improves areal estimates of rainfall and reduces underestimation of cumulative rainfall (Bárdossy and Das, 2008; St-Hilaire *et al*., 2003). Xu *et al.* (2013) demonstrate that a dense rain gauge network improves the estimation of the Mean Annual Precipitation (MAP), and that runoff estimates are improved with rain gauges that are strategically located rather than rain gauge density (St-Hitlaire *et al.*, 2003).

The responsibility for the collection of rainfall data resides primarily with the South African Weather Services (SAWS), though some rainfall data is also collected by the Agricultural Research Council (ARC) for agricultural applications and the Department of Water and Sanitation (DWS) collects limited rainfall data next to major dams for water balances. According to Pegram *et al*. (2016) the current rain gauge network in South Africa consists of approximately 1200 gauges compared to approximately 3800 rain gauges in the 1970s, and this rain gauge network is steadily declining every year. Pitman (2011) observed that the number of open rainfall stations that were useful for water resource assessments in 2004 is far below the number of rainfall stations in the 1920s as illustrated in Figure 3. This number of operational rainfall stations is steadily declining each year due to budget cuts and weakening technical and institutional capacity in the data collection agencies. The decline in observation networks is associated with periods of social and political upheaval according to Rodda *et al.* (2016).

Lately data collection agencies have resorted to imposing a fee to access the rainfall data with strict conditions on the sharing and distribution. By imposing fees and strict conditions on access and sharing of rainfall data the data collection agencies are crippling the efforts to prudently manage water resources in a country whose variable water resources are becoming scarcer due to population growth and increasing drought intensities and frequencies. However, there are earth observation (EO) technologies on rainfall estimation that the country could take advantage of to supplement the shrinking *in situ* rainfall observation networks. These technologies are discussed later in section 3.

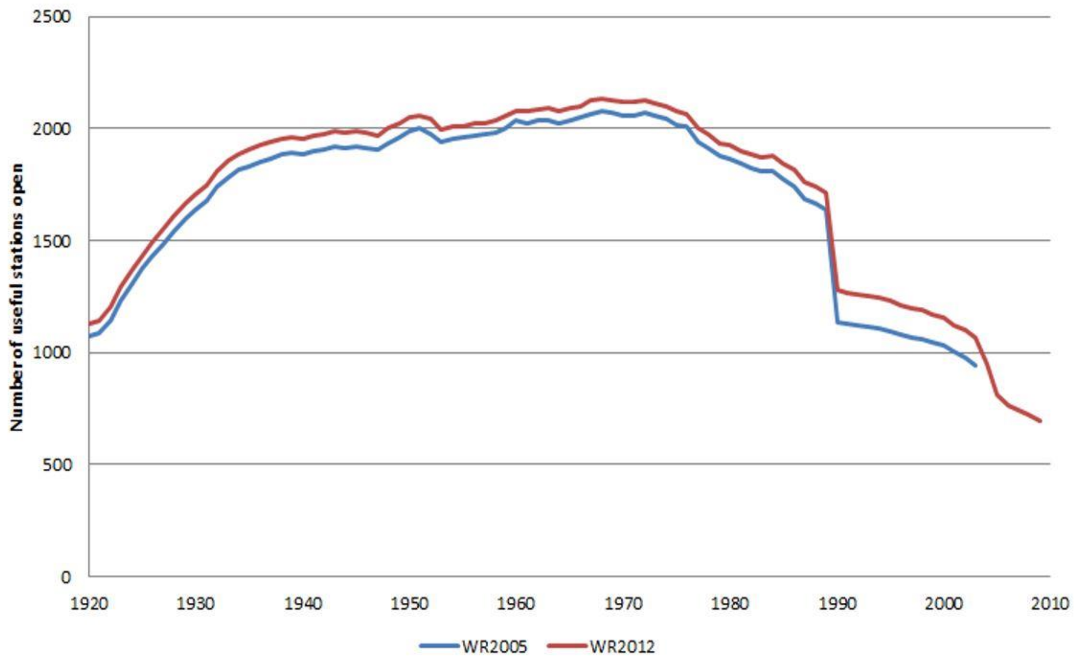

Figure 4: Number of useful rainfall stations for water resource assessment (Pitman, 2011; WR2012)

