



Quantifying increased groundwater demand from prolonged drought in the East African Rift Valley

Evan A. Thomas^{a,*}, Joseph Needoba^b, Doris Kaberia^c, John Butterworth^d, Emily C. Adams^{e,f}, Phoebe Oduor^g, Denis Macharia^g, Faith Mitheu^g, Robinson Mugo^g, Corey Nagel^c

^aMortenson Center in Global Engineering, University of Colorado, Boulder, CO, United States

^bOregon Health & Science University–Portland State University School of Public Health, Portland, OR, United States

^cUniversity of Arkansas, Little Rock, AR, United States

^dIRC Wash, Addis Ababa, Ethiopia

^eEarth System Science Center, University of Alabama in Huntsville, United States

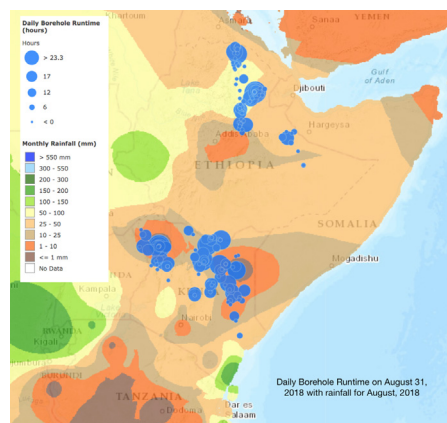
^fSERVIR Science Coordination Office, NASA Marshall Space Flight Center, United States

^gRegional Centre for Mapping of Resources for Development, Nairobi, Kenya

HIGHLIGHTS

- We examined rainfall against groundwater use at 221 water points serving over 1.34 million people in the arid regions of Kenya and Ethiopia.
- A 22.3% increase in borehole runtime follows weeks with no rainfall.
- A 1 mm increase in weekly rainfall was associated with a 1.0% decrease in borehole use.
- Groundwater boreholes are critical infrastructure in drought prone regions.

GRAPHICAL ABSTRACT



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ABSTRACT

Millions of people in the arid regions of Kenya and Ethiopia face water scarcity and frequent drought. Water resource forecasting and reliable operation of groundwater distribution systems may improve drought resilience. In this study, we examined three remote sensing data sets against in-situ sensor-collected groundwater extraction data from 221 water points serving over 1.34 million people across northern Kenya and Afar, Ethiopia between January 1, 2017 and August 31, 2018. In models containing rainfall as a binary variable, we observed an overall 23% increase in borehole runtime following weeks with no rainfall compared to weeks preceded by some rainfall. Further, a 1 mm increase in rainfall was associated with a 1% decrease in borehole use the following week. When surface water availability is reduced during the dry seasons, groundwater demand increases. Our findings emphasize the imperative to maintain functionality

* Corresponding author.

E-mail address: ethomas@colorado.edu (E. A. Thomas).

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of groundwater boreholes in these regions which often suffer drought related emergencies. Funding provided by the United States Agency for International Development, the World Bank, the National Science Foundation, and the Cisco Foundation. The views expressed in this article do not necessarily reflect the views of the United States Agency for International Development or the United States Government.

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1. Introduction

Globally, access to freshwater is a key challenge, exacerbated by the changing climate (Vörösmarty et al., 2000; Arnell, 1999). By 2025, 1.8 billion people will be living in countries or regions with absolute water scarcity, and two-thirds of the world's population could be living under water stressed conditions, 80% of whom live in developing countries (Schlosser et al., 2014).

Millions of people living in the arid, drought prone regions of the East African Rift Valley, including parts of Ethiopia and Kenya, are facing significant threat from a lack of safe, reliable and affordable water (Shiferaw et al., 2014; Viste et al., 2013). The region has experienced increasing frequency and severity of drought conditions as a result of decreased rainfall during the long rainy season from March through May (Lyon, 2014), and drought is expected to increase in severity and frequency over the coming years (Masih et al., 2014; Ahmadalipour and Moradkhani, 2018). The 2011 drought in East Africa caused food shortages for over ten million people and over 260,000 deaths (Nicholson, 2014; Shabelle, 2011). The more recent 2016 drought in Kenya resulted in over 3 million people facing food insecurity (Uhe et al., 2017). These recent drought conditions represent an acute threat, and highlight the urgency of environmental changes driving water shortage and creating a public health and security emergency.

Average rainfall in East Africa has been declining over the past several decades. In parts of this region, average rainfall has decreased over 20% since 1990. This trend in rainfall is in stark contrast to global climate model (GCM) predictions of an increase in regional rainfall caused by climate change – a conundrum known as the East Africa Climate Paradox (Rowell et al., 2015; Tierney et al., 2013). The reason for the discrepancies between climate models and observed conditions are not precisely known, but are likely related to global and regional inconsistencies in ocean-atmosphere forcing by GCMs as well as to short term environmental variability not captured by the models (Uhe et al., 2017; Dai, 2011; Lyon and Dewitt, 2012).

In the arid regions of Kenya and Ethiopia, people are predominantly farmers and pastoralists reliant on reliable water sources for agricultural, livestock and human uses. A mix of surface and groundwater use is common. Surface water use, including streams, rivers, lakes and other rain-filled depressions and ponds, is regular practice during the rainy seasons when surface water is readily available (Mutiga et al., 2010; Opiyo et al., 2015; Hurni et al., 2005). Prolonged drought is especially severe for smallholder farmers and pastoralists reliant on surface water sources including streams, rivers and lakes.

A majority of farmers in Kenya report perceiving climate change impacts on agricultural yields and have adopted some adaptation strategies including changing crop varieties, planting dates and crop types (Bryan et al., 2013). However, very few studies have attempted to quantify the behavior of vulnerable populations in response to the current drought conditions, and there is a relative absence of data on water use patterns. Climate forecasting, in particular rainfall estimates and subsequent groundwater demand (Luseno et al., 2003), as well as timely information used to maintain functionality of groundwater provisioning systems, would likely be of benefit for managing risks faced by pastoralist communities in Kenya and Ethiopia.

For example, rainfall shocks in the Awash river basin in Ethiopia, serving parts of the Afar Region, have a direct impact on agricultural

yields which propagate through the wider economy. A recent study (Borgomeo et al., 2018) estimated that a rainfall decrease could lead to a 10% decline in agricultural gross domestic product (GDP) and a 5% decline in overall regional GDP. This study estimated greater negative impacts among poorer households. When drought occurs, these vulnerable populations are highly reliant on groundwater supply to meet basic needs, typically by utilizing boreholes pumping deep groundwater (Worqlul et al., 2017; Okotto et al., 2015).

The total global economic losses associated with inadequate water supply and sanitation are estimated at \$260 billion annually. The capital cost for achieving universal access to water is estimated by the World Health Organization (WHO) to be \$141 billion – with rural communities accounting for \$62.3 billion of that total (WHO, 2012). Recurrent operations and maintenance costs for universal access amount to approximately 10% of the capital costs, about \$1.2 billion per year. While considerable funding and effort is aimed at providing increased access to water supplies, interventions designed to provide these services often lack sustained support. As the demand for groundwater increases, access to functional boreholes becomes a limiting factor across the vast region of East Africa. However, reliable functionality and regular maintenance of these groundwater supplies is lacking, often leading to significant service gaps and exacerbating water stress (Hope et al., 2012; Koehler et al., 2018; Foster et al., 2018; Nagel et al., 2015). For example, a recent study estimates between 30 and 50 % of the millions of community-managed water pumps installed in Africa are broken in the first 18 months (Foster, 2013).

2. Study context

Groundwater availability in the relatively deep aquifers in northern Kenya and Afar Ethiopia fluctuates based on both natural and human factors – the major drivers being rainfall which influences subsequent access to surface water resources as well as aquifer recharge, while the major driver of groundwater use is availability of working groundwater pumps. In Afar, the groundwater aquifers are influenced by active volcanic centers and thermal springs. Volcanic aquifer depth range from 60 to over 150 m. Due to geothermal activity, the groundwater at the point of borehole extraction is often over 50C (Kebede et al., 2008), and pipes are hot to the touch. These volcanic aquifers are recharged through annual mountain runoff and are thus susceptible to drought conditions. In addition, groundwater reserves are limited because of horizontal flux to the rift plains (Ayenew et al., 2008).

In northern Kenya comprehensive mapping of groundwater resources has not been completed, but several indicators suggest that groundwater extracted from boreholes is largely from fossil aquifers and therefore is water that is not annually recharged. In 2013, five fossil aquifers were discovered in northern Kenya, predominately in Turkana. These aquifers are located 100 m or more beneath the surface (Gramling, 2013). While some news reports indicate high salinity above WHO limits (Migiro, 2015), these aquifers are currently being exploited for livestock and agricultural uses.

Activity associated with borehole pumps is difficult to estimate, in particular because there are few observation wells and no institutionalized groundwater monitoring networks. To compensate for a lack of quantitative monitoring, efforts to measure groundwater extraction include estimating the potential precipitation in the region by combining in-situ and satellite-based remote sensing measurements.

Examples include regionally calibrated satellite derived precipitation data (Funk et al., 2015), and stream flow modeling. However, the relationship between rainfall and groundwater use in Africa is not well established, and is constrained by limited observational data sets (Taylor et al., 2009). Regional water use surrounding the Lake Naivasha in Kenya (van Oel et al., 2013) and the Geba River basin in Ethiopia (Gebreyohannes et al., 2013) have been estimated with water balance models that often lack groundwater abstraction data.

Data for groundwater collected by in-situ borehole sensors has recently become available via two USAID funded programs, Lowland WASH in Ethiopia and the Kenya Resilient Arid Lands Partnership for Integrated Development (Short et al., 2018). Designed to address information gaps in water service delivery and enable improved response to broken pumps, sensors measuring groundwater pump function have been installed across northern Kenya and Afar, Ethiopia. The sensors (SweetSense Inc. Portland, Oregon, United States) provide high temporal resolution data on borehole usage and report over cellular and satellite networks as a means to directly

measure water service delivery. Here, we use this “Internet of Things” network to estimate groundwater usage across the region and correlate the data to satellite remote sensing as a means to quantify borehole usage and to document relationships between direct extraction of groundwater (borehole use) and estimates of surface water availability (rainfall).

3. Data and methods

3.1. Groundwater extraction data collection

We collected groundwater extraction data from 221 water points across northern Kenya and Afar Region, Ethiopia serving a total of over 1.34 million people. 171 of these sites were monitored with satellite connected sensors. Additionally, approximately 50 sites were monitored with cellular connected sensors, however between November 2017 and April 2018, the Ethiopian government restricted cellular data service in the region, rendering the data collection

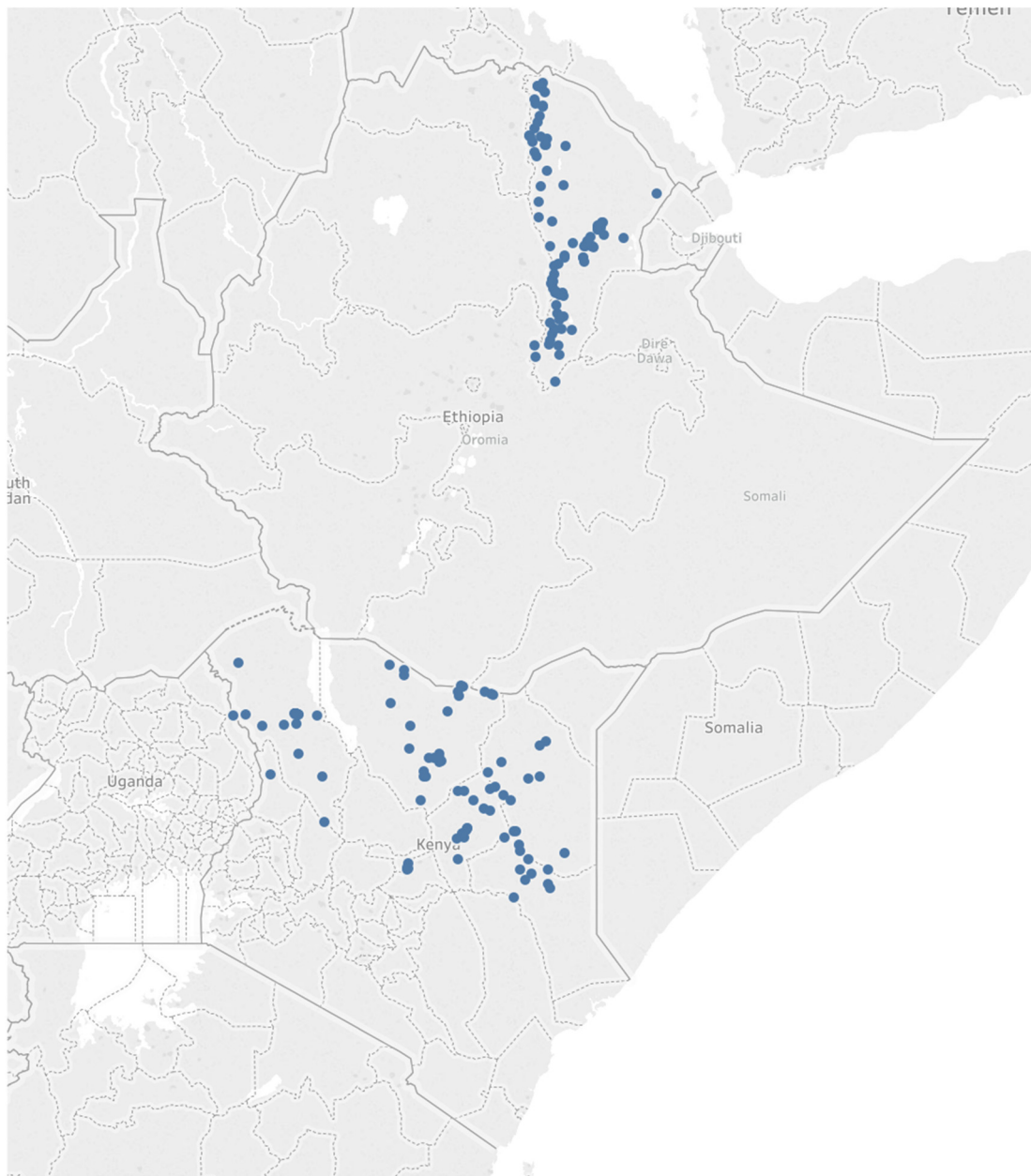


Fig. 1. Locations of sensor installations at groundwater boreholes in northern Kenya and Afar, Ethiopia.

from these sites non-viable for this period. Each of these extraction points consisted of electrically powered motorized pumps, extracting water from depths ranging between 4 and 276 m. Each site distributed water to elevated tanks and local distribution networks. Water uses include livestock, irrigation, and drinking water, and we estimate the pumps sampled in this study were used by an estimated average of 2000 people in Kenya and 250 people in Ethiopia. Distribution schemes range between local access at the borehole site up to pipes running 35 km away. The sensors function by monitoring the electrical current associated with borehole pump operation. The sensors have a sampling frequency of 40 min, and record the duration of use of the each pump each day, with an error of up to 40 min (the sampling window) per each separate activation of the pump. The borehole monitoring in this study is representative of water supply across northern Kenya and Afar, Ethiopia. Total population in Afar is approximately 1.75 million (CSA and Bank, 2013), and in the five northern Kenyan counties is 2.57 million (Kenya National Bureau of Statistics, 2014). See Fig. 1 for a map of installation locations.

The sensor data indicates runtime of each groundwater extraction pump. The sensors report daily over satellite or cellular networks regardless of pump runtime, thereby allowing an identification of a failed sensor differently from a non-operational pump. Time periods in which sensor data suggests a non-running pump may be attributed to one of several scenarios including: a) planned downtime inclusive of seasonal disuse, b) mechanical or electrical failures of the water pump or water scheme, c) management or institutional considerations such as budgetary constraints including buying fuel, human resources, or communication challenges, and d) false-negatives caused by sensor failure, including accidental or deliberate tampering with the sensor device.

3.2. Survey data sets

Borehole water system characteristics were collected for the majority of sites instrumented with sensors. Staff affiliated with partner organizations and local government authorities were trained in data collection, and use of a smartphone based survey tool, mWater

(New York, United States). In both countries, this survey data was collected as part of comprehensive asset inventory efforts. Water point characteristics, including age, well depth, average yield, and operating characteristics were collected through interviews of local operators and cognizant authorities. In most cases, original installation records are not readily available, and as such the survey data presented should be considered local knowledge. Surveys were conducted across the five northern Kenya counties, and in Afar Region, Ethiopia.

3.3. Remote sensing data sets

For this study, we examined three remote sensing data sets and attempted to correlate these to the sensor-collected groundwater extraction data. First, we examined daily rainfall data at a given well location. We used the Monthly Climate Hazards Group InfraRed Precipitation with Station (CHIRPS) v2.0 (Funk et al., 2015). This is a 30+ year quasi-global rainfall dataset that incorporates 0.05 degree (5 km) resolution satellite imagery with in-situ station data to create gridded rainfall time series. Sensor locations provided in shapefile formats were used as zonal locations of wells. Daily rainfall values for the wells for 2017–2018 were extracted from the CHIRPS grids and exported in form of tables for correlation analysis.

Second, we examined the vegetation response anomalies during the same time period as normalized difference vegetation index (NDVI). Data used for deriving NDVI was obtained from USGS Landsat 8 Collection 1 Tier 1 and real-time data top-of-atmosphere reflectance collection. In Ethiopia, the boreholes serve on average 250 households, within proximity of the borehole site (Table 1). In Kenya, the boreholes often have piped water lines extending on average 5 km from the pumping site. A buffer of 2.5 km from the borehole site was chosen to capture local influence of water pumping on NDVI, as well as up to 50% of the mean service area radius from the borehole site, as the assumed area of influence of water pumping on NDVI.

Finally, we used the NASA Gravity Recovery and Climate Experiment (GRACE) dataset. Launched in March 2002, the twin GRACE satellites mapped variations in the Earth's gravity field until the end

Table 1

Descriptive Statistics of Sensor and Survey Data for boreholes in Afar, Ethiopia and northern Kenya. Notes: Total population estimates based on 4.7 persons/household in rural Kenya (Kenya National Bureau of Statistics, 2014) and 5.1 persons/household in rural Ethiopia (CSA and Bank, 2013). Rain/Dry season borehole runtime disaggregation unavailable for Ethiopia data.

	n	Mean	SD	Min.	Max.
<i>Northern Kenya</i>					
Sensor – Observational Period (Days)	122 sites	256.89	169.30	19	610
Sensor – Daily Run Time (Hours)	31,340 site-days	5.90	6.90	0	23.33
Survey – Service Area (km radius)	126	5	5	0	35
Survey – Well Age (years)	106	10	10	1	52
Survey – Well Depth (meters)	92	118	81	4	276
Survey – Runtime - Wet Season (Hrs/Day)	109	7	6	0	24
Survey – Runtime - Dry Season (Hrs/Day)	127	10	6	1	24
Survey – Estimated Average Yield (m ³ /hour)	132	19	20	2	125
Survey – Households Served/Borehole	127	2060	3837	5	24,000
Survey – Population Served/Borehole	127	9681	18,034	0	112,800
Survey – Total Population Served	127	1,219,862			
<i>Afar, Ethiopia</i>					
Sensor – Observational Period (Days)	99 sites	257.89	169.30	11	610
Sensor – Daily Run Time (Hours)	25,512 site-days	4.09	6.16	0	23.33
Survey – Service Area (km radius)	n/a	n/a	n/a	n/a	n/a
Survey – Well Age (years)	94	16	7	9	44
Survey – Well Depth (meters)	14	76	44	35	192
Survey – Runtime (Hours/Day)	103	9	6	0	24
Survey – Estimated Average Yield (m ³ /hour)	46	18	21	1	119
Survey – Households Served/Borehole	101	250	413	0	3090
Survey – Population Served/Borehole	101	1274	2107	0	15,759
Survey – Total Population Served	101	127,393			

of the science mission in October 2017. By observing changes in the Earth's gravity field, changes in the amount of water stored in a region can be derived (Tapley et al., 2004; Wahr et al., 2004). Many studies that assess regional groundwater availability and depletion incorporate additional parameters when comparing GRACE with well data, including precipitation, soil moisture, surface waters, and biomass, either through in-situ measurements or through models, as the GRACE satellites data represent total water storage, not exclusively groundwater (Rodell et al., 2009; Yeh et al., 2006; Long et al., 2013).

Although this data set is only available at a coarse scale of 100 km spatial resolution and once a month, the dataset provided an independent assessment of the regional groundwater condition. The monthly GRACE anomalies were compared against the groundwater extraction data. The comparisons were made against individual well points, as well as the means of all the extraction data that fell within a single GRACE pixel.

3.4. Statistical methods

The three remote sensing data sets were initially examined independently for seasonal and spatial variability. The NDVI data set did not exhibit significant variability. The GRACE data coarse spatial scale, encapsulated most of the boreholes under observation, and therefore did not allow site-wise analysis. There was also limited temporal overlap between the GRACE data and the borehole extraction data. In addition since GRACE data are at monthly time steps, there were very few points for comparison. Therefore, only the CHIRPS rainfall data was analyzed against the borehole runtime data.

We examined the relationship between borehole use and rainfall during the period January 1, 2017 to August 31, 2018. Because sensors were being actively installed on boreholes during the study period, the duration of the monitoring period was variable (unbalanced) across the individual boreholes. Borehole runtime (in hours) and total rainfall (in mm) were summed over successive one-week periods at each site. Incomplete weekly borehole runtime data due to sensor malfunctions or data transmission issues were recorded as missing. In addition, boreholes that had no usable data during the entire study period were excluded from the analysis.

This combination of data on individual borehole use with site specific-rainfall estimates resulted in a time-series cross-section (TSCS) data structure, consisting of 221 site-specific bivariate time series. Because the monitored boreholes were spread across a large geographic area, aggregating these data into a single bivariate time series for each country would limit our ability to examine the hypothesized relationship of borehole use with local rainfall events. Therefore, we employed a regression modeling approach to TSCS data that allowed us to estimate the pooled effect of local rainfall across individual study sites while accounting for the presence of between-borehole heterogeneity, autocorrelation, non-independence of errors, and unbalanced data. Specifically, we fit time-series regression models of the relationship between weekly borehole runtime and one-week lagged rainfall, including a borehole fixed-effect to control for unmeasured, time-invariant heterogeneity across borehole sites and a lagged dependent variable to account for temporal autocorrelation. We used robust standard errors to adjust for within-borehole clustering. Because weekly borehole runtime was right-skewed and overdispersed, all regression models were specified using the negative binomial distribution. We fit a model combining all sites across the study region as well as separate country-specific models and tested for the presence of non-linear effects by fitting models with higher order polynomial terms (quadratic, cubic). Parameter estimates for higher-order polynomial terms were non-significant and were dropped from the final models.

In addition to models including prior week rainfall as a continuous variable, we examined the impact of lack of rainfall in the prior week by fitting a series of models regressing borehole runtime on a binary indicator of no rainfall vs. any rainfall. With the exception of dichotomizing rainfall, these models were constructed identically to those containing rainfall as a continuous measure. For models containing rainfall as a continuous measure, we exponentiated model coefficients to yield the percent reduction in borehole runtime associated with a unit (mm) increase in one-week lagged rainfall and we generated marginal estimates of runtime across the range of rainfall levels observed during the study period. For models including a binary measure of rainfall, exponentiated coefficients represent the percent increase in borehole use associated with no rainfall in the prior week. All statistical analyses were conducted using Stata 15 (Stata Corporation, College Station, TX).

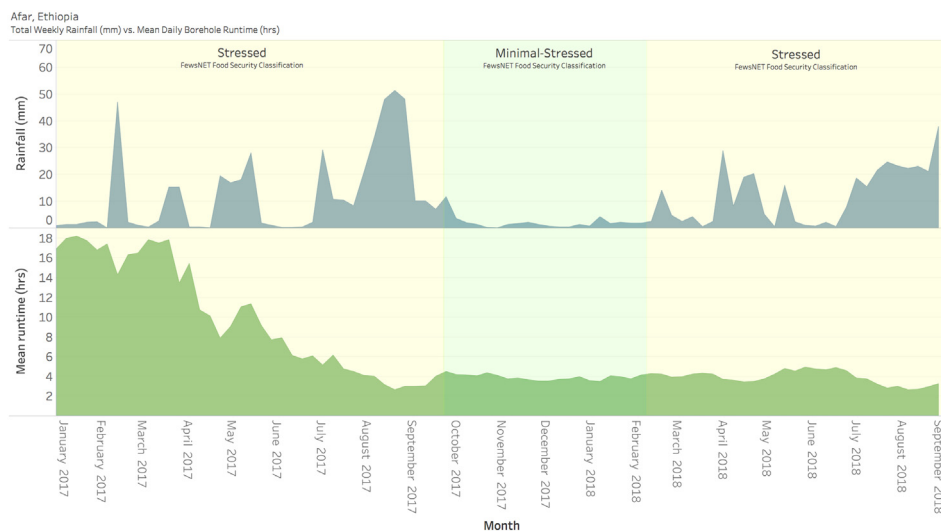


Fig. 2. Afar Ethiopia total weekly rainfall (mm) vs mean daily borehole runtime (hrs) January 1, 2017–August 31, 2018. Shaded areas indicate FEWSNet Food Security Classification (FEWSNet, 2019).

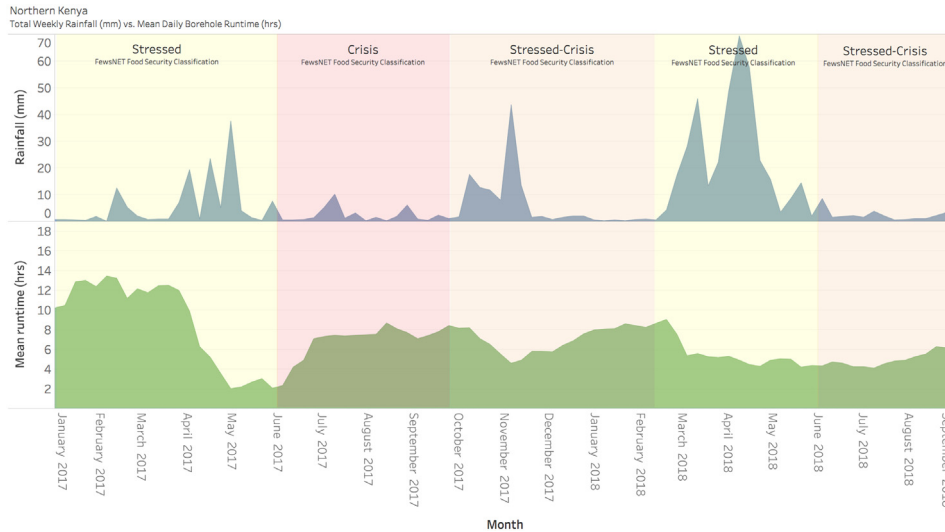


Fig. 3. Northern Kenya total weekly rainfall (mm) vs mean daily borehole runtime (hrs) January 1, 2017–August 31, 2018. Shaded areas indicate FEWSNet Food Security Classification (FEWSNet, 2019).

4. Findings

After excluding 3 boreholes that did not have usable data, a total of 221 boreholes were included in the analysis. In Kenya, 122 boreholes contributed a total of 4289 pump weeks of data available for analysis, with an average of 35.2 (SD = 24.1) weeks of data per site. In Ethiopia, 99 boreholes contributed a total of 3543 pump weeks of data, with an average of 35.8 (SD = 21.1) weeks of data per site. The mean weekly borehole runtime was 36.2 hours (SD = 44.4) during the study period. Consistent with weather patterns in this arid region, weekly rainfall totals were right skewed, with a mean of 7.84 mm (SD = 18.8) and a median of 0 mm (IQR = 5.3) in Kenya and a mean of 9.60 (SD = 15.7) and a median of 2.35 mm (IQR = 13.0) in Ethiopia. Low rainfall conditions were prevalent across the study area, with no observed rainfall during 65.7% of weekly intervals in Kenya and 47.7% in Ethiopia.

See Figs. 2 and 3 for total weekly rainfall and mean daily borehole runtime during the study period for Afar, Ethiopia and northern Kenya. The shaded areas indicate the Famine Early Warning Systems Network (FEWSNET) Food Security Classification during this period. The FEWSNET model is based in part on rainfall estimates using remote sensing data. As food security stress is forecast based on estimated agricultural yields after periods of rainfall, higher food security stress classifications lag periods of low rainfall. FEWSNET is a service adopted by the governments of both Ethiopia and Kenya (FEWSNet, 2019).

Our graphical abstract indicates borehole runtime on August 31, 2018, and rainfall during August 2018. The size of the points indicates the magnitude of borehole runtime from 0 to 24 h per day.

Table 1 presents descriptive statistics of survey and sensor data collected at borehole sites.

Estimated water production yields per borehole based on survey data indicated 18 m³ per hour in Ethiopia and 19 m³ per hour in Kenya, with high variability between sites. Therefore in our analysis we compared directly measured hourly runtime data rather than estimated water yields.

We observed a statistically significant relationship between borehole runtime and 1-week lagged rainfall in each of the country-specific models. In Kenya, a 1.0mm increase in rainfall was associated with a 1.1% decrease in borehole use the following week (RR = 0.989, 95% CI = 0.988 – 0.992, *p* < .001) after controlling

for time-invariant, site-level heterogeneity. Similarly, in Ethiopia, a 1.0 mm increase in rainfall was associated with a 1.3% decrease in borehole use (RR = 0.987, 95%CI = 0.985 – 0.990, *p* < .001). Combined, a 1 mm increase in rainfall was associated with a 1.1% decrease in borehole use the following week (RR = 0.989, 95% CI = 0.988 – 0.991, *p* < .001). In models containing rainfall as a binary variable, we observed an overall 22.9% increase (RR = 1.229, 95%CI = 1.166 – 1.296, *p* < .001) in borehole runtime following weeks with no rainfall compared to weeks preceded by any rainfall. Across sites in Kenya, we observed a 19.9% increase (RR = 1.199, 95%CI = 1.109 – 1.297, *p* < .001), while in Ethiopia we observed a 27.1% increase in borehole

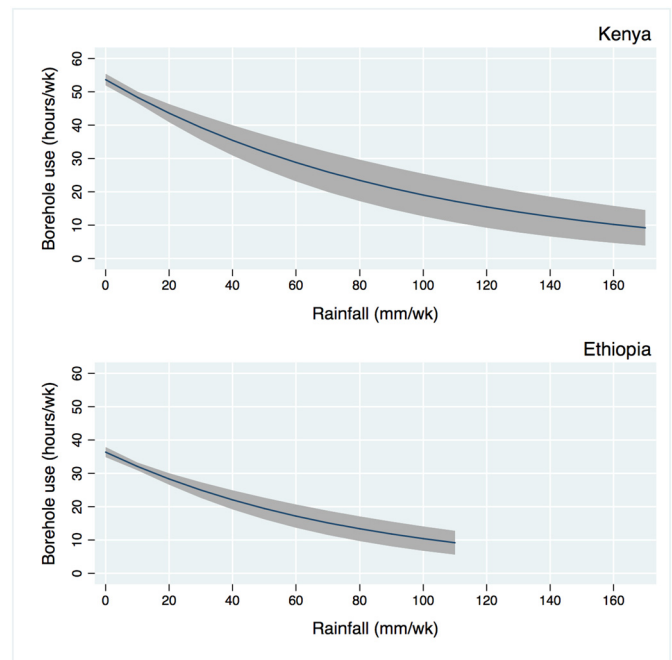


Fig. 4. Model-estimated borehole runtime by total prior week rainfall. Shaded area represents 95% confidence interval.

runtime following weeks with no rainfall ($RR = 1.271$, $95\%CI = 1.186 - 1.362$, $p < .001$).

Fig. 4 displays model-estimated borehole use across the levels of rainfall observed during the study period. Note that the maximum observed rainfall in Afar, Ethiopia was considerably less than observed in northern Kenya during this period.

5. Discussion

This study quantifies borehole use using in-situ sensors and thus represents a direct measure of regional population response to low rainfall. We identified a negative correlation between satellite estimated rainfall and groundwater use in parts of the East African Rift Valley that likely reflects a general pattern of freshwater availability in a drought prone environment. Our findings are consistent with another recent study comparing rainfall to handpump use, wherein a 34% reduction in groundwater use during the wet season compared to the dry season was observed (Thomson et al., 2019). We interpret the increased use of groundwater during the dry seasons as revealing a preference for surface water sources, and that when these sources are dry, the alternative is groundwater use.

The NDVI data analyzed did not show significant variability that allowed a statistical comparison to groundwater pumping. The buffer chosen of 2.5 km from the pump site may be imprecise and future work could attempt to better characterize pump sites that are used for irrigation, and estimate service area on a per pump site basis, allowing for a more refined analysis.

With respect to the GRACE groundwater estimates, as GRACE measures total water storage, future work should attempt to assess the relationship between GRACE, groundwater and other indicators of water including soil moisture and surface water, to better characterize the groundwater in the region. Our work was a first step in exploring these relationships and we had relatively few GRACE data points because of the spatial and temporal scale of GRACE data compared to the length of time and spatial extent of the sensors. Future work could incorporate hydrologic modeling including the Famine Early Warning Systems Network Data Assimilation System.

6. Policy implications

The dry seasons in this region often results in drought emergencies which highlight the importance of functional groundwater sources as well as expansion and maintenance of surface water retention efforts, including rainwater catchment. Yet, maintaining functionality of groundwater boreholes and water access is an on-going challenge.

National budget allocations and international donors have prioritized new water system installations in this region, with the assumption that local communities and regional governments will successfully manage operation, maintenance and service delivery (Butterworth et al., 2010; Moriarty et al., 2013). However, the reality is that funding and accountability for service delivery falls short of meeting water demands, resulting in a high degree of water system failures (Hope et al., 2012; Foster et al., 2018; Nagel et al., 2015). As noted earlier, when these failures occur during dry seasons or drought conditions, negative consequences are exacerbated. The combination of drought conditions and preventable water system failures increases water stress and the costs of emergency drought response.

In Kenya, UNICEF estimates that 35% of rural water supplies were non-functional prior to the 2016 drought, increasing to over 55% of systems, either because of mechanical failures or depleted groundwater, causing a ten-fold increase in the cost of water (UNICEF, 2017). During drought emergencies, the Kenya National Drought Management Authority has two key drought response activities: a) Maintenance of groundwater boreholes, and b) Provisioning of water

trucking (NDMA, 2013). While not all water trucking sites correlate to groundwater borehole failures, increased failures and lengthy repair intervals exacerbate the impact and costs of drought. USAID recently estimated that an early, proactive and planned humanitarian response to drought, rather than a reactive and late response, would save USAID over 780 million dollars over 15 years in Kenya alone (Venton, 2018).

In Ethiopia, a recent study estimated the costs of emergency water trucking attributable to water system failures at over two thousand dollars per person over ten years, based on an estimated failure rate of rural water systems of 50% (Godfrey and Hailemichael, 2017).

Therefore, the relationship we observed between groundwater use and rainfall underlines the significance of the operation and maintenance of borehole pumps as an imperative to maintain water access at the regional scale. This work demonstrates that sensor network implementation across large spatial scales can provide both practical benefits, for example providing real-time monitoring for pump malfunction, as well as broader benefits such as providing quantifiable information on water extraction that is otherwise difficult to collect. Such results can further on-going work to use sensor data collected at boreholes to enable and incentivize improved operation and maintenance programs across the regions that can effectively reduce drought emergencies.

Additionally, these types of sensor networks and data can be linked to distributed weather data networks such as the Trans-African HydroMeteorological Observatory (van de Giesen et al., 2014) and remote sensing based forecasting models including FewNET (McNally et al., 2017). Together, these tools can enable opportunities to improve drought resilience in east Africa.

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