Waterlines, 41:2, 138–157
<http://doi.org/10.3362/1756-3488.21-00016>

Incentivizing clean water collection during rainfall to reduce disease in rural sub-Saharan Africa with weather dependent pricing

Will Ingram and Patrick Thomson

Abstract: *In much of rural sub-Saharan Africa, households tend to shift water collection during rainfall periods away from cleaner groundwater sources, which they often have to pay for, towards free alternative sources. This increases disease risk and decreases sustainability of service provision. New approaches are needed to incentivize households to maintain clean water use and mitigate this environmental health challenge. We propose a pricing mechanism for 'water ATMs' – now possible with their pre-payment and remote monitoring capabilities – derived from measured reductions in collection over rainfall periods. Appropriate price elasticity ranges (–0.5 to –1) and relative risk of diarrhoeal disease from this intervention (0.4 to 0.8) determined from the literature are used to estimate the cost per capita and cost per disability-adjusted life year (DALY) averted. These are estimated to be between US$5 and 50 per DALY averted in the scenarios studied here, which would compare favourably against other water quality interventions. Cost and value would depend on elasticity of demand and potential health gains across different communities. Considerations for implementation are discussed. The potential for accurate subsidy transfers to service providers is outlined, along with the added resilience to climate change.*

Keywords: seasonality, rural water supply, rainfall, diarrhoea, price elasticity, relative risk

In rural communities across sub-Saharan Africa, households tend to use a variety of water sources of varying quality (Elliott et al., 2019; Daly et al., 2021), and the choice between them is based on interactions between cost, price, and value (Hope et al., 2020). Households' reliance on higher-quality groundwater sources such as motorized boreholes or handpumps tends to be lower during periods of rainfall in favour of cost-free rainwater harvesting or surface water (Hopkins et al., 2004; Arouna and Dabbert, 2010; Cook et al., 2016; Kulinkina et al., 2016; Kelly et al., 2018). This phenomenon has more recently been quantified using new monitoring technologies (Thomas et al., 2019; Thomson et al., 2019; Armstrong et al., 2021).

Will Ingram, Postdoctoral Researcher (will.ingram@ouce.ox.ac.uk) and Patrick Thomson, Senior Research Associate (patrick.thomson@ouce.ox.ac.uk), School of Geography and the Environment, University of Oxford, UK
© The authors, 2022. This open access article is published by Practical Action Publishing and distributed under a Creative Commons Attribution Non-commercial No-derivatives CC BY-NC-ND licence http://creativecommons.org/licenses/by-nc-nd/4.0/.
www.practicalactionpublishing.com, ISSN: 0262-8104/1756-3488

Copyright

It is well known that use of ‘unimproved’ water sources contributes significantly to the burden of disease (Hutton, 2006). Accordingly, water-related illnesses, in particular diarrhoeal disease, often increase during rainy seasons in these settings (Thiam et al., 2017; Kraay et al., 2020). For instance, freely available harvested rainwater from rooftops is significantly more likely to be contaminated than borehole groundwater (Baguma et al., 2010; Bain et al., 2014; Hamilton et al., 2019). As well as seasonal effects, extreme rain is shown to increase the risk of diarrhoeal disease, particularly when following a dry period, as concentrated pathogens can be flushed into water sources (Kraay et al., 2020), and individual days of heavy rain have been shown to have a disproportionate influence on households’ choice to turn away from improved groundwater sources to free ones (Hoque and Hope, 2018; Thomson et al., 2019). Heavy rainfall days are likely to become more frequent in sub-Saharan Africa under climate change (Fischer and Knutti, 2016; Kendon et al., 2019; Jackson et al., 2020). In comparison, groundwater is generally considered to be of better quality, especially compared to surface water that is particularly vulnerable to contamination (Lawrence et al., 2001; Parker et al., 2010; Katuva et al., 2020).

New approaches to address this environmental health challenge could help limit diarrhoeal disease morbidity and reduce adverse seasonal effects of this drop in water collection on the operation and management of rural water systems (Arouna and Dabbert, 2010; Behnke et al., 2017; Foster, 2017; Kelly et al., 2018).

In recent years, pre-payment ‘water ATMs’ or ‘smart meters’ have been deployed as part of rural water systems. These have improved revenue collection, monitoring, and user access, and generated high-quality data for research (Ingram and Memon, 2020; Komakech et al., 2020), providing a potential alternative to the pervasive vendor-based collection or non-payment. These technologies allow credit-based digital pre-payment using tags, real-time and remote adjustments of price, and 24-hour access for users.

The objective of this paper is to introduce a novel mechanism of ‘weather dependent pricing’. This mechanism is based on remotely reducing volumetric price of water at water ATMs from its current uniform rate during specified periods of rainfall in order to incentivize users to maintain collection of clean groundwater during these times. First, this is conceptualized and quantified using measured responses of water collection to rainfall in Tanzania and The Gambia and other existing literature. Next it is examined in terms of cost and cost per potential health benefit. Finally, we propose how such a mechanism might be applied to improve community health, bring in direct subsidy transfers to service providers, and build resilience to climate change. Because simple assumptions around pricing can lead to incorrect outcomes (Nauges and Whittington, 2017), we consider pricing elsewhere, magnitude of required price changes, potential for behaviour change and health gains, value for money, sensitivity to different variables, uncertainty of outcomes, and behavioural and practical factors. Households make nuanced decisions around water collection and payments; potential limitations to such pricing incentives from alternative non-consumptive uses of less clean seasonal water are also highlighted here.

