

Seasonal local rainfall and hydrological forecasting for Limpopo communities – A pragmatic approach

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ABSTRACT

This paper describes the development and testing of a simple local seasonal forecast system of rainfall and hydrological conditions. The primary target group is agricultural extension officers who communicate forecasts to small-scale farmers at local level. Two pilot areas within the Limpopo river basin in South Africa were used, one in the Luvuvhu river basin in Vhembe district and the other in the Letaba river basin in Mopani district. Local rainfall and hydrological forecasts of runoff, soil moisture and evapotranspiration were produced, built on readily available deterministic seasonal meteorological forecasts for large-scale rainfall from CSIR (Council for Scientific and Industrial Research, South Africa), produced from an ensemble of seasonal forecasts using the CCAM (Conformal-Cubic Atmospheric Model) global forecast model. Hydrological forecasts were produced through a “proxy” approach, whereby outputs from the ACRU (Agricultural Catchment Research Unit) agro-hydrological model provided expected hydrological responses from observed years that are representative of the rainfall anomalies predicted by the global seasonal forecast. Locally monitored soil moisture augmented the hydrological forecasts. The local seasonal forecast system does not require sophisticated calculations or a complex operational environment and complements coarser scale forecasts disseminated by the provincial departments of agriculture. Results of three rainfall seasons from 2013 to 2016 in the pilot areas showed the proxy approach to have relatively good matches between forecasts and available observations, showing better predictability for below normal rainfall seasons with exception for an extreme monthly rainfall event. The forecasts matched observed conditions best during the strong El Niño phase of ENSO (El Niño Southern Oscillation) for 2015/2016.

Practical implications

- Seasonal climate forecasts are routinely used and distributed by national meteorological agencies in many countries, including South Africa (Hansen et al., 2011; Archer et al., 2018; Muiita et al., 2021; WMO, 2021b). They provide information of the rainfall and temperatures that are likely to occur in the coming months. These forecasts do not provide small-scale spatial resolution or project hydrological conditions, e.g. water flow in rivers or soil moisture. A simple local seasonal forecast system

projecting likely levels of rainfall, runoff, soil moisture and evapotranspiration was tested in the Luvuvhu and Letaba River Basins, South Africa. The forecast uses a “proxy” approach that estimates hydrological conditions from the meteorological conditions that were observed in the past that are similar to the current forecast. The local forecasts were compared to observations of district and local rainfall, soil moisture from locally situated sensors and streamflow of near-lying stations for the rainy seasons (Oct–April) of 2013/2014, 2014/2015 and 2015/2016.

- Results indicate that the rainfall forecasts in both river basins matched observations relatively well in wetter and dryer-than-normal years. The rainfall forecast predicted the near normal

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to wetter-than-normal rainy season of 2013/2014. The forecast of the very dry season of 2015/2016 closely matched observations while the 2014/2015 forecast accurately indicated lower-than-normal rainfall for most months, yet failed to capture the high rainfall in December. River flow forecasts in both basins generally responded as expected to the rainfall forecasts with high river flows following normal to above normal rainfall, e.g. in 2013/2014, and lower river flows following below normal rainfall, e.g. in 2015/2016. Runoff forecasts for all three seasons for the most part matched well with observations for the Letaba basin. For Luvuvhu the runoff forecasts matched well with observations for 2013/2014 and 2015/2016, but not for 2014/2015 where deviations to observations were larger. River flow observations in Luvuvhu, however, are likely more affected by upstream storage than for Letaba. Soil moisture forecasts accurately projected the wetter (2013/2014) and dryer (2014/2015) conditions as verified by soil moisture sensors situated in two pilot communities in the river basins.

- The approach shows potential for provision of rainfall and hydrological forecasts at local scale to supplement the nationally distributed seasonal forecasts of rainfall and temperature at coarser spatial resolution, but should be subjected to more rigorous testing. Its strengths are that it does not require sophisticated calculations or operational modelling. The outputs from a hydrological model set-up for local conditions contribute as a database of rainfall and hydrological conditions from observations of past years. Using such outputs, the spatially coarser seasonal rainfall forecast can be robustly transferred into a local rainfall and hydrological forecast. This pragmatic approach to climate services would provide high gain for small input and manpower. The procedure does not require a high level of hydrological or meteorological expertise. Short training programs within relevant provincial departments, e.g. the Limpopo Department of Agriculture and Rural Development (LDARD), could provide sufficient understanding of meteorology and hydrology to create the local forecasts. Good cooperation would however be needed with a national or regional provider of meteorological seasonal forecasts.
- Local rainfall and hydrological forecasts created by this proxy approach increase the relevance of forecast information for local extension officers and small-scale farmers as it projects the likely conditions of agricultural soils, grazing pastures and water bodies. Advance knowledge of whether the coming season is more likely to be dryer, wetter, or to display normal conditions would help planning of appropriate crop varieties, planting areas, irrigation demands and livestock management. Verifying the forecasts against local observations of rainfall and soil moisture collected by and with community members was found to increase their understanding, interest and trust in the forecasts (Wilk et al., 2017; Andersson et al., 2020).

Introduction

Climate variability is a factor that farmers and water resource managers worldwide deal with as they know that each new growing season will vary from the previous one. Receiving relevant information on expected conditions in advance of or at the beginning of the rainy season could play a role in planning for and potentially adapting to the coming season. Seasonal climate forecasts are routinely produced to this end. They can vary in complexity, but typically provide an outlook on a rather coarse spatial scale over the coming months as to the precipitation amounts and temperatures to be expected, most often expressed as *above normal*, *normal*, or *below normal*. Standard seasonal forecasts do not typically include hydrological conditions. According to Sutamto et al. (2020), development of hydrological drought forecasting will be increasingly beneficial as droughts become more frequent as a result of climate change. Information on expected local rainfall and hydrological conditions, including soil moisture, could potentially provide farmers with even better insight into the coming season (Sheffield et al., 2014;

Winsemius et al., 2014). In this paper, we present a simple system to produce locally relevant seasonal rainfall and hydrological forecasts that could aid agricultural extension officers and farmers in planning and decision-making, particularly early in the rainy season.

Background

Farmers in Africa are subject to widely varying climatic conditions whereby rainfall, soil moisture and streamflow can be quite different from season to season. Furthermore, it appears that this variability may be increasing over time with rising global temperatures and higher occurrences of drought conditions. Of weather-related disasters in Africa in the last 50 years, droughts accounted for 95% of deaths (WMO, 2021a). From a review of observed data from 1900 to 2013, Masih et al. (2014) found that droughts over Africa in general have become more frequent, intense, and widespread in the last 50 years. Regarding the future for southern Africa, they state “a high likelihood of increased droughts in central and southern Africa” is suggested by global climate models (GCMs). South Africa reported the highest number of disasters to WMO in 1970–2019 of Africa’s 57 countries and territories (WMO, 2021a). It also had three of the top ten ranked disasters according to economic losses in 1987, 1990 and 2017 (ibid).

To cope with increasing rainfall variability and drought frequency, tools that project rainfall forecasts at a finer spatial resolution are needed. Coordinated drought management needs to contain understandable information on local rainfall and hydrological impacts for intended users and recommendations and guidance of appropriate coping and adaptation strategies (Pulwarthy and Sivakumar, 2014). To increase user take-up, forecasts should additionally have high spatial resolution, contain comparisons to previous years as well as be reliable, locally relevant, co-produced and disseminated on time (Johnston et al., 2004; Andersson et al., 2020; Muita et al., 2021; Klemm and McPherson, 2017). An assessment of climate services in 22 African countries identified insufficient engagement with information users as the weakest component (WMO, 2021b). Commercial farmers in Australia and South Africa found seasonal forecasts useful for planning of stocking rates, crop choices, planting dates and fertilizer purchase (Landman et al., 2020; Marshall et al., 2011). Farmers’ uptake of forecast information relies heavily on additional factors, such as seed and fertilizer subsidies, labor, farming inputs, credit, social capital, strategic skills and/or finances, especially for smallholders (O’Brien and Vogel, 2003; Marshall et al., 2011; Wilk et al., 2017). Agricultural extension services play an important role in Africa as knowledge facilitators with small-scale farmers to boost productivity and standards of living (Msuya et al., 2017; Amegnaglo et al., 2017). A study of 400 extension officers across nine African countries including South Africa recommended training in emerging technologies, ICT and communication to complement agricultural expertise (Msuya et al., 2017).

Seasonal forecasting provides information that can be used by various sectors that are highly weather dependent (Hammer et al., 2001; Winsemius et al., 2014). Its potential is well documented (Charney and Shukla, 1981; Slingo and Palmer, 2011), however forecasts are not universally applicable and can only be used in regions that have documented forecast skill. Most seasonal forecast systems are based on relationships derived from the physical mechanism ENSO (El Niño Southern Oscillation) that can be represented in global circulation models (GCMs). Predictability based on ENSO has been shown to exist for rainfall over southern Africa (Landman et al., 2001; Landman et al., 2005; Reason et al., 2005). However, the skill of such forecasts varies between the phases of ENSO. Landman and Beraki (2012) found the strongest predictability to exist for drought during El Niño years and floods during La Niña years, particularly for the months December, January, and February. Winsemius et al. (2014) found better skill in predicting above normal and below normal conditions than normal conditions. Better skill has also been reported in prediction of average conditions events while forecasts of extreme weather have proved less

reliable (Becker et al., 2013; Pepler et al., 2015; Cowan et al., 2019; MacLeod and Klassen, 2019; King et al., 2020).

