Rainfall and groundwater use in rural Kenya

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Abstract

This study examines the relationship between rainfall and groundwater use in rural Kenya, using automatically-transmitted hourly data from handpumps (n = 266), daily rainfall records (n = 19), and household survey data (n = 2508). We demonstrate a 34% reduction in groundwater use during the wet season compared to the dry season, suggesting a large shift from improved to unimproved sources in the wet season. By cross-correlating handpump and rainfall time series, we also reveal substantial short-term changes in groundwater pumping observed immediately following heavy rainfall. Further investigation and modelling of this response reveals a 68% reduction in pump use on the day immediately following heavy rain.

We then investigate reasons for this behavioural response to rainfall, using survey data to examine the characteristics, concerns and behaviours of households in the area where the reduction in pump use was most marked. In this area rainwater harvesting was widespread and only 6% of households reported handpumps as their sole source of drinking water in the wet season, compared to 86% in the dry season. These findings shed light on the impact increasing rainfall variability may have on the Sustainable Development Goal of “universal and equitable access to safe and affordable drinking water for all”. Specifically, we suggest a flaw in the water policy assumption that the provision of improved sources of drinking water—in this case community handpumps—translates to consistent use and the associated health benefits. We note that failure to understand and account for actual water use behaviour may result in adverse public health outcomes and maladapted WASH policy and interventions.

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HIGHLIGHTS

- Groundwater use is inversely correlated to rainfall at seasonal and daily time-scales.
- A large short-term reduction in pumping is observed immediately following heavy rain.
- This relationship between rainfall and pumping is modelled and tested.
- The existence of improved water supplies does not guarantee their use.
- The expected health gains of rural WASH systems may not be realised.

GRAPHICAL ABSTRACT

This study examines the relationship between rainfall and groundwater use in rural Kenya, using automatically-transmitted hourly data from handpumps (n = 266), daily rainfall records (n = 19), and household survey data (n = 2508). We demonstrate a 34% reduction in groundwater use during the wet season compared to the dry season, suggesting a large shift from improved to unimproved sources in the wet season. By cross-correlating handpump and rainfall time series, we also reveal substantial short-term changes in groundwater pumping observed immediately following heavy rainfall. Further investigation and modelling of this response reveals a 68% reduction in pump use on the day immediately following heavy rain.

We then investigate reasons for this behavioural response to rainfall, using survey data to examine the characteristics, concerns and behaviours of households in the area where the reduction in pump use was most marked. In this area rainwater harvesting was widespread and only 6% of households reported handpumps as their sole source of drinking water in the wet season, compared to 86% in the dry season. These findings shed light on the impact increasing rainfall variability may have on the Sustainable Development Goal of “universal and equitable access to safe and affordable drinking water for all”. Specifically, we suggest a flaw in the water policy assumption that the provision of improved sources of drinking water—in this case community handpumps—translates to consistent use and the associated health benefits. We note that failure to understand and account for actual water use behaviour may result in adverse public health outcomes and maladapted WASH policy and interventions.

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1. Introduction

Rural Africans remain one of the most marginalised populations in terms of water supply, being almost four times more likely to be still reliant on unimproved sources than urban residents, and with rural on-premises supply only creeping forward from 6% in 2000 to 10% in 2015 (WHO & UNICEF, 2015). While small-piped schemes and submersible pumps are available in some places, handpumps which lift groundwater of generally reasonable quality and availability (MacDonald and Calow, 2009) remain a dominant method of supply across rural Africa. Conservative projections from work done by Sansom and Koestler (2009) suggest that there are likely to be more than half a million handpumps in Africa, potentially serving over 100 million people. Despite the SDG goal that everyone has “safely managed” water, in reality a thinly veiled reference to a piped household supply, handpumps will remain an important source of water for many millions of people for decades to come.

A systematic review of faecal contamination of drinking-water in low- and middle-income countries (Bain et al., 2014b) showed that water abstracted from boreholes did not exhibit significantly worse compliance with WHO drinking water standards than piped water, with the studies assessed averaging 35% and 33% sample non-compliance respectively. While certainly an interim or second-best solution to rural water supply, handpumps still warrant attention during the inevitably phased transition to safely managed water. Table 1 shows the WHO/UNICEF Joint Monitoring Programme’s definitions for water service levels and the 2015 baseline achievement levels for Sub-Saharan Africa (WHO & UNICEF, 2017b).

Achieving further progress towards universal drinking water security could be complicated by future climate variability. A particular issue is uncertainty in the extent and nature of rainfall extremes and individual rain events, and their impact on water resources and supply systems (Hennessy et al., 1997; Shongwe et al., 2009; Shongwe et al., 2011; Trenberth et al., 2003; Owor et al., 2009; Taylor et al., 2012). Furthermore, we do not fully understand how the biophysical impacts of climate change may affect individual water use behaviour, collective action and the social systems linked to these natural systems (Tversky and Kahneman, 1981; Ostrom, 2010; Guswa et al., 2014; Foster and Hope, 2016). These uncertainties are compounded by scarcity of measured data on rural water use and on the underlying groundwater resources.

In this study we combine novel quantitative data on handpump use with traditional rainfall measurements to examine the empirical relationship between pump use and rainfall. In particular we focus on the effects of extreme rainfall events, and test the hypothesis that handpump users respond to heavy rainfall by reducing the volume of water they pump. Investigating the reasons why this may be may in turn shed light on the impact that increasing rainfall variability, likely to be experienced under climate change, could have on the recently agreed Sustainable Development Goal for “universal and equitable access to safe and affordable drinking water for all” (United Nations, 2015).

2. Study context

The study site is in Kwale County on Kenya’s southern coast, around 50 km south of Mombasa. The study site covers an area of approximately 1500 km², with a majority rural population. It receives around 1400 mm of rainfall per year with over half the annual rainfall occurring during April, May and June. Geology in the area is variable, with karstic coral formations at the coast, transitioning into sands as elevation increases to the northwest. Population density is high along the coastal strip near the main Kenya-Tanzania highway, becoming lower inland. The urban areas by the coast are served by piped water systems, while the rural population is heavily reliant on around 600 Afridev handpumps installed between the mid-1980s and mid-1990s (Foster and Hope, 2016). This study focuses on these pumps. That Kwale is not geographically, hydrologically or socially homogeneous makes it a good research area and the handpump users in different parts of the county experience many of the same geographical and social problems associated with poor service provision that are observed across rural Africa.

A waterpoint mapping exercise in August 2013 recorded 571 Afridev handpumps in the study area, and collected corresponding technical, operational and social information about each pump and its users. Of these 571 pumps, 337 were identified as functional and in use, with 300 selected for the study and fitted with an experimental Waterpoint Data Transmitter (WDT). Developed at Oxford University, the WDT uses a low-cost solid-state accelerometer to sense changes in the movement of the pump handle in order to measure pump use and estimate volumetric abstraction (Thomson et al., 2012). It can be fitted to the handle of any handpump; in this case it was installed in the Afridev handle. In order to test the hypothesis that improved information can lead to faster handpump repairs the data from these transmitters were used to trigger a free maintenance service for 213 of these pumps, with 87 pumps being monitored for use and breakdown but not receiving an augmented repair service. The primary purpose of collecting these data was to inform this rapid maintenance service that succeeded in reducing average downtimes by an order of magnitude to less than two days (University of Oxford, 2014; Thomson and Koehler, 2016; Thomson et al., 2015). These transmitters also provided hourly data on water use patterns. Looking at these pump use patterns revealed an apparent relationship with rainfall. By further interrogating these data this study aims to test the hypothesis that rainfall influences handpump use, and to characterise this relationship. We then discuss the reasons for this relationship and its implications.

3. Data and methods

To examine the relationship between rainfall and pump use we used two data sources. The first was the hourly data generated by the WDTs installed in the Afridev handpumps. Of the 300 pumps selected 266 produced useful data. (Messages were lost mainly due to poor network coverage, some through vandalism and damage, and in a few cases

Table 1: UNICEF/WHO Joint Monitoring Programme service levels.

<table>
<thead>
<tr>
<th>Service level</th>
<th>JMP definition</th>
<th>Sub-Saharan Africaa</th>
<th>SSA urbanb</th>
<th>SSA ruralb</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Safety managed”</td>
<td>Drinking water from an improved water source that is located on premises, available when needed and free from faecal and priority chemical contamination.</td>
<td>24%</td>
<td>46%</td>
<td>0%</td>
</tr>
<tr>
<td>“Basic”</td>
<td>Drinking water from an improved source, provided collection time is not &gt;30 min for a round trip, including queuing.</td>
<td>34%</td>
<td>36%</td>
<td>43%</td>
</tr>
<tr>
<td>“Limited”</td>
<td>Drinking water from an improved source for which collection time exceeds 30 min for a round trip, including queuing.</td>
<td>14%</td>
<td>10%</td>
<td>16%</td>
</tr>
<tr>
<td>“Unimproved”</td>
<td>Drinking water from an unprotected dug well or unprotected spring.</td>
<td>19%</td>
<td>7%</td>
<td>27%</td>
</tr>
<tr>
<td>“Surface water”</td>
<td>Drinking water directly from a river, dam, lake, pond, stream, canal or irrigation canal.</td>
<td>10%</td>
<td>2%</td>
<td>14%</td>
</tr>
</tbody>
</table>

a Improved sources include: piped water, boreholes or tubewells, protected dug wells, protected springs, rainwater, and packaged or delivered water.
b Baseline estimates (2015) for population reaching SDG service levels.
where the unit failed to function for a reason that was never fully determined. Pump use is represented in terms of calculated litres pumped each hour. The WDTs across the study site were not individually calibrated, but a test of a representative subset and the original testing of the technology (Thomson et al., 2012) both suggest an accuracy of around ±15% against measured volume abstracted. This level of accuracy does not allow for parsing out fine differences between individual pumps experiencing similar use, but is suitable for analysing broader spatial and temporal trends. These automated hourly handpump data were gathered from across the study area for 2014. A daily time series of average pump use across the study area was created from the data from individual pumps. The second source of data was readings from 19 rain gauges spread across the study site. Once obvious transcription errors had been corrected, readings were aggregated to generate a single time series of average daily rainfall for the study area. Rainfall and pumping data through 2014 can be seen in Fig. 1. In addition to the average daily rainfall, measured in mm, further binary time series were generated to indicate which percentile that day’s rainfall fell into (50th to 60th, 60th to 70th, 70th to 80th, 80th to 90th, and greater than 90th highest percentile).

The daily average handpump use time series was cross-correlated with the rainfall time series, the output of this cross-correlation being a time series of lagged correlation coefficients. This was first done with the millimetres rainfall time series, to determine if there was indeed a correlation and—if so—how rainfall and pumping lagged/led each other. Then the process was repeated with the time series of the different rainfall percentiles, in order to determine how this correlation varies with rainfall intensity. We then endeavoured to characterise pump use around an isolated heavy rainfall day, ideally one with no rainfall in the days immediately before or after. All heavy rainfall days were preceded or succeeded by days of lighter rainfall, so such an atypical day did not exist. However December 1st saw 99 mm of rainfall on a nearby day being 3 mm on December 2nd, so this day was used. We took the litres pumped on December 1st and the seven following days from 138 pumps. This reduced set of pumps was used for a number of reasons: firstly there were fewer pumps working towards the end of the study due to attrition variously from battery life, vandalism and water ingress; secondly for this part of the analysis we required data with no gaps over the relevant period, as opposed to other analyses for which a small proportion of dropped messages would have no consequences; finally, pumps with very low usage (<300 l per day) were excluded as they were neither representative of very many users and had very noisy data. For each pump we expressed the daily use as percentage of the average handpump abstraction for the five days prior to December 1st, in order to remove the effect of longer period seasonal variation and to focus on only the short term relationship between pumping and rainfall. We then hypothesised that the resulting mean values represented a response function of pumping to immediate rainfall. In signal processing terms this would be a Finite Impulse Response (FIR), a response whose output (in our case change in pumping) is affected only by the input (in our case rainfall) and has finite duration (in our case seven periods/days). The response to rainfall modelled by this function is represented in Fig. 2d.

To test whether this function was a useful representation of how pumping changes in response to rainfall, we had to disaggregate the short-term changes in pumping from the longer-term seasonal variation. To do this we generated a smoothed two-week maximum, to describe the upper envelope of the observed data during 2014 (Fig. 2b). Two weeks was chosen as it is double the duration of the response function we were using to model the short-term effect. This acted as a low pass filter, leaving only the longer-term change. We then subtracted the observed use (Fig. 2a) from this envelope function. This leaves a residual representing the only short-term fluctuations that we hypothesised were linked to rainfall (Fig. 2c). To test how closely the modelled pumping response compared to the observed short-term fluctuations we used two metrics commonly used for evaluating hydrological models: the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and the ratio of the “root mean square error to the standard deviation of the observations” (RSR) (Moriasi et al., 2007).

To examine the water use behaviours behind the changes in groundwater abstraction using handpumps, we used data from two surveys. The first was a household survey conducted in October and November 2013 at 2508 households who had access to a functioning handpump during 2013. A questionnaire included questions on: household make up and demographics; socio-economic status, including key consumption and wealth indicators; basic self-reported health indicators for each household member; water use, collection and storage; waterpoint institutional arrangements, payment policies and behaviour. Households were randomly selected from those using each functional handpump identified during the 2013 waterpoint mapping exercise.

![Fig. 1. Rainfall and pumping.](image)
(mean of 6.3 households per waterpoint, 4.6 residents per household). This is referred to as the “household survey”.

Following the identification of the relationship between pump use and rainfall, the pump-by-pump reductions where mapped and a cluster of pumps near Mwananyamala, in the south west of the study area, were identified as having the largest drop in use. An additional survey was then conducted in this area. This is subsequently referred to as the “transect survey” or “transect area” and involved identifying and geo-referencing all the households within a 3 km by 1.5 km area using satellite imagery. These 118 households were interviewed in May 2016 on water use and behaviour. In contrast to the household survey, which was done by a team of enumerators, this survey was conducted by one individual with the specific aim of teasing out more information about water use changes in response to rainfall. Respondents were asked about handpump use, use of other sources in both wet and dry seasons, and animal ownership. The extent of household rainwater harvesting and water storage was also recorded. (It should be noted that during the 2013 household survey a sample of 37 households within the transect area were interviewEd.)

4. Results

Overall precipitation in 2014 was typical of the long-term average at 1475 mm, but the onset was late, with only 7% of the year’s rain falling in April compared to the long term average of 18%. For all the sites monitored, the mean daily abstraction from community handpumps is around 1500 l per pump. This equates to 450 m³ per day or 164,000 m³ over the whole year for all 300 pumps. Handpump use is highly heterogeneous, varying both between pumps and over time. While the heterogeneity in pump use varies across the cohort of pumps with a coefficient of variation (standard deviation divided by mean) in weekly use ranging from less than 20% to over 200%, there are trends in pumping behaviour related to the duration and intensity of rainfall events.

Comparison with rainfall data from weather stations in the study area showed that over weekly or monthly timeframes abstraction is inversely correlated to rainfall. The week with the largest total abstraction (an average of 2335 l per pump per day) was the first week of March, just before the onset of the long rains, and was three times greater than that in the second week of May around the peak of the rains (an average of 789 l per pump per day). Examining the cross-correlation of the pumping and rainfall time series, a negative correlation was seen when the pumping lags the rainfall for around 50 days, after which the correlation becomes positive. Likewise, the correlation coefficient is slightly positive for the 30 days leading rainfall. This is consistent with well-documented seasonal reductions in groundwater use as other sources, e.g., rainwater and surface water become available (Blum et al., 1987; Thomson, 2016; Kelly et al., 2018; Elliott et al., 2017).

Fig. 1 also shows that there were immediate short-term drops in pumping in response to individual rainfall events, in addition to these seasonal trends in water use. The cross-correlation between the rainfall and pumping time series is greatest (negative) when the pumping lags rainfall by one day, shown in Table 2. Taking the cross-correlation between pumping and rainfall by decile shows that this correlation only exists in relation to days of heavy rainfall with the strongest correlation being with days receiving rain above the 90th percentile. The cross-correlation captures all the rainfall and pumping information and therefore cannot disaggregate the short-term and seasonal effects or the effect of rainfall on preceding or succeeding days. To isolate the short-term effect we now examine pumping on December 1st, a day of heavy rainfall (99 mm) with no rain on the days immediately preceding it and only very light rainfall the day after (3 mm). Fig. 3 shows the pumping on and for the week following December 1st as a percentage of the average of the five preceding days for 138 pumps included in this analysis, illustrating the reduction in pumping seen immediately following heavy rainfall.

The daily mean percentage reductions in pumping following the isolated day of rainfall on December 1st are used to generate the impulse response function that is then applied to the rainfall data time series.
This produces a time series of expected reduction in use due to rainfall (Fig. 2d) which we then test against the observed short-term response using the Nash-Sutcliffe Efficiency (NSE) (Nash and Sutcliffe, 1970) and the ratio of the “root mean square error to the standard deviation of the observations” (RSR) (Moriasi et al., 2007). As the upper envelope we are using to remove the long-term variation will be inevitably higher than a hypothetical use less the short-term effect, and what is of interest here is the variation in use, the residual response was adjusted so that the means of the residual and the modelled response were the same, giving an offset of 160 l (Fig. 2c). The calculated NSE and RSR are 0.58 and 0.65 respectively. According to the criteria defined by Moriasi et al. (2007) these two values would indicate “satisfactory” performance for a hydrological model.

While this reduction in pump usages was observed across the study area, it was more pronounced for a cluster in the south west of the study area around Mwananyamala, the average reduction in pumping on December 2nd in that area being 85% as opposed an average of 68% for all measured pumps in the study area. Responses from the household survey showed how this area differed from the rest of the study area. Certain household characteristics and concerns can be seen in Table 3. Households in the transect area were respectively 3.5 times and 4.6 times more likely to be concerned about water quantity for domestic use and livestock watering than others, but less concerned about the quality and cost of the water. While they were only marginally more likely to own animals, and this difference was not statistically significant, households in the transect area were much more likely to be concerned about water availability for livestock. The number of large animals per person was also higher at 0.94, in contrast to 0.42 outside the transect area. The transect area had very few surface water sources that were consistently available year-round. Speaking to committee members at some of the most heavily used pumps, we were told that in the dry season handpumps are vital for providing water for livestock and that cattle “drink as much water as a family”, a statement broadly consistent with literature suggesting that one head of cattle drinks between 50 and 100 l per day (Rouda et al., 1994; Nicholson, 1985). In the weeks just prior to the delayed onset of rains in 2014, one handpump was being used for 24 h each day: for household water collection during the day and then through the night for watering cattle.

During the dry season 86% of households in the transect area stated that their main source of water was a handpump, with over half of these stating that it was the only source of water. In the wet season this dropped to 6% stating that their only source of water was a handpump. Most households (55%) used multiple sources, the most common types being rainwater harvesting (75%), followed by collecting water from natural springs or wells (50%). Observation data from the transect survey was consistent with these responses, with 35% of households having ‘extensive’ rainwater harvesting (RWH) infrastructure, defined by having a metal roof, guttering and dedicated harvesting tank. The mean storage capacity of these systems was 183 l. A further 31% of households had ‘some’ RWH infrastructure, defined as having a metal roof, but no guttering, or a roof made from makuti (woven coconut leaves) with guttering or another similar intermediate status, with the remaining 34% of households having no visible RWH infrastructure. This extensive use of rainwater harvesting in the transect area, which enables many households to be self-sufficient during the wettest months and provide some buffer into drier months is a rational response to the stated concern about the quantity of water available for

**Table 2**

<table>
<thead>
<tr>
<th>Rainfall</th>
<th>Day +1</th>
<th>Day +2</th>
<th>Day +3</th>
<th>Day +4</th>
<th>Day +5</th>
<th>Day +6</th>
<th>Day +7</th>
</tr>
</thead>
<tbody>
<tr>
<td>mm</td>
<td>−0.17</td>
<td>−0.34</td>
<td>−0.42</td>
<td>−0.29</td>
<td>−0.23</td>
<td>−0.17</td>
<td>−0.16</td>
</tr>
<tr>
<td>P₉₅ to P₉₀</td>
<td>+0.09</td>
<td>+0.07</td>
<td>+0.05</td>
<td>+0.08</td>
<td>+0.09</td>
<td>+0.10</td>
<td>+0.04</td>
</tr>
<tr>
<td>P₈₅ to P₇₅</td>
<td>+0.00</td>
<td>−0.02</td>
<td>−0.09</td>
<td>−0.11</td>
<td>−0.12</td>
<td>−0.05</td>
<td>−0.05</td>
</tr>
<tr>
<td>P₇₅ to P₆₅</td>
<td>−0.09</td>
<td>−0.08</td>
<td>−0.11</td>
<td>−0.05</td>
<td>−0.07</td>
<td>−0.02</td>
<td>−0.05</td>
</tr>
<tr>
<td>P₆₅ to P₅₅</td>
<td>−0.15</td>
<td>−0.20</td>
<td>−0.16</td>
<td>−0.10</td>
<td>−0.06</td>
<td>−0.01</td>
<td>−0.00</td>
</tr>
<tr>
<td>Over P₅₅</td>
<td>−0.17</td>
<td>−0.34</td>
<td>−0.41</td>
<td>−0.32</td>
<td>−0.27</td>
<td>−0.22</td>
<td>−0.18</td>
</tr>
</tbody>
</table>

(Correlation coefficients with absolute value >0.20 in bold for emphasis.)
livestock watering and domestic purposes. Households in the transect area were 1.8 times more likely to have a metal roof than households outside, whereas there was no difference in the likelihood of having improved floors or walls. Taken with the concerns about water quantity, this suggests that improvements in roofing in the transect area were specifically undertaken to practise rainwater harvesting rather than a more general indicator of household wealth, and the ability to upgrade one’s dwelling.

For household use, those with extensive rainwater harvesting infrastructure can quickly build up a supply of water after the first few weeks of the rains. Livestock watering can switch from groundwater to surface water when the latter becomes available, be that in rivers and streams or springs, reducing reliance on handpumps. Both these effects are lagged, so do not provide an explanation for the immediate but short-lived impact that would be consistent with the observed effect.

5. Limitations

The transect survey was undertaken specifically for this study; the other data sources used in this study were not gathered exclusively in support of it. Therefore there are inevitable limitations. Firstly, the protocol for measuring rainfall is to take a daily reading at 9am and classify that as the previous day’s rainfall. A lot of handpump use comes an implicit assumption that water users will consistently use improved infrastructure rather than switch to other sources for reasons of cost, taste or convenience?

While the concept of an improved water source and its usefulness is contested, and the definitions being used to monitor the SDGs are more nuanced and service oriented (WHO & UNICEF, 2015; WHO & UNICEF, 2017a; Clasen, 2012), the improved water source remains a key concept and has effectively been carried over into the SDG monitoring framework in the form of “basic water”. While only one of a number of improved sources, handpumps abstracting water from boreholes or protected hand-dug wells remain a means of providing water across much of rural Africa, and will continue to be for some time to come. They are still used operationally in rural water programmes, be they implemented by governments, NGOs or development agencies (Foster, 2013), providing a low-cost and resilient means of supply (Luh et al., 2017; MacDonald et al., 2011). With this implementation there often comes an implicit assumption that water users will consistently use improved sources throughout the year if those are available. But what are the implications if users choose to use such infrastructure selectively? Will the assumed health benefits of an improved water supply be reduced if users switch to other sources for reasons of cost, taste or convenience?

Table 3
Household concerns and characteristics from 2013 household survey.

<table>
<thead>
<tr>
<th>Household concerns:</th>
<th>Inside transect (n = 37)</th>
<th>Outside transect (n = 2471)</th>
<th>Inside w.r.t. outside</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reliability of handpump</td>
<td>6 16%</td>
<td>800 32%</td>
<td>0.50 0.040</td>
</tr>
<tr>
<td>Distance to handpump</td>
<td>9 24%</td>
<td>692 28%</td>
<td>0.87 0.72</td>
</tr>
<tr>
<td>Queues at handpump</td>
<td>15 41%</td>
<td>655 27%</td>
<td>1.53 0.062</td>
</tr>
<tr>
<td>Cost of water</td>
<td>0 0%</td>
<td>241 10%</td>
<td>n/a 0.044</td>
</tr>
<tr>
<td>Safety (drinking)</td>
<td>0 0%</td>
<td>350 14%</td>
<td>n/a 0.007</td>
</tr>
<tr>
<td>Seasonality of source</td>
<td>5 14%</td>
<td>265 11%</td>
<td>1.26 0.59</td>
</tr>
<tr>
<td>Quantity for agriculture</td>
<td>5 14%</td>
<td>61 2%</td>
<td>n/a 1.00</td>
</tr>
<tr>
<td>Quantity for livestock</td>
<td>3 8%</td>
<td>44 2%</td>
<td>4.55 0.031</td>
</tr>
<tr>
<td>Quantity for domestic use</td>
<td>8 22%</td>
<td>155 6%</td>
<td>3.45 0.002</td>
</tr>
<tr>
<td>Concern re. storage</td>
<td>0 0%</td>
<td>168 7%</td>
<td>n/a 0.17</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Household characteristics:</th>
<th>Inside transect (n = 37)</th>
<th>Outside transect (n = 2471)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved roof</td>
<td>22 59%</td>
<td>804 33%</td>
</tr>
<tr>
<td>Improved floor</td>
<td>8 22%</td>
<td>749 30%</td>
</tr>
<tr>
<td>Improved walls</td>
<td>11 30%</td>
<td>1059 43%</td>
</tr>
<tr>
<td>Improved toilet</td>
<td>12 62%</td>
<td>1256 51%</td>
</tr>
<tr>
<td>Grow crops</td>
<td>35 95%</td>
<td>1865 75%</td>
</tr>
<tr>
<td>Own animals</td>
<td>17 46%</td>
<td>964 39%</td>
</tr>
<tr>
<td>Secondary education</td>
<td>22 59%</td>
<td>982 40%</td>
</tr>
<tr>
<td>Own bicycle</td>
<td>22 59%</td>
<td>1051 42%</td>
</tr>
<tr>
<td>Own radio</td>
<td>34 92%</td>
<td>1714 69%</td>
</tr>
<tr>
<td>Own mobile phone</td>
<td>30 81%</td>
<td>2087 84%</td>
</tr>
</tbody>
</table>

* Two-tailed Fisher exact (bold indicates p < 0.05).
This study demonstrates that households adapt to their hydro-societal situation, with decisions based on a portfolio of water supply alternatives more or less suited to an array of uses, be that for drinking, livestock watering, laundry, washing or bathing. This adaptive capacity manifests itself here in water users switching away from using pumped groundwater in response to both immediate rainfall and seasonal variations. The rate at which water was pumped in the first three months of 2014, before the rains came, was 53% higher than during the final nine months. The short-term response corresponds to around 11,500 m$^3$ of water across the whole year for all pumps under monitoring. While it is not possible to infer whether and from where the water ‘not pumped’ was replaced, this is the equivalent of 7% of total observed pumping of 164,000 m$^3$, around 26 days of water use. While this study shows that the volume of water involved in these changes is significant, the evidence so far as to which alternative sources are used for what purpose, is mixed. If the switch were in favour of using contaminated sources for drinking water there may be significant health impacts, over and above the trend for higher faecal contamination being found in drinking water sources in the wet season (Kostyla et al., 2015). In the specific case of rainfall harvesting, which is also classed as an improved source, it may be a safer source of drinking water than surface water but is certainly not without risk of both microbial and chemical contamination (Lyé, 2002; Boele et al., 2013; Gwenzi et al., 2015; Ahmed et al., 2008; Stewart et al., 2016). Indeed, a meta-analysis by Bain et al. (2014a) found collected rainwater more likely to be contaminated with faecal indicator bacteria than water from boreholes. Failure to discard the “first flush” of rainwater, especially after a period without rain, will increase the likelihood of pollutants and pathogens ending up in the harvested rainwater. Safety of the drinking water from these systems is dependent on them being both well designed and built, and used and maintained according to the proper procedures (Lyé, 2009), conditions which are not likely to be fulfilled in all instances.

In this area the large changes in use may not correspond to large changes in water consumption patterns, even though the decision to continue using pumped groundwater for drinking, rather than water from other cheaper and more convenient sources, may be as much related to taste as to health considerations. That said, the wider range of water sources used here—including more unimproved sources—may increase the likelihood water from those sources being inadvertently drunk or mixed with household drinking water that would otherwise be at lower risk of being contaminated. This study did not examine water quality or directly address health impacts, but in light of evidence of an association between heavy rainfall events and diarrhoea (Carlton et al., 2014; Eisenberg et al., 2014) more investigation is needed to understand the health effects of such short-term changes in the quality of water consumed. While the epidemiological evidence is inconclusive (Waddington et al., 2009; Arnold and Colford, 2007), modelling suggests that even very short term exposure to contaminated water can have a significant adverse effect (Enger et al., 2012; Hunter et al., 2009; Howard et al., 2006; Brown and Clasen, 2012).

The choices made by rural communities may well be optimal given current information and constraints, but may be a consequence of long-term experience and an intuitive understanding of the local environment rather than aetiological knowledge of water-related diseases and formal understanding of the hydrological cycle. Similarly, institutional interventions may be based on what has been effective in the past rather than designed for an expected future. Notwithstanding that the pattern of precipitation change under a changing climate is not clear (Sun et al., 2012; Good et al., 2016), the weather experienced in East Africa may change to one with more intense wet seasons (Shongwe et al., 2011; Shongwe et al., 2009). Weather-induced behaviour change analogous to that presented here is likely to take place. With effective adaption being dependent on scale (Vincent, 2007) and institutional arrangements (Agrawal and Perrin, 2008), maladaptation is possible or even likely if these arrangements are not actively considered (Barnett and O’Neill, 2010).

7. Policy implications

As the SDGs take on a more service-oriented approach to making global drinking water estimates, the assumption that if infrastructure is built it will be used must be challenged. Health is one of the driving forces behind why moving up the service ladder is viewed as desirable. Achieving “basic” water services through access to a well-sited, well-maintained handpump that accesses groundwater can be no less safe to drink than treated piped water. But if seasonal effects or just a single day of heavy rainfall results in people effectively having only “unimproved” water, the putative health gains of having “basic” water may never be realised.

Further research should investigate the actual health impacts of environmental or operational shocks that may, either permanently or temporarily, move households down the JMP’s service ladder. Climate change can only exacerbate this as households have to respond to weather patterns they have no previously experience of. While climate-induced changes in disease are well studied, albeit contested (Hunter, 2003; Patz et al., 2005; Liang and Gong, 2017; Watts et al., 2017; Wu et al., 2016), research should not neglect weather-induced changes in the behaviours of households and individuals as these will undoubtedly influence disease patterns and morbidity.

If the health benefits of “basic” water are precarious, one response is simply to redouble efforts to push towards “safely managed” water for all. However, the danger of purely focusing effort on this is that there will be backsliding down the ladder from “basic” water. The perfect must not become the enemy of the good; “basic” water services must also be strengthened. This can be through proper resourcing of the parts, tools and personnel that maintain these systems, but also through institutional reform and a move away from the community maintenance paradigm, which has not resulted in sustained high levels of service (Golooaba-Mutebi, 2012; Chowns, 2015; Foster et al., 2018; Cronk and Bartram, 2017; Foster, 2013), and towards more pluralist approaches (Koehler et al., 2018).

The metrics used to measure progress towards the SDGs must take into account the actual temporal and spatial variations in water use behaviour that infrequent, periodic surveys will not capture. Monitoring technologies for rural water systems designed to improve system performance by putting near real-time data into the hands of those managing and maintaining the system (Thomson et al., 2012; Nagel et al., 2015; Wilson et al., 2017; Thomson and Koehler, 2016), can also provide real data on use patterns and system downtimes to inform policy and SDG monitoring (Thomson and Koehler, 2016). If policy and practice are informed by different data there will be an inevitable dislocation between policy and practice. Linking Monitoring and Evaluation to Operations and Maintenance will reduce the risk of high-level reporting being based on a caricature of actual practice—and this caricature becoming the basis of policy—the consequences of which can only be poor outcomes and wasted resources.

8. Conclusion

This paper has combined novel and traditional data sources to shed light on actual handpump use behaviour in rural Kenya. As well as seasonal variations we have shown that there is a large and immediate reduction in handpump use following heavy rainfall. Examination of the reasons for this raises issues concerning a possible mismatch between actual water use behaviour and behaviour upon which WASH policy is predicated, specifically the health gains that may—or may not—be realised from “basic” water services. We
therefore urge further empirical research into actual rural water use behaviour and health dynamics, and how they interact with changing weather. We also believed that serious consideration is given to what sources of data that will be most effective for monitoring progress towards the SDGs and ensuring that the progress is real.

References


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