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LETTER

Groundwater and resilience to drought in the Ethiopian highlands

A M MacDonald[1,7], R A Bell[2], S Kebede[3], T Azagegn[3], T Yehualaeshet[3], F Pichon[4], M Young[5], A A McKenzie[6], D J Lapworth[6], E Black[5] and R C Calow[4]

[1] British Geological Survey, Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, United Kingdom
[2] British Geological Survey, Keyworth, Nottingham, NG12 5GG, United Kingdom
[3] Dept of Earth Sciences, Addis Ababa University, Addis Ababa, Ethiopia
[4] Water Policy Programme, Overseas Development Institute, 203 Blackfriars Rd London SE1 8NJ, United Kingdom
[5] Dept of Meteorology, University of Reading, Whiteknights, Reading RG6 6AH, United Kingdom
[6] British Geological Survey, Maclean Building, Crowmarsh Gifford, Wallingford OXON OX10 8BB, United Kingdom
[7] Author to whom any correspondence should be addressed.

E-mail: amm@bgs.ac.uk

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Supplementary material for this article is available online

Abstract

During drought, groundwater is often relied on to provide secure drinking water, particularly in rural Africa where other options are limited. However, the technology chosen to access groundwater significantly affects local water security. Here we examine the performance of springs, hand-dug-wells and boreholes in northern Ethiopia through direct high frequency monitoring of water-levels ($n = 19$) and water quality ($n = 48$) over an 18 month period and gathering information on community impacts of declining water access during the El Niño 2015/2016 drought. We found that shallow boreholes equipped with handpumps were the most reliable water supply, recovering within hours to daily abstraction throughout all conditions. Recovery and performance of most hand-dug-wells and springs declined significantly throughout the extended dry season, although in specific aquifer conditions they were reliable. All sources types had negligible measured contamination from Thermo-tolerant Coliforms through the extended dry season, but were contaminated during the rains marking drought cessation. Boreholes were least affected, median 10 cfu/100 ml, compared to 190 and 59 cfu/100 ml for hand-dug-wells and springs respectively. Many communities who relied solely on springs, wells or rivers experienced severe water shortage in the El Niño drought with mean daily collection times up to 12 h and volumes collected reducing to 3–5 litre per-capita-per-day. This led to reports of violent conflict, missed meals, reduction in school attendance and farm activity and increased health impacts. From this study there is a clear case for improving resilience to drought by installing boreholes equipped with handpumps where feasible even if collection times are >30 min.

Introduction

Groundwater is relied on as a source of resilient drinking water during times of drought (Calow *et al* 1997, Taylor *et al* 2013). As demand for water increases and rainfall and surface water flows become more erratic, groundwater becomes more attractive to develop and supply both urban centres and dispersed rural communities. This is particularly apparent in East Africa, where rainfall variability is already high and projected to increase (Masih *et al* 2014, Nicholson 2017), and where a rapid investment in water supply is required just to meet the basic services as defined by the Sustainable Development Goals (WHO and UNICEF 2017). Groundwater offers storage of a different magnitude than annual rainfall or river flow (MacDonald *et al* 2012) and across the African continent appears resilient to droughts of several years. No significant longterm regional decline in groundwater storage has been observed over the past 20 years (Bonsor *et al* 2018) despite shorter term variability (Kolusu *et al* 2019) and longer term decline (>1000 years) associated with increasing aridity from longer climate process across northern African aquifer basins (e.g. Gossel *et al* 2004, Edmunds 2009).

Although groundwater storage is vast at a regional scale, local groundwater availability is limited by the aquifer conditions, technology for accessing groundwater, and the demand for groundwater placed on individual water supplies (Calow *et al* 2010). Water technologies can respond differently to intense rainfall and periods of drought, offering different levels of service to the communities that depend on them (Howard *et al* 2016). Therefore, in drought prone areas it is important to invest in technologies that are most resilient to changes in climate.

Access to reliable water either through favourable hydrology or large infrastructure and institutional development has been associated with increased national wealth (Grey and Sadoff 2007). For example, within Ethiopia the economy is sensitive to large scale hydrologic drought (Conway and Schipper 2011), and many other studies across Africa have demonstrated the inherent sensitivities of semi-arid agro-ecosystems to variations in rainfall—due to reliance on rainfed agriculture and pastoralism (Tucker *et al* 2014a). However there have been fewer studies that have examined changes in access to domestic water (water for drinking, cooking, hygiene and washing clothes) during drought—and the corresponding impacts on communities. One such study examined water use in the wet and dry season and showed a reduction in water use to less than 10 litres per capita per day (lpcpd) in the dry season with hygiene being limited (Tucker *et al* 2014b). Research in East Africa during and since the last major El Niño drought in 1997/98, suggested that access to reliable groundwater sources is a major contributory factor to livelihood resilience, particularly for the poorest and especially for women and children (Calow *et al* 2013). However, increasing access to reliable sources can be problematic in remote economically marginalized areas, where infrastructure and services are generally lacking (Cooper *et al* 2008, Maestre *et al* 2012).

During the strong El Niño event of 2015/16, Ethiopia experienced significant rainfall perturbations including strong drought particularly in the north-western Ethiopian Highlands where seasonal rainfall totals were well below normal during June–July–August 2015 (figures 1(b), (e)). Philip *et al* (2018) suggest the return period was in excess of 1 in 60 years. There was considerable impact on food and water security with the government of Ethiopia setting up an emergency response which included food distribution and water tankering which mitigated the human impact of the drought when compared to earlier droughts, such as in 1983–85 (Alem 2018). In this study we examine the differential response of springs, hand-dug-wells and boreholes in northern Ethiopia to changes in rainfall through directly monitoring water levels and water quality for an 18 month period and also gather information on the performance of water services during the 2015/2016 drought and the subsequent impact on communities. Our hypothesis is that there is a measurable difference in the performance for both water quantity and quality of different water sources during and after extended dry season and drought, which corresponds to increased collection times and reduction in use with consequent detrimental impacts on communities.

Methods

We evaluate water security within 2 Woredas (districts) in the Ethiopian Highlands: Kobo and Lay Gayint in Amhara region (figure 1). Lay Gayint is within the central highlands, while Kobo is on the Western Escarpment and includes part of the lowland plains of the Afar Basin. Together these two Woredas provide a transect from high mountains through remote highland plateau to escarpment and lowland plain. The highlands are underlain by flood basalts and tuffs, with thick alluvium on the plains within Kobo. Satellite-based rainfall estimates from Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT; Maidment *et al* 2017) were used to provide an overview of seasonal rainfall conditions over Ethiopia (figure 1). To help examine the groundwater response to the 2015 rainfall deficit, TAMSAT estimates were combined with rain gauge data from the Kobo and Lay Gayint districts provided by the Ethiopian National Meteorological Agency.

Ten hand-dug-wells, five shallow boreholes (40–100 m deep) and four springs were instrumented with pressure transducers to measure water levels every 15 min within the source. All water sources were improved, with the hand-dug-wells and boreholes equipped with handpumps, and the springs capped and fed into a springbox. Data were collected from July 2016 to October 2017. This was at the end of the main drought, so captured water quality of the first rains, and source behaviour during the hydrological year after the drought. The performance of the water sources was assessed by measuring the recovery time after daily pumping. For every day in the first week of each calendar month, the time taken to recover to 50% of the morning rest water levels was calculated, and an average taken for the week (see supplementary material).

To measure changes in water quality, Thermotolerant Coliforms (TTCs) were measured for 17 hand-dug-wells, 15 shallow boreholes and 19 springs approximately every 2 months using plate counting after incubating for 18 h using a Delagua® incubator.

Semi-structured interviews were carried out with focus groups in each Kebele (sub district and lowest administrative unit). The Focus Groups comprised a mixture of wealth groups within each community (Questions are given in the supplementary material). The discussions focused on experience of water supply during a normal year and the El Niño drought, and the impacts experienced by different parts of the community during a normal dry season, and during times of water scarcity. Interviews were also conducted with the Kebele administrator, and staff at each health