There is a recognized need for providing seasonal hydrological forecast information (Malherbe et al., 2014; Hao et al., 2018; Sutanto et al., 2020), which is of particular importance for users in Sub-Saharan Africa (Hansen et al., 2011; Sheffield et al., 2014; Shukla et al., 2014). In South Africa, the coupling of atmospheric climate models to models for the ocean, the land surface and sea ice, has improved seasonal forecasts (Landman et al., 2012). Other studies have developed more complex methods to transfer meteorological forecasts into hydrological forecasts (e.g., Trambauer et al., 2015; Yuan et al., 2013). Sutanto et al. (2020) found that hydrological drought forecasts outperformed meteorological drought forecasts for the pan-European region. Such approaches have provided promising results that could contribute to information on expected hydrological conditions, however they require substantial effort and resources. There is also a documented discrepancy between creating relevant forecast information and creating forecast information that is used (O'Brien and Vogel, 2003; Marshall et al., 2011).

Aim of the approach

The approach presented in this paper describes the calculation and compilation of rainfall and hydrological forecast information at sub-catchment scale in a simplified way that could be made operational with limited resources. The forecast system transforms the seasonal meteorological forecast at a 1×1 degree horizontal resolution into a seasonal rainfall and hydrological forecast at sub-catchment scale. Building on readily available seasonal meteorological forecasts for rainfall, the system calculates expected sub-catchment rainfall, runoff, soil moisture and evapotranspiration for the coming months.

The study was performed as part of a three-year project that assessed if and how the local forecast system was useful for agricultural extension officers and farmers of two communities in Limpopo, South Africa. The research team worked closely with researchers and extension officers from the Limpopo Department of Agriculture and Rural Development (LDARD) to co-produce the local forecast system in line with the needs of extension services and small-scale farmers. Agricultural extension officers from LDARD have the main role in communicating existing seasonal forecasts of expected rainfall and temperature to farmers (Andersson et al., 2020; Wilk et al., 2017).

The forecasts for the rainy seasons (Oct–Apr) 2013/2014, 2014/2015 and 2015/2016 were verified against available observations. Simplified presentations of the forecasts were presented to local agricultural extension officers and farmers in the pilot communities before each rainy season to discuss and explore their responsive actions. As the rainfall forecasts had to a high degree matched observed conditions, barring the heavy rains in December 2014, both extension officers and farmers reported the forecasts as having been useful for their planning at a workshop held after the first two rainy seasons (Andersson et al., 2020). In contrast to the African commercial farmers who used seasonal forecasts to plan their month-to-month operations (Landman et al., 2020), small-scale farmers used the information primarily to guide their planting date and as a general indicator of seasonal hydrological conditions, such as grazing conditions. Farmers in response to the forecast planned measures such as early ploughing, water harvesting, mulching and buying animal fodder. However, not all of the activities could be performed because they lacked labour and subsidies (Andersson et al., 2020). Extension officers could appreciate the graphical forecast information presented together with local climatological values and considered the local forecasts useful to better prepare assistance, guidance, and resources for farmers (Wilk et al., 2017). They also found local monitoring of soil moisture helpful in communicating forecast information to farmers and increasing its acceptance by farmers.

Study area

Two river basins situated in the northeast of the Limpopo Province of South Africa – Groot Letaba and Luvuvhu, as shown in Fig. 1 – were used to represent the hydrology of the two pilot communities in this study. Both river basins lie near the border with Mozambique as part of the Limpopo River system. The climate of Limpopo Province is highly variable, spatially, and temporally (Mulenga et al., 2003; Reason et al., 2005; Taljaard, 1986; Usman and Reason, 2004). Most of the rainfall occurs in the summer months between November and March, with the peak rainfall months being January and February.

The Groot Letaba River Basin covers 4951 km² of the full Letaba catchment area (13 670 km²; DWAF, 2006). The pilot community of Mokwakwaila lies within this catchment. The Groot Letaba River has its headwaters in the high rainfall Drakensberg Mountain range and flows into dryer and arid regions in a northeasterly direction through the Kruger National Park where it joins the Olifants River that flows into Mozambique. The mean annual precipitation over the Groot Letaba catchment area ranges from 1500 mm per year in the mountainous regions (2121 m.a.s.l.) to 450 mm per year in the dryer, more arid regions (155 m.a.s.l.). Agriculture is the main economic activity in the region, both commercial and subsistence farming.

The Luvuvhu River Basin covers 5946 km² and is situated just north of Groot Letaba. The pilot community of Lambani lies within the Luvuvhu catchment area, which is drained by the Luvuvhu and Mutale Rivers that join to the Limpopo River on the South African and Mozambique border. The mean annual precipitation over the Luvuvhu catchment area ranges from 1870 mm per year in the mountainous regions (1360 m.a.s.l.) to 300 mm per year in the dryer, lower regions (200 m.a.s.l.). A substantial proportion of the catchment area is under subsistence agriculture, with the lower reaches falling within the boundaries of Kruger National Park, an important conservation and ecotourism area.

Methods

The methodology applied consisted of using current seasonal meteorological forecasts produced by numerical weather prediction models to predict expected hydrological responses with a hydrological model. The seasonal forecasts were taken from a well-known South African research institute, CSIR (Council for Scientific and Industrial Research), as described below. The hydrological responses, and thus hydrological forecast, were produced using the well-established South African ACRU (Agricultural Catchment Research Unit) agrohydrological model (Schulze, 1995). Forecasts from the hydrological model were produced through a “proxy” approach whereby the current seasonal forecast is matched with climatological values used to identify appropriate analogue years that provide representative hydrological outcomes for the forecast.

Hydrological model

The ACRU agrohydrological model is a multi-purpose, daily time-step, physically based conceptual model that has been applied extensively in South Africa, and is sensitive to land management and changes thereof (e.g. Jewitt and Schulze, 1999; Schulze, 2000; Jewitt et al., 2004; Warburton et al., 2012), as well as to climate input and changes thereof (Perks, 2001; Schulze, 2005; Forbes et al., 2010; Graham et al., 2011). As it was developed for South African conditions, it is well-suited for use in producing hydrological forecasts for the Limpopo region. The model's hydrological output (e.g., runoff, peak discharge) has been widely verified under a range of climate conditions including the Luvuvhu catchment, as have its internal state variables, such as soil moisture content (Warburton et al., 2010). Input parameters to the ACRU model are not typically calibrated to produce a good fit. Rather, input parameters are estimated from the physical characteristics of the



Fig. 1. Location map for Luvuvhu and Groot Letaba River Basins in the Limpopo Province in north-eastern South Africa. For reference, the Limpopo River Basin is shown in red. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

catchment using available geo-physical information. The model inputs and configuration used for the Luvuvhu catchment in this study is documented in [Warburton et al. \(2010\)](#); the same methodology and databases were used for the Groot Letaba catchment. The inputs and configuration are briefly outlined below.

The Luvuvhu and Groot Letaba catchment areas were delineated into 52 and 40 sub-catchments, respectively, that reflect topography, soil properties, broad land cover and water management. These sub-catchments can be considered relatively homogeneous in terms of climate and soils; however, the land use within each sub-catchment varies. For this reason, each sub-catchment was further divided into major land use units for modelling purposes, with 263 and 231 homogeneous land use units in the Luvuvhu and Groot Letaba catchment areas, respectively. The ACRU model requires daily rainfall and daily reference potential evaporation; the latter can be computed from daily minimum and maximum temperature if not provided explicitly. Representative rainfall stations were chosen for each of the sub-catchments and daily rainfall was extracted from a rainfall database compiled for South Africa by [Lynch \(2004\)](#) that covers the period 1961–1999. As rainfall recording stations in South Africa fell from approximately 1250 to 800 between 2000 and 2009 with a further decline in the last decade ([Pitman and Bailey, 2021](#)), the 1961–1999 database was used in the study. The climatic conditions during the three years of study were within the ranges in the database despite climate change and could therefore be used. Daily minimum and maximum temperatures were extracted from a spatial database of daily temperatures for South Africa ([Schulze and Maharaj, 2004](#)) at a point closest to the centroid of each sub-catchment representing the median altitude of the sub-catchment. As daily A-pan observations of evaporation were not available, the [Hargreaves and Samani \(1985\)](#) temperature-based evaporation equation was used to estimate evapotranspiration values.

The ACRU model revolves around a daily multi-layer soil water budget using surface layer characteristics and two active soil layers, i.e. a topsoil and subsoil, into which infiltration of rainfall occurs and in which root development and soil water extraction take place through evaporation and transpiration, as well as capillary movement and saturated drainage. Input information for both soil horizons on depths,

soil water content at the soil's permanent wilting point, field capacity and saturation, as well as the fraction of 'saturated' soil water to be redistributed daily from the topsoil to the subsoil, and from the subsoil into the intermediate/groundwater store is required ([Schulze, 1995](#)). Values for these variables were obtained from the data accompanying the "South African Atlas of Climatology and Agro-hydrology" ([Schulze et al., 2008](#)). In ACRU, the streamflow response variables govern the portion of generated stormflow and baseflow exiting a catchment on a particular day. For this study, it was assumed that 30% of the total stormflow generated in a sub-catchment would exit the same day as the rainfall event that generated the stormflow, this being a typical value for South African sub-catchments of the size in this study ([Schulze et al., 2004](#)). On any day it is assumed that 0.9% of the groundwater store will become baseflow, a representative value of large parts of southern Africa (*ibid*).

Land use of the catchments was determined from the [National Land Cover \(NLC, 2000\)](#) imagery. For each vegetation cover, vegetation and water use parameters were obtained from [Schulze et al. \(2004\)](#). Surface areas of the reservoirs, obtained from 1:50,000 topographic maps, were used to calculate the capacity of the reservoirs using the algorithm developed by [Tarboton and Schulze \(1992\)](#). No environmental flow estimates were available for the dams in the catchments thus environmental flows were assumed to be equal to seepage as suggested in [Schulze \(1995\)](#). Irrigation areas were identified from the NLC and the irrigation schedule was set at 20 mm applied in a fixed 7-day cycle, with the cycle interrupted only after 20 mm of rain on any given day. Spray evaporation and wind drift losses were input at 12% and conveyance losses at 10% following typical values summarized by [Smithers and Schulze \(2004\)](#).

The seasonal forecasts

Deterministic seasonal forecasts from CSIR (Council for Scientific and Industrial Research, South Africa) were used, based on many years of development with various models and approaches ([Archer et al., 2018](#); [Landman, 2014](#)). These were produced from an ensemble of global seasonal forecasts using the CCAM (Conformal-Cubic

Atmospheric Model) global forecast model (Engelbrecht et al., 2011; McGregor and Dix, 2008) at a horizontal resolution of 1x1 degree. The CSIR forecast was derived from 12 ensemble members from CCAM and summarized to an ensemble mean forecast. We opted for using this deterministic ensemble mean forecast over a probabilistic forecast as it was readily available and could be transferred more directly into the hydrological forecast. We had also noted from previous discussions with extension agents in the field that they did not fully understand probabilistic forecasts, even though they had been provided with them for many years (Wilk et al., 2017). Although application and communication of probabilistic seasonal forecasts for agriculture has been shown by others to be valuable (e.g. Hammer et al., 2001; Hansen et al., 2011; Landman et al., 2020), we chose to test application of a deterministic approach. During the period of the pilot studies, the 12-member ensemble forecast was updated at the middle of each month and the results made publicly available on the CSIR FTP site.

Given the coarse resolution of the global forecast model and the known fact that all forecast and climate models are subject to biases, particularly for rainfall, forecasted rainfall values from the deterministic seasonal forecast were not used directly. Forecasted rainfall anomalies were the primary forecast signal used. Assuming that model biases are mostly systematic, the use of rainfall anomalies helps to minimize the effect of such biases, as both the seasonal forecast and climatological values for calculating anomalies come from the same model. The anomalies thus represent the primary seasonal forecast trend for precipitation, although some effects from model biases likely remain. The anomalies were provided directly by CSIR in the monthly forecast updates, based on climatology from long-term hindcast simulations using CCAM. Each forecast consisted of rainfall anomalies summarized for the coming three-month periods lagged by one month, such as September–October–November (SON), October–November–December (OND) and November–December–January (NDJ). Although seasonal forecasts for temperature were also produced by CSIR, they were not used in this study. Temperature values used for the hydrological forecast are the observed temperatures associated with each chosen year from the historical record, as described in more detail below.

Proxy hydrological forecasts

As mentioned above, forecasts from the ACRU hydrological model were produced through a “proxy” approach. This means that the model outputs were used to provide proxy hydrological responses for years that are representative of what the seasonal forecast predicts. This assumes that hydrological events that happened in the past can be used to predict future events given similar meteorological conditions (Day, 1985). For semi-arid conditions, such as for the Limpopo River Basin, meteorological forcing has been found to dominate hydrological predictability (Shukla et al., 2013; Youssef et al., 2013).

As the hydrological model was set up and verified with observed rainfall and temperature for the period 1961–1999, this period constitutes the climatological hydrological responses used for the proxy forecast. Rainfall anomalies from the current seasonal forecast were matched to observed rainfall anomalies from the hydrological modelling period to identify analogue years that represent expected rainfall conditions. Modelled hydrological responses from the identified analogue years were then used as the proxy hydrological forecast. Five analogue years were chosen for each forecasted rainfall anomaly to provide a relevant range of results. These were chosen according to “best match” of the rainfall anomaly value and the four most closely lying values to the best match.

For the purposes of this study, the terms *proxy* and *analogue* were adopted to distinguish between the forecast produced and the representative conditions obtained from the hydrological model, as further defined here. By proxy, we mean that the forecast acts in place of creating a more rigorous numerically-based forecast. By analogue, we mean that the chosen years are analogous, i.e. similar, to conditions

shown by the meteorological seasonal forecast and can provide representative years for compiling the hydrological forecast.

The general procedure for conducting the proxy hydrological forecast is:

- Obtain meteorological deterministic forecast (CSIR), with the following characteristics:
 - 3-month rainfall anomalies (from normal climatological mean)
 - 1 to 4-month lead time
- Identify 5 representative years from observations as analogue years for the hydrological forecast of the coming season (as further described below).
- Summarize relevant outputs from hydrological model for the analogue years.

Choosing representative years consists of:

- Calculating 3-monthly running mean values of deviation from the mean for accumulated observed rainfall for the entire hydrological modelling period (1961–1999).
- Sorting 3-monthly observed rainfall deviation from the mean from lowest to highest.
- Choosing the historical year where 3-month observed rainfall deviation from the mean most closely matches 3-month anomaly from meteorological seasonal forecast.
- Choosing 2 additional years to either side of this in the sorted list (in terms of rainfall deviation from the mean), i.e., 2 above and 2 below.
- Using appropriate variable outputs from the hydrological model from the 5 selected analogue years as proxy forecast variables.

The proxy hydrological forecast procedure is to:

- Make a first forecast for October and forward, update after one month for November and forward, update after two months for December and forward.
- Summarise forecast variables including rainfall, runoff, evaporation and soil moisture.
- Disseminate forecasts through LDARD via agricultural extension officers (see Andersson et al., 2020).

Simplified format

The proxy hydrological forecast variables taken from the ACRU Model outputs were processed for three 3-month periods each lagged by one month, e.g., October–November–December (OND), November–December–January (NDJ) and December–January–February (DJF). To create a simpler overview that is easier to understand, these were combined into a single forecast that covers 5 months. For this process, where forecasts overlap, the earliest 3-month forecast was given a higher weight than forecasts lagging after, i.e. the forecasted values for the months of October, November and December were taken from the first forecast period (OND) and those for January and February from the second (NDJ) and third (DJF) forecast periods, respectively. For each forecasted variable, the median values from the five analogue years were summarized and presented together with the maximum and minimum values. This blending operation does filter the information provided to some extent, but it was seen as essential to make the forecasts more easily understood. Climatological values also show the long term monthly mean of each value. To what degree forecasted variables deviate from normal conditions can easily be compared with this simplified format.

An example of the graphical forecast information used for workshops with extension officers and farmers is shown in Fig. 2. This was presented to agriculture extension officers together with discussion on potential impacts to farmers. The forecasted values were presented as the “likely” scenario for the coming season, also pointing out the possible

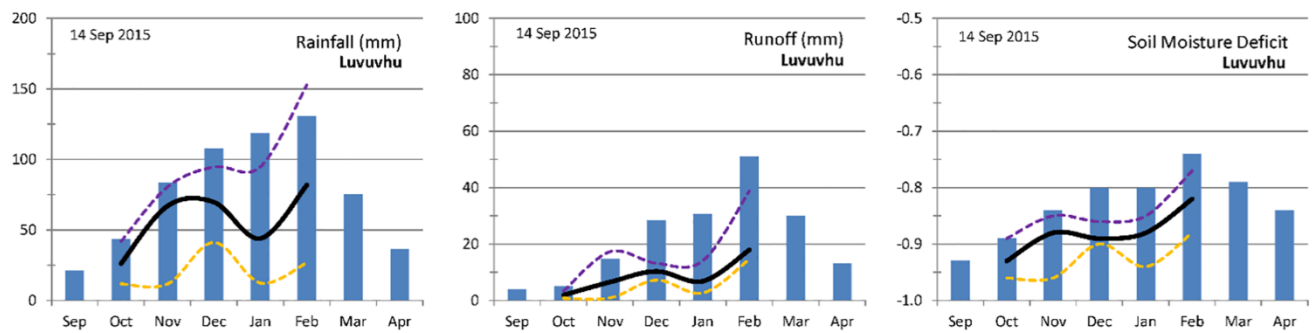


Fig. 2. Graphical forecast information used for workshops with extension officers and small-scale farmers showing rainfall, runoff and soil moisture deficit for the 2015/2016 rainfall season over Luvuvhu. The lines show the proxy forecast values, where the solid line is the forecast median and the dashed lines show maximum and minimum values. Blue bars show “normal” local conditions in the basin, which are monthly climatological values over the period 1961–1999. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

range between maximum and minimum forecasted values. Although no probabilities were given, the extension officers expressed their own understanding that this was a “forecast” and only indicative of how the rainfall season might develop. They also expressed the importance of conveying this message to farmers so that they would not get the impression that it was an absolute prediction (Andersson et al., 2020). Furthermore, they appreciated receiving the information in such a format that easily compared to climatological normal values (Wilk et al., 2017).

Five analogue years were chosen to offer a range of outcomes and thus a range of uncertainty from the hydrological outcomes in the proxy forecasts, given the constraints of the analogue selection criteria. The number was arbitrarily chosen; it could just as well have been seven, but using higher numbers would have added to the complexity of the forecast system. An alternative approach would have been to use the rainfall anomaly from each ensemble forecast member to choose 12 analogue years. Use of additional analogue years, whether chosen around the ensemble mean forecast or using each ensemble forecast member would likely provide a larger range of uncertainty around the hydrological proxy forecast. Whether or not the use of five years is a sufficient representation of uncertainty for communication of the proxy forecasts is, however, a question to be pursued in further research.

Observation data

Rainfall data for individual weather stations in South Africa is not easily accessible, the best available data being monthly summaries of station data within 94 homogenous rainfall districts from the South African Weather Service (SAWS). Data from two of these districts was used as observed rainfall for retrospective verification in the two pilot river basins, where we have selected the observations that most closely represent the two pilot river basins. Both the rainfall from the proxy forecasts and the observed district rainfall are area-wide approximations from point observation stations. It is recognized that these are area averaged observations containing considerable variability. It is also recognized that the rainfall stations used for the district rainfall are different from those used as rainfall input data for the ACUR model, which could cause discrepancies. A simple monthly adjustment based on a long-term correlation between the two datasets was therefore derived and used to make the district rainfall more comparable to the historical rainfall data used by ACUR.

River discharge for several observation stations located on the Luvuvhu and Letaba Rivers was obtained from online data provided by the South African Department of Water and Sanitation. For the purposes of this study, one station in each of these two river basins was used to illustrate river flow conditions during the forecasted time periods. Although these stations were chosen as far upstream as possible to avoid the influence of river regulation from dams, there are some regulation

effects on the observed river flows.

Sensors for local monitoring of soil moisture were installed at three sites in each of the two pilot communities – Lambani and Mokwakwaila – to collect local near real time observations and to encourage awareness and involvement within the pilot communities. The sensors were in home gardens and fields of community members or in schoolyards. Residents along with agricultural extension officers and researchers determined the locations where the sensors were installed and suitable soil depths for monitoring soil moisture. Each site had a similar configuration installed, using commercially available soil moisture sensors at three different depths – 200, 400 and 600 mm. Combined, they sense the volumetric water content in different volumes (0.2, 0.5 and 1 L) as well as temperature and conductivity. Maintenance and uploading of the soil moisture data were carried out by community members and their respective extension officers, as well as by the project team while on site visits. The choice of sensors was made to provide a system that is inexpensive, flexible, easy to install and energy efficient.

As soil moisture observations provide current information on conditions in the soil, they could also potentially be used to determine antecedent moisture conditions as an additional factor in choosing analogue years for the proxy forecast. However, the antecedent soil moisture conditions for this region are consistently dry at the onset of the rainy season and including the observations as a selection criterium was not thought to produce much impact on the initial forecasts. Using observed soil moisture to provide antecedent conditions for follow-up forecasts after the rains have started could perhaps add more benefit, but this was not investigated in this study. For such an application, it would be important to use a larger network of soil moisture sensors, preferably reporting remotely, to get better estimates of area-wide soil moisture observations.

Results

The seasonal local rainfall and hydrological forecasting system was set up and refined during the rainy season of 2013/2014. Following the procedures outlined under section 2, seasonal hydrological forecasts were produced for the 2013/2014, 2014/2015 and the beginning of the 2015/2016 rainy seasons. The proxy forecast variables from analogue years were processed into monthly median values and shown together with maximum and minimum values. Examples from the forecasted seasons are shown in Figs. 3–5. The forecasts were verified with observational data when it became available, which is also shown in Figs. 3–5. Groot Letaba is referred to as “Letaba” in the figures and sections below.

Forecasts for 2013–2015

For each of the forecasted seasons, first forecasts were made in September for October to February. Rainfall, runoff and soil moisture

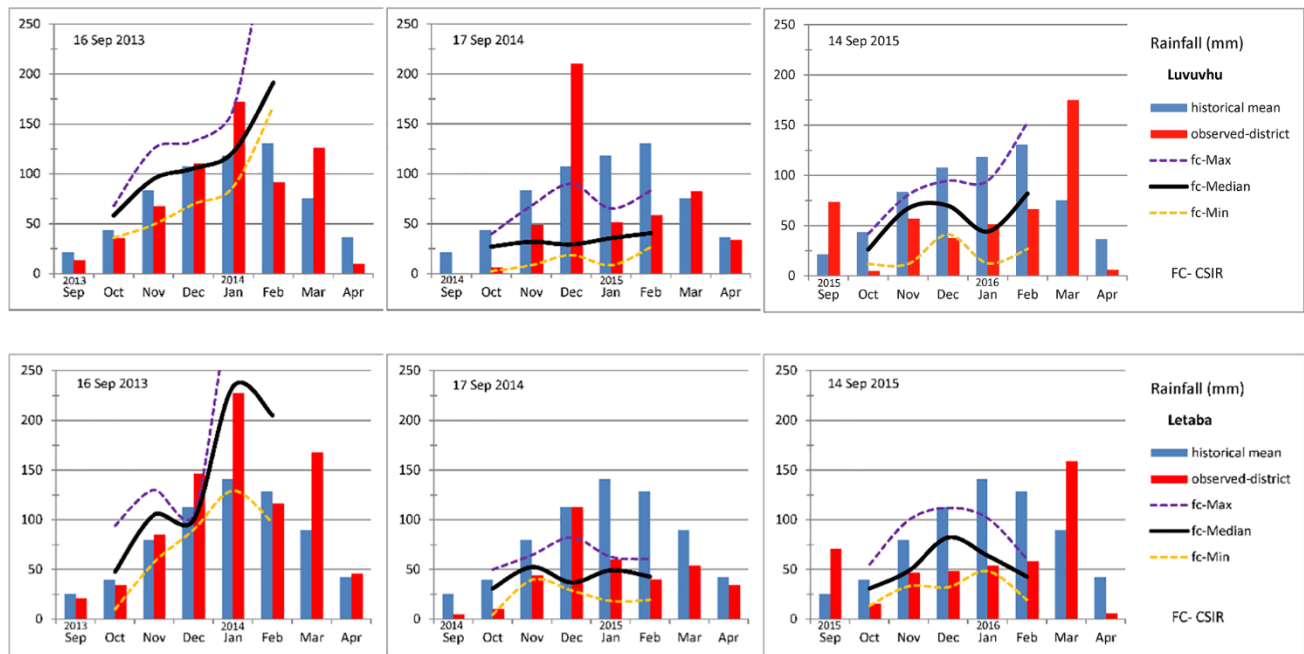


Fig. 3. Seasonal rainfall forecast for 2013/2014, 2014/2015 and 2015/2016, October and forward for Luvuvhu (upper) and Letaba (lower) River Basins. The lines show the median proxy forecast values (fc), together with the maximum and minimum values from the analogue years (note that the maximum forecast values for 2013 extend beyond the range of the Y-axis). Blue bars show monthly climatological values over the period 1961–1999 as reference. Red bars show monthly observations from SAWS district rainfall. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

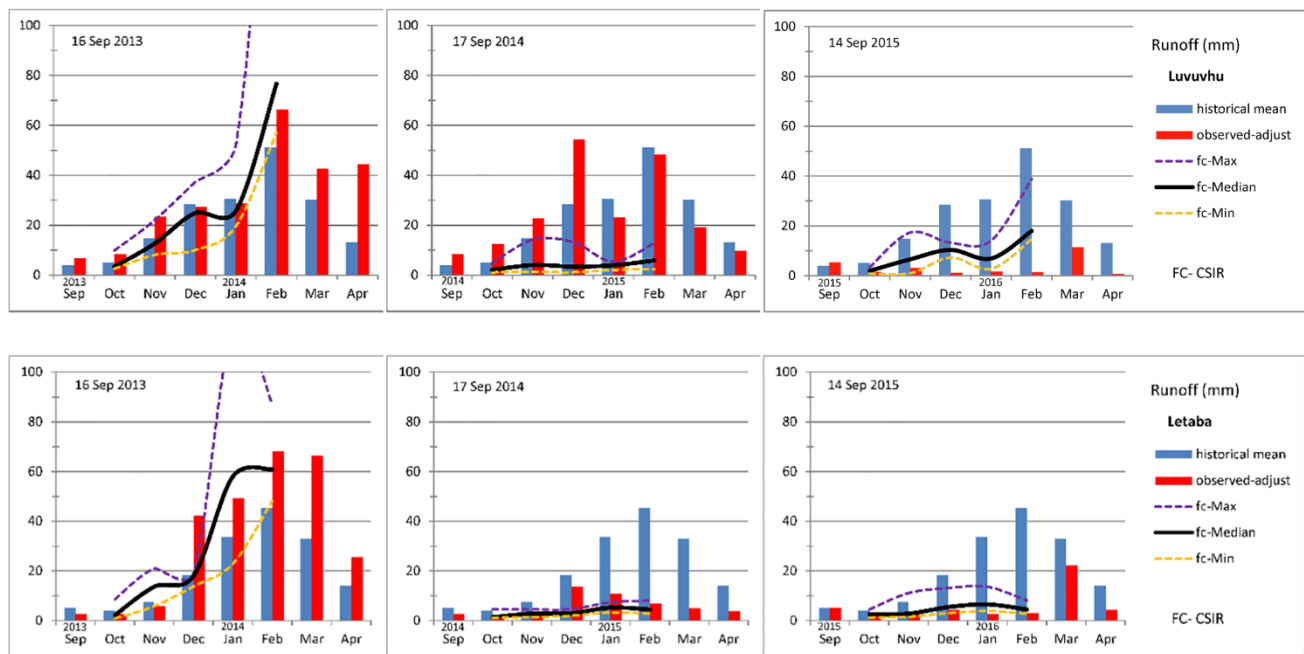


Fig. 4. Seasonal runoff forecast for 2013/2014, 2014/2015 and 2015/2016, October and forward for Luvuvhu (upper) and Letaba (lower) River Basins. The lines show the median proxy forecast values (fc), together with the maximum and minimum values from the analogue years (note that the maximum forecast values for 2013 extend beyond the range of the Y-axis). Bars show monthly climatological values over the period 1961–1999 as reference. Red bars show adjusted observed river flow from Nooitgedacht (Luvuvhu) and Grysappel (Letaba). The observed flows were first normalized to percent of normal river flow, which was then multiplied to the climatological ACRU river flows to get adjusted observed river flow values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

variables are presented for Luvuvhu and Groot Letaba in Figs. 3–5, respectively.

The proxy forecast for rainfall can be seen as a translation from the large scale forecasted 3-month rainfall anomalies to forecasted monthly rainfall over each of the two river basins. This puts the seasonal rainfall

forecast into terms that are more related to local conditions and locally expected climatological values. The first forecast for 2013 showed close to normal or normal rainfall for October through January for Luvuvhu, followed by above-normal rainfall for February (Fig. 3). This was similar for Letaba, except that even January rainfall was forecasted as above

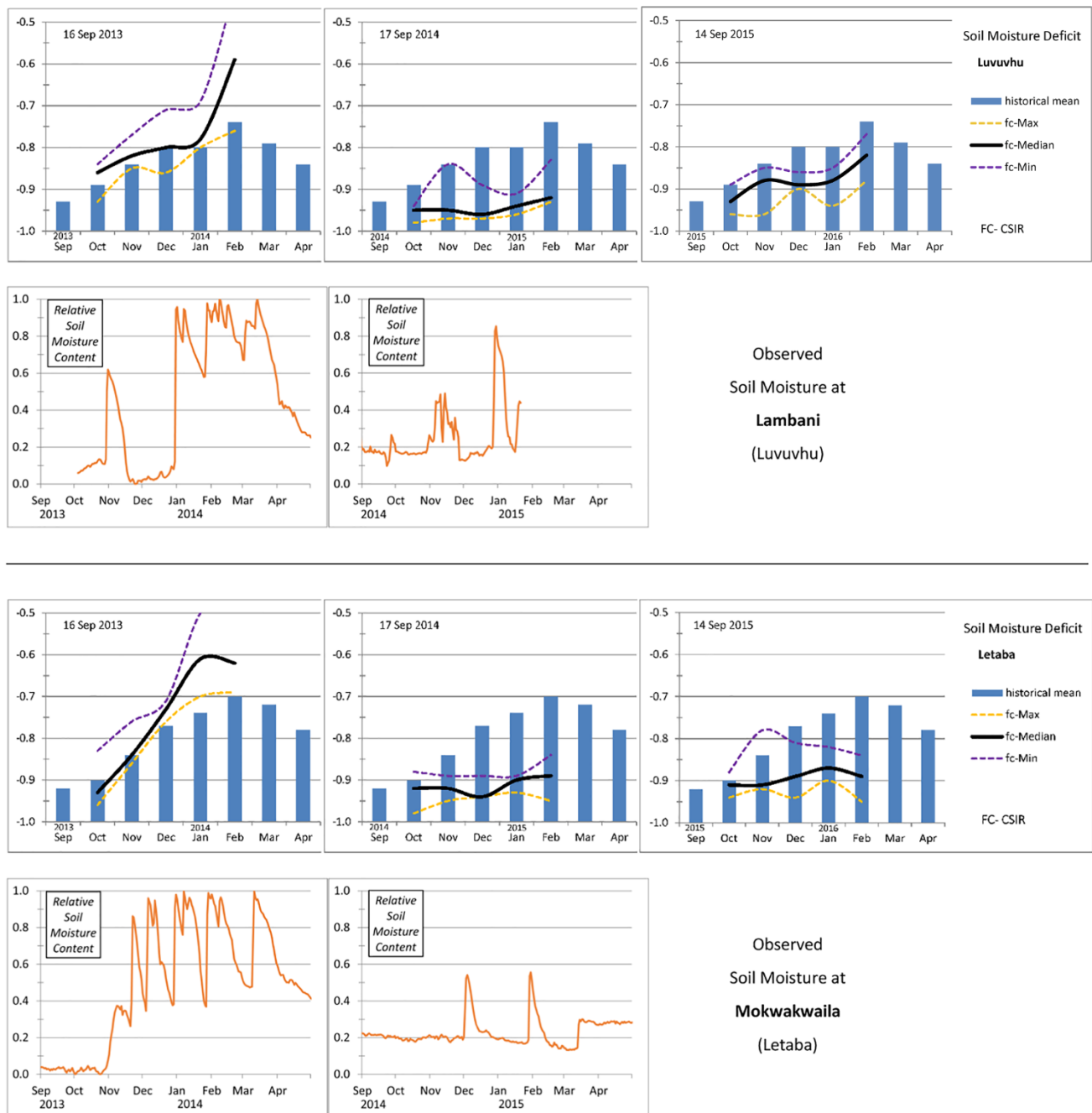


Fig. 5. Seasonal soil moisture forecast for 2013/2014, 2014/2015 and 2015/2016, October and forward for Luvuvhu (upper) and Letaba (lower) River Basins. Expressed as normalised soil moisture deficit – with values from -1 to 0 – where -1 indicates full deficit, i.e. complete lack of soil water. (Note that the Y-axis starts at -1 and that the minimum forecast values for 2013 extend beyond the range of the Y-axis). The lines show the median proxy forecast values (fc), together with the maximum and minimum values from the analogue years. Bars show monthly climatological values over the period 1961–1999 as reference. Observed relative soil moisture is shown below each forecast at Lambani (Luvuvhu) and Mokwakwaila (Letaba) – with values from 0 to 1 – where 1 is maximum observed soil moisture. Soil moisture observations were not available for the 2015/2016 rainfall season.

normal. The forecasted runoff followed the forecasted rainfall closely with near normal values for October through December for both river basins (Fig. 4). Above normal runoff was forecasted in January to February for Letaba and in February for Luvuvhu. Soil moisture values were also forecasted to be near normal early in the rainy season then above normal during January and February (Fig. 5).

The forecast for 2014 showed below normal rainfall in both Luvuvhu and Letaba, in some cases much below normal (Fig. 3). In response, in both river basins, runoff was forecasted to be much below normal (Fig. 4) with quite low soil moisture conditions (Fig. 5). The forecast for

2015 also showed below normal rainfall (Fig. 3) in both river basins. Runoff was forecasted to be much below normal (Fig. 4) and soil moisture conditions consequently as below normal (Fig. 5).

Verification

The proxy forecasts for rainfall are shown together with rainfall observations in Fig. 3 for the 2013/2014, 2014/2015 and 2015/2016 forecast seasons. For 2013/2014, the general trends in forecasted rainfall match rather well with observed outcomes. Overestimation and

underestimation of rainfall amounts is apparent, but not unreasonably so, except for January for Luvuvhu. For 2014/2015, the rainfall forecast indicated and matched observations of below normal rainfall during all months, except for December where it failed to capture the observed high rainfall, which was more than double climatological values for Luvuvhu. The forecast for 2015/2016 showed lower rainfall than normal for the entire forecast period, which is verified by the observations. Observed rainfall amounts were mostly lower than the median forecast for both Luvuvhu and Letaba.

Although it is difficult to find representative river observation stations, Fig. 4 includes observed river flow from one gauging station each on the Luvuvhu and Letaba Rivers, at Nooitgedacht and Grysappel, respectively. The observed river flows were first normalized to percent of normal river flow, which was then multiplied to the climatological ACRU river flows to get representative observed river flow values for comparison to the forecasts. River flows on the Luvuvhu derived from the Nooitgedacht station show above normal or near normal for most of 2013 and 2014, followed by below normal from early 2015. For the Letaba derived from the Grysappel station, flows were slightly below normal to above normal for 2013, followed by below normal starting in mid-2014, and extending into 2015 and 2016.

The river flow observations reflect expected responses to the observed rainfall for Letaba but are not completely in sync for Luvuvhu. Both stations show response to the higher-than-normal rainfall in January 2014 with higher river flows in successive months and both reflect the dryer conditions for the 2015/2016 season with lower river flows. Trends for the runoff forecasts for all three seasons for the most part matched well with observations for the Letaba basin. For Luvuvhu the runoff forecasts matched well with observations for 2013/2014 and 2015/2016, but not for 2014/2015 where deviations to observations were larger.

Although the two river observation stations were chosen as far upstream as possible to avoid effects of river regulation, there is some storage upstream, adding lag time between rainfall events and observed river flow. It is suspected that Nooitgedacht (Luvuvhu) is more affected by upstream storage than Grysappel (Letaba). Thus, some rainfall during wet and normal years can be stored and released as river flow over the course of the season. The response during dry years, however, appears quicker in the form of lower-than-normal river flows. This can partially explain the river flow response seen in Fig. 4, which well verifies the runoff response for dry years, but is not as conclusive for other years.

Observed relative soil moisture from one station each in Lambani and Mokwakwaila communities is shown in Fig. 5 together with the forecasts for Luvuvhu and Letaba river basins, respectively, for the 2013/2014 and 2014/2015 seasons when observations were available. As these are point measurements with only a brief period of observation, it is not relevant to compare them directly with the area-wide soil moisture deficit values produced from hydrological modelling. However, they give an indication of how wet or dry the soils are in relative terms on a scale of 0 to 1, where 0 represents the driest and 1 maximum observed soil moisture. The observed soil moisture reflects the normal to wetter conditions that were both forecasted and observed for the 2013/2014 rainfall season and the dryer conditions for 2014/2015.

Given the coarseness of available observation data and recognition of the mismatch in the location of observation stations, it is difficult to perform a rigorous verification of the forecast values. However, a skill test was applied using the limited data that was available. The Heidke Skill Score as defined by the IRI ([The International Research Institute for Climate and Society, 2021](#)) was used to assess the forecast. This skill score is used for forecasts where the value of the forecast probability is ignored and is thus suited to the type of forecasts produced here. It builds upon the hit proportion that tallies all of the forecasts that are considered correct according to observed values, and reflects discrimination, reliability and resolution.

The Heidke Skill Score is defined as below, where the expected number of hits is defined by chance. According to this test, the level

reflecting all hits is 1 and the level reflecting no skill is 0. It is also possible to attain negative values, which reflects skill lower than chance.

$$\text{Heidke Skill Score} = \frac{\# \text{hits} - \text{expected } \# \text{hits}}{\text{total } \# \text{forecasts} - \text{expected } \# \text{hits}}$$

Where,

$$\text{Expected } \# \text{hits} = \frac{\text{total } \# \text{forecasts}}{3}$$

(# = number counted)

For tallying the number of hits, a *hit* was defined as a forecast that corresponds with subsequent observed values that fall within the range for forecasted maximum and minimum values for each respective month. Table 1 shows the corresponding hit rates for both precipitation and runoff for the three seasons of forecasts performed. The total number of forecasts for each season is five.

Table 2 shows the Heidke Skill Score for precipitation and runoff corresponding to the hit rates in Table 1. The values in the table show that skill is indicated for rainfall in both Luvuvhu and Letaba for all three seasons. The skill for runoff is lower and shows better values for Letaba than for Luvuvhu for 2014/2015 and 2015/2016. In particular, Luvuvhu shows a negative skill for 2014/2015 and low skill for 2015/2016.

As mentioned above, a plausible explanation to the runoff response in Luvuvhu for 2014/2015 is the suspected effects of dam storage upstream in the basin. If that is the case, the high rainfall that occurred in December – more than double the climatological mean – could have been stored and released during the following months of January and February. Similarly, some of the above normal late rainfall from the previous season could have been stored and released during October and November. The skill for runoff for Luvuvhu may therefore be higher than indicated here. However, the data is insufficient to adequately check this hypothesis as there are no available observation stations further upstream in the basin. Regardless of whether the low skill for Luvuvhu depends on river storage effects, other complications with available observations or a poor forecast, further study is needed.

It is interesting to note that the forecast for Luvuvhu did correctly indicate below normal runoff for Luvuvhu for all forecast months for 2015/2016. The observations, however, show even lower runoff than the forecasted minimum. If the definition of hits for the Heidke Skill Score were relaxed to be below the forecasted maximum for below normal conditions, the skill in this case would be 1 instead of 0.1; the same goes for rainfall. Although the skill scores provide a quantitative means for verifying the forecasts, with consideration to the quality and scale of observations, we evaluated them together with a qualitative assessment of the outcomes from the forecasts.

Limitations

The work presented here is based on one set of seasonal forecasts produced by CSIR. This forecast implicitly includes a range of seasonal predictions by using an ensemble mean approach, but the size of the ensemble is limited and based on only one forecast model. The primary

Table 1

Hit rates for forecasted values for Luvuvhu and Letaba for rainfall seasons 2013/2014, 2014/2015 and 2015/2016.

	2013/2014	2014/2015	2015/2015	3-season Total
Rainfall				
Luvuvhu	3 (of 5)	4 (of 5)	3 (of 5)	10 (of 15)
Letaba	4 (of 5)	4 (of 5)	5 (of 5)	13 (of 15)
Runoff				
Luvuvhu	4 (of 5)	0 (of 5)	2 (of 5)	7 (of 15)
Letaba	4 (of 5)	3 (of 5)	4 (of 5)	11 (of 15)

Table 2

Heidke Skill Score for forecasted values for Luvuvhu and Letaba for rainfall seasons 2013/2014, 2014/2015 and 2015/2016.

	2013/2014	2014/2015	2015/2016
Rainfall			
Luvuvhu	0.40	0.70	0.40
Letaba	0.70	0.70	1.00
Runoff			
Luvuvhu	0.70	−0.50	0.10
Letaba	0.70	0.40	0.70

motivation for using these forecasts is that 1) they have been tested in the region for some time, 2) they provide a deterministic forecast that can easily provide inputs to the hydrological forecast, and 3) they were readily available. We have not made any attempt to use other seasonal forecast products. When applying this approach to other regions, a preliminary assessment of appropriate seasonal forecast products for that region should first be made. Also, increasing the size of the global rainfall forecast ensemble and/or more explicitly using the ensemble forecast members could potentially enhance the quality of the forecast. However, this would have to be weighed against ease of access; if such ensemble forecast products are not readily available, this would increase the level of complexity for producing the hydrological forecast.

An alternative approach to using the anomaly forecast would have been to apply bias-correction techniques directly to the forecasted rainfall fields produced by CCAM (e.g., [Yang et al., 2010](#)). Such an approach was rejected as, 1) the amount of bias could be substantial, 2) it is questionable if such an approach is scientifically sound for the spatial scales being applied, 3) access to adequate observations data is limited, and 4) the aim was to use a pragmatic approach that can easily be applied and that requires few inputs. Applying only anomaly values limits the influence of systematic biases from the global forecast model.

All forecasts presented in this paper are based on seasonal rainfall forecasts. No attempt has been made to include information from the seasonal temperature forecast. The assumption was made that rainfall in the test region is correlated with temperature, such that rainfall could in the first instance be used as the primary predictor for the hydrological forecast. A next step in further developing this approach could be to test if inclusion of the temperature forecast would improve the hydrological forecast. If this proved to be the case, it would imply that a multi-criteria approach that includes both rainfall and temperature could be used for selecting the proxy events that form the hydrological forecast.

Tests over three seasons show promise, as forecasted local rainfall matched observations relatively well, with exception of the extreme rainfall event in December 2014. Yet a much more rigorous testing is warranted for additional rainfall seasons and other river basins to further assess the approach. In identifying additional river basins for testing, greater emphasis should be placed on availability of adequate local observations for rainfall, river flow and soil moisture. Good cooperation was attained with researchers and extension officers from LDARD during the pilot project, including training on creating local forecasts with this system. Further development would benefit from more extensive collaboration with and training of local and regional officers.

Conclusions and recommendations

This paper describes a simple local seasonal forecast system for calculating rainfall and hydrological conditions expected in the coming months, particularly before and at the beginning of the rainy season. Transforming seasonally forecasted anomalies of rainfall into proxy forecast values could be considered a “poor man’s” downscaling of rainfall from global seasonal forecasts to local catchment values. Use of identified analogue years transforms the seasonal rainfall anomalies into

local rainfall and additional hydrological forecast information. The simple approach could be useful to agricultural extension officers and small-scale farmers as local rainfall forecasts provide more relevant information for their needs, and forecasted river flow and soil moisture conditions could help guide their planting and herd management strategies.

Results indicate that for the three years of the study, the local rainfall forecasts matched the observations relatively well in both the wetter (2013/2014) and dryer (2014/2015, 2015/2016) than normal seasons. The forecast matched best for the wettest season (2013/2014) and the driest season (2015/2016). For 2014/2015 the forecast predictions for dryer conditions were close to those observed except for the month of December, which was characterised by extremely high rainfall in Luvuvhu and near normal rainfall in Letaba, greatly exceeding the forecast for this month. The Heidke Skill Score indicates skill for rainfall for both basins during all three seasons.

The forecasted runoff in the wetter (2013/2014) and dryer (2015/2016) seasons also matched the trends in river flow observations in both river basins. For 2014/2015, the forecasted runoff predicted below normal conditions for Letaba that matched well with observations with the exception for December where observed values were closer to normal. The forecasted river flow trends for Luvuvhu, however, were considerably lower than observations for 2014/2015. Correspondingly, the Heidke Skill Score shows some skill for both basins during all three seasons, with the exception for Luvuvhu during 2014/2015. Some of the runoff mis-match may be explained by upstream river regulation that is thought to have greater impact on river flow observations from the Luvuvhu station than for the Letaba station or it may be the result of a poor forecast; further testing is thus needed.

Data from the simple soil moisture sensors in the two pilot communities reflected the wetter conditions forecasted and observed in the 2013/2014 rainfall season and the dryer conditions of 2014/2015. Soil moisture observations were not available for 2015/2016. More extensive use of such observations could provide additional information to help confirm or deny forecast information as the rainfall season progresses.

The forecasts produced can therefore be said to provide indicative assessments of hydrological conditions, based on the three years in this study, but the predictability could differ depending on ENSO phases. The local rainfall forecasts showed higher skill than those for runoff. The forecasts showed best predictability in the two pilot areas during the strong El Niño phase of ENSO during 2015/2016. They proved somewhat less predictable during the weak El Niño phase of 2014/2015 and during the neutral conditions of 2013/2014. This generally follows conclusions by other studies that have identified a stronger forecast relationship for El Niño rainfall in this region (e.g., [Landman and Beraki, 2012](#)). As it is well established that El Niño usually results in dry summer conditions for the Limpopo River Basin ([Reason et al., 2005](#)), this indicates that the forecasts may be more usable for predicting dryer rainfall seasons.

The methods used in the proxy approach do not require sophisticated calculations or a complex operational environment. Although the initial setup entails hydrological modelling that covers the target area, continuous operational modelling is not needed to produce the hydrological forecast. This provides a robust way to transfer the seasonal rainfall anomaly forecast into the seasonal hydrological forecast, which in principle would not necessarily require hydrological or meteorological experts to run operationally. However, a good level of understanding for meteorology and hydrology is recommended, which could be attained through collaborative training events for regional extension officers. As a key aim was to keep the forecast methodology simple and pragmatic, the possibility to establish this as a service at provincial departments should be investigated, on the condition that good cooperation is established with a national or regional provider of meteorological seasonal forecasts.

Although promising results were obtained for this three-year study, it

is recognized that the period of study was too short for more rigorous testing and verification. Further testing over additional forecast seasons is certainly warranted. In addition, the methodology could potentially be further improved and tested by:

- 1) techniques to incorporate the seasonal temperature forecast and further refine selection of analogue forecast years,
- 2) extension of the historical database and updating hydrological model results to include more recent years, and
- 3) extended use of locally monitored data such as rainfall and soil moisture.

CRedit authorship contribution statement

L. Phil Graham: Conceptualization, Methodology, Formal analysis, Software, Investigation, Writing – original draft. **Lotta Andersson:** Conceptualization, Methodology, Investigation, Project administration, Funding acquisition, Writing – review & editing. **Michele Warburton Toucher:** Methodology, Formal analysis, Software, Writing – original draft. **J. Jacob Wikner:** Conceptualization, Methodology, Software, Investigation, Project administration, Funding acquisition, Writing – review & editing. **Julie Wilk:** Conceptualization, Methodology, Investigation, Funding acquisition, Writing – original draft.

Declaration of Competing Interest

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.

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References

- Amegnaglo, C.J., Anaman, K.A., Mensah-Bonsu, A., Onumah, E.E., Gero, F.A., 2017. Contingent valuation study of the benefits of seasonal climate forecasts for maize farmers in the Republic of Benin, West Africa. *Clim. Serv.* 6, 1–11. <https://doi.org/10.1016/j.cliser.2017.06.007>.
- Andersson, L., Wilk, J., Graham, L.P., Wikner, J.J., Mokwatlo, S., Petja, B., 2020. Local early warning systems for drought – could they add value to nationally disseminated seasonal climate forecasts? *Weather Clim. Extremes* 28. <https://doi.org/10.1016/j.wace.2019.100241>.
- Archer, E., Engelbrecht, F., Hänsler, A., Landman, W., Tadross, M., Helmschrot, J., 2018. Seasonal prediction and regional climate projections for southern Africa. In: *Climate change and adaptive land management in southern Africa – assessments, changes, challenges, and solutions* (ed. by Revermann, R., Krewenka, K.M., Schmiedel, U., Olwoch, J.M., Helmschrot, J. and Jürgens, N.), pp. 14–21. *Biodiversity & Ecology*, 6, Klaus Hess Publishers, Göttingen & Windhoek:10.7809/b-e.00296.
- Becker, E.J., van den Dool, H., Peña, M., 2013. Short-term climate extremes: Prediction skill and predictability. *J. Clim.* 26 (2), 512–531.
- Charney, J.G., Shukla, J., 1981. Predictability of monsoons, in: *Monsoon Dynamics*, edited by: Lighthill, S.J. and Pearce, R.P., Cambridge University Press., Cambridge, UK, 99–110.
- Cowan, T., Wheeler, M.C., Alves, O., Narsey, S., de Burgh-Day, C., Griffiths, M., Jarvis, C., Cobon, D.H., Hawcroft, M.K., 2019. Forecasting the extreme rainfall, low temperatures, and strong winds associated with the northern Queensland floods of February 2019. *Weather Clim. Extremes* 26, 100232.
- Day, G., 1985. Extended Streamflow Forecasting Using NWSRFS, J. Water Resour. Plann. Manag. 111, 157–170. [https://doi.org/10.1061/\(ASCE\)0733-9496\(1985\)111:2\(157\)](https://doi.org/10.1061/(ASCE)0733-9496(1985)111:2(157)).
- Engelbrecht, F.A., Landman, W.A., Engelbrecht, C.J., Landman, S., Roux, B., Bopape, M. M., McGregor, J.L., Thatcher, M., 2011. Multi-scale climate modelling over southern Africa using a variable resolution global model. *Water SA* 37, 647–658.
- Forbes, K.A., Kienzie, S.W., Coburn, C. A., Byrne, J.M., Rasmussen J., 2010. Simulating the hydrological response to predicted climate change on a watershed in southern Alberta, Canada. *Clim. Change*, 10.1007/s10584-010-9890-x.
- Graham, L.P., Andersson, L., Horan, M., Kunz, R., Lumsden, T., Schulze, R., Warburton, M., Wilk, J., Yang, W., 2011. Using multiple climate projections for assessing hydrological response to climate change in the Thukela River Basin, South Africa. *Phys. Chem. Earth*. 36, 727–735.
- Hammer, G.L., Hansen, J.W., Phillips, J.G., Mjeldec, J.W., Hill, H., Love, A., Potgieter, A., 2001. Advances in application of climate prediction in agriculture. *Agric. Syst.* 70, 515–553.
- Hansen, J.W., Mason, S.J., Liqiang, S., Tall, A., 2011. Review of seasonal climate forecasting for agriculture in sub-Saharan Africa. *Expr. Agr.* 47, 205–240.
- Hao, Z., Singh, V.P., Xia, Y., 2018. Seasonal drought prediction: Advances, challenges, and future prospects. *Rev. Geophys.* 56, 108–141. <https://doi.org/10.1002/2016RG000549>.
- Hargreaves, G.H., Samani, Z.A., 1985. Reference crop evapotranspiration from temperature. *Trans. ASAE* 1, 96–99.
- International Research Institute for Climate and Society (IRI), 2021. Descriptions of the IRI Climate Forecast Verification Scores. Downloaded Nov 2021. <https://iri.columbia.edu/wp-content/uploads/2013/07/scoredescriptions.pdf>.
- Jewitt, G.P.W., Schulze, R.E., 1999. Verification of the ACRU model for forest hydrology applications. *Water SA* 25, 483–489.
- Jewitt, G.P.W., Garratt, J.A., Calder, I.R., Fuller, L., 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Phys. Chem. Earth* 29, 1233–1241.
- Johnston, P.A., Archer, E.R.M., Vogel, C.H., Bezuidenhout, C.N., Tennant, W.J., Kuschke, R., 2004. Review of seasonal forecasting in South Africa: producer to end-user. *Clim. Res.* 28, 67–82.
- King, A.D., Hudson, D., Lim, E.P., Marshall, A.G., Hendon, H.H., Lane, T.P., Alves, O., 2020. Sub-seasonal to seasonal prediction of rainfall extremes in Australia. *Q. J. R. Meteorol. Soc.* 146 (730), 2228–2249.
- Klemm, T., McPherson, R.A., 2017. The development of seasonal climate forecasting for agricultural producers. *Agric. For. Meteorol.* 232, 384–399.
- Landman, W.A., 2014. How the International Research Institute for Climate and Society has contributed towards seasonal climate forecast modelling and operations in South Africa. *Earth Perspect.* 1, 22.
- Landman, W.A., Beraki, A., 2012. Multi-model forecast skill for mid-summer rainfall over southern Africa, 2012. *Int. J. Climatol.* 32, 303–314.
- Landman, W.A., Botes, S., Goddard, L., Shongwe, M., 2005. Assessing the predictability of extreme rainfall season over southern Africa. *Geophys. Res. Lett.* 32, L23818. <https://doi.org/10.1029/2005GL023965>.
- Landman, W.A., DeWitt, D., Lee, D.-E., Beraki, A., Lötter, D., 2012. Seasonal rainfall prediction skill over South Africa: 1- vs. 2-tiered forecasting systems. *Weather Forecast.* 27, 489–501. <https://doi.org/10.1175/WAF-D-11-00078.1>.
- Landman, W.A., Mason, S.J., Tyson, P.D., Tennant, W.J., 2001. Retro-active skill of multi-tiered forecasts of summer rainfall over southern Africa. *Int. J. Climatol.* 21, 1–19. <https://doi.org/10.1002/joc.592>.
- Landman, W.A., Archer, E.R., Tadross, M.A., 2020. Citizen science for the prediction of climate extremes in South Africa and Namibia. *Front. Clim.* 2, 5. <https://doi.org/10.3389/fclim.2020.00005>.
- Lynch, S.D., 2004. The Development of a Raster Database of Annual, Monthly, Daily Rainfall for Southern Africa, Water Research Commission, South Africa, Rep. 1156/1/04.
- MacLeod, D., Klassen, S., 2019. A practical guide to seasonal forecasts, Issues 1–5. Science for Humanitarian Emergencies & Resilience (SHEAR).
- Malherbe, J., Landman, W.A., Olivier, C., Sakuma, H., Luo, J.-J., 2014. Seasonal forecasts of the SINTEX-F coupled model applied to maize yield and streamflow estimates over north-eastern South Africa. *Meteorol. Appl.* 21, 733–742.
- Marshall, N.A., Gordon, L.J., Ash, A.J., 2011. The reluctance of resource-users to adopt seasonal climate forecasts to enhance resilience to climate variability on the rangelands. *Clim. Change* 107, 511–529.
- Masih, I., Maskey, S., Mussá, F.E.F., Trambauer, P., 2014. A review of droughts on the African continent: a geospatial and long-term perspective. *Hydrol. Earth Syst. Sci.* 18, 3635–3649. <https://doi.org/10.5194/hess-18-3635-2014>.
- McGregor, J.L., Dix, M.R., 2008. An updated description of the Conformal-Cubic Atmospheric Model. In: Hamilton, K., Ohfuchi, W. (Eds.), *High Resolution Simulation of the Atmosphere and Ocean*. Springer, pp. 51–76.
- Muita, R., Dougill, A., Mutemi, J., Aura, S., Graham, R., Awolala, D., Nkiaka, E., Hiron, L., Opjah, F., 2021. Understanding the role of user needs and perceptions related to sub-seasonal and seasonal forecasts on farmers' decisions in Kenya: a systematic review. *Front. Clim.* 3 <https://doi.org/10.3389/fclim.2021.580556>.
- Mulenga, H.M., Rouault, M., Reason, C.J.C., 2003. Dry summers over NE South Africa and associated circulation anomalies. *Clim. Res.* 25, 29–41.
- Muya, C.P., Annor-Frempong, F.K., Magheni, M.N., Agunga, R., Igodan, C., Ladele, A.A., Huhela, K., Tselaesele, N.M., Msatiolomo, H., Chowa, C., Zwane, E., 2017. The role of agricultural extension in Africa's development, the importance of extension workers and the need for change. *Int. J. Agric. Extens.* 5 (1), 51–58.
- National Land Cover (NLC), 2000. Produced by Council for Scientific and Industrial Research (CSIR) and Agricultural Research Council (ARC) consortium. Pretoria, South Africa.
- O'Brien, K., Vogel, C., 2003. Coping with Climate Variability: The Use of Seasonal Climate Forecasts in Southern Africa. Ashgate, Aldershot, UK.

- Pepler, A.S., Díaz, L.B., Prodhomme, C., Doblas-Reyes, F.J., Kumar, A., 2015. The ability of a multi-model seasonal forecasting ensemble to forecast the frequency of warm, cold and wet extremes. *Weather Clim. Extremes* 9, 68–77.
- Perks, L. A., 2001. Refinement of Modelling Tools to Assess Potential Agrohydrological Impacts of Climate Change in Southern Africa, Ph.D thesis, School of Bioresources Engineering and Environmental Hydrology, University of Natal, South Africa, 463 pp.
- Pitman, W.V., Bailey, A.K., 2021. Can CHIRPS fill the gap left by the decline in the availability of rainfall stations in Southern Africa? *Water SA* 47 (2), 162–171. <https://doi.org/10.17159/wsa/2021.v47.i2.10912>.
- Pulwarthy, R.J.S., Sivakumar, M.V.K., 2014. Information systems in a changing climate: early warnings and drought risk management. *Weather Clim. Extremes* 3, 14–21.
- Reason, C.J.C., Hachigonta, S., Phaladi, R.F., 2005. Interannual variability in rainy season characteristics over the Limpopo region of southern Africa. *Int. J. Climatol.* 25, 1835–1853. <https://doi.org/10.1002/joc.1228>.
- Schulze, R.E. (Ed.), 1995 Hydrology and Agrohydrology: A Text to Accompany the ACRU 3.00 Agrohydrological Modelling System. Water Research Commission, South Africa, 552 pp.
- Schulze, R.E., 2000. Modelling hydrological responses to land use and climate change: A southern African Perspective. *Ambio* 29, 12–22.
- Schulze, R. E., 2005. Selection of a suitable agrohydrological model for climate change impact studies over southern Africa, in: Schulze, R.E. (Ed): *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*, Water Research Commission, South Africa, Rep. 1430/1/05, 95–110.
- Schulze, R.E., Lorentz, S., Kienzie, S., Perks, L., 2004. Case Study 3: Modelling the impacts of land use and climate change on hydrological responses in the mixed underdeveloped/developed Mgeni Catchment, South Africa. In: Kabat, P., Claussen, M., Dirmeyer, P.A., Gosh, J.H.C., De Guenni, L.B., Meybeck, M., Pielke, R. A., Vörösmarty, C.J., Hutjes, R.W.A., Lütkeemeier, S. (Eds.), *Vegetation, Water, Humans and the Climate: A new perspective on an interactive system*. Springer, Germany, pp. 441–453.
- Schulze, R. E., Maharaj, M., 2004. Development of a Database of Gridded Daily Temperatures for Southern Africa, Water Research Commission, South Africa, Rep. 1156/2/04, 83 pp.
- Schulze, R. E., Maharaj, M., Warburton, M. L., Gers, C. J., Horan, M.J.C., Kunz, R. P., Clark, D. J., 2008. Electronic data accompanying the South African Atlas of Climatology and Agrohydrology, Water Research Commission, South Africa, Rep. 1489/1/08.
- Sheffield, J., Wood, E.F., Chaney, N., Guan, K., Sadri, S., Yuan, X., Olang, L., Amani, A., Ali, A., Demuth, S., Ogallo, L., 2014. A drought monitoring and forecasting system for Sub-Saharan African water resources and food security. *Bull. Am. Meteorol. Soc.* 95, 861–882. <https://doi.org/10.1175/BAMS-D-12-00124.1>.
- Shukla, S., McNally, A., Husak, G., Funk, C., 2014. A seasonal agricultural drought forecast system for food-insecure regions of East Africa. *Hydrol. Earth Syst. Sci.* 18 (10), 3907–3921. <https://doi.org/10.5194/hess-18-3907-2014>.
- Shukla, S., Sheffield, J., Wood, E.F., Lettenmaier, D.P., 2013. On the sources of global land surface hydrologic predictability. *Hydrol. Earth Syst. Sci.* 17, 2781–2796. <https://doi.org/10.5194/hess-17-2781-2013>.
- Slingo, J., Palmer, T., 2011. Uncertainty in weather and climate prediction. *Philos. Trans. Roy. Soc. A* 369, 4751–4767. <https://doi.org/10.1098/rsta.2011.0161>.
- Smithers, J.C., Schulze, R.E., 2004. ACRU Agrohydrological Modelling System: User Manual Version 4.00, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, South Africa.
- Sutanto, S.J., Wetterhall, F., Van Lanen, H.A., 2020. Hydrological drought forecasts outperform meteorological drought forecasts. *Environ. Res. Lett.* 15 (8), 084010.
- Taljaard, J.J., 1986. Change of rainfall distribution and circulation patterns over Southern Africa in summer. *J. Climatol.* 6, 579–592.
- Tarboton, K.C., Schulze, R.E., 1992. Distributed hydrological modelling system for the Mgeni Catchment. Water Research Comm., South Africa, Rep.
- Trambauer, P., Werner, M., Winsemius, H.C., Maskey, S., Dutra, E., Uhlenbrook, S., 2015. Hydrological drought forecasting and skill assessment for the Limpopo River basin, southern Africa. *Hydrol. Earth Syst. Sci.* 19, 1695–1711. <https://doi.org/10.5194/hess-19-1695-2015>.
- Usman, M.T., Reason, C.J.C., 2004. Dry spell frequencies and their variability over southern Africa. *Clim. Res.* 26, 199–211.
- Warburton, M.L., Schulze, R.E., Jewitt, G.P.W., 2010. Confirmation of ACRU model results for applications in land use and climate change studies. *Hydrol. Earth Syst. Sci.* 14, 2399–2414.
- Warburton, M.L., Schulze, R.E., Jewitt, G.P.W., 2012. Hydrological impacts of land use change in three diverse South African catchments. *J. Hydrol.* <https://doi.org/10.1016/j.jhydrol.2011.10.028>.
- Wilk, J., Andersson, L., Graham, L.P., Wikner, J.J., Mokwatlo, S., Petja, B., 2017. From forecasts to action – what is needed to make seasonal forecasts useful for South African smallholder farmers? *Int. J. Disaster Risk Reduct.* 25, 202–211.
- Winsemius, H.C., Dutra, E., Engelbrecht, F.A., Archer van Garderen, E., Wetterhall, F., Pappenberger, F., Werner, M.G.F., 2014. The potential value of seasonal forecasts in a changing climate in southern Africa. *Hydrol. Earth Syst. Sci.* 18, 1525–1538. <https://doi.org/10.5194/hess-18-1525-2014>.
- World Meteorological Organization (WMO), 2021a. Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes (1970–2019). MO-No. 1267. Geneva, Switzerland.
- World Meteorological Organization (WMO), 2021b. State of Climate Services, Water. MO-No. 1278. Geneva, Switzerland.
- Yang, W., Andréasson, J., Graham, L.P., Olsson, J., Rosberg, J., Wetterhall, F., 2010. Distribution based scaling to improve usability of regional climate model projections for hydrological climate change impacts studies. *Hydrol. Res.* 41, 211–229.
- Yossef, N.C., Winsemius, H., Weerts, A., van Beek, R., Bierkens, M.F.P., 2013. Skill of a global seasonal streamflow forecasting system, relative roles of initial conditions and meteorological forcing. *Water Resour. Res.* 49, 4687–4699. <https://doi.org/10.1002/wrcr.20350>.
- Yuan, X., Wood, E.F., Chaney, N.W., Sheffield, J., Kam, J., Liang, M., Guan, K., 2013. Probabilistic Seasonal Forecasting of African Drought by Dynamical Models. *J. Hydrometeorol.* 14, 1706–1720. <https://doi.org/10.1175/jhm-d-13-054.1>.