Evidence in the Horn of Africa of the resilience of rural water supply to drought

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Abstract

Groundwater is often relied on to provide secure drinking water, particularly in rural Africa, where other options are limited. The increased incidence of drought and its likely escalation due to climate change raise questions as to how resilient groundwater is to drought, and how the performance of different technologies used to access groundwater compares during drought. Here we report the results of three research studies undertaken in Ethiopia to directly address these questions. We first examine hydrographs from 19 wells, springs and boreholes during the 2015/16 El-Niño drought and the years following. Secondly, we report the results of a survey of groundwater recharge for 50 sampled boreholes from 4 woredas (districts) and, lastly, we examine the response of >5,000 different water points from across Ethiopia from January to April 2016 as the drought evolved.
The results from the three studies all give a consistent story: groundwater supplies, particularly those accessing groundwater deeper than 15 metres, are resilient to the short-term effects of drought and become increasingly important as other water sources (e.g., springs) fail. Hand-pump-operated boreholes were often the most reliable sources during drought periods, although motorized boreholes, if accompanied by active monitoring and maintenance, also proved so. Springs and hand-dug wells were generally, but not universally, severely impacted by drought, with those at higher elevations most affected. Recharge studies using environmental tracers suggested that the mean residence time of groundwater (<100 metres deep) is in the order of several decades across the Ethiopian Highlands. This indicates modern recharge is occurring but is not reliant on very recent rainfall; thus, groundwater is both resilient to drought and renewable when managed appropriately. Additional pressures put on groundwater supplies by the drought were shown to be mitigated by an active and sustained campaign of monitoring and maintenance as drought evolved.

Introduction

The Horn of Africa is highly vulnerable to the impacts of drought. Studies of the impact of climate change on future drought suggest that most of Africa will experience significant increases in drought frequency and magnitude (Naumann et al., 2018) and rapid population growth is expected to lead to an increased number of people exposed to drought (Liu et al., 2018). Furthermore, El-Niño events are predicted to double in frequency as a result of climate change (Cai et al., 2014) and will have consequences for drought frequency and magnitude across Africa. Throughout sub-Saharan Africa, roughly 73 per cent of people rely on point-source water supplies, while 47 per cent use improved and 26 per cent use unimproved point sources (WHO & UNICEF, 2019). Understanding how these sources perform during drought is fundamental to designing climate-resilient water-supply programmes and infrastructure (Howard et al., 2016). Groundwater is typically a resilient water resource (Cuthbert et al., 2019), but few studies have directly compared the performance of different rural water-supply technologies accessing groundwater during drought or assessed the resilience of groundwater to drought.

This study reports the results of various research efforts led by the British Geological Survey in collaboration with Addis Ababa University to directly address these questions. Firstly, we give some contextual information from two social science studies which offer evidence for how communities and households can be impacted by unreliable water supplies. We then provide results from three studies to examine drought resilience in respect of different types of water-supply infrastructure. Study 1 was a focused study in two woredas (districts) where the performance of 19 different water sources were intensely monitored over a period of 18 months (MacDonald et al., 2019). Study 2 reports a multimethod recharge analysis using 50 hand-pumped boreholes across the Ethiopian Highlands, while Study 3 reports the results of a large survey of 5,000 water points during the El-Niño drought of 2105/16 (MacAllister et al., 2020a). Together, these studies provide a strong evidence base in respect of the climate resilience of different types of water-supply infrastructure in the Horn of Africa.

Evidence of the human impact of water insecurity

Two surveys were recently undertaken in Ethiopia to assess the impact that water insecurity can have on households and communities. The first study involved detailed household surveys in a highland-to-lowland transect in Oromia (Tucker et al., 2014), while the second survey was undertaken in two districts in Amhara and comprised community discussions and interviews with officials from kebeles (administrative wards), healthcare facilities and schools (MacDonald et al., 2019). These studies indicate that (Tucker et al., 2014; MacDonald et al., 2019):

- water use declines to dangerous levels (3–5 litres per capita per day) as water sources fail and collection times increase (*see Figure 1*);
- water use for hygiene is sacrificed, with the most water-insecure households using no water for hygiene during the dry season, or drought;
- poorer households use consistently less water; and
- increased collection times (up to 12 hours) led to incidents of violent conflict, missed meals, reduction in school attendance and farm activity, and increased health impacts, particularly on infants.

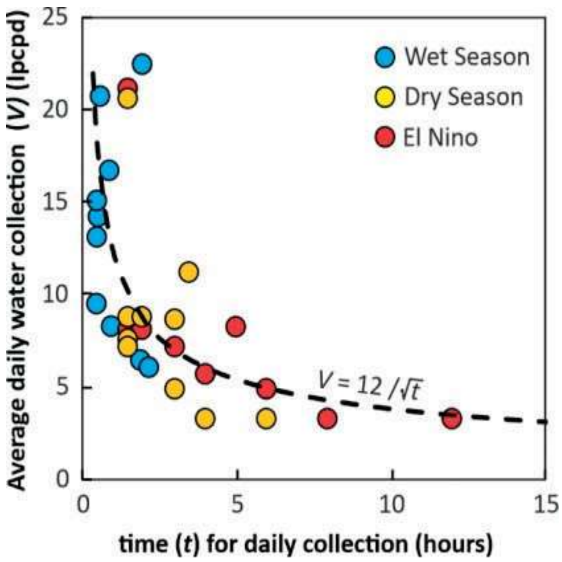

Figure 1: The relationship between average daily collection times and the volume of water collected per person and how this evolves from wet season to drought
Source: MacDonald et al. (2019).

Study 1 – High-frequency monitoring of springs, wells and boreholes in Amhara

Nineteen wells, boreholes and springs were equipped with high frequency (30 minute) water level dataloggers over a two-year period to assess their performance during and after the El-Niño drought of 2015/16, and the subsequent two rainy seasons and dry seasons (MacDonald et al., 2019). A typical example of the water level variation in a spring box, hand-dug-well and borehole is shown in Figure 2 along with rainfall. The research showed a striking difference in performance with respect to the different water sources (MacDonald et al., 2019):

- Boreholes with handpumps performed most reliably, with negligible change in the daily recovery time after pumping throughout the wet season, dry season and drought.
- Many smaller springs dried up completely and people were forced to move to sources further afield.
- Hand-dug wells had variable performance depending on the hydrogeological context. In the highland areas, daily recovery times were long and many dried out during the dry season (*see Figure 2*). However, those located in alluvial deposits in the plain continued to offer a good supply through drought.
- All types of sources showed evidence of contamination during heavy rain at the end of the extended drought, but boreholes equipped with handpumps were least affected.

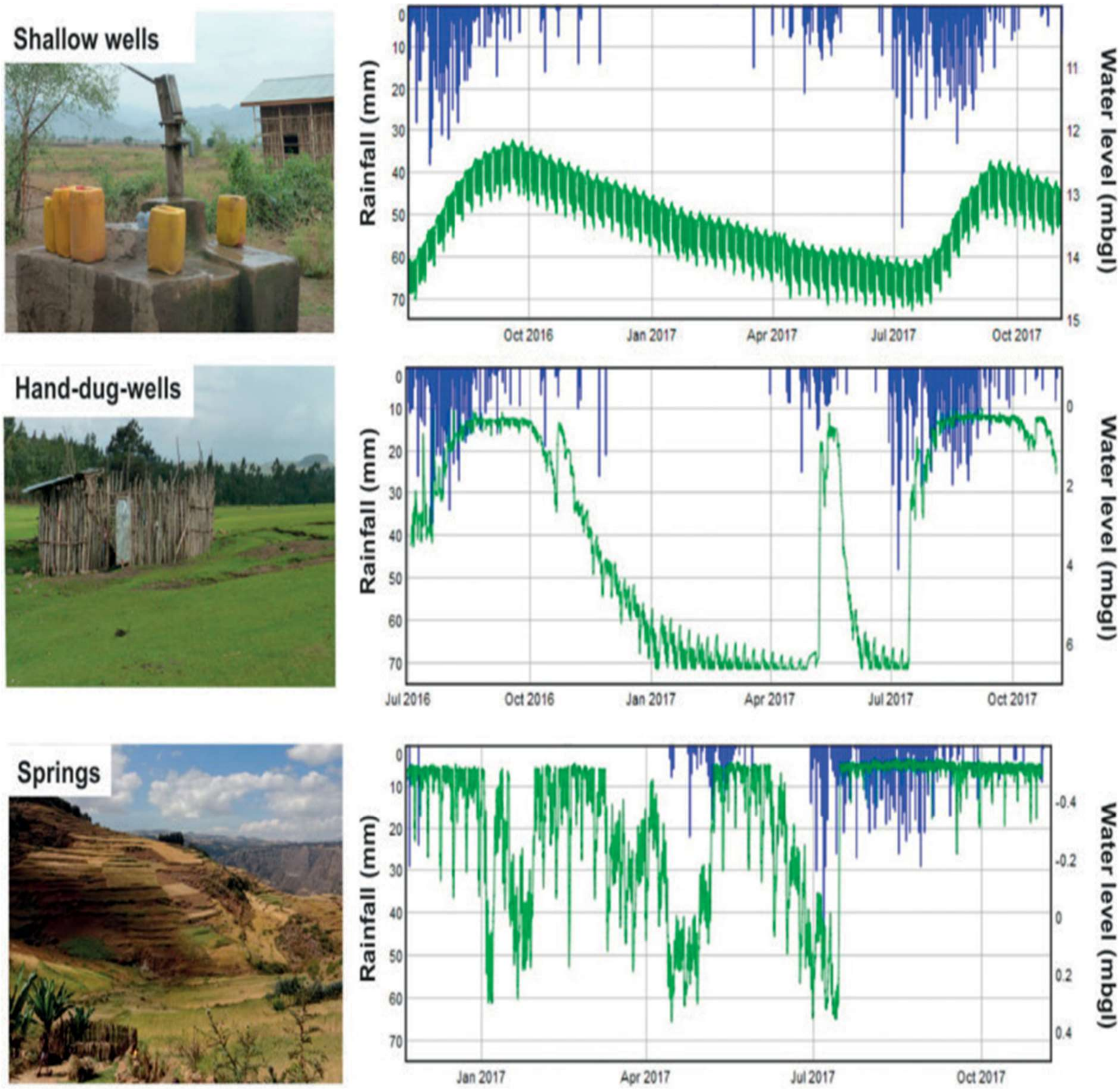

Figure 2: Examples of the response of boreholes with handpumps (top), hand-dug wells (centre) and springs (bottom) in the study area in Amhara during the 2016–2017 study period
Note: The borehole response to pumping did not change, thus providing secure water throughout the dry season and drought. The performance of the hand-dug wells declined rapidly at the end of the wet season, recovering slowly after the rains resumed. Although the yield of springs also declined after the end of the wet season, they recovered quickly as rains returned.
Source: MacDonald et al. (2019).

Study 2 – Estimates of groundwater recharge across the Ethiopian Highlands

Fifty boreholes equipped with hand pumps were examined in a 2018 study across the Ethiopian Highlands to estimate their long-term recharge and recharge pathways. A variety of environmental tracers was used (dissolved anthropogenic gases, i.e., chlorofluorocarbons/CFCs and sulphur hexafluoride/SF_6; stable isotopes of water; and chloride) and interpreted to give a consistent picture of recharge and recharge processes. The study found the following (Banks et al., 2020):

- The stable isotopes of water showed no evidence of enrichments due to evaporation prior to recharge. In addition, there was a slight bias of heaver isotopes in groundwater when compared with their presence in average rainfall, indicating that more intense rainfall events are those that dominate groundwater recharge.

- The chloride mass balance indicates that groundwater was being recharged in the range of 50–250 millimetres per year (interquartile range).
- The presence of dissolved CFC and SF_6 gases at all sites implies that groundwater recharge had occurred in these shallow boreholes recently, i.e., during the past few decades (*see Figure 3*). From simple modelling of the data it could also be inferred that groundwater was being recharged in the range of 30–300 millimetres per year.

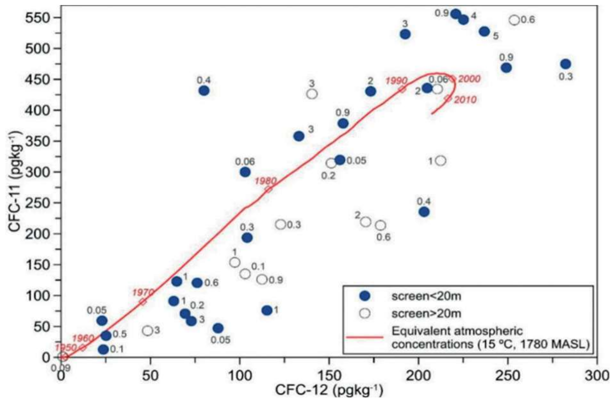

Figure 3: Cross plot of CFC-12 and CFC-11 sampled from 50 hand-pumped boreholes randomly selected across the Ethiopian Highlands
Note: The presence of these anthropogenic gases in shallow groundwater (<100-metre depth) indicates that recharge is recent, i.e. within the past few decades.
Source: British Geological Survey ©UKRI 2020 and Banks et al., 2020.

Therefore, groundwater recharge in these highland areas, where rainfall is >750 millimetres per year, generally suffices to support hand-pumped boreholes in providing secure drinking water. Where groundwater recharge tends towards the higher side of the annual range, some of these boreholes may also be able to sustain higher-yielding motorized pumps. The bias of recharge to heavier rainfall events also provides some confidence that climate change may not dramatically reduce groundwater recharge, since forecasts predict that intense rainfall events will become more frequent in the future.

Study 3 – Comparison of the performance of water sources during the El-Niño drought

Using a unique temporal data set, we compared the performance of 5,196 rural water-point supplies during the 2015/16 El-Niño drought in Ethiopia (MacAllister et al., 2020a). These data were collected from January to May 2016 by teams commissioned by the United Nations Children's Fund (UNICEF) following the severe drought in Ethiopia. Information was collected weekly by trained enumerators using questionnaires to gather quantitative and qualitative data from water-point attendants, water, sanitation and hygiene committee members or another knowledgeable local authorities. The surveys were conducted using a mobile monitoring platform called Akvo Flow developed by the Akvo Foundation. Different source types were captured: hand-pumped boreholes, motorized boreholes, open sources, protected hand-dug wells and springs (*see Figure 4, which shows a summary of functionality, user numbers, travel times and volumes extracted, by water-source type*).

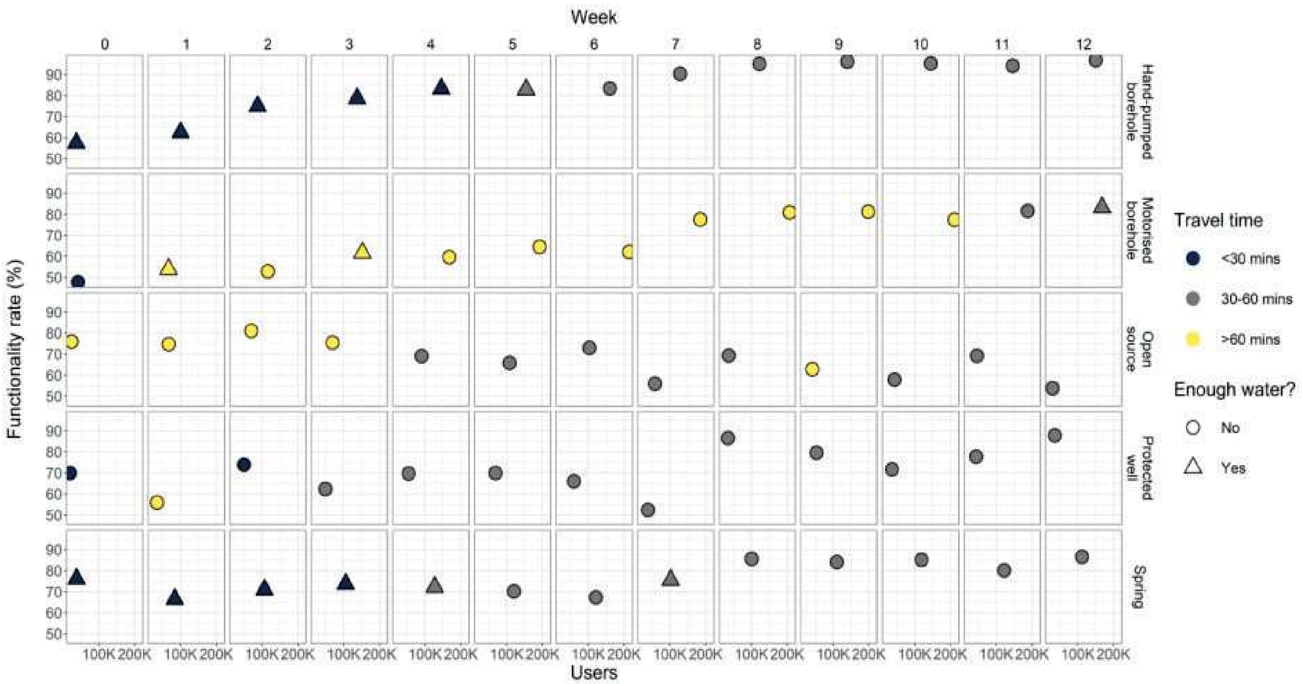

Figure 4: Summary of functionality, user numbers, travel times and volumes extracted by water-source type

Note: The position of the points in the individual panels represents the functionality and overall user numbers for each water-source type (approximately 830,000 people relied on the sources included in the monitoring programme); colours represent modal travel times for water collection; and shapes represent users' perceptions of the adequacy of the water supply.

Source: MacAllister et al., 2020b; British Geological Survey ©UKRI 2020.

The evolution of the performance of each water-source type (in terms of functionality, usage, access and extractions) reveals six key points:

1) Hand-pumped boreholes experienced the most consistent overall increases in functionality (due to a responsive maintenance programme), with most users travelling for <60 minutes (<30 minutes in the first 6 weeks) to collect water.
2) Motorized boreholes had low initial functionality (<50 per cent) and slower increases in functionality throughout the drought period. Users of motorized boreholes had to travel for >60 minutes to access water throughout the intervention period.
3) In general, boreholes that accessed deep groundwater, i.e., those that were hand-pumped or motorized, were a very important water source for many people during the drought.
4) Springs performed reasonably well, providing water to approximately 100,000 people via travel times of <60 minutes.
5) People reported collecting adequate quantities of water from springs and hand-pumps until week 6 of the monitoring period. After week 6, and for all other source types, people reported collecting inadequate quantities of water.
6) Open sources experienced large declines in functionality.

From the perspective of drought, three results are particularly useful (MacAllister et al., 2020a):

a) Mean functionality ranged from 60 per cent for motorized boreholes to 75 per cent for hand-pumped boreholes. Real-time monitoring as well as responsive operation and maintenance led to rapid increases in functionality of hand-pumped and, to a lesser extent, motorized boreholes throughout the monitoring period.

b) Increased demand was placed on motorized boreholes in lowland areas as springs, hand-dug-wells and open sources failed. Most users travelled >1 hour to access motorized boreholes or <30 minutes to access hand-pumped ones.
c) Boreholes that performed best during the drought were those accessing deep groundwater, i.e., >30 metres below the surface, by way of hand pumps or motor generators.

Therefore, the study suggests prioritising access to groundwater via multiple improved sources and a portfolio of technologies, such as hand-pumped and motorized boreholes, supported by responsive and proactive operation and maintenance. These factors will increase rural water-supply resilience during drought.

Conclusions

The three reported studies conducted in Ethiopia from 2014 - 2020 have provided a rich evidence base on the climate resilience of water infrastructure in the Horn of Africa, with a particular focus on hand-pumped boreholes, springs and hand-dug wells.

- Access to reliable groundwater is key to developing climate-resilient drinking-water supplies. For complex hydrogeological environments, this means that investment needs to be targeted to mapping groundwater and accurately siting water supplies in the most productive parts of aquifers.
- Hand-pumped boreholes have a key role to play in any water-supply programme. Shallow boreholes (<100 metres deep) equipped with hand pumps were consistently the most reliable water supply. They performed well throughout the drought period and were easier to maintain and quicker to fix than motorized schemes.
- Motorized boreholes were significant for many communities during the drought but were most important in the lowland areas of Ethiopia. At present, however, there is a lack of skills to maintain these technologies and communities generally need to travel longer to access motorized boreholes when compared to their hand-pumped counterparts.
- Other sources, such as hand-dug wells and springs, although more unreliable, could provide secure water in certain hydrogeological environments. They often recovered quickly once rainfall had returned, thereby reducing pressure on borehole sources (cf. Calow et al., 2010).
- Even where reliable sources are located >30 minutes away in terms of collection time (and, therefore, are classed as a limited service under Sustainable Development Goal 6 on water and sanitation), they can significantly reduce the impact of water insecurity on households and communities.
- Maintenance matters. The active monitoring and subsequent maintenance of water supplies during the 2015/16 drought were vital in keeping infrastructure working. This, along with other studies (e.g., Whaley et al., 2019), raises questions about the roles of communities, government and the private sector in water-supply maintenance.
- Groundwater recharge is generally enough to support a hand pump, and climate change is unlikely to change this. However, the much larger yields required for reticulation and irrigation will need greater scrutiny as regards their reliability.

Acknowledgements

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References

Banks, E.W., et al., ‘Environmental tracers to evaluate groundwater residence times and water quality risk in shallow unconfined aquifers in sub Saharan Africa’, *Journal of Hydrology*, 125753, 2020, <https://doi.org/10.1016/j.jhydrol.2020.125753>.

Cai, W., et al., ‘Increasing Frequency of Extreme El Niño Events due to Greenhouse Warming’, *Nature Climate Change*, no. 4, 2014, pp. 111–116, <https://doi.org/10.1038/nclimate2100>.

Calow, R. C., et al., ‘Ground Water Security and Drought in Africa: Linking availability, access, and demand’, *Groundwater*, no. 48, 2010, pp. 246–256, <https://doi.org/10.1111/j.1745-6584.2009.00558.x>.

Cuthbert, M. O., et al., ‘Observed Controls on Resilience of Groundwater to Climate Variability in Sub-Saharan Africa’, *Nature*, no. 572, 2019, pp. 230–234, <https://doi.org/10.1038/s41586-019-1441-7>.

Howard, G., et al., ‘Climate Change and Water and Sanitation: Likely impacts and emerging trends for action’, *Annual Review of Environment and Resources*, no. 41, 2016, pp. 253–276, <https://doi.org/10.1146/annurev-environ-110615-085856>.

Liu, W., et al., ‘Global Drought and Severe Drought-affected Populations in 1.5^{o} and 2^{o} C Warmer Worlds’, *Earth System Dynamics*, no. 9, 2018, pp. 267–283, <https://doi.org/10.5194/esd-9-267-2018>.

MacAllister, Donald J., et al., ‘Comparative Performance of Rural Water Supplies during Drought’, *Nature Communications*, no. 11, 2020a, 1099, <https://doi.org/10.1038/s41467-020-14839-3>.

MacAllister, Donald J., et al., ‘Comparative Performance of Rural Water Supplies during Drought – Dataset’. 17 January 2020b, <https://doi.org/10.5285/cb950f2f-4c79-4ea8-ba9a-92a6dcc4f388>.

MacDonald, Alan M., et al., ‘Groundwater and Resilience to Drought in the Ethiopian Highlands’, *Environmental Research Letters*, no. 14, 2019, 095003, <https://doi.org/10.1088/1748-9326/ab282f>. Used under Creative Commons Attribution 3.0 International License, <http://creativecommons.org/licenses/by/3.0/>.

Naumann, G., et al., ‘Global Changes in Drought Conditions under Different Levels of Warming’, *Geophysical Research Letters*, no. 45, 2018, pp. 3285–3296, <https://doi.org/10.1002/2017GL076521>.

Tucker, J., et al., ‘Household Water Use, Poverty and Seasonality: Wealth effects, labour constraints, and minimal consumption in Ethiopia’, *Water Resources and Rural Development*, no. 3, 2014, pp. 27–47, <https://doi.org/10.1016/j.wrr.2014.04.001>.

Whaley, L., et al., ‘Evidence, ideology, and the policy of community management in Africa’, *Environmental Research Letters*, no. 14, 2019, 085013, <https://doi.org/10.1088/1748-9326/ab35be>.

WHO & UNICEF/World Health Organization and United Nations Children’s Fund, *Progress on Household Drinking Water Sanitation and Hygiene 2000–2017: Special focus on inequalities*, WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, New York, 2019.