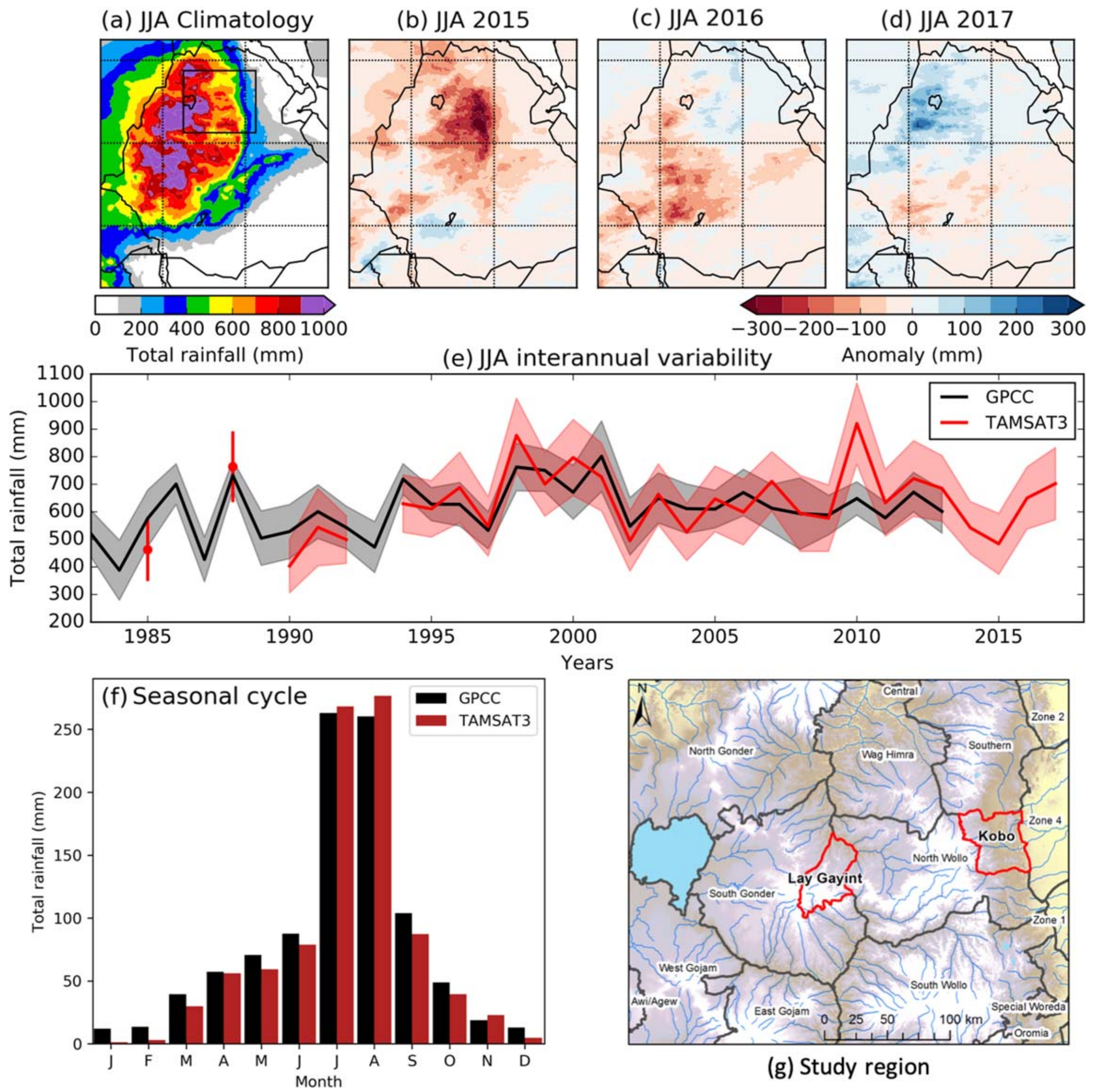

Figure 1. Location of study areas and summary of total rainfall estimated by TAMSAT during June–July–August (JJA): (a) 1983–2013 JJA climatology with location of study area marked by the black box; (b)–(c) 2015, 2016 and 2017 JJA anomalies relative to (a); (e) interannual variability in JJA total rainfall over the study area from TAMSAT and the station-based GPCC Full Data Reanalysis version 8 (Schneider *et al* 2018)—the solid lines represent the regional mean while the shading represents the regional standard deviation; (g) monthly mean total rainfall during 1983–2013 and (g) location of study areas Lay Gayint and Kobo in northwest Ethiopia with elevation shaded. Contains Rainfall Data TAMSAT© University of Reading (Maidment *et al* 2017) and data from the digital chart of the World (ESRI).

centre and school. For three of the remotest Kebeles in Lay Gayint, the focus group discussions (FGD) were carried out together. Data were codified and cross checked to give summary data on the length of time taken in water collection, the volumes of water collected and the impacts on health, education, hunger, migration and conflict.

Results

Typical water level variations for hand dug wells, shallow wells and boreholes are given in figure 2, and the recovery time and TTCs for each monitored source in figure 3. Each type of water supply responds differently to rainfall and abstraction.

Shallow boreholes

Groundwater levels in the monitored boreholes in Kobo and Lay Gayint show a similar pattern. Groundwater levels generally decline through the dry season and recover fully during the main rains in July and August (figure 2). The yields available from the shallow boreholes does not decline significantly through the year, and recovery times after pumping remain rapid with daily recovery to 50% in under 1 h (figure 3).

Hand-dug-wells

In the mountainous area of Lay Gayint water levels in hand-dug-wells decline rapidly after the cessation of the rainy season in August (figure 2), and are often drawn down to the level of the pump intake with the recovery overnight declining sharply as the dry season

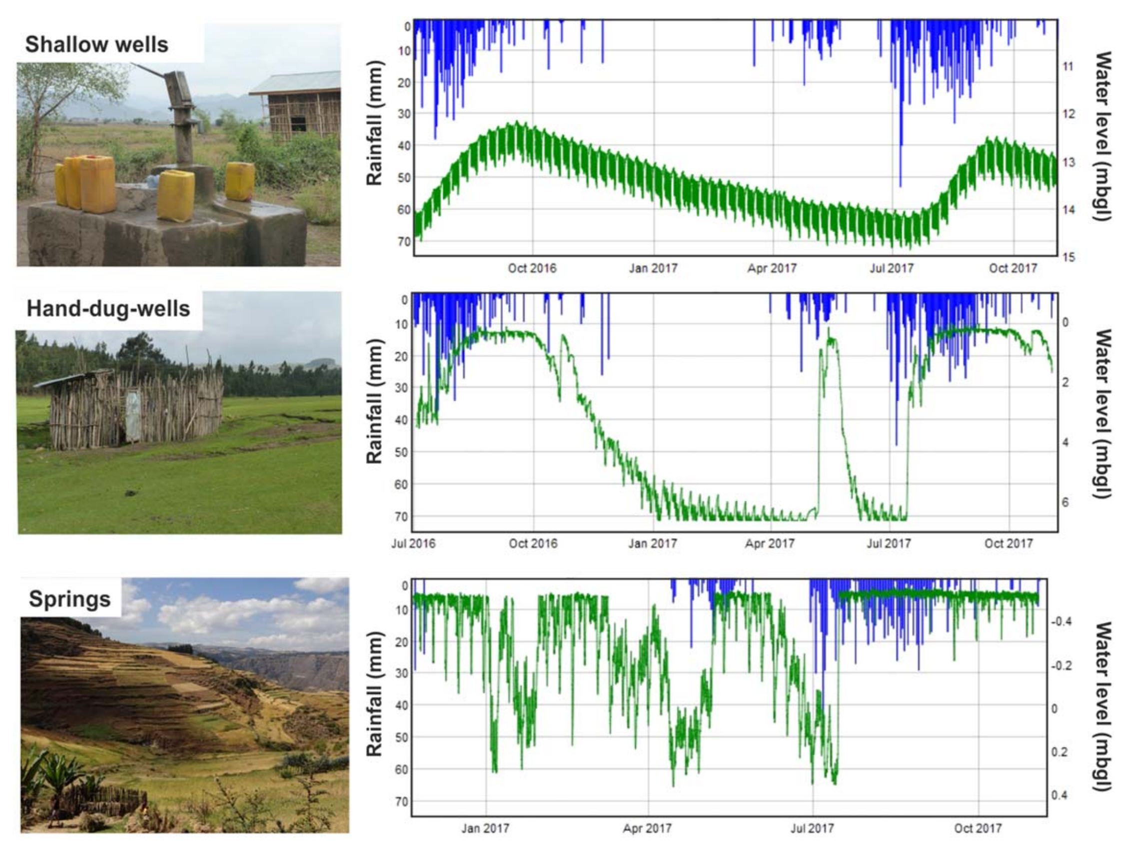

Figure 2. Examples of measured groundwater level in three monitored sources (green): shallow borehole, hand-dug-well and springs with weekly rainfall totals from TAMSAT for comparison (blue). For the spring, the water-level is the level in the spring box reservoir. Rainfall Data TAMSAT© University of Reading (Maidment *et al* 2017).

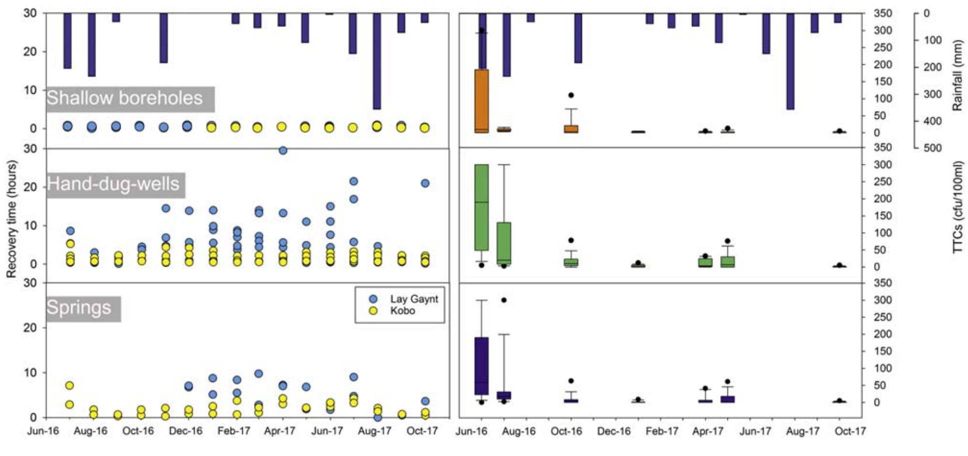

Figure 3. Performance of shallow boreholes, hand-dug-wells and springs measured by the time to recover to 50% of morning rest water level, monthly rainfall over the period from TAMSAT is shown for comparison. Summary TTC measurements at different times of the year for all measured sources are shown on the right: 15 shallow boreholes 17 hand-dug-wells, and 19 springs table S2 gives summary statistical data.

progresses (figure 3). Recovery of the water-levels in the hand dug well is rapid after rain, but is not sustained for long after the short Belg (spring) rains and require the main rains of July and August to fully recover. Hand-dug-wells in the alluvial plains of Kobo can sustain much higher yields, and water levels do not decline so significantly throughout the dry season. Here the recovery time of the hand-dug-wells remains largely the same all year round, although one well showed slower recovery times at the end of the El Niño impacted hydrological year of 2015/16.

Springs

In Lay Gayint, springs tend to be moderate to low yielding and related to topographic changes of slope. The springs decline in yield throughout the dry season

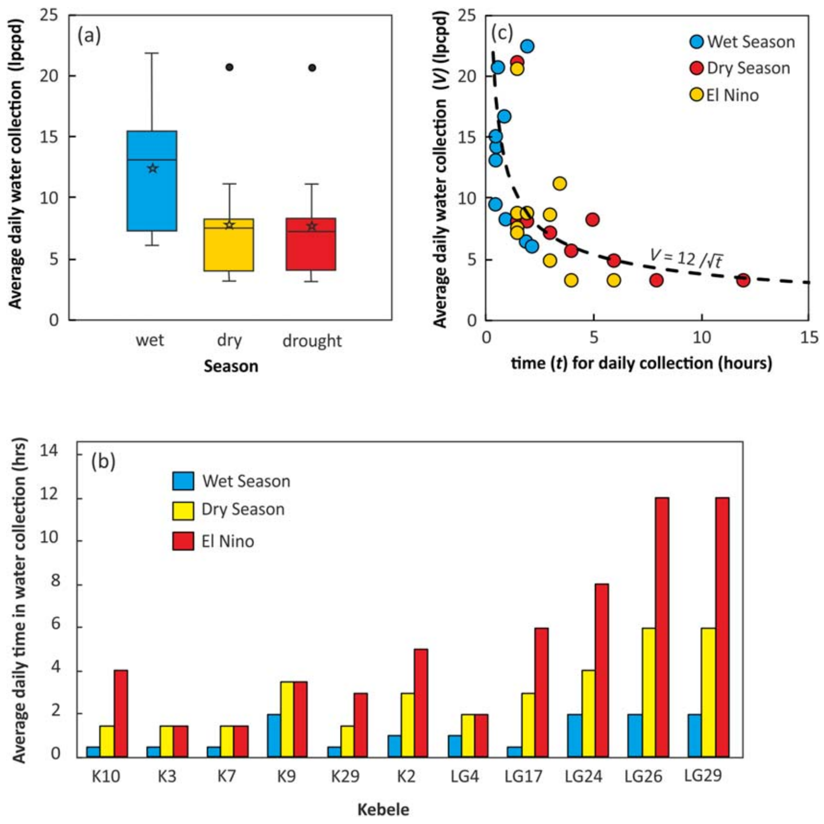

Figure 4. Daily water collection from 11 Kebeles in Kobo and Lay Gayint (a) volume of water collected per capita in wet season, dry season and during drought; (b) average time take to collect water during wet season, dry season and during drought and (c) the relationship between volume collected and time to collect water.

and spring boxes often do not recover fully overnight (figure 3). The springs flows often recover quickly with rainfall and the yield increases (as shown by recovery time, figure 2). The springs in Kobo are higher yielding and mainly located near the base of the escarpment within the basalt. During the hydrological year of 2016/17 the spring boxes recovered fully overnight although yields declined slightly as shown by the recovery time. At the end of the El Niño impacted hydrological year of 2015/16 the yields of some springs did reduce markedly as shown by the increased daily recovery time (figure 3) and the decline of water levels within the spring box.

The water quality of all sources as determined by TTC showed a similar overall pattern (figure 3 and table S2 is available online at stacks.iop.org/ERL/14/095003/mmedia). TTC counts at the start of the rains marking the end of the drought of 2015/16 were high, with the maximum counts greater than 300 cfu/100 mls in all types of water sources, (figure 3) putting them in the high risk category as determined by the World Health Organisation >100 cfu/100 mls (WHO 1997). The shallow boreholes showed the least impact from the rainy season with median values of 10 cfu/100 ml compared to 190 cfu/100 mls for the hand-dug-well and 59 cfu/100 mls for the springs. As the dry season progresses the TTC count in all sources declines to <12 cfu/100 mls, putting them mostly in the low risk category of <10 cfu/100 ls (WHO 1997). Although still contaminated, the shallow boreholes have lowest TTC counts throughout the year and within the rainy season. Up to 80% of shallow boreholes sampled showed TTC <10 compared with 64% for springs and 50% for hand dug wells.

The volumes collected for all domestic purposes and time taken to collect water in the wet and dry season and during the El Niño year are shown in figure 4. These are based on individual estimates in FGD and in discussion with Kebele administrators. Volumes at all times of year are low with median volumes of 13, 7.4 and 7.1 litres per capita per day (lpcpd) for wet, dry and El Niño drought respectively. In the dry season as well as during the El Niño drought more than 50% of the Kebeles sampled have less than the minimum volume for basic water set by the Sphere Project for humanitarian emergency situations (7.5–15 lpcpd) and of the WHO for basis water requirements for health, 7.5 lpcpd (Howard and Bartram 2003). The general findings are aligned with those of Tucker *et al* (2014b), however within the median values there are several communities that are surviving on even less – <5 litres per capita per day used in 4 communities in a normal dry season and during the El Niño drought.

The typical length of time used in water collection in the 11 sampled Kebeles is shown in figure 4(b). There are large differences between wet season, dry

Kebele	Main Source	L per person per day			hours collecting			Changed behaviour				Impacts				Health impacts		
		wet	dry	El Nino	wet	dry	El Nino	Change source	Continue Hygiene	Men collecting	Collect at night	Queing conflict	Missing meals	Education	Migration	Scabies	diarrhoea	Malnutrition
Kobo 2	River	8	8	8	1	3	5	Y - close	yes	No	No	Yes	Yes	Increase	Normal	Yes	Yes	Yes
Kobo 3	BH	21	8	8	0.5	1.5	1.5	No	reduce	No	No	Yes	No	None	Normal	Yes	Yes	Yes
Kobo 7	HDW	13	21	21	0.5	1.5	1.5	No	yes	No	No	Severe	No	Late	Inward	Yes	No	Yes
Kobo 9	Spring	22	11	11	2	3.5	3.5	Y - cattle	reduce	Yes	Yes	Severe	Yes	Absent	Increase	Yes		
Kobo 10	HDW	15	7	6	0.5	1.5	4	Y - cattle	reduce	No	No	Yes	No	Late	None	Yes	No	No
Kobo 29	Spring	14	7	7	0.5	1.5	3	Y - far	reduce	No	No	Yes	Yes	Late	Less	No	Yes	No
LG 4	Spring	17	8	8	1	2	2	No	yes	No	No	Yes	Severe	Late	Increase	No	No	
LG17	HDW	10	5	5	0.5	3	6	Y - far	yes	Yes	Yes	Yes	Yes	Late	Increase	Yes	No	Yes
LG 24	Spring	6	3	3	2	4	8	Y - far	None	Yes	Yes	Severe	Severe	Absent	Severe	Yes	Yes	Yes
LG 26	Spring	6	3	3	2	6	12	Y - far	None	Yes	Yes	Severe	Severe	Absent	Severe	Yes	Yes	Yes
LG 29	Spring	6	3	3	2	6	12	Y - far	None	Yes	Yes	Severe	Severe	Absent	Severe	Yes	Yes	Yes

Figure 5. Summary of impacts experienced in communities due to water shortage. Green is no or minimal impact; orange is significant impact associated with behaviour change; and red is severe impacts associated with major behaviour change. See supplementary material for categories.

season and drought, as well as differences between the rural highland Lay Gayint areas and more lowland Kobo Woreda. In the wet season water collection generally takes less than 1 h, rising to >1.5 h in the dry season and up to 12 h during the El Niño drought. Longest collection times in the dry season and drought were experienced in the highland area, and the impact of drought on collection times greatest. Figure 4(c) shows a strong relationship between the volume of water collected and the length of time taken in water collection governed by the power relation $\text{volume} = 12/\sqrt{(\text{time})}$. The data and relationship suggest little change in the volume of water collected after approximately 3 h, with volumes already critically low <5 lpcpd with little possibility for reducing volumes further. A summary of information on the impacts of domestic water scarcity during the El Niño drought from FGD and key stakeholder interviews is given in figure 5. The information are presented in different clusters: impacts on volumes and collection times; changed water collection behaviour; wider impacts reported by communities; and increased prevalence of scabies, diarrhoea and malnutrition reports by health clinics. Most communities had to change the water source they used with the remote upland communities having to travel to much further sources down in the valleys, and remote lowland communities having to travel further upstream in riverbeds that had run dry. Most communities reduced water for hygiene with the worst affected completely stopping water use for hygiene purposes. For most of the water sources where water collection times were high, men became involved in water collection which often entailed long queues, collecting at night and some tension and arguments over queuing and distribution. The two most widespread impacts of the decrease in water security reported were conflict over queuing and having to miss breakfast with subsequent impacts on infant feeding, being late or absent from the farm and children being late for or absent from school. Other more extreme impacts were experienced in the remote areas where hunger was constant, cooking was changed to low water activities such as bread making, and men and male children migrated for the season with any cattle to live by the water sources in another Woreda, causing school attendance to drop. In some Kebeles with good water sources, inward migration increased, and outward migration decreased as demand for labour reduced. In these Kebeles, migrants were reported to have brought scabies with them. Most health centres reported increases in cases of scabies, acute watery diarrhoea and malnutrition (particularly amongst infants).

Discussion

The performance of boreholes, wells and springs

There is a significant difference in the performance of different types of water source during the dry season and drought, albeit moderated by the surrounding groundwater environment. Boreholes equipped with handpumps are more reliable than springs or hand-dug-wells, and the performance does not change markedly seasonally or during drought. This is consistent with other studies in semi-arid areas, where boreholes have generally performed well through meteorological drought, (Calow *et al* 1997, 2010, Taylor *et al* 2013, Howard *et al* 2016); due in part to their ability to capture to capture deeper groundwater of longer residence times (Lapworth *et al* 2013). Such behaviour has also been forecast from numerical modelling which indicates that borehole performance is more sensitive to aquifer conditions and abstraction rates than climate (MacDonald *et al* 2009). Therefore a well sited borehole should be little impacted by drought. A potential complication with boreholes is poor functionality rates, with less than 50% of hand pumps equipped boreholes fully functional in Ethiopia (Kebede *et al* 2017) with similar results for other African countries (Mwathunga *et al* 2017, Owor *et al* 2017). Reasons for poor functionality are complex with poor siting, maintenance and corrosion (Foster 2013, Fisher *et al* 2015, Bonsor *et al* 2018) often being cited as greater predictors of failure than drought. The implications are clear, ensuring that households have access to a well sited borehole equipped with a handpump, and investing in maintenance to improve functionality, is an excellent way to improve access to secure water through extended dry seasons and drought. For locations where boreholes are not straightforward, due either to being inaccessible to conventional drilling rigs or located on poorly permeable aquifers special measures may be required. These could include resorting to other supply options such as reticulated systems, investing in lightweight drilling rigs and increased investment in mapping aquifers and siting boreholes.

Although in general hand-dug-wells and springs performed more poorly then boreholes, some of them provided a reliable supply during dry season and drought. The springs and hand dug wells that performed best were in Kobo at the base of the escarpment. Here the hand-dug-wells were located in a high yielding high storage alluvial aquifer, where there was plenty of groundwater. Likewise the more sustainable springs tended to have much larger catchments and therefore like to discharge older groundwater less coupled to recent rainfall. Therefore, springs and hand-dug-wells can have a place within climate resilient water supply infrastructure—but only if accompanied with a thorough investigation of the hydrogeological environments of individual sources.

Water quality

A clear temporal trend in water quality is observed in the TTC data. Highest contamination is observed in all sources with the rains in July 2016 which marked the end of the El Niño drought. This coincided with some communities discussing their water smelling foul. After this first flush of poor quality water, water quality improved markedly even during the heavy rains of August. Water quality was best in February 2017, when there had been several months without rainfall, and deteriorated a little with the smaller rains of the early Belg rainfall in March–June. However, the greatest contamination was the first major rains after the drought. This observation is consistent with others (Howard *et al* 2003) and underlies the importance of public health messages for treating drinking water during heavy rainfall at the end of the dry season and drought. Boreholes were less contaminated than wells and springs, however, boreholes were not immune from contamination, as found in some other studies where water quality in boreholes is often found to be much better than springs or wells during rainfall but not universally uncontaminated (e.g. Bonsor *et al* 2014). Poor construction of the boreholes is likely to be a major contribution to the observed contamination. Properly sealing the top 3–5 m of the borehole and constructing a sanitary seal and safe soakaway is required to help minimise surface contamination.

Impacts of water insecurity

Most significant from the Ethiopian study is the length of time people spent in water collection during both the dry season and drought, and the very low total volumes of water reported for domestic use <5 litres per capita per day. This volume is below the minimum (7.5 l) suggested by the WHO to meet basic needs and coupled with fetching times of $\gg$30 min indicates very high health risks (Howard and Bartram 2003). Such low volumes were collected in both the dry season and drought. In most cases water for hygiene was sacrificed and in the most extreme cases food preparation changed. At these low volumes there was little elasticity with collection times, and people were routinely collecting for more than 10 h. However, overall there was a significant relationship between collection time and volumes collected, with a reduction in water use reported from 30 min to approximately 5 h, where water volumes appeared to level out at a minimum for survival. This is consistent with, and extends, the conceptual model of Cairncross and Feachem (1983) which demonstrates much higher use if water is within 3 min of the house, then inelastic to 30 min, thereafter reducing again with time taken for collection. Here we have identified a relationship, volume $= 12/\sqrt{(\text{time})}$ for the reduction after 0.5 h, until a minimum water use for survival of 3–5 l is reached.

The longer collection times experienced in the dry season and by extension into drought had serious implications for households. The scarcity of water led to conflict, both within communities where tensions over queuing were regular and sometimes expressed violently, but also within households where the impacts were experienced by all. The physical burden placed on women was often expressed as an impact to breastfeeding children and in induced miscarriages in the most remote Kebeles. Men took on the role of water collection, skipping breakfast and sometimes lunch, and often led to being late to the farm or missing farming altogether. School attendance was down in all but one district because breakfast was often late, children were involved in water collection and in some cases children were responsible for bringing livestock to further water sources. Schools attempted to mitigate decrease in attendance by tying receiving food aid to attendance. This appeared to work in one district, but in others the pressures to migrate out to follow water were greater than the food aid incentives provided by the school. The health centres all reported increases in disease during the El Niño drought, and some reported problems with water supply for their own centres, with employees paying for water collection to keep the centre functioning. Such widespread impacts all directly attributable to water scarcity emphasise the important role of water supply in achieving many development goals particularly under drought conditions.

Early warning?

In most cases the water insecurity experienced through failure or reduction of yield from domestic sources during drought is an extension of the water insecurity experienced during the dry season. Similarly, the severity of impacts, in terms of collected volumes, collection times and consequent impacts on nutrition, conflict, school attendance and health are extensions of insecurity through a normal year. Therefore, examining water supply performance and coping strategies in a normal dry season is a useful predictor of how communities will cope during drought years.

Conclusions

Shallow boreholes (<100 m) equipped with handpumps were the most reliable source of water in the study area in the Ethiopian highlands during the drought of 2015/16 and similarly through the extended dry season. Borehole yields varied little throughout the year, and water quality was better than springs and hand-dug-wells, although contamination by TTC was observed in boreholes at the end of the El Niño drought. Springs and hand-dug wells could also give a reliable supply where the aquifer conditions were favourable. Many communities who relied on springs, wells and riverbed experienced severe water shortage in the El Niño drought with mean daily collection times of up to 12 h. This led to reports of conflict, sometimes violent, missed meals, reduction in time farming and increased health impacts. In addition, a clear relationship between volume of water and time taken to collect was observed for collection times from 30 min to 5 h until a floor of 3–5 litres per capita per day was reached. Given that these impacts are predictable from the type of source communities have access to, and behaviour during a normal dry season it should be possible to prioritise improvements to water supply with largest impact on livelihood security. From this study there is a clear case for improving resilience to drought by installing boreholes equipped with handpumps even if they are >30 min from a household, and giving a much greater emphasis to ongoing maintenance and functionality.

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ORCID iDs

A M MacDonald https://orcid.org/0000-0001-6636-1499
D J Lapworth https://orcid.org/0000-0001-7838-7960

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