REMOTE SENSING

Remote sensing monitoring of soil moisture for South African wetlands

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Surface soil moisture is an essential climate variable (ECV; https://gcos.wmo.int/en/essential-climate-variables/soil-moisture) which is monitored to inform our understanding of changes in the atmosphere and earth. Soil moisture is also an important indicator, in addition to vegetation and soil types, of the presence of a wetland.

According to the South African National Water Act, Act 36 of 1998 (RSA, 1998:18), wetlands are defined as '***land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil***'. Only the top 50 cm of soil is used for wetland identification and delineation (DWAF, 2005). Therefore, to be able to detect a wetland using soil moisture as an indicator, we should be able to detect and monitor changes in soil moisture up to 50 cm of depth.

In South Africa, wetlands make up < 7% of the extent of the land mass, however, we have not detected all our wetlands yet (Van Deventer et al., 2020). Wetlands were also found to be the most threatened realm both globally (IPCC, 2019) as well as in the two South African National Biodiversity Assessments (NBAs) of 2011 (Nel and Driver, 2012) and 2018 (Van Deventer et al., 2019). Detection and monitoring of a wetland's soil moisture would not only contribute to the improved representation of their extent in the National Wetland Maps of South Africa, but also allow for quantifying changes in extent, health and their hydrological regime (Van Deventer et al., 2021). If these methods can be applied also elsewhere in the world, we can monitor these changes for reporting to global targets of freshwater ecosystems in the Kunming-Montreal Global Biodiversity Framework (GBF; CBD, 2022).

What has been done to date, and why do we need to improve it?

Currently, remote sensing is used to globally monitor changes in surface soil moisture up to 5 cm depth (Bauer-Marschallinger et al., 2019). For the world this is measured at a spatial resolution (pixel width) of 12.5 km, and for Europe at 1 km (Soil Water Index | Copernicus Global Land Service). These spatial resolutions are too coarse to detect wetland extent, and monitor their health for reporting to the GBF targets. More particularly, these global products will be insufficient for the detection and monitoring of wetland ecosystem health in South Africa, where most of our systems are shallow, narrow, and covered with vegetation. Remote sensing products with a 30 m spatial resolution, such as the Global Surface Water products (Pekel et al., 2016), has shown an underrepresentation of South Africa's wetlands by 87% (Van Deventer, 2021), in comparison to the latest National Wetland Map version 5 (Van Deventer et al., 2020). This is because only about 11% of the extent of South Africa's wetlands are open water bodies, and since optical and radar sensors can detect and monitor changes to these type of wetlands, if they are more than about 1 m in depth, the global products can detect and monitor only these 11% of our wetlands.

The majority of South Africa's wetlands are, however, ranging from vegetated or palustrine wetlands in the eastern parts of the country, to ephemeral wetlands in the western, arid regions which appear only briefly, and are usually muddy and shallow at times of inundation. Therefore, to improve the detection of wetland extent for palustrine wetlands and wetlands in the arid regions, we need to improve the spatial resolution and accuracy with which we can detect and quantify soil moisture.

The depth at which soil moisture can be detected by the current space-borne satellite sensors, is also limited to 5 cm at the moment (Bauer-Marschallinger et al., 2019). This means that the geographic variation and seasonal changes in soil moisture at depths >5-50 cm below ground, for the detection and monitoring of wetlands, are not detected. If vegetation covers the wetland, it makes it even more difficult for the sensors to detect the soil moisture below the canopy and above-ground biomass.

Radar sensors flown on aerial platforms such as airplanes and drones, however, can improve the depth of sensing compared to the current space-borne sensors. Further work is however, required in South Africa, to test the capabilities of sensors across platforms and assess and develop methods for optimising the predictions.

Colbyn Wetland Nature Reserve as a choice for monitoring teal carbon

The Colbyn Wetland Nature Reserve (CWNR) is a small 70 ha reserve within the City of Tshwane Metropolitan Municipality (CTMM) at about 25°44′21.67″S; 28°15′15.35″E (Gangat et al., 2020; Figure 1). It forms part of the headwaters of the Limpopo River, with the Hartbeesspruit draining through a valley-bottom wetland. The wetland was previously farmed in the 1940s, and a railway line still runs through the reserve. The wetland transitions from grass and sedges in some parts to large macrophytes such as *Phragmites australis* (common reed) and *Typha capensis* (bulrush) in other places, and areas with terrestrial grassland which occur towards the east.

Riparian trees line the river channel, adding to the challenge of detecting and monitoring changes in soil moisture across the reserve, for two reasons: (i) trees contain a high amount of above-ground biomass that interferes with radar and optical signals, making it challenging to detect soil moisture in these places; and (ii) they cause a significant draw-down in soil moisture, to depths where it is difficult for the sensors to detect soil moisture. CWNR offers an important variation in soil moisture regimes, from a terrestrial to seasonal, and also highly, permanently saturated wetland areas. In addition, a variety of vegetation structures in the wetlands, ranging from marsh vegetation to large macrophytes and trees, offers the diversity of interactions that occurs in the landscape where soil moisture ranges should be quantified and detected. Furthermore, the quantification of the above-ground biomass, enables more advanced radiative transfer modelling to compensate for vegetation in wetlands.

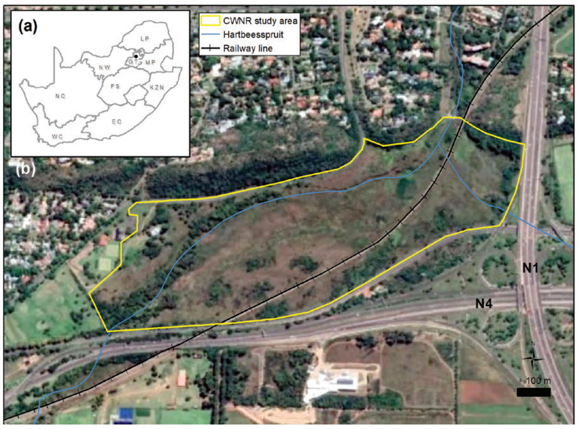

Figure 1: Location of the Colbyn Wetland Nature Reserve (CWNR) in (a) the Gauteng Province of South Africa and (b) relative to the upper reaches of the Hartbeesspruit in Pretoria.

How can we measure soil moisture from satellite images?

Soil moisture is traditionally measured by collecting soil samples in the field, and determining the water content per mass or volume of the soil sample in a laboratory. However, this technique is incredibly time consuming and laborious, thereby constraining continuous soil moisture monitoring. Alternative methods have therefore been developed to continuously measure a soil's water content, which have been predominantly driven by the agricultural sector. In South Africa, DFM capacitance probes (DFM Software Solutions, South Africa) use the dielectric constant (the ratio of the electric permeability of the material to the electric permeability of free space) to measure changes in a soil's water content. DFM capacitance probes are able to monitor water content and temperature at six interval depths, as well as surface temperature. Probes are installed into the soil surface using either a soil auger or a driving pin to create a hole slightly larger than the diameter of the probe. Thereafter the probe is inserted into the ground, and soil slurry applied to remove any air pockets.

The soil moisture measured by the probes is used to statistically link ground and satellite data using regression (Wang and Qu, 2009). Regression relationships between reflectance or backscatter values extracted from satellite imagery and data collected by soil moisture probes are measured using parametric or nonparametric models (e.g., Gangat et al., 2020). These statistical methods need to be calibrated to achieve consistency between ground and satellite data. Calibration involves the collection of both ground-based measurements and satellite imagery under identical conditions, such as at the same time of day. Regression relationships can quantify soil moisture variation over large areas over time, even in areas where no soil moisture probes are not installed but still within the calibration domain (Bosch et al., 2006).

(a) (b) (c)

Figure 2: Soil moisture probes are inserted in the ground (a) to measure water content at different depths. (a) Here the DFM company, Mr Lee-Matt Isaks (from DFM Technologies), holds the 80-cm long DFM probe before installation at Colbyn Wetland Nature Reserve (CWNR). Several students volunteered to support the team with installation, including Ms Sisipho Ngebe (on the left), Mr Ayabonga Gangatele and Mr Tlotlisang Nkhase. (b) A photograph of an installed DFM Capacitance probe. Values recorded by these probes will be used to relate to the satellite images, to determine the accuracy to which we can measure soil moisture for different depths at CWNR.

The Gauteng Multi-sensor Campaign (GMC)

In the first semester of 2022, the team working on teal carbon estimation with remote sensing, were able to join the Gauteng Multi-sensor Campaign (GMC). The GMC was a collaborative campaign focused on collecting and generating a large multi-sensor dataset covering various remote sensing application domains and areas of interest. The CSIR captured multi-temporal airborne synthetic aperture radar (SAR) images as part of the campaign. Dual-frequency (C- and L-band) polarimetric SAR data was obtained with a temporal resolution of approximately two weeks over a three-month timeframe between January and May 2022, utilising the CSIR's Department of Science & Innovation's (DSI's) airborne SAR facility. The image below shows an example of a multi-looked C-band SAR image captured over the CWNR. This image was processed to 1-m spatial resolution, without any additional auto focusing.

Figure 3: Side-looking view on the Colbyn Wetland Nature Reserve generated from airborne radar data. The wetland is located north-west of the N1-N4 interchange.

The ARC provided the probes for the monitoring of the soil moisture at the CWNR, while the CSIR funded the initial installation of the probes and batteries, as well as replacement of the batteries in 2024. The outputs of this project will be used in a 'EO4Wetlands' project that the National Research Foundation (NRF) will fund between 2025 and 2027, and a PhD student analysing the potential improvements of soil moisture monitoring for wetlands in the country.

References

- Bauer-Marschallinger, B.; Paulik, C.; Hochstöger, S.; Mistelbauer, T.; Modanesi, S.; Ciabatta, L.; Massari, C.; Brocca, L. & Wagner, W. 2019 Soil Moisture from Fusion of Scatterometer and SAR: Closing the Scale Gap with Temporal Filtering. Remote Sensing, 1030. https://doi.org/10.3390/rs10071030

- Bosch, D.D., Lakshmi, V., Jackson, T.J., Choi, M. and Jacobs, J.M., 2006. Large scale measurements of soil moisture for validation of remotely sensed data: Georgia soil moisture experiment of 2003. Journal of Hydrology, 323(1-4), pp.120-137. https://www.sciencedirect.com/science/article/abs/pii/S0022169405004166 CBD (Secretariat of the Convention on Biological Diversity). (2016). Fifth edition of the Global Biodiversity Outlook, national reporting and indicators for assessing progress towards the Aichi biodiversity targets. Available at: https://www.cbd.int/doc/meetings/sbstta/sbstta-20/official/sbstta-20-13-en.pdf. [Accessed 31 July 2022]

- Convention on Biological Diversity (CBD), 2022. Nations adopt four goals, 23 targets for 2020 in landmark UN biodiversity agreement. CBD, Montreal, Canada. https:// www. cbd. int/ artic le/ cop15- cbd- press- relea se- final- 19dec2022. Accessed 9 Mar 2024

- DWAF (Department of Water Affairs and Forestry). 2005. A practical field procedure for identification and delineation of wetlands and riparian areas. DWAF, Pretoria, South Africa.

- Gangat, R.; Van Deventer, H.; Naidoo, L. & Adam, E. 2020. Estimating soil moisture using Sentinel-1 and Sentinel-2 sensors for dryland and palustrine wetland areas. South African Journal of Science, 116(7/8): Art. #6535, 9 pages. https://doi.org/10.17159/sajs.2020/6535.

- Grundling, P-L.; Grundling, A.T.; Van Deventer, H. & Le Roux, J.P. 2021. Current state, pressures and protection of South African peatlands. Mires & Peat, 27, article 26. https://doi.org/10.19189/MaP.2020.OMB.StA.2125

- IPBES (2019) Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services. Díaz, S.; Settele, J.; Brondízio, E.S.; Ngo, H.T. and 26 others (Eds.), Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES), IPBES secretariat, Bonn, Germany, 56 pp. http://doi.org/10.5281/zenodo.3553579

- Nel J.L. & Driver A. 2012. South African National Biodiversity Assessment 2011: Technical Report. Volume 2: Freshwater Component. Council for Scientific and Industrial Research (CSIR) Report Number CSIR/NRE/ECO/IR/2012/0022/A. CSIR: Stellenbosch, South Africa.

- Pekel, J-F.; Cottam, A.; Gorelick, N. & Belward, A.S. 2016. High-resolution mapping of global surface water and its long-term changes. Nature, 540: 418–422. https://doi.org/10.1038/nature20584

- Republic of South Africa (RSA). 1998. National Water Act (NWA), Act 36 of 1998. Government Printers, Pretoria, South Africa.

- Skowno, A.L.; Poole, C.J.; Raimondo, D.C.; Sink, K.J.; Van Deventer, H.; Van Niekerk, L.; Harris, L.R.; Smith-Adao, L.B.; Tolley, K.A.; Zengeya, T.A.; Foden, W.B.; Midgley, G.F. & Driver, A. 2019. National Biodiversity Assessment 2018: The status of South Africa's ecosystems and biodiversity. Synthesis Report. South African National Biodiversity Institute, an entity of the Department of Environment, Forestry and Fisheries, Pretoria. http://hdl.handle.net/20.500.12143/6362

- Ulaby, F. T., R. K. Moore, and A. K. Fung, (1981). Microwave Remote Sensing Active and Passive Volume I - Fundamentals and Radiometry, 1st Edition. D.S. Simonett, (Ed.). Addison-Wesley Publishing Company, Inc., Reading, Massachusetts 01867, USA, p. 456.

- Van Deventer, H. 2021. Monitoring changes in South Africa's surface water extent for reporting Sustainable Development Goal sub-indicator 6.6.1.a. South African Journal of Science, 117 (5/6) Art. #8806. https://doi.org/10.17159/sajs.2021/8806

- Van Deventer, H.; Smith-Adao, L.; Collins, N.B.; Grenfell, M.; Grundling, A.; Grundling, P-L.; Impson, D.; Job, N.; Lötter, M.; Ollis, D.; Petersen, C.; Scherman, P.; Sieben, E.J.J.; Snaddon, K.; Tererai, F. & Van der Colff, D. 2019. South African National Biodiversity Assessment 2018: Technical Report. Volume 2b: Inland Aquatic (Freshwater) Component. Council for Scientific and Industrial Research (CSIR) and South African National Biodiversity Institute (SANBI), Pretoria, South Africa. CSIR report number CSIR/NRE/ECOS/IR/2019/0004/A. SANBI handle: http://hdl.handle.net/20.500.12143/6230

- Van Deventer, H.; Linström, A.; Durand, J.F., Naidoo, L. & Cho, M.A. 2022. Deriving the maximum extent and hydroperiod of open water from Sentinel–2 imagery for global sustainability and biodiversity reporting for wetlands. Water SA 48, (1) 75–89. https://doi.org/10.17159/wsa/2022.v48.i1.3883.

- Van Deventer, H.; Van Niekerk, L.; Adams, J.; Dinala, M.K.; Gangat, R.; Lamberth, S.J.; Lötter, M.; Mbona, N.; MacKay, F.; Nel, J.L.; Ramjukadh, C-L.; Skowno, A. & Weerts, S.P. 2020. National Wetland Map 5 – An improved spatial extent and representation of inland aquatic and estuarine ecosystems in South Africa. Water SA, 46(1): 66–79. https://doi.org/10.17159/wsa/2020.v46.i1.7887

- Wang, L. and Qu, J.J., 2009. Satellite remote sensing applications for surface soil moisture monitoring: A review. Frontiers of Earth Science in China, 3(2), pp.237-247. https://link.springer.com/article/10.1007/s11707-009-0023-7