2.2 Streamflow/hydrometric network

The first long-term stage measurement in South Africa started in 1865 in the Port Elizabeth Town council (Wessels and Rooseboom, 2009). This was followed by daily stage measurements at the Vaal River in Riverton in 1885 and another gauging station was established in 1898 on the Breede River near Robertson (Wessels and Rooseboom, 2009). Therefore, South Africa has a long history of streamflow measurements using conventional flow measurements methods such as weirs, flumes, *etc*. Figure 4 shows the growth and decline in streamflow measurements in South Africa from 1920 to 2010 (WR2012). The rapid growth in flow measurements started between the 1950s and peaked to approximately more than 1200 stations around the 1990s. However, there was a rapid decline in the number of operational gauges shortly after 1990 due to the closure of a number of stations that were found to be non-compliant with gauging standards (Wessels and Rooseboom, 2009). However, the steady decline in the number of open stations continued long after 1990 to reach approximately 450 stations that were regarded as useful for water resource assessments (Pitman, 2011). Although Wessels and Rooseboom (2009) attributed this decline in flow measurements to financial constraints, however, the dwindling technical and institutional capacity within the Department of Water and Sanitation (DWS) plays a major role in the country's (in)ability to maintain and sustain the hydrometric networks.

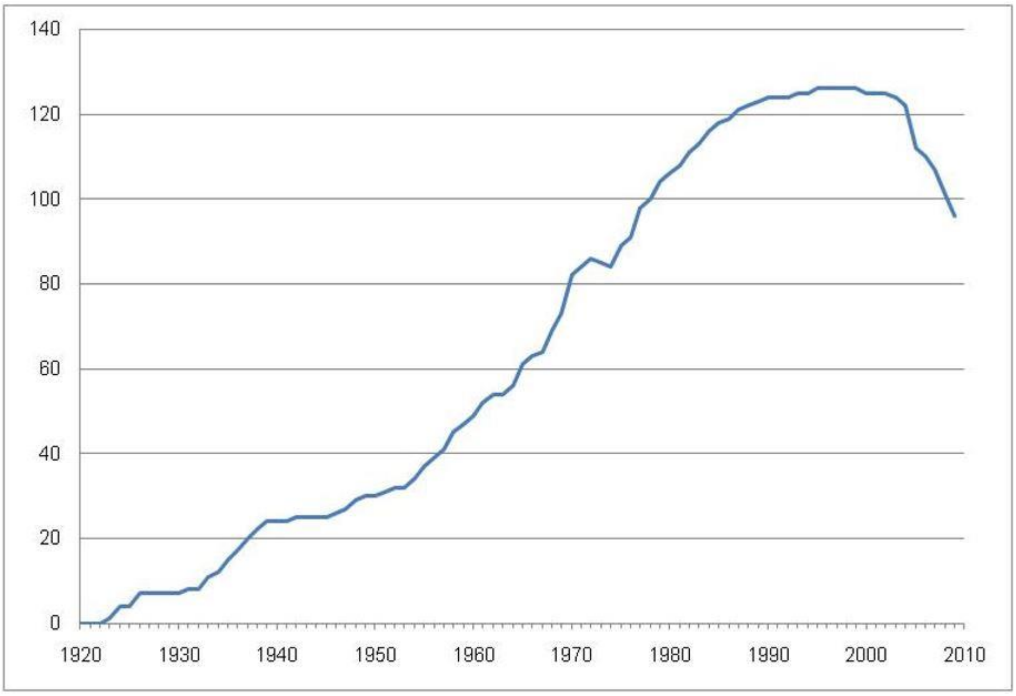

Figure 5: The growth and decline of flow measurements since the 1920s (after WR2012). The y-axis is the number of flow measuring stations x10.

The Department of Water and Sanitation (DWS) has the primary responsibility for the monitoring of streamflow in South Africa (Pitman, 2011). The flow measurements in South African rivers are complex due to high variability in rainfall which leads to high variability in water discharges coupled with heavy sediment and debris loads (Wessels and Rooseboom, 2009). Therefore, the loads in flows have negative impacts on the quality and reliability of gauged streamflow data and this necessitates the calibration of the flow gauging stations at least twice a year. Furthermore, the quality of the flow data may be affected by the discontinuation of the flow gauging, stage damage, and the exceedance of a discharge table which results in the failure to record high flows (van Bladeren *et al*., 2007).

There are emerging innovative technologies for streamflow estimation that may be useful to supplement the declining flow measurement networks, and these will be discussed in the next section.