Copyright

Methods and data

Weather dependent pricing is conceptualized as service providers remotely reducing the volumetric price of water from ATMs for the length of the rainy season ('seasonal block') or for shorter periods of heavy rainfall ('responsive pricing'), thereby increasing demand during these periods. Suitable price reductions for this form of third-degree price discrimination are calculated using observed current decrease in demand during rainfall, along with a determined price elasticity value. Community health benefits are estimated from proxy relative risks of disease.

Influence of rainfall on volume collected

Decreases in daily volumetric data measured with pre-payment 'smart meters' ('ATMs') on communal distribution points of piped systems in two small, rural communities in Tanzania and The Gambia (Communities A and B) were combined with three available satellite rainfall estimates over three years (as reported in Ingram and Memon, 2021). Seasonal, daily, and fortnightly, and specified days of heavy rainfall were modelled. These are supplemented with similar measurements reported from the four additional published studies, and presented in Table 1.

The length of each period of price reduction depends on the length of the rainfall period in the setting in question, and annual variation in season onset. In addition, specific days of heavy rainfall are shown to have a disproportionate influence on groundwater collected. In Tanzania (Community A) (Ingram and Memon, 2021) water collection drops by an average of 32 per cent (and up to 80 per cent) following days of rainfall greater than 8 mm, and in Kenya (Thomson et al., 2019) an average reduction of 68 per cent on days following heavy rain is recorded, with the most pronounced effect in the upper 10th percentile of rainfall. A further price change could also be implemented to counter this. Such days are not predictable, making this a greater technical challenge.

While the influence of rainfall on water collection varies between settings and depends on multiple determinants, these separate pieces of evidence suggest a general decrease in collection of groundwater over rainy periods of about 20–30 per cent. This corresponds to the need to achieve an increase in collection of between a quarter and a half, with an approximate average of 32 per cent. This indicates the magnitude of pricing incentive required.

Pricing adjustments required

Price elasticity (E_P) is a measure of the response of households to the price change, and refers to the percentage change in quantity demanded that results from a percentage change in price:

$$E_P = \frac{\%\Delta Q}{\%\Delta P}$$

While price is not the sole determinant for a household's choice of water source or volume collected, the improved any-time access to pre-payment ATMs is likely

Copyright

Table 1 Quantification of impact of rainfall on groundwater collection across sub-Saharan Africa

Location and study	*Average decrease in groundwater volume collected over rainy season*	*Desired increase in demand over rainy season*	*Volume data source*	*Rainfall data source*	*Verification*
Northern Tanzania (Community A)	−21%	+26%	13 (A) and 28 (B) pre-payment 'smart meters' on communal distribution points of piped system	Combined GPM, CHIRPS, and TAMSAT satellite estimates[1]	79% of respondents in Tanzania reported rainwater harvesting during rainfall; total roof area ample to account for collection shortfall
Central Gambia (Community B) (Ingram and Memon, 2021)	−23%	+29%			
South-east Kenya (Thomson et al., 2019; Armstrong et al., 2021)	−34%	+52%	266 'smart handpump' sensors	19 rain gauges across the study site	6% of households reported handpumps as sole source of drinking water in rainy season compared to 86% in dry season
Kenya, Malawi, Tanzania, and Uganda (Armstrong et al., 2021)	−22% *(with pay-as-you-fetch modality in Kenya, Tanzania, Uganda)*	+28%	25 rural piped schemes with digital water meters, including kiosks and piped systems	CHIRPS satellite estimates	Monthly user payment modality did not see rainy season decrease in collection
Northern Kenya and Northern Ethiopia (Kulinkina et al., 2016; Thomas et al., 2019; Turman-Bryant et al., 2019)	1.0 mm increase in rainfall associated with 1.1% decrease in borehole use the following week	n/a	221 motorized boreholes with remote sensors	CHIRPS satellite estimates	Overall 23% increase in borehole runtime following weeks with no rainfall
Eastern Ghana (Kulinkina et al., 2016)	~ −30% *(wettest compared to driest months)*	+43%	54 manual water meters from piped systems in four small towns	Meteorological stations 5–15 km from the towns	100 mm increase in rainfall corresponded to an average reduction of 16% in monthly water consumption

Note: [1] GPM = Global Precipitation Measurement (Skofronick-Jackson et al., 2018); CHIRPS = Climate Hazards Group InfraRed Precipitation with Station data (Funk et al., 2015); TAMSAT = Tropical Applications of Meteorology using SATellite data and ground-based observations (Maidment et al., 2017).

Copyright

Table 2 Example price elasticities determined for water supply

Study context	*Study*	*Reported price elasticity for communal water point (EP)*
Rural Zimbabwe; rural Kenya. Choice of using water kiosks with respect to monthly tariff.	World Bank Water Demand Team (1993)	–0.7; –0.4
Urban Jordan. Demand from piped water when alternative sources are accounted for.	Coulibaly et al. (2014)	–1.33
Urban Vietnam. Demand for piped water when multiple sources are used.	Cheesman et al. (2008)	–0.51
Urban Sri Lanka. Demand for piped water when multiple sources are used.	Nauges and van den Berg (2008)	–0.37
Rural Tunisia. Low revenue population.	Zekri and Dinar (2003)	–0.24
Rural Kenya. Estimated from individual sources rather than aggregated source type.	Wagner et al. (2019)	–0.56
Rural Benin. Communities with low service coverage.	Gross and Elshiewy (2019)	–0.26
Urban Indonesia. Demand from multiple sources.	Rietveld et al. (2000)	–1.2

to significantly reduce overall collection time (Ingram and Memon, 2020) and price can be more confidently used as a major determinant here. Knowledge of price elasticity therefore allows calculation of a suitable price reduction needed to achieve the desired increase in demand over rainfall periods.

Price elasticities depend on multiple contextual determinants. Some studies have determined specific price elasticities in different contexts in the Global South, presented in Table 2.

The limitations of relying on divergent studies with different baselines and payment modalities notwithstanding, there is strong evidence to suggest that demand for clean groundwater in the setting investigated here would be even more price elastic (i.e. closer to –1.0) and households more responsive to price changes:

- Demand for a good should become more price-elastic with increasing numbers of substitutes (Coulibaly et al., 2014), in this case with users turning to free, alternative sources. Price elasticities in Jordan, Vietnam, and Sri Lanka are recorded to be greater when more than one source is used (e.g. –0.51 in Vietnam, up from –0.06 when only municipal water is used (Cheesman et al., 2008)). It has been specifically speculated that rural households' choice of water source will be sensitive to changes in prices of water from different sources (Nauges and Whittington, 2010).
- Groundwater is cleaner than alternatives and should be a more desirable good.
- Where there is a functioning piped system and ATM, and therefore reduced water scarcity, price elasticity is likely to be higher. Low price elasticities

Copyright

Table 3 Example 'seasonal block' price adjustments for predicted price elasticity range

	Baseline price	*'Seasonal block' price*	
		$E_p = -1$	$E_p = -0.5$
Community A	US$0.54 per m^3 (TSH 1.25 per litre)	US$0.40 per m^3 (TSH 0.93 per litre)	US$0.26 per m^3 (TSH 0.60 per litre)
Community B	US$0.49 per m^3 (GMD 0.025 per litre)	US$0.35 per m^3 (GMD 0.018 per litre)	US$0.21 per m^3 (GMD 0.011 per litre)

Note: US$1 = TSH 2,316; US$1 = GMD 52 (as of 2021)

elsewhere have been partly explained by significant water scarcity because households are willing to pay more for water supply (Arouna and Dabbert, 2010) (as also seen on a global scale (Garrone et al., 2019)).

- A decreasing price may act to lift an 'affordability cap' that previously limited households' volume collected in this context, and therefore have a correspondingly greater elasticity.

Therefore, a likely range of price elasticity values in rural communities where weather dependent pricing would be deployed is considered to be –0.5 to –1.

As an example, this expected range of E_p values combined with the measured desired increase in demand in Communities A and B over rainy seasons (Table 1) would give the reductions in price shown in Table 3.

This suggests that for a conservative estimate of elasticity within the expected range, approximately halving the price of water should produce the desired increase in demand in these communities. The desired increases in demand over rainy seasons along with the price elasticity range presented above are used to calculate the lost revenue and therefore 'cost' of weather dependent pricing, and percentage of full 'business-as-usual' revenue, presented below. These calculations account for increased *volume* collected.

Because days of heavy rainfall have much greater desired increases in demand if considered on a daily basis, corresponding price reductions over specific days would be very large even with high price elasticities. Free water on these days ('responsive pricing') is discussed below.

Determination of community health benefits

The majority of disability-adjusted life years (DALYs) for diarrhoeal disease are for children aged 0 to 14 (61 per cent in Tanzania, 76 per cent in The Gambia) (World Health Organization, 2018), meaning weather dependent pricing has greater impact potential for children (also because of the long-term health impacts which are unaccounted for in DALYs estimates (Troeger et al., 2017)). In Communities A and B, DALYs attributable to diarrhoeal disease can be approximately calculated as:

- Community A (population ~1,770) = 61 DALYs, or 0.34 per person
- Community B (population ~1,840) = 54 DALYs, or 0.29 per person

Copyright

Table 4 Relative risks of diarrhoeal disease during rainy season from different studies and relative risk estimates of avoidance of diarrhoeal disease with weather dependent pricing

Study description/Location	*Reference*	*Relative risk of diarrhoeal disease during rainy vs. dry season*	*Relative risk of avoidance of seasonal risk (1/RR)*
Senegal	Thiam et al. (2017)	1.70 (95% CI: 1.29–2.24)	0.58 (95% CI: 0.45–0.78)
Ethiopia	Alemayehu et al. (2020)	RR = 1.40* (95% CI: 1.32–1.48)	0.71 (95% CI: 0.68–0.76)
Meta-value for low-income countries (all pathogens)	Kraay et al. (2020)	1.81 (95% CI: 1.15–2.85)	0.55 (95% CI: 0.35–0.87)
As above, but only 'storm events' i.e. extreme rainfall	Kraay et al. (2020)	2.51 (95% CI: 2.03–3.10)	0.40 (95% CI: 0.32–0.49)
Study description/Location	*Reference*		*Relative risk of diarrhoeal disease with proxy intervention*
A new source, supply or connection	Risebro and Hunter (2011)		0.75 (95% CI 0.62–0.91)
Piped water to premises vs. unimproved baseline	Wolf et al. (2018)		0.25 (95% CI: 0.09–0.67)
Counterfactual scenario with household filtering/boiling	Prüss-Ustün et al. (2019)		0.52 (95% CI: 0.35–0.77)
Handpump repair within 24 hrs vs. slower repair	Thomson (2018)		0.44 (95% CI: 0.21–0.93)

Note: * From: RR = 1.0016 per 1 mm increase in average monthly rainfall; 250 mm of monthly

The health impact of weather dependent pricing is difficult to accurately estimate, not least because diarrhoeal disease has complex causes beyond contaminated water. We use relative risks (RR) derived from existing studies that have quantified the existing increased risk of diarrhoeal disease during rainy seasons, and the reduced risk from proxy interventions, to estimate the RRs that might be expected from weather dependent pricing, presented in Table 4.

These values can be used as proxies for the binary distinction that would come from a pricing-induced behaviour change. Water quality interventions at source can reduce diarrhoea among children by 20–70 per cent (Waddington and Snilstveit, 2009), and only short relapses to contaminated water have disproportionate health impacts (Hunter et al., 2009; Brown and Clasen, 2012). Therefore, a significant proportion of annual diarrhoeal disease, and therefore DALYs in the community, could be averted by maintained use of clean groundwater during periods of rainfall. Based on the available evidence, RR values within a range of 0.4 to 0.8 are considered likely here.

Copyright

Averted DALYs are estimated here as current DALYs multiplied by 1–RR. The cost per DALY averted is estimated by dividing the lost revenue from the price reductions by averted DALYs. Sensitivity analysis using the one-at-a-time method was conducted on the inputs of: 1) desired increase in volume collected during rainfall, 2) price elasticity, and 3) relative risk of disease. Uncertainty analysis was conducted on expected outputs using Monte Carlo simulation with 2,000 trials per run. Along with Communities A and B, a number of additional hypothetical scenarios of varying country (i.e. DALY burden), population, influence of rainfall, length of seasonal block, days of heavy rainfall, and price elasticity were also tested to better understand applicability in different types of community.

Results

Figure 1 presents the estimated cost per capita, percentage of full revenue expected, and estimated cost per DALY averted, across ranges of price elasticity and relative risk, if weather dependent pricing were implemented. These are presented for Communities A (Tanzania) and B (The Gambia), along with two indicative hypothetical scenarios that demonstrate what moderate and extreme cases in specific communities might result in: Scenario A represents a community where a moderate version of weather dependent pricing could be deployed with a desired increase in collection (+10 per cent) below the average seen in Table 1 (+20 per cent to +30 per cent). Scenario B is an extreme version (+40 per cent) above this average.

These results indicate that for likely ranges of elasticity and risk ratio discussed earlier, weather dependent pricing may offer high value for money in terms of health gains (between $5 and $50 per DALY averted). These outcomes are dependent on community characteristics.

In Community B, the cost per capita and the cost per DALY averted are likely to be greater than Community A because of a combination of: higher desired increase in collection, higher volume per capita, fewer DALYs in The Gambia, and different baseline price. The percentage of full annual ‘business-as-usual’ revenue is not much different from Community A, largely because of the greater volume per capita, which is a more pertinent result for service providers than funders. Even in Scenario B, the most extreme example with larger desired increase in demand and many days of free water, service providers could still expect to collect the majority of full revenue, and they would only expect to lose a very small proportion (~10 per cent) in likely scenarios (e.g. Scenario A and the two real communities).

If price elasticity is very low, the price can become negligible or theoretically negative, as can be seen with Scenario B below $E_p = -0.5$. In such circumstances, ‘responsive pricing’ (i.e. free water for targeted periods) may be suitable. Similarly, cost per DALY averted is likely to become large in comparison to other possible interventions when RR values are high and when E_p values are low.

Overall, in order for weather dependent pricing to be more effective in a community, greater response to reduced pricing along with a greater reduction in disease from maintained use of cleaner water are needed. This relationship is indicated in Figure 2 in order to illustrate suitable communities.

Copyright

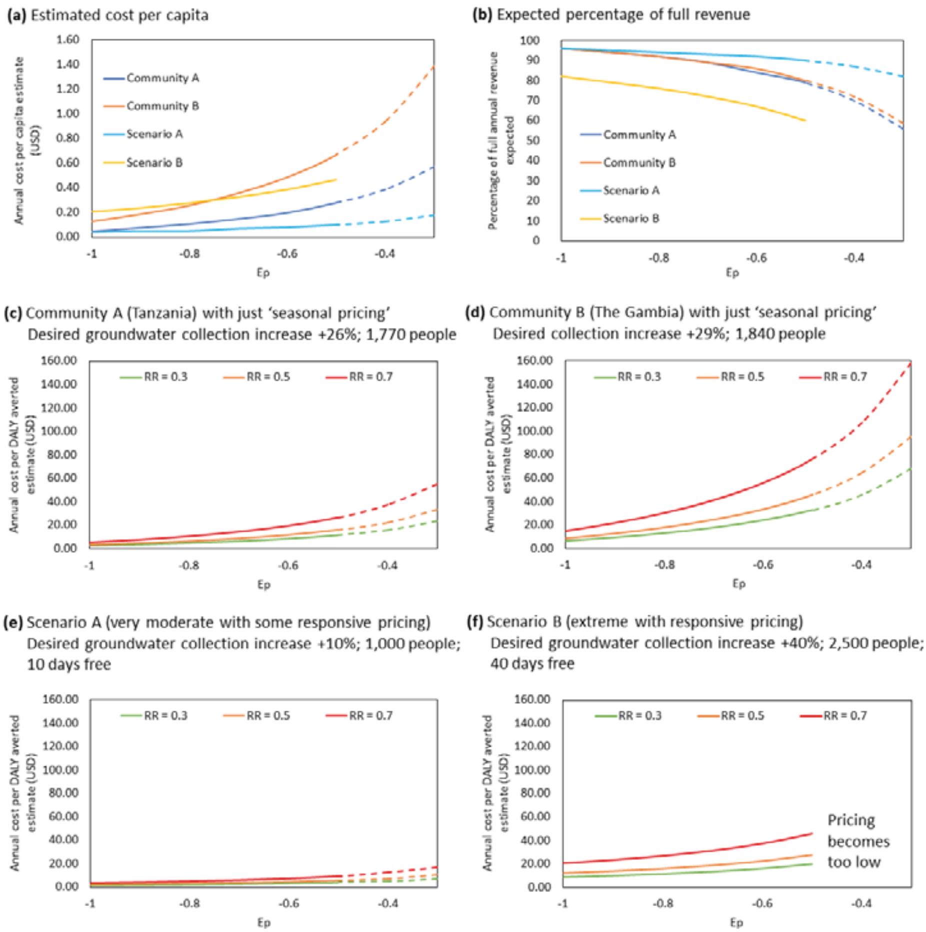

Figure 1 (a) Estimated cost, (b) percentage of full annual revenue, and cost per DALY averted of weather dependent pricing for different community characteristics across likely price elasticity (E_p) and relative risk (RR) ranges, for (c) Community A, (d) Community B, (e) Scenario A, and (f) Scenario B. Dashed lines indicate E_p values beyond the expected range. Baseline price, approximate litre per capita, length of rainy season, and DALYs are set for Tanzanian characteristics.

A community in Quadrant 1 would have a stronger response to price reductions, and therefore the cost per capita would be lower. However, the potential health gains from the intervention would be smaller and so the cost per DALY averted would not be correspondingly low. This might reflect a 'do it anyway' choice for service providers because it would be relatively low cost, and could be done as a complementary activity to other health interventions because of its relative ease. A high price elasticity (e.g. –0.9) in a moderate scenario such as Scenario A, with higher relative risk of disease from weather dependent pricing (e.g. of 0.7), could give such a choice.

A community in Quadrant 2 would have a stronger response to price reductions and lower cost per capita, and in tandem, the potential health gains would be higher,

Copyright

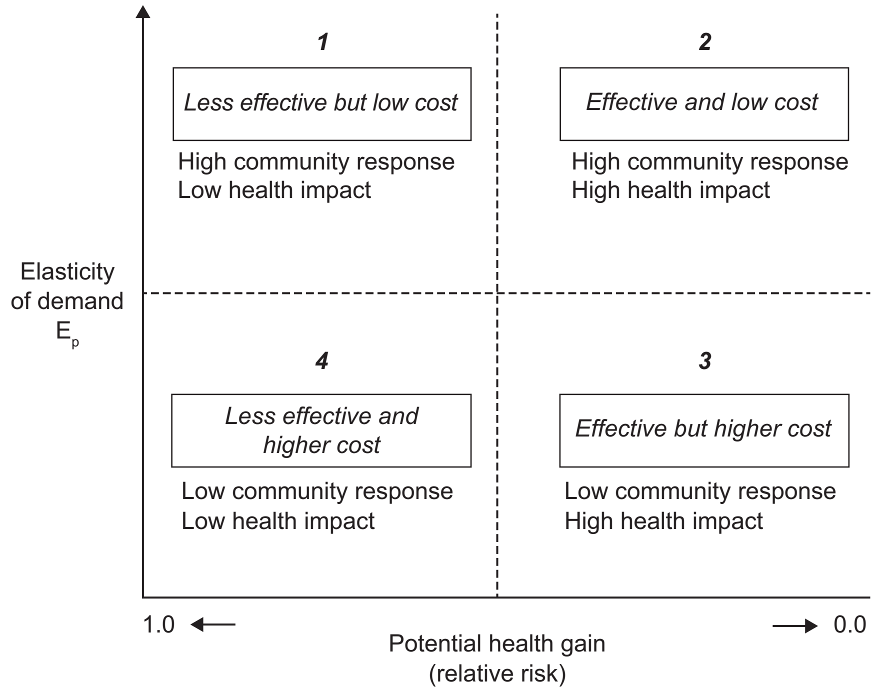

Figure 2 Community response to pricing vs. health impact of intervention

meaning lower cost per DALY averted. This represents a favourable community for implementation of weather dependent pricing, with potentially high value for money. For instance, high price elasticity (e.g. –0.9) in Scenario A with low relative risk (e.g. 0.3) could mean cost per capita might be as low as $0.05 and cost per DALY averted under $3.

A community in Quadrant 3 would have a weaker response to price reductions and therefore higher cost per capita because price reductions would need to be greater. However, this could result in higher potential health gains. This situation would require careful consideration and depend more on other community characteristics such as total volume per capita collected or length of 'seasonal block'. The wide range of possible outcomes here can be seen in the comparison between Community A and B in Figure 1(c–d), which show different costs per DALY averted with the same E_p and RR values. For communities in this quadrant, weather dependent pricing could be customized if necessary, such as only focusing on 'responsive pricing' days of free water.

Lastly, a community in Quadrant 4 would have a weaker response to price reductions, and therefore the cost per capita would be higher. The potential health gains would also be smaller and therefore the cost per DALY averted would be even higher. This represents an unfavourable scenario for weather dependent pricing, and one where other health interventions should be prioritized. In such a community, households' response may be weak because of, for example, strong attachment to

Copyright

particular alternative sources (discussed more below); and reduced disease from the intervention could be limited by, for example, primacy of non-water-related diarrhoeal infection pathways or poor household storage practices.

Despite these crude divisions here, pricing, length of seasonal block, and responsive pricing could be tailored to different communities to minimize cost and cost per DALY averted.

Sensitivity of calculated outputs is similar between price elasticity, relative risk, and desired increase in volume collected, and increases as E_p tends to 0.0 and RR tends to 1.0. Outputs also depend partly on volume collected per capita; however in the rural settings under investigation here this is assumed to be relatively low (Ingram and Memon, 2020). Uncertain inputs manifest as relatively uncertain outputs, with probability distributions of outputs showing high relative width values for Communities A and B (cost per capita = ~0.51; cost per DALY averted = ~0.74). However, these distributions significantly skew towards lower cost and lower cost per DALY averted, suggesting higher likelihoods of favourability.

Discussion

Weather dependent pricing appears to have the potential, in certain situations, to cheaply and cost-effectively mitigate the risk of disease that comes with rainfall in rural communities across sub-Saharan Africa.

Estimated costs per DALY averted here are likely to compare favourably against estimates of the costs of DALYs averted from other water quality interventions in sub-Saharan Africa, such as chlorination ($53), solar disinfection ($61), filtration ($142), source-based ($123), and flocculation and disinfection ($472) (Edwards, 2011). Furthermore, common additional household treatment by boiling water has additional cost, biomass collection time and energy commitments, air pollution, and ecological destruction (Clasen et al., 2008) which could be reduced here.

Low costs per capita compare well against other estimates of economic benefits from improved rural water supply, which originate from less health care expenditure, more productive time, and reductions in premature mortality. The average cost of childhood diarrhoeal illness in low- and middle-income countries is estimated to be about $37 per outpatient episode and $160 per inpatient episode (Baral et al., 2020).

When ‘responsive pricing’ is included as days of free water, cost per DALY averted estimates presented are likely to be more favourable in reality because of the disproportionate impact on health during heavy rain. Populations for Communities A and B are conservatively estimated, also meaning estimates are likely to be more favourable in reality.

This pricing mechanism has potential as a flexible and remote intervention with good value for money and no need for additional capital expenditure or maintenance costs. Free water has been noted as an emergency response to shocks such as the Covid-19 pandemic; however, as far as evident, third-degree price discrimination for domestic water is not recorded anywhere as being used as a direct tool to incentivize the use of clean sources in this manner. Another

Copyright

way to see the mechanism is as the inverse of the deleterious situation where efforts to improve cost-recovery through raised tariffs causes users to turn instead to alternative, poor-quality free sources, resulting in attendant negative health impacts (Cardone and Fonseca, 2003). Pre-payment ATMs can now avoid the common complication to water pricing management of households failing to pay. Pricing of rural water supply services tend to have many confounding determinants mostly revolving around signals to households and financial sustainability (McMullen and Bergman, 2018). Because this mechanism does not involve amended baseline prices, concerns around selection of the best price in the long term are less relevant.

Weather dependent pricing can also facilitate year-round operation of water points. Continuity of water services for rural populations is a long-standing challenge (DuChanois et al., 2019). It is reported in Kenya's Kitui County that even when all piped water systems are functional some operators have to close operations in the rainy season because users go to alternative, free water sources, making the businesses unviable (Nyaga, 2019). Even pre-payment ATMs are seen to close during rainy seasons (Komakech et al., 2020). This is the most egregious manifestation of the seasonality problem because the overall reduction in demand means that access to better quality water is cut off even to those households who may still want to collect it. This also means that no revenue at all can be collected over these periods. Therefore, this mechanism has strong potential to improve equity in access *and* result in greater total annual revenues for service providers.

It is well established that households often use rainwater and surface water sources when seasonably available for a range of non-consumptive uses, such as washing, (small-scale) irrigation, and cleaning (Hoque and Hope, 2018; Elliott et al., 2019); therefore, seasonal reduction in collection of water from ATMs does not necessarily correspond to a reduction in *consumption* of water from ATMs. Users naturally avoid paying for water services when possible, and choose water sources depending on the intended use in a highly rational way (Odhiambo and Almedom, 1994). This decision-making around collection of and payment for clean and contaminated water is complex and influenced by the availability of money and responses to health risks; in some cases this will result in consumption of contaminated water and attendant adverse health impacts. We hypothesize that the influence of a well-communicated price change may go some way to cut through this complexity and result in an increased household demand to some degree as postulated. We are not proposing that such an intervention will behaviourally change complex household decision-making in a linear way, and the scenarios described in Figure 2 illustrate the unpredictability of this, but if such a price-drop does incentivize continued collection of clean water from ATMs for drinking purposes then this could lead to health benefits.

Overall, weather dependent pricing is envisaged as a new tool to move these new Internet-of-things pre-payment technologies beyond just monitoring and revenue collection towards sophisticated, accountable remote management, and therefore further support a professionalized service delivery approach, especially as these technologies scale across sub-Saharan Africa.

Copyright

Considerations for implementation

Implementing weather dependent pricing would be a non-trivial exercise and require understanding of specific community characteristics and preferences. The first basic requirement is that a target community has an operational water ATM; such communities are increasingly common across many sub-Saharan African countries, and the fundamental mechanism would be applicable across different countries and types of community. Beyond this, behavioural considerations and risk perceptions are important alongside price (Anthonj et al., 2018). For instance, households may exhibit some 'present bias' by deciding to use convenient rainwater harvesting at their property rather than travel to communal water points. 'Nudging' to change habits, which has gained currency in WASH interventions, could help overcome such behavioural hurdles, for example with SMS messages combining information on pricing and timing with health reminders. This would come with additional cost, and must not substitute full and transparent engagement with the community. 'Conditional credit transfers' direct to individual household tags if they are recorded to be used during rainfall events could be a straightforward upgrade. A more challenging behavioural hurdle is hypothesized to be the process of reintroducing higher payments on the return of dry seasons, because people feel losses more than gains; however, the physical onset of the dry season will perhaps psychologically couple to this price change. The method of changing price will depend on the pre-payment modality in question, but free credit rather than altering currency-litre conversions may convey the powerful idea of having 'won' something that needs to be used.

'Responsive pricing' to days of heavy rainfall in the form of days of free water (with a cap on collection) might overcome the well-known limitations to free water because: 1) number of days per year would be low, 2) it would convey a much stronger signal to households, and 3) the health risk from heavy rain run-off and effluent contamination of alternative water sources is disproportionate. Accurate localized measurement of rainfall in specific communities remains a challenge, with satellite estimates currently unable to indicate days of heavy rainfall with the required spatial resolution. This requires further investigation.

Depending on the setting, the risk of diarrhoeal diseases can be concentrated at the start of the rainy season because pathogens accumulated over dry periods tend then to be washed into water sources (Kraay et al., 2020). This might suggest that weather dependent pricing could be most effective at the start of rainfall seasons. While affordability hurdles would be theoretically lowered during rainfall periods, seasonal income variation in agricultural communities may enhance or limit the responsiveness to price changes. Inverse application for drought conditions is not considered here as the health-rainfall relationship in such contexts has different dynamics.

Some potential limitations that require further investigation are: 1) households not knowing the price to enough precision to be influenced by price changes; 2) reduced pricing falsely communicating that the water is of lower quality or less desirable; 3) non-consumptive uses of the alternative sources in question; 4) seasonal barriers to collection from communal ATMs from, for example, degradation of paths

Copyright

by rainfall; and 5) the requirement for a fully functioning system with high water quality throughout rainfall seasons.

Combination with direct subsidy transfers

Subsidizing provision of rural water services is increasingly viewed as necessary to achieve universal, sustainable access, but such subsidies are often blunt instruments that fail to achieve their goals (Rogers et al., 2002; Whittington et al., 2012; Andres et al., 2019; McNicholl et al., 2019). A key challenge has been identifying service delivery models and technologies that make subsidies more effective (Null et al., 2012), and unlocking household payment behaviours will underpin this (Hope and Ballon, 2019). Weather dependent pricing using pre-payment ATMs may provide one response.

Precisely calculated lost revenues from individual ATMs over precise timescales presents a mechanism for subsidizing water services by amounts directly derived from operations rather than projections, while achieving a specific outcome of reduced disease. Immediate *ex-post* payments would avoid long existing routes of financial flows. Going directly to local service providers, or even water users themselves as has been demonstrated with direct cash transfers, would maintain accountability and efficiency and avoid negative spill-over while promoting decentralization and subsidiarity. This would avoid the current cross-subsidization from dry-season use, which is a limit to sustainability, and contribute financial resilience to unexpected stresses such as major operation and maintenance work (Foster, 2013). Subsidies must be predictable, transparent, targeted, and sufficient (Winpenny, 2011), all of which could be achieved here. Common limitations of water subsidies such as exclusion of households in more remote settings would be avoided. Similarly, the risk of subsidies primarily advantaging richer households or commercial users with false price blocks is reduced.

Practically, this 'smart' format of subsidy could be appealing to funders because: 1) it could be relatively cheap and good value; 2) it could constitute a form of payment-by-results to service providers; 3) the dual benefits of health and financial sustainability are an opportunity to improve the benefit-cost ratio of money spent; 4) it is very compatible with decentralized climate finance schemes; and 5) it allows direct combination of water and health budgets. It benefits from simplicity and minimal appraisal or monitoring and evaluation and could be offered as a package by a service provider to donors, NGOs, or corporate social responsibility budgets of companies based on precise projected benefits as above.

If done successfully, weather dependent pricing could help support the shift towards a professionalized service delivery approach while improving service levels and community health. Groundwater shows promise as a potential buffer to climate change (Lapworth et al., 2013; Bonsor et al., 2018; Cuthbert et al., 2019), but the full benefits of this will only be realized if rural communities can use this supply year-round. Weather dependent pricing could complement other socio-economic, physical, and governance initiatives to support systemic resilience to climate

Copyright

change, by promoting this year-round use. The flexibility of seasonal pricing and responsiveness to heavy rainfall can help build resilience to increasing unpredictability and intensity of rainfall. Reduced affordability barriers for households can help build socio-economic resilience, in line with the 'wicked' nature of rural water supply in the face of climate change.

Data availability

Rainfall data is available from the following sources: Global Precipitation Measurement (GPM) (Skofronick-Jackson et al., 2018) at Giovanni EarthData platform (https://giovanni.gsfc.nasa.gov); Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) (Funk et al., 2015) (https://chc.ucsb.edu/data/chirps); Tropical Applications of Meteorology using SATellite data and ground-based observations (TAMSAT) (Maidment et al., 2017) (www.tamsat.org.uk).

Acknowledgements

We would like to acknowledge the useful inputs of C. Nyaga; F.A. Memon; T. Taylor, J. Fisher, and J. Winpenny. We acknowledge the funding from: the REACH programme, funded by the Foreign and Commonwealth Office (AIRES code 201880), and the Engineering and Physical Sciences Research Council Doctoral Training Partnership (EPSRC DTP).

References

Alemayehu, B., Ayele, B., Melak, F. and Ambely, A. (2020) 'Exploring the association between childhood diarrhea and meteorological factors in Southwestern Ethiopia', *Science of The Total Environment* 741: 140189 <https://doi.org/10.1016/J.SCITOTENV.2020.140189>.

Andres, L., Thibert, M., Lombana Cordoba, C., Danilenko, A., Joseph, G., Borja-Vega, C. (2019) *Doing More with Less: Smarter Subsidies for Water Supply and Sanitation* [online], World Bank, Washington, DC <https://doi.org/10.1596/32277>.

Anthonj, C., Fleming, L., Godfrey, S., Ambelu, A., Bevan, J., Cronk, R., Bartram, J. (2018) 'Health risk perceptions are associated with domestic use of basic water and sanitation services: evidence from rural Ethiopia', *International Journal of Environmental Research and Public Health* 15(10): 2112 <https://doi.org/10.3390/ijerph15102112>.

Armstrong, A., Hope, R. and Munday, C. (2021) 'Monitoring socio-climatic interactions to prioritise drinking water interventions in rural Africa', *npj Clean Water* 4(1): 1–3 <https://doi.org/10.1038/s41545-021-00102-9>.

Arouna, A. and Dabbert, S. (2010) 'Determinants of domestic water use by rural households without access to private improved water sources in Benin: a seemingly unrelated Tobit approach', *Water Resources Management* 24: 1381–98 <https://doi.org/10.1007/s11269-009-9504-4>.

Baguma, D., Loiskandl, W. and Jung, H. (2010) 'Water management, rainwater harvesting and predictive variables in rural households', *Water Resources Management* 24(13): 3333–48 <https://doi.org/10.1007/S11269-010-9609-9>.

Copyright

Bain, R., Cronk, R., Hossain, R., Bonjour, S., Onda, K., Wright, J., Yang, H., Slaymaker, T., Hunter, P., Prüss-Ustün, A., Bartram, J. (2014) 'Global assessment of exposure to faecal contamination through drinking water based on a systematic review', *Tropical Medicine & International Health* 19(8): 917–27 <https://doi.org/10.1111/TMI.12334>.

Baral, R., Debellut, F., Agyemang, S., Clark, A., Pecenka,. C.(2020) 'Cost of illness for childhood diarrhea in low-and middle-income countries: a systematic review of evidence and modelled estimates', *BMC Public Health* 20(619): 1–12 <https://doi.org/10.1186/s12889-020-08595-8>.

Behnke, N., Klug, T., Cronk, R., Shields, K., Lee, K., Kelly, E., Allgood, G., Bartram, J., (2017) 'Resource mobilization for community-managed rural water systems: evidence from Ghana, Kenya, and Zambia', *Journal of Cleaner Production* 156: 437–44 <https://doi.org/10.1016/J.JCLEPRO.2017.04.016>.

Bonsor, H., Shamsudduha, M., Marchant, B., MacDonald, A., Taylor, R., (2018) 'Seasonal and decadal groundwater changes in African sedimentary aquifers estimated using GRACE products and LSMs', *Remote Sensing* 10(6): 904 <https://doi.org/10.3390/RS10060904>.

Brown, J. and Clasen, T. (2012) 'High adherence is necessary to realize health gains from water quality interventions', *PLoS ONE* 7(5): e36735 <https://doi.org/10.1371/JOURNAL.PONE.0036735>.

Cardone, R. and Fonseca, C. (2003) *Financing and Cost Recovery: Thematic Overview Paper 7*, IRC, The Hague.

Cheesman, J., Bennett, J. and Son, T.V.H. (2008) 'Estimating household water demand using revealed and contingent behaviors: evidence from Vietnam', *Water Resources Research* 44(11) <https://doi.org/10.1029/2007WR006265>.

Clasen, T., Thao, D., Boisson, S., Shipin, O. (2008) 'Microbiological effectiveness and cost of boiling to disinfect drinking water in rural Vietnam', *Environmental Science and Technology* 42(12): 4255–60 <https://doi.org/10.1021/ES7024802>.

Cook, J., Kimuyu, P. and Whittington, D. (2016) 'The costs of coping with poor water supply in rural Kenya', *Water Resources Research* 52(2): 841–59 <https://doi.org/10.1002/2015WR017468>.

Coulibaly, L., Jakus, P.M. and Keith, J.E. (2014) 'Modeling water demand when households have multiple sources of water', *Water Resources Research* 50(7): 6002–14 <https://doi.org/10.1002/2013WR015090>.

Cuthbert, M., Taylor, R., Favