Agricultural groundwater management strategies and seasonal climate forecasting: perceptions from Mogwadi (Dendron), Limpopo, South Africa

A. L. Fallon, K. G. Villholth, D. Conway, B. A. Lankford and G. Y. Ebrahim

ABSTRACT

This paper explores the agricultural groundwater management system of Mogwadi (Dendron), Limpopo, South Africa – an area associated with intensive use of hard rock aquifers for irrigation – and the potential contribution of seasonal forecasts. These relatively shallow aquifers are often perceived as 'self-regulating', yet climate variability and infrequent recharge episodes raise the question of whether seasonal forecasting could contribute to more sustainable groundwater use. Hydro-meteorological observations, interviews and repeat focus groups with commercial farmers were used to examine this question for the 2014–15 rainfall season, with follow-up interviews during the 2015–16 El Niño season. Two long-term borehole series showed effects of episodic recharge events and management interventions. Comparison of formal and informal management practices highlighted important contrasts: a perceived lack of formal coordination within governing bodies, contrary to high levels of informal coordination between farmers despite a persistent 'tragedy of the commons' problem. Seasonal forecast use was limited due to lack of awareness and understanding of their relevance, low credibility and trust of forecasts, and poor dissemination. Farmers expressed increased interest in such information after the 2015–16 drought, if tailored to their needs. Increased uptake is, however, contingent on complementary groundwater monitoring network improvements and enhanced cooperation between stakeholder groups.

Key words | agriculture, climate variability, commercial farmers, groundwater management, seasonal forecast, South Africa

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INTRODUCTION

South Africa's groundwater and climate variability

Much of southern Africa has a semi-arid rainfall regime (400–650 mm yr^{-1}) with high inter-annual variability, presenting challenges for water resources management in the region. Regional stream flows are unevenly distributed and display high levels of variability and widespread ephemeral character across a range of spatial and temporal scales (Conway *et al.* 2009).

High potential evapotranspiration results in exceptionally low conversion of rainfall to runoff (e.g., on average 5.1% in the Orange and Limpopo River Basins (Ashton & Hardwick 2008). Extensive regions within Africa regularly experience prolonged droughts that are often followed by intense rainfall events. In East Africa (Tanzania), highly episodic recharge events have been observed to occur from anomalously intense seasonal rainfall associated with the El Niño-Southern Oscillation and the Indian Ocean Dipole modes of climate variability (Taylor *et al.* 2013). This suggests nonlinear

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relationships between rainfall and recharge. However, apart from isolated case studies, the interactions between climate variability (on daily to seasonal timescales), recharge and groundwater storage are generally poorly understood, particularly in semi-arid and southern African contexts.

It has been argued that more use of groundwater is critical in helping communities and countries build resilience to climate change and its effects on variability in runoff and recharge, yet there is limited knowledge of African groundwater resources and their response to climate variability and change (MacDonald *et al.* 2011, 2012). Groundwater resources are also seen as increasingly important in drought adaptation in sub-Saharan Africa by providing a buffer to surface water during dry seasons or drought (Hetzel *et al.* 2008; Braune & Xu 2010). However, policy response to drought in the region is generally short-term and reactive with ad-hoc expansion of groundwater drilling and abstraction, thus undermining groundwater's potential role in long-term integrated planning for water security (Wellfield Consulting Services & British Geological Survey 2003).

Shallow (less than 100 m deep) aquifers are frequently perceived as 'self-regulating', indicating that the inherent relatively small storage volume will be the key constraining factor putting a break on pumping, as opposed to deep and large-storage aquifers that will not, in the short term, show signs of physical exhaustion (Scanlon *et al.* 2012). Similarly, these aquifers will relatively easily and naturally recuperate during large recharge events. Hence, it could be argued that pro-active management is less dire. This is particularly the case for hard rock aquifers that typically display shallow and fractured characteristics. However, these aquifers underlie relatively large population densities across southern Africa and are particularly prone to drought, and therefore represent vulnerable contexts for water security (Villholth *et al.* 2013). Where climate variability is high, recharge episodes can be infrequent and subsequent drought leads to extra pressure on aquifers, raising questions about the need for and suitability of additional management efforts. Such efforts include seasonal climate forecasting, which could enhance the sustainable use of these aquifers, in particular their use as a buffer during periods of drought.

Seasonal forecasts and agricultural water use

The South African agricultural sector faces chronic stress associated with extreme weather events and multi-year climate variability, yet adoption of seasonal climate information in agricultural decision-making has been limited (Haigh *et al.* 2015). This is paradoxical since farmers in South Africa tend to respond to seasonal variability rather than projections of future climatic change (Thomas *et al.* 2007).

Seasonal climate forecasts provide outlooks of rainfall and temperature for the rainy season of a region, typically produced at least once a month, in advance of the next rainy season progressively as a three-month average (Johnston 2008). They provide early warnings of dry conditions with implications for climate-sensitive sectors. Such forecasts have been identified as a useful entry-point for addressing climate change and variability by dealing with short-term climate-related problems, and building capacity to utilise climate information (Ziervogel *et al.* 2010; Conway 2011). This is particularly pertinent in semi-arid countries such as South Africa, with highly variable rainfall regimes (Johnston *et al.* 2004), in part associated with El Niño events, which typically bring about below-average rainfall conditions and drought (Nicholson & Kim 1997).

There are, however, constraints to the use and benefits of seasonal forecasts in agriculture, often between end-users and producers. These include credibility (i.e., perceived technical quality and authority of information), salience (i.e., the utility of information and perceived relevance to users' needs), legitimacy (i.e., perception that the forecast producers seek the users' interests) and understanding of the forecasts (see, for example, Blench 1999; Cash *et al.* 2003; Patt *et al.* 2007; Ziervogel *et al.* 2010; Hansen *et al.* 2011).

While seasonal forecasts are generally applied to rainfed agriculture (Johnston 2008), this paper rather considers their potential as a tool for medium-term (seasons to years) management of heavily exploited shallow aquifers in South Africa, where groundwater is critical for irrigation and seasonal forecasts are produced nationally and downscaled for provincial use.

Aims

This paper examines groundwater management in the farming town of Dendron (now formally known as 'Mogwadi' for political reasons, after a country-wide shift away from

Afrikaans-named towns) in the Limpopo River Basin in South Africa, and considers current and potential use of seasonal forecasts in long-term resource management and in the context of intensive use for agriculture. The linkages between climate variability and management strategies are explored for the benefit of agricultural groundwater use. The contention is that with better knowledge and planning of groundwater replenishment as informed by seasonal forecasts, farmers could improve the formulation of their cropping and irrigation plans, and be better equipped to collectively manage their groundwater resources sustainably.

The paper explores the following questions and is structured accordingly. First, what is the current understanding among farmers regarding climate variability and groundwater interactions? Second, how are groundwater resources managed in Mogwadi (Dendron), and what is the perceived effectiveness of formal and informal strategies in sustaining its aquifers? Third, how are seasonal climate forecasts utilised within this management system, and what are the key influencing factors? Finally, how can seasonal forecasts, and broader groundwater management strategies, be improved within the context of Mogwadi (Dendron)?

The surge of focus and activity surrounding seasonal forecasting in southern Africa following the 1983–84 El Niño has waned in recent years (Hansen *et al.* 2011). However, with a strong but eventually incorrect El Niño forecast in 2014–15 and a strong and correct El Niño forecast for the 2015–16 rainfall season in southern Africa (associated with widespread drought during October–December), it is particularly timely to revisit seasonal forecast applications but in a more novel context (groundwater management).

Mogwadi (Dendron) was chosen as a case study due to historical extensive use of groundwater. Further, despite a high number of consultancy reports published since the 1960s raising concerns of over-abstraction, there has been little evidence of positive outcomes of actions being taken to address declining water levels (Abtmaier 1969; Dziembowski 1976; Jolly 1986; Masiyandima *et al.* 2002). Furthermore, seasonal forecast skill is high in parts of southern Africa, particularly in the Limpopo River Basin – although this is dependent on location, time of year and the behaviour of the El Niño-Southern Oscillation (Conway *et al.* 2015).

The remainder of this paper is structured as follows. First, a review of the case study of Mogwadi (Dendron) and the methodology utilised is presented, followed by the results and discussion section, which examines management approaches and the utility of seasonal forecasts. Finally, the conclusions and recommendations drawn from the study are given.

METHODS

Case study: Mogwadi (Dendron), Limpopo

Mogwadi (Dendron) is located 60 km northwest of the city of Polokwane, Limpopo. The study area (Figure 1) partly covers a sub-catchment (locally referred to as the 'Doringlaagte' Catchment) of the Hout River Catchment, a 509 km^2 area which eventually drains into the Limpopo river in the northeast. The total catchment covers 2,478 km^2, while the aquifer in the area is reported to be 1,600 km^2 (Masiyandima *et al.* 2002), although it is not well mapped.

Hydrogeological characteristics of the aquifer

The geology is characterised by crystalline (granite) complex of the Hout River Gneiss throughout the catchment. Geologically, the aquifer is broadly divided into an upper weathered aquifer and a lower fractured aquifer. According to Jolly (1986), the lower zone is high-yielding, while the upper weathered formation is low-yielding with low storage. The fractured aquifer represents the zone screened by most production wells in the area. Dolerite dikes cut across the greater area in various directions (Busari 2008), as seen locally in Figure 1. Secondary fractures formed by dyke intrusion have been targeted for groundwater development all over South Africa (Du Toit 2001). As indicated by Murray & Tredoux (2002), due to the weathering, the aquifers are partly infilled with clay or sediment, which leads to decreased permeability, and the development of a less permeable layer between the weathered and fractured zone. Hence, the weathered aquifer is regarded as unconfined to semi-confined and the fractured rock aquifer as confined (Jolly 1986). Open fractures in the lower zone act

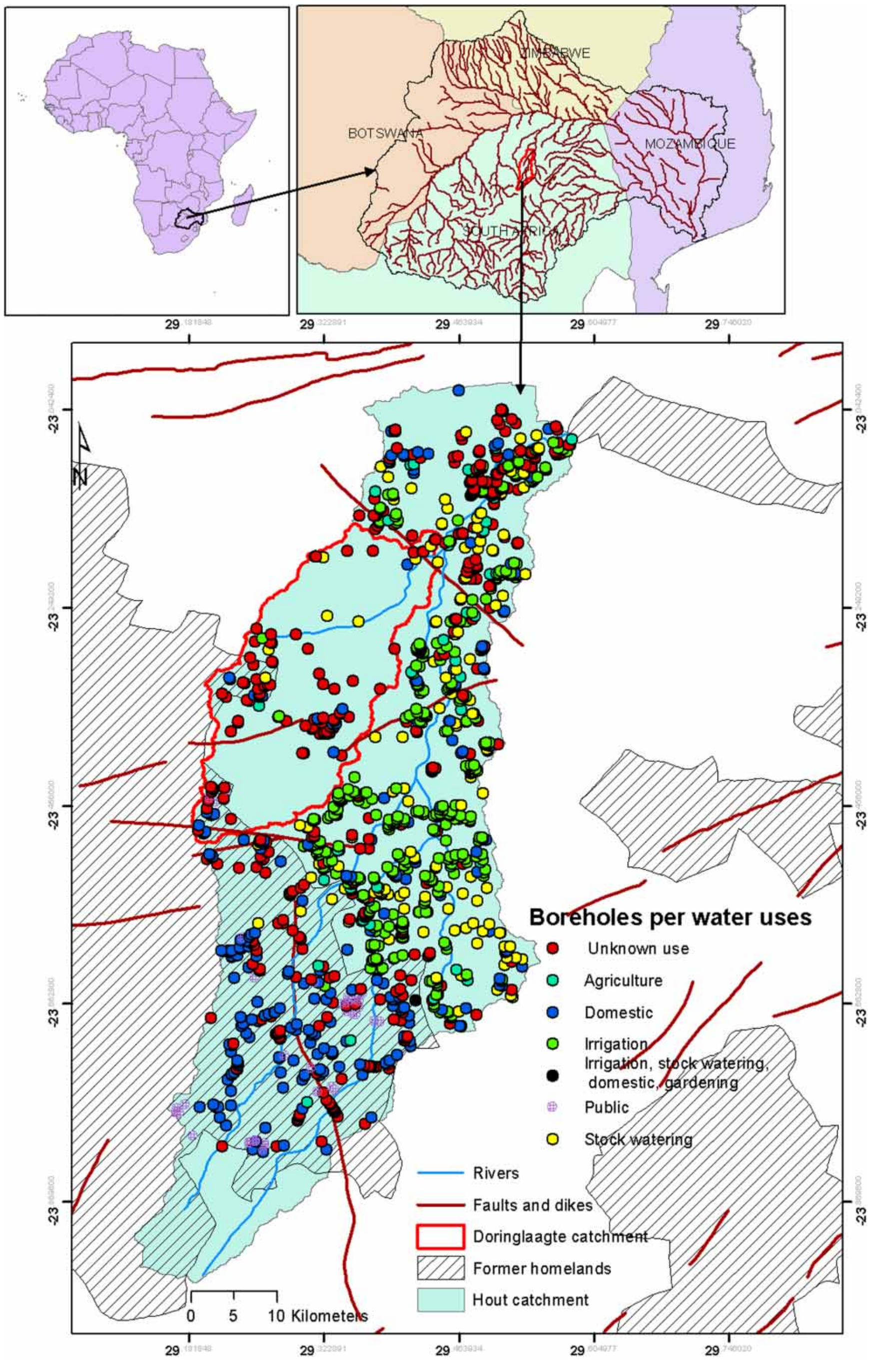

Figure 1 | Map of the Hout Catchment.

as main collectors or conduits of water flow. Alluvium deposits occur along the Hout River. A study conducted in the adjacent Sand River Catchment indicated that the alluvial deposit thickness can reach 25 m, consisting of upper clayey sands, overlying coarser sands and gravel boulder layers towards its base (Murray & Tredoux 2002). Underlying the local alluvium deposits are the Hout River Gneiss complex.

The area receives low rainfall (mean annual rainfall of 354 mm yr^{-1}), resulting in rivers rarely flowing

(Dziembowski 1976). Most rainfall occurs during the summer months between November and March/April (Masiyandima et al. 2002), as shown in Figure 2. Long-term annual recharge to the aquifer has been estimated at around 3.8% total annual rainfall (Masiyandima et al. 2002), between $6 \times 10^6\ m^3yr^{-1}$ and $7.2 \times 10^6\ m^3yr^{-1}$ for the Doringlaagte Catchment (Dziembowski 1976; Jolly 1986).

Groundwater in Mogwadi (Dendron) has served as the sole source of irrigation water for commercial agriculture for more than two decades (Masiyandima et al. 2002), and it has been reported that groundwater levels declined in two farm wells by up to 50 m from the 1970s until 2000 (Masiyandima et al. 2002) with an average water table decline of approximately 20 m over the aquifer from 1969 to 1986. The area has a long history of commercial potato cultivation, as well as crops such as tomatoes and onions. Irrigation occurs all year round, but predominantly during the rainy season (October–April), and potato planting is generally rotated on a five-year basis (i.e., irrigation plots are left fallow for five years on rotation to decrease the risk of disease). Farmers in the area grow animal fodder and maize in smaller fully irrigated stretches during the dry winter season.

Studies estimate that the area under irrigation almost tripled from 1,319 ha in the 1960s to 3,579 ha in 1986. Groundwater abstraction concurrently increased from $9.2 \times 10^6\ m^3yr^{-1}$ to $21.7 \times 10^6\ m^3yr^{-1}$, while groundwater levels were estimated to have decreased from 18 m to 43 m below ground level (i.e., a 25 m drop) (Abtmaier 1969; Dziembowski 1976; Jolly 1986). Comparing abstraction data with the long-term recharge estimates above indicates a negative water balance for the area.

Two long-term (30–50 year) groundwater records from monitoring wells have been maintained in the study area by the Department of Water and Sanitation (DWS), and are shown with monthly rainfall (Figure 3). Both depict a dynamic pattern of groundwater levels, and highlight a relatively rapid aquifer response, particularly to high rainfall events. The drop in water levels over time is less than those recorded in the literature (Abtmaier 1969; Dziembowski 1976; Jolly 1986) and may indicate localised effects. Only episodic high-rainfall events lead to significant recharge, such as the extreme flood year of 2000. The records demonstrate very different dynamics of the groundwater as influenced mostly by differences in pumping patterns and geology. Monitoring well A7N0019 is from a sandy aquifer adjacent to the river, while A7N0524 is from the hard rock aquifer further from the river. The response to rainfall events is therefore much more subdued in the latter due to the deeper depth of the water table. Well A7N0019 is influenced by its proximity to the river, presumably entailing additional focused recharge and hence a quicker and more pronounced response. The general trend described above of groundwater level declines in the hard rock areas from the 1960s to 2000 is also seen in A7N0524. It is also clearly apparent that the exceptionally wet year of 2000 – which generated flooding in large parts of the Limpopo Basin – helped replenish the aquifer substantially in a relatively

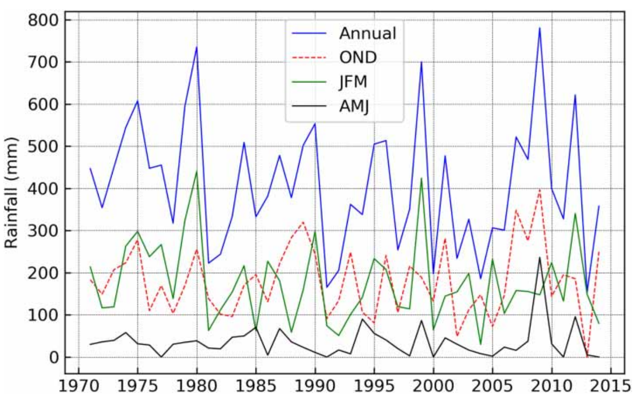

Figure 2 | Annual and seasonal precipitation in Mogwadi (Dendron), Limpopo, 1971–2015 (data from SAWS 2016). OND: October, November, December; JFM: January, February, March; AMJ: April, May, June. *Note:* July–September is not included (dry season with negligible rainfall).

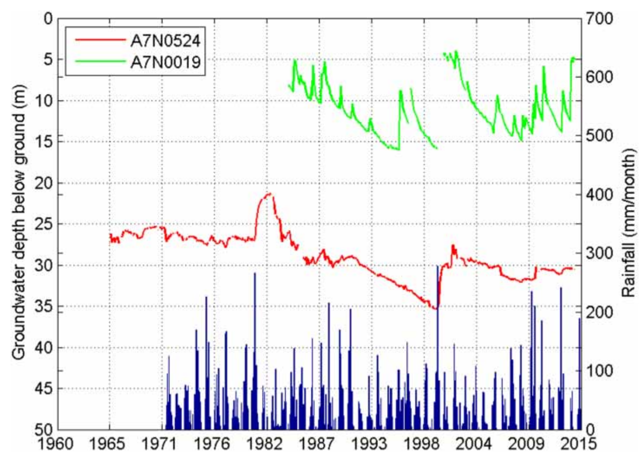

Figure 3 | Groundwater levels at monitoring sites A7N0524 (1965–2015) and A7N0019 (1986–2015), and monthly rainfall (1971–2015) (data from DWS 2015; SAWS 2016).

short period. This indicates a multi-year pattern of groundwater depletion and rainfall-induced recovery in the area, and further illustrates the importance of having continuous information on groundwater levels and the potential role of forecasting information of rainfall in agricultural groundwater use. It is also important to note that while these wells are not pumped, they could be influenced by nearby groundwater abstraction, as often the monitoring wells are located close to intensive use areas (Verster 2016, personal communication).

In the 1980s, work was carried out to determine the 'safe yield' of the aquifers in Mogwadi (Dendron). Jolly (1986) states that the 'safe yield' for the aquifer is 8.6×10^6 m^3yr^{-1}, based on a constant fraction (approximately 4%) of the annual rainfall, which roughly equates to estimated recharge rates (Masiyandima *et al.* 2002). However, the usefulness of the 'safe yield' concept is heavily debated in the literature, with several authors noting that a fixed yield is not an operational rule that works under all climatic conditions, and that yields vary over time alongside environmental conditions (Sophocleous 1997; Loáiciga 2017; Jarvis 2014). This is particularly important in environmental conditions such as those experienced in Mogwadi (Dendron), where rainfall, and therefore recharge of shallow aquifers, vary significantly between wet and dry seasons, and between years.

Furthermore, Pierce *et al.* (2013) argue that a single number is insufficient in guiding groundwater management and policy. Therefore, the physical science component of the safe yield concept can be integrated with the consensus yield concept – derived from stakeholders' preferences – into an aquifer-yield continuum (Pierce *et al.* 2013). Such an approach ensures that any management strategy conceived can withstand social pressures, while also being technically feasible (Pierce *et al.* 2013). This study therefore takes a step toward a more integrated approach to groundwater management that not only considers science-based approaches, such as seasonal forecasts and monitoring data, but also community engagement and the socio-political realities of a local situation.

Data collection and analysis

Findings are drawn from field research conducted in Mogwadi (Dendron). Thirteen stakeholders were interviewed in July 2014, comprising five commercial farmers, two emerging farmers (under an upliftment scheme run by the government), one water resource manager responsible for borehole management of several large farms in the study area, two DWS representatives, one representative from the Department of Rural Development and Land Reform, and two members of the Pietersburg Agricultural Union. The interviews focused on the physical status of groundwater in the area and evidence of recent change, and management strategies. Observations were also collated of rainfall, groundwater levels and groundwater abstraction licensing data from DWS. A second phase of data collection in June 2015 consisted of a needs-analysis workshop with six farmers, followed by interviews and questionnaires with four additional farmers and representatives of DWS and the Agricultural Research Council (ARC). Here, the primary aim was to examine the use of seasonal forecasts for agricultural groundwater management, constraints, and the potential for expanding and improving their use within the current management system. A final follow-up workshop with representatives from the farming community and DWS was then conducted in Mogwadi (Dendron) (November 2015) to determine the feasibility of suggested options and to feed back on initial findings.

Analysis was framed around formal and informal approaches to groundwater management, and the utilisation of both scientific data and local knowledge of groundwater dynamics. Several theories were drawn on to analyse the utility of seasonal forecasts as a component of groundwater management, and their potential value to a sample of commercial farmers, by examining their perceptions of utility and barriers to uptake (e.g., Klopper 1999; Cash *et al.* 2003; Johnston 2008; Hansen *et al.* 2011; Ziervogel *et al.* 2010). In doing so, this study reflects on such existing literature and illustrates their importance in a local context.

RESULTS AND DISCUSSION

Climate variability and groundwater

In resource governance, users' perceptions of the physical situation is important for analysing resource management decisions. Interviews and workshops conducted highlighted varied understanding among farmers regarding the relationship between climate variability and groundwater levels, although most felt that seasonal climate variability and long-term climate change pose a threat to groundwater resources and play an important role in management. This was mainly due to the fact that groundwater in the area is observed to depend predominantly on episodic rainfall events, either as diffuse or focused recharge alongside the Hout River (which flows for only 2–3 weeks per year) and the confluent Sand River. Most interviewees agreed that groundwater levels in the hard rock areas only respond to high rainfall periods (typically above 250–300 mm over three months). However, this is also affected by factors such as local geology, slope and surface land use. Drought events impact groundwater in the area at a much slower rate, although a DWS hydrogeologist interviewed asserted that drought is felt sooner in Mogwadi (Dendron) than surrounding areas due to higher abstraction rates.

Most interviewees had noticed changes in climate behaviour in the past ten years. Perceptions included increasing average annual temperatures, more extreme temperature differences between summer and winter, and shifting seasons (e.g., delays in the arrival of the rainy season). Interviewees reported varied experiences regarding changes in groundwater levels; several commented that they had seen widespread depletion over the past ten years, while two interviewees stated that levels in some areas were, in fact, increasing due to better borehole management. Table 1 identifies key years and climatic events as remembered by the sample of farmers.

Table 1 | Climatic events and impacts as perceived by farmers ($n = 10$)

Year of climatic event	Nature of event	Main perceived impacts
1967	Drought (>6 months)	Groundwater levels declined; shift to alternative crops and farming methods on many farms
1987	Drought (>1 year)	Poor groundwater levels – level often used as 'benchmark' for perceived issues
1995	Drought (<6 months)	Groundwater levels declined
2000	Flood (<3 months)	Loss of crops and transportation issues (road damage); significant recharge event
2015	Low rainfall (>6 months)	Expected to impact farming outputs negatively

Groundwater management system

Numerous strategies for groundwater management are carried out in the Mogwadi (Dendron) area, which can be separated into formal and informal approaches. Here, formal management refers to the top-down regulatory governance system in place under the South African National Water Act (1998). Informal management refers to management strategies that occur outside of this system, without direct input from governing bodies, by users in a bottom-up approach – either by spontaneous individual or organised joint action. Table 2 summarises both components evident in Mogwadi (Dendron).

Table 2 | Groundwater management strategies in Mogwadi (Dendron)

Formal strategies	Informal strategies Demand-side
Regulatory licensing system – implemented by DWS	
Monitoring well sites across study area (13 sites – DWS)	Groundwater monitoring (individual by farmers)
Quarterly reports of groundwater status (DWS)	Group meetings (farmers' union) – sharing of data, experiences and ideas; peer accountability
Water user association – not yet formally established (negotiations ongoing)	Alterations to crop type, planting times and cropping area
Pietersburg farmers' agricultural union	Night-time irrigation
	Supply-side
	Well siting and spacing between farmers (termed by the farmers as a 'gentleman's agreement')
	Impoundments (for recharge)
	Increased borehole drilling

Formal management effectiveness

Formally, Mogwadi (Dendron) farmers are regulated via the licensing system under the 1998 National Water Act, whereby users must apply for a license for every borehole on their farm used for irrigation (domestic use is not licensed, but classed as 'Schedule 1' use, which is the permissible use of water under the National Water Act 1998, for purposes such as reasonable domestic use, domestic gardening, animal watering, fire-fighting and recreational use) and their associated water abstraction (NWA 1998). These licenses are valid for 40 years and must be assessed every five years. DWS is responsible for approving, monitoring and enforcing water licenses. DWS also has a network of 13 monitoring wells within the study area.

Formal management was perceived to be very ineffective among interviewees, citing issues of institutional capacity, cross-departmental coordination and department-stakeholder relationships. Formal strategies were scored at 30% effectiveness in ensuring sustainable groundwater use. An internal licensing database obtained from DWS identifies just 9% of registered water use within the study area as lawful, with the remaining 91% still to have lawfulness determined, primarily due to a backlog in license assessments. Seven interviewees stated that there is 'no formal groundwater management' in Mogwadi (Dendron), with a DWS representative verifying that it has 'never been regulated'. There was little evidence of abstraction license possession or groundwater abstraction monitoring. Interviewees also felt that little progress had been made in addressing serious issues such as unlicensed drilling and illegal dam-building along the Hout River.

DWS has been producing detailed quarterly groundwater status reports for the Limpopo River Basin since 2007 (see: http://www.dwa.gov.za/Groundwater/GroundwaterOffices/Limpopo/Reports.aspx), providing information on the physical status, areas of concern, some limited seasonal forecast information on the previous season, and justifications for enhancing conservation efforts. However, no farmers interviewed were aware of these reports due to a lack of capacity within DWS to distribute and utilise the information in groundwater-user engagement, although the producer of said reports stated that the mailing list of recipients 'keeps growing'. All farmers at the workshops deemed the reports extremely useful for long-term abstraction planning, as well as to enhance understanding of groundwater dynamics. Such information would allow a shift in focus from irrigation-management to resource-management.

A perceived lack of coordination between governing bodies also hindered the effectiveness of formal strategies in place. Five interviewees stated that the link between land tenure and groundwater is not adequately considered as part of integrated water management efforts and the ongoing national land redistribution process, as attested by Van Koppen & Schreiner (2014). This was particularly contentious due to the fact that many interviewees viewed groundwater as a riparian right linked to their land ownership. However, a representative from the Department of Rural Development and Land Reform stated that meetings within DWS do occur when discussing land redistribution.

Such issues have led to strained relationships between DWS and commercial farmers in Mogwadi (Dendron), the latter lacking trust in the government to monitor and regulate those who 'waste water', or to support efforts in establishing a Water User Association (WUA). Water Users' Associations were established under the National Water Act 1998, in Chapter 8. They are intended to operate at a restricted localised level, and are co-operative associations of individual water users who wish to undertake water-related activities for their mutual benefit (often transitioned from existing irrigation boards, subterranean water control boards, and water boards.) Four farmers cited a high staff turnover rate in DWS as the key factor in negotiation breakdown for the WUA, as well as solving the issue of the controversial upstream Hout River Dam ('Matlala Dam'). Several interviewees were also frustrated with an announcement by the newly appointed Agricultural Minister for the Limpopo Province that the agricultural sector would be having its water allocations re-assessed due to 'water wastage'. The consensus among interviewed farmers was that the government's focus is wrongly on the economic value of water, favours the mining industry's needs over the agricultural sector, and has a consequent lack of concern for rural livelihoods and local food security.

Informal management effectiveness

Informal management strategies were perceived to be much more effective than formal management, rated at 70% effectiveness by interviewees. This was due to a high level of coordination between farmers, alongside individual actions – although in many cases, these successes were self-proclaimed.

One approach taken is a 'gentlemen's agreement', whereby boreholes on farms are drilled at a minimum distance of 50–100 m from farm borders to ensure that farmers' abstraction activities do not impact neighbouring farms, which one farmer claimed 'reduces [the risk of] conflict between farmers'. Sixty per cent of farmers also claimed to irrigate during the night when evapotranspiration is low, thus reducing water consumption. However, this strategy may be undertaken primarily due to cheaper electricity rates during off-peak hours, rather than concern for groundwater levels, and has not yet been verified. Three interviewees monitor groundwater levels to ensure long-term sustainability of the aquifer, and stated that evidence of dropping water levels is the main motivation for reducing irrigation pumping. Interviewees who measure their groundwater levels stated that this has led to fewer incidences of pump failure due to over-pumping, and overall improved the status of their individual groundwater levels due to more cautious pumping practices. Nine interviewees claimed to reduce the amount of land irrigated if dry spells are experienced during the wet season, and a few adjusted planting times. Others built impoundments near boreholes to enhance recharge from rainfall. Note that it was more likely for those with an existing interest in water management to attend the workshops, thus these claims cannot be taken as representative of the entire farming community; workshop attendees stated that there are many farmers who do not measure their water levels or take any actions to conserve water.

During the 2015–16 drought, most farmers interviewed reported little to no change in groundwater usage despite a perceived decline in water availability during that time. Rather, the higher temperatures and lack of rainfall led to an increase in water used for land preparation. In contrast, however, a groundwater resource manager for one of the largest commercial potato farming companies in the area reported stable groundwater levels on the farms managed by himself, due to efforts to maintain boreholes at 2009 levels as a buffer during the period of drought.

Figure 4 shows an example of such groundwater management supported by the resource manager interviewed. By presenting farmers with graphs of borehole water levels, he demonstrated the link between over-pumping and declining water levels – as well as the opposite – thus incentivising farmers to monitor and regulate water abstraction more carefully. The abstraction borehole in Figure 4 depicts a decline in groundwater levels of 23 m (from 98 m to 121 m below ground), over a six-month period between July 2012 and January 2013. The borehole was shut down in April 2013 to enable recovery, which occurred by June 2013. The borehole manager stated that the 'biggest hurdle is the lack of knowledge of the issue [of groundwater over-abstraction]', and that only by farmers measuring and tracking water levels and abstraction rates can they effectively monitor the situation and react accordingly.

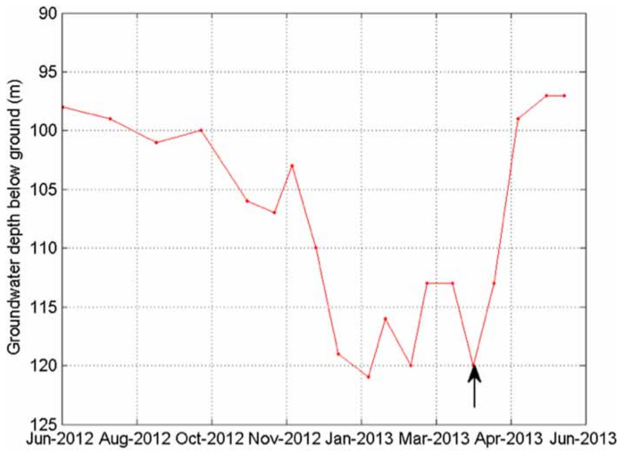

Figure 4 | Borehole water levels at a site within the study area, Mogwadi (Dendron) (arrow indicates application of pumping restrictions).

It is important here to clarify the difference between irrigation-management and resource-management; several farmers interviewed had more interest in managing their short-term water availability for private groundwater-irrigation than for collectively managing groundwater for the common good, supporting a 'tragedy of the commons' analysis of the situation.

However, there is a high level of coordination between farmers in Mogwadi (Dendron) under the forum of the long-established Pietersburg Farmers' Agricultural Union – an informal response to the lack of a WUA. This was seen to encourage accountability and regulation of individual water consumption, although these were still perceived to be the main challenges within informal management among interviewees. This supports Loáiciga's (2004) statement that without effective enforcement within groundwater systems, non-cooperation and unsustainable aquifer mining result. While many farmers 'keep check' of one another, interviewees observed that 'many farmers do not comply' with such influences, and are 'reluctant to share data with one another'. It is thus clear that a lack of formal regulation means compliant farmers are still trapped in a prisoner's dilemma of managing their individual and collective resources because of concurrent non-compliance.

Seasonal forecasts in Mogwadi (Dendron)

Farmers in Mogwadi (Dendron) were also interviewed about their use of scientific climatic information for groundwater management, with the aim of enhancing understanding of how such material's usefulness can be enhanced in local settings. Across South Africa, seasonal climate forecasts are produced by meteorological services and academic institutions. The Southern Africa Regional Climate Outlook Forum (SARCOF) amalgamates all data in the Southern Africa Development Community (SADC) region, into a yearly regional outlook (Johnston 2008). Nationally, the South African Weather Service (SAWS) produces monthly national advisories for each season through the National Agro-Meteorological Committee, based on the consolidation of seasonal forecasting data, together with the Department of Agriculture, Forestry and Fishery's Climate Change and Disaster Management (DAFF-CCDM) and the Agricultural Research Council's Institute for Soil, Climate and Water (ARC-ISCW). The Disaster Management Act 2002 urges provinces, individuals and farmers to assess and prevent the risk of disasters by using such early warning information. The ARC-ISCW utilises these seasonal forecasts to develop advisories for farmers, such as the ongoing Umlindi Project (The Umlundi Project has been ongoing since 2004. For example, http://www.arc.agric.za/arc-iscw/Newsletter%20Library/UMLINDI%20Issue%202016-01,%2014%20January%202016.pdf) and a radio broadcasting project in the Limpopo and Northwest Provinces. University groups such as the University of Cape Town's Climate Systems Analysis Group (CSAG), and research institutes such as the Council for Scientific and Industrial Research (CSIR), also produce seasonal forecasts. However, CSAG has recently discontinued their publications due to low forecasting skill.

Seasonal forecasts are downscaled and made available on the website of the Limpopo Department of Agriculture (LDA), providing forecasts for the upcoming season of minimum/maximum rainfall and temperature, normalised difference vegetation index (NDVI) maps, and standardised precipitation index (SPI) maps. This is followed by suggested strategies for sectoral responses, such as the uptake of drip irrigation and adherence to water restrictions during dry seasons (LDA Representative 2015). However, the reports are not kept up-to-date and, as of the time of writing, are not easily accessible through the website.

Utility of seasonal forecasts

Cash *et al.* (2003) state that scientific information is only effective in influencing responses if the information is perceived to be credible, salient and legitimate by stakeholders, while Hansen *et al.* (2011) expand this to include understanding of the information. In Mogwadi (Dendron), seasonal forecasts are not utilised successfully, with evidence from a focus group discussion supporting all of these factors. Table 3 details the factors influencing farmers' use of seasonal forecasts, separated into technological, cognitive and institutional causes.

The main influencing factors were related to the access to, timing and consistency of dissemination of forecasts; the LDA website not being kept up-to-date or accessible, training not being provided for farmers (which is necessary due to a low understanding of key terminology used in the reports, such as 'probabilistic forecasts'), and low communication between forecasters and end-users. The latter means that forecasts are not adequately tailored to farmer needs in terms of information provided and the timing of dissemination.

Johnston (2008) states that in order for seasonal forecasts to be beneficial to users, the cultural, socioeconomic and political processes that frustrate the use and uptake of forecasts must be understood. This is supported by evidence in Mogwadi (Dendron) of institutional issues, such as a lack of interaction and trust between forecasters and end-users (Archer *et al.* 2007; Ziervogel *et al.* 2010). One interviewee identified this lack of communication as the 'key reason nothing gets done'. Farmers generally held low interest in forecasts due to a lack of trust in governing bodies.

Farmers tended to use short-term weekly weather forecasts for decision-making, alongside present climate and groundwater levels, rather than anticipatory predictions. There was a high level of mistrust in the SAWS forecasts – both weekly weather and seasonal climate forecasts – due to experiences of inaccurate forecasts, supporting Klopper's (1999) assertion that farmers often have little trust in the

Table 3 | Factors of seasonal forecast utility in Mogwadi (Dendron)

Technological	Cognitive	Institutional
Production	Low importance given to (seasonal) climate information – use short-term weather forecasts	Dissemination low due to capacity issues
Resolution and accuracy low [credibility]	Interpretation/understanding of forecasts low [salience]	Tenuous relationships between governing bodies, forecast producers, and end-users (farmers) [legitimacy and credibility]
(Ground)water specifics lacking, other information low detail	Low awareness of LDA website	
Distribution	Adherence to traditional management strategies	
Access limited to internet (not mobile/radio)	Low understanding of context/ environment	
Dissemination inconsistency (rarely published)	Prior experience with forecasts reduce trust [legitimacy]	
Dissemination timing (rarely in time for planting season)	Trust in forecast producers and governing bodies [legitimacy]	
Presentation	Indigenous environmental experiences (e.g., drought)	
Language(s) used (English, not local)		
Poor terminology and explanation of terms		

accuracy of forecasts through personal experience. Traditional beliefs and theories about local weather and climate can influence the way the scientific information is perceived and interpreted (Klopper *et al.* 2006). Due to a low level of trust in the accuracy of forecasts, three farmers adhered to traditional forecasting methods such as using lunar phases, prayer and anthill sizes as a rainfall predictor. This also supports Gettelman's (2003) claim that forecasts often provide information that is contrary to personal beliefs, culture or understanding of the climate system.

Interest in using seasonal forecasts increased between workshops held in 2015 and 2016, which could be partly explained by the 2015–16 drought, indicating the influence of environmental experiences on scientific information utilisation. The interest could also have been enhanced through the personal interaction with and between farmers as part of the engagement process of this study.

Improving seasonal forecasts for farmers

It is clear that there are many ways in which seasonal forecast utility can be improved, based on the aforementioned influencing factors for current low levels of application within agricultural groundwater management. For example, improved tailoring of forecasts to farmers' needs could be achieved via feedback workshops and relationship building in order to address issues of salience and legitimacy. Training for seasonal forecast use would also greatly increase their value; an interviewee from the ARC asserted that in areas of South Africa where farmers have been trained to interpret and use seasonal forecasts, they benefited significantly in terms of preparing for climatic variability.

Results also showed that farmers in Mogwadi (Dendron) preferred email and cell phone dissemination methods, and 80% of interviewees felt forecasting information would only be beneficial if shared well in advance of the rainy season (i.e., around September). Much of this is beyond the current level of forecast ability, particularly the request for intra-seasonal rainfall. Forecasts may therefore also have to be developed to cater for groundwater use by including groundwater level data – for example, by combining climate forecasts with the quarterly reports compiled by DWS. An 'ideal forecast' is characterised in Table 4.

Table 4 | Characteristics of an 'ideal seasonal forecast' for commercial farmers in Mogwadi (Dendron)

Aspect of forecast	Details
Technical information	• Rainfall amount (total and intra-seasonal distribution) • Groundwater levels at start of rainy season • Temperature (max and min) • Specific recommendations for groundwater use in farming
Presentation	• In conjunction with groundwater status reports – short- and long-term groundwater trends • Explanation of terminology • Contact details of local forecast producers
Dissemination	• Active sharing of reports (email, WhatsApp/cell phones, radio) • Well in advance of rainy season

Beyond seasonal forecasts?

Forewarning without the capability of forearming is counterproductive (Johnston 2008) – that is, merely providing seasonal forecast information is not enough in itself if end-users do not have the necessary governance system or tools in place. Seasonal forecasts could be useful in situations where there is high likelihood of drought, coupled with antecedent low groundwater levels at the beginning of a new abstraction season, assuming some ability to translate the seasonal forecast to impacts on groundwater levels, and some guarantee of collective user compliance with any restrictions. Indeed, while there are many ways in which forecasting data can be developed further, in situations such as Mogwadi (Dendron) there is a need to ask the question of whether or not it is worth focusing on such approaches when more fundamental issues must be addressed first. For example, while timely forecasts indicating upcoming rainfall projections would be beneficial, they would be significantly undermined if groundwater irrigation in the study area continued to be unregulated. Strategies to cope with a dry spell could assist farmers in decision-making for crop types or planting times, but not if they have little idea of how future rainfall events impact the shallow aquifers upon which they depend so heavily. Also, formal or informal agreement on necessary action and regulations to be triggered by the forecasts would be needed.

Figure 5 demonstrates the processes involved in the production and utilisation of both groundwater and seasonal forecasting data, associated weaknesses, and entry points for action. Actions not sufficiently taking place (i.e., recommended) are highlighted in bold, while relevant stakeholders are shown above each stage.

As shown, groundwater monitoring and data collection ideally feeds into the prediction stage, where data are utilised for status reports and seasonal forecasts. This could be supported by continuous hydro-geological modelling, where model prediction results are retrospectively improved using updated monitoring data, and gradually obtaining a 'trained' model. Such a model could be held by DWS, ensuring adequately trained personnel. This predicted information is then disseminated by the relevant stakeholders (e.g., ARC-ISCW/DAFF) at a critical period of time within the cropping season, when it is used (or not used) by farmers for groundwater-related decision-making. The value of this information is then ideally fed back into stages of the process, particularly for prediction and dissemination, to enhance the utility of the forecasts and groundwater data collected.

Groundwater levels in the Mogwadi (Dendron) area show multi-year patterns of variability, mostly influenced by pumping rates and periodic heavy rainfall events. It is therefore necessary for farmers to consistently and collectively monitor their groundwater levels and pumping activities, which would assist in the understanding of recharge mechanisms and impacts of pumping and to relate the rainfall and temperature forecasts with groundwater status – possibly through the modelling approach described above. This would in turn improve the credibility of the data produced for 'prediction' in Stage 2. Monitoring should be increased by both DWS and the farming community, either through increasing the amount of DWS-owned monitoring boreholes, or the encouragement or enforcement of monitoring on farms. It is important that regular feedback is provided to farmers, and that they are encouraged to implement their own monitoring schemes (Conrad & Carstens 2014). There is a need, therefore, to implement and maintain cost-effective and reliable monitoring networks (Calow *et al.* 1997). However, the entity responsible for such schemes was heavily contested among interviewees, suggesting an immediate need for enhanced communication and coordination between stakeholders.

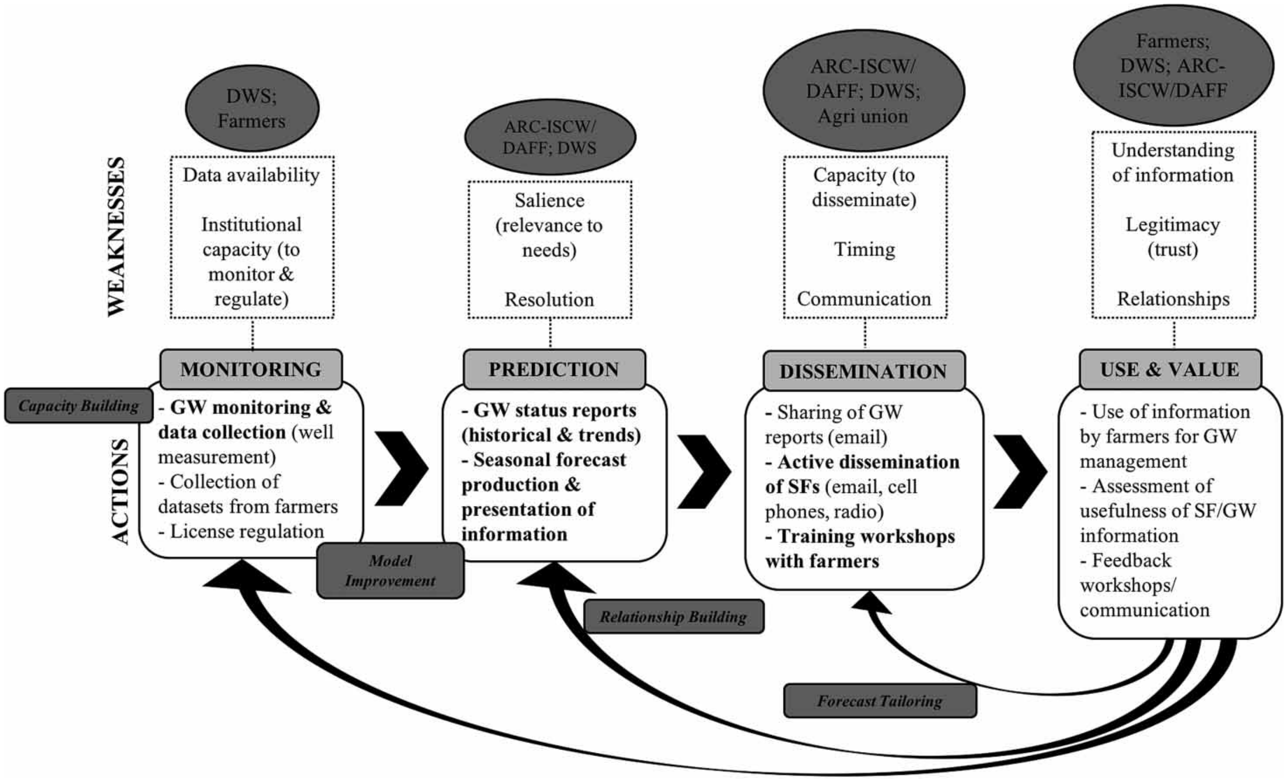

Figure 5 | Weaknesses and actions for improved utility of seasonal forecasting and groundwater information.

With the resources available, existing seasonal forecasts could be publicised more widely by ARC-ICSW/DAFF and the LDA, and integrated with the groundwater status reports from DWS. This facility would provide both historical and forecasting information to farmers for decision-making regarding groundwater use. A more extensive groundwater monitoring network is required in the area to enhance understanding of aquifer characteristics and their responses to rainfall and abstraction practices, which should feed into the production of the groundwater reports, possibly through a continuously updated modelling tool. Such developments could enhance capacity to utilise seasonal forecast information.

CONCLUSIONS

This paper has presented the case study of Mogwadi (Dendron), Limpopo, and its ongoing issues surrounding groundwater management. The study examined current understanding across main stakeholders in the study area regarding groundwater dynamics and management strategies, and then assessed the potential utility of seasonal climate forecasts within this context.

It was found that limited forecasting information is available for commercial farmers in the area, which is not fully utilised due to issues of saliency, legitimacy, credibility and understanding of the forecasts. A key constraint was limited communication between forecast producers, DWS and farmers. It was also found that the lack of use of forecasting information was related to poor understanding of the information provided and unclear linkages to groundwater management. There was interest in future use of forecasts, if tailored for farmers' needs (interest was stimulated by an intervening drought between separate consultations).

Mogwadi (Dendron) is a particularly interesting and important case study of a water user group trapped in a prisoner's dilemma, with a lack of regulation coupled with increasing socio-economic and environmental pressures.

While enhancing seasonal forecasts and monitoring networks have some feasible opportunities as presented here, it is imperative to ask the question: what can be done now, if resources and capacity are limited, and forecasting skill is elusive?

For Mogwadi (Dendron), this will revolve around the farmers' own Agricultural Union, which should continue to provide pressure for individual conservation and monitoring efforts without the need for government intervention. While capacity issues may not be immediately solved within DWS, there was a significant response to the quarterly groundwater status reports – improved dissemination of these among farmers would increase awareness of the issues surrounding groundwater irrigation, and thereby begin to address the tragedy of the commons occurring in the study area. Existing seasonal forecast reports could also be more widely publicised by the LDA and ARC-ICSW/DAFF. Finally, improved dialogue between DWS, forecast producers and farming communities can undoubtedly be achieved. This would not only facilitate communication regarding responsibilities and resources, but also enhance knowledge transfer in a reciprocal manner.

Further research and engagement with commercial farmers would be beneficial in order to ascertain the value of seasonal forecasts in long-term management of shallow aquifers, through a detailed analysis of the performance of different response strategies given historical forecast skill, coupled with more detailed hydrological modelling of the climate-groundwater response. Such understanding would have wider implications for the realisation of groundwater's role as a sustainable buffer in periods of drought – a phenomenon projected to increase in frequency in southern Africa under climate change.

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