3. Opportunities for deploying innovative technologies for hydrological monitoring

Over the last twenty years the accuracy and precision in the assessment of water resources in South Africa has become uncertain and less reliable due to the declining observation networks and the deteriorating data quality. Large parts of the country have become ‘ungauged’ and thus their water stores and flows cannot be assessed with certainty. The high cost of traditional hydrological monitoring is always cited as the main reason that hamstrings the sustenance and expansion of *in situ* or ground-based observation networks. However, the development of remote sensing technologies such as satellite imagery and smart sensors provide opportunities to generate substantially more data at less cost, and at high spatial and temporal resolutions. These remote sensing technologies are increasingly cheaper and efficient (i.e. doing more for less) in that frequent site visits are not necessary. However, it should be emphasised that the remotely sensed technologies have been developed and deployed as a supplementary source of data collection; they still need dense gauge networks for ground referencing and calibration (Pegram *et al*., 2016).
The section below provides a brief overview of the existing remote sensing infrastructure that can aid the country in monitoring its water stores and flows.

3.1 Remote sensing technology for rainfall

3.1.1 Radar network

Weather radars provide quantitative estimates of rainfall/precipitation with high spatial and temporal resolution. They are deployed largely to observe extreme weather phenomena. With more than half of the country being semi-arid with a mean annual precipitation (MAP) of less than 500 mm rainfall, South Africa tends to receive large-scale flood events which are often triggered by prolonged periods of drought. A large fraction of this rainfall results from convective storms which lead to the formation of rain fields with high variability in space and time (Terblanche *et al*., 2001). The rain fields are not well captured by standard rain gauge networks and therefore the deployment of radar network was intended to address this problem. Terblanche *et al*, (2001) investigated the potential use of radar in hydrological application in South Africa, and their promising findings led to the development of a Radar Data Acquisition System which was not fully utilised due to limited resources. Developed countries such as the UK, USA and other European countries have successfully integrated weather radar data with *in situ* rain gauges for hydrological applications such as drought and flood warning and water resource management systems.

The erstwhile Department of Water and Environmental Affairs invested approximately R240 million in a new, state-of-the-art national weather radar network (Figure 6) which includes nine (9) single-polarised S-band radars, one (1) dual-polarised S-band radar, two (2) mobile X-band research radars and five (5) C-band radars. South Africa should utilise this national radar network to vigorously pursue the integration of the rain gauge networks and weather radar data for hydrological applications.
There is a wealth of local knowledge and radar data-rain gauge data integration systems that have been developed through WRC-funded research over the last twenty years (Mittermaier and Terblanche, 2000; Pegram and Clothier, 2001; Terblanche, Pegram and Mittermaier, 2001; Clothier and Pegram, 2002; Pegram and Sinclair, 2002; Kroese, 2004; Kroese *et al*., 2006; Sinclair and Pegram, 2004 and 2009; Wesson and Pegram, 2006; Vischel *et al*., 2008, etc) but these systems remain to be integrated operationally in the national monitoring infrastructure.
It should be noted that raw radar data alone has many errors especially when estimating floods, and therefore it must be calibrated and combined with in situ rain gauge data (Sun *et al*., 2000). Furthermore, the maximum range of radars is approximately 300 km and thus

they have limited coverage, as shown in Figure 6. To address the errors, Bárdossy and Pegram (2017) developed a methodology to combine daily precipitation observations and radar measurements to estimate sub-daily extremes at point locations.

Latterly, a WRC-funded project (Burger, *et al*, 2019) pointed out that only 54.3% of the radar data collected over the last 12 months is available but most of it is unusable as most of the radars are not calibrated. The calibration of the radar is hamstrung by the lack of technical capacity and resources within South African Weather Services (SAWS) which struggles to keep the radars operational. This issue needs to be resolved if the country is to benefit from its multimillion rand investment in national radar network.

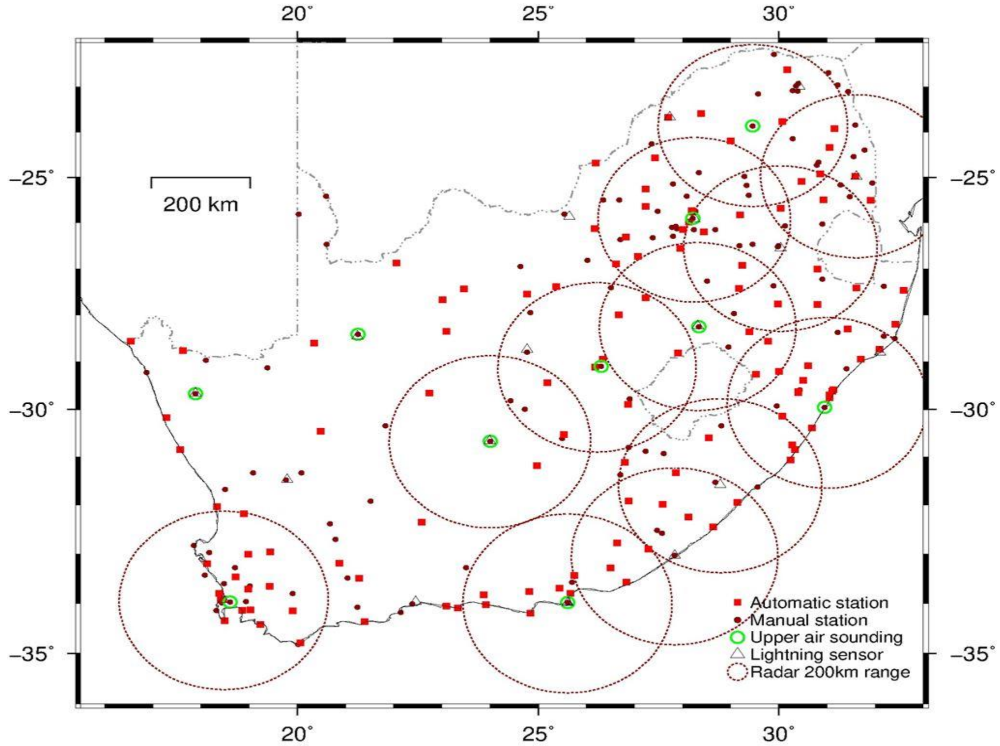

Figure 6: Current weather radar network in South Africa (Burger, et al 2019)

3.1.2 *Rainfall from satellites*

Rainfall is the main driver of the water/hydrological cycle and it is variable in space and time. Therefore, an accurate record of its coverage is necessary to improve weather and climate forecasting and predictions. With the decline of ground-based point measurements such as rain gauge networks, rainfall can be estimated remotely, either from ground-based weather radars (as described in Section 3.1.1) or from satellites. There is a number of weather satellites orbiting the space from which rainfall can be estimated, and these include, among others, MeteoSat, Tropical Rainfall Measuring Mission (TRMM) which was decommissioned in 2015, the Global Precipitation Measurement (GPM) which builds on TRMM successes, *etc.* The GPM was deployed by NASA to provide full global coverage of precipitation every 2–3 hours to assist researchers in improving the forecasting of extreme events, studying global climate, and adding to current capabilities for using such satellite data to benefit society. Globally, satellites provide three quarters of the data used in numerical weather prediction models, and in France satellites provide 93% of data used in numerical weather forecasting models (OECD, 2014). In countries with sparse rain gauge networks, rainfall may be estimated using satellites. Several studies have also used satellite-derived rainfall to estimate streamflow. Grimes and Diop (2003) investigated the feasibility of using satellite-derived daily rainfall as input to a rainfall-runoff model for a river flow forecasting in a poorly gauged catchment in West Africa. The study proved that satellite-derived rainfall estimates gave more accurate river flow forecasts than when using rain gauge data alone. Another study conducted in South Africa by Sawunyama and Hughes (2008) confirmed the potential of using satellite-derived rainfall to extend rainfall data for water resource modelling. Botai *et al* (2018) investigated the spatial-temporal variability and trends of precipitation concentration across South Africa using the Tropical Rainfall Measuring Mission (TRMM) satellite precipitation data sets spanning 1998-2015; while Bárdossy and Pegram (2017) developed a methodology to combine daily precipitation observations and radar measurements to estimate sub-daily extremes at point locations.

Tauro *et al* (2018) declare that all possible rainfall data sources such as rain gauges, radar data, satellite-derived data, *etc* need to be consolidated to provide better rainfall estimation. This assertion is pertinent to South Africa where *in situ* rain gauge network has been steadily declining for three decades.

The processed and raw weather satellite data is freely accessible from NOAA, and the South African National Space Agency (SANSA) which "…was created to promote the use of space and strengthen cooperation in space-related activities while fostering research in space science, advancing scientific engineering through developing human capital, and supporting industrial development in space technologies" (SANSA website) and the South African Weather Services (SAWS) have the infrastructure to access and process raw weather data, and disseminate it to the nation.

3.2 Soil moisture from satellites

Water stored in the 5 cm to 17 cm of the topsoil represents a key variable in the climate and hydrology systems as it modulates the exchange of moisture and energy between the land surface and the atmosphere (McColl, *et al.*, 2017). Therefore, the knowledge of this subsurface water component (soil water content) is essential for water balance studies, irrigation water use efficiency, floods and droughts applications. However, it is difficult to quantify the behaviour and dynamics of soil moisture due to sparse and uneven observations (McColl, *et al.*, 2017). Soil moisture is estimated using soil moisture probes, time-domain reflectometry (TDR), gravimetric methods, *etc* but the measurements from these methods have proved laborious with sparse observation networks. Over the past decade satellite remote sensing of soil moisture has significantly advanced to the extent that there are two dedicated missions in space (Tauro *et al*, 2018) and these missions include Soil Moisture Ocean Salinity (SMOS) and Soil Moisture Active and Passive (SMAP) which was launched by NASA in 2015. SMAP was specifically designed to provide globally comprehensive and frequent measurements of the moisture in the topsoil, and the observations are collected globally every two to three days. After almost two years of data collection, the efficacy of SMAP was evaluated by McColl *et al* (2017) and found to provide unprecedented levels of detailed information on the amount of water stored in the topsoil layer.

In South Africa, two different approaches (i.e. hydrological modelling and remote sensing) of soil moisture estimation have been used. For example, a series of WRC-funded projects (K5/1683 and K5/2024) produced a national soil moisture modelling framework running at 3-hour time-steps. The approach was automated to model soil moisture state in detail over Southern Africa using the PyTOPKAPI hydrological model forced by rainfall and evapotranspiration estimates. This led to the development of an operational soil moisture from satellite system (temporarily hosted by ARC) in which the soil water content is estimated every three (3) hours, and this work was extended to the SADC Region through the HYLARSMET project (K5/2324). Furthermore, the hydrological modelling approach and the remote sensing method were compared and found to have a good correspondence.

In conclusion, an operational national scale soil moisture modelling in which the modelling of national soil moisture status at 3 hour intervals is already set-up. Although updated monthly, it is capable of near-real-time operation.

Another relatively new ground-based technique for soil moisture estimation is the Cosmic Ray Probe (CRP) which provides area-averaged soil moisture estimates over hundreds of metres. The measurement depth ranges between 12–72 cm and is dependent on the soil moisture status. The Cosmic Ray Probes have been installed in parts of KwaZulu-Natal, Gauteng and Limpopo Provinces but the network is sparse.

3.3 Surface water observations

This section is liberally using the text by:

- Tauro, F. *et al* (2018). Measurements and observations in the XXI century (MOXXI): innovation and multi-disciplinarity to sense the hydrological cycle. Hydrological Sciences Journal, **63**(2): 169-196
- Tauro, F., Petroselli, A. and Grimaldi, S. (2018). Optical sensing for stream flow observations: a review. Journal of Agricultural Engineering, Vol. **XLIX**: 836

Tauro *et al* (2018) declare that the scarcity of streamflow observations is a major source of uncertainty in hydrology and water resource management. Streamflow cannot be directly measured either with ground-based instruments or with satellite remote sensors; it is estimated from water level or velocity measurements of surface. The decline in ground-based streamflow monitoring networks due to budget cut-backs is a major impediment in frequent monitoring campaigns or the implementation of dense networks of measurement stations. For that reason the hydrology research community has adopted image-based techniques such as satellite imagery, laser altimetry, radar altimetry, unmanned aerial vehicles (UAV) or drones, *etc* to measure water levels. Furthermore, remarkable effort has been devoted to the development of non-contact or non-intrusive flow sensing observations such as the large-scale particle image velocimetry (LSPIV). LSPIV entails the imaging of the field of view and image ortho-rectification through transformation scheme, and image processing by high-speed cross-correlation.

In the developed countries such as the US, UK, etc these alternative flow sensing technologies are implemented and integrated in the standard ground-based observations, and the results are encouraging. South Africa should glean experience from the implementation of these technologies from elsewhere in the world and to investigate their potential deployment and implementation in this country.

3.4 Citizen monitoring

There exist many opportunities for the implementation of citizen monitoring e.g. for rainfall/climate, stream flow measurement, etc.

Frameworks to integrate citizen data with the mainstream national datasets have been developed here in South Africa and elsewhere in the world. These frameworks can be implemented seamlessly if the proper coordination mechanisms are established.

4. Other interventions

4.1 Collation and coordination of water-relevant data (central repository or hydrology data centre)

The analysis above has demonstrated that alternative technologies for water stores and flows exist and have been tested elsewhere in the world and even here in South Africa. The country has some infrastructure and the systems to implement these technologies but there is a lack of coordination at a strategic level to pool the resources. Therefore, it is proposed to establish a national central repository to coordinate all water-relevant data in which the new technologies could be tested and disseminated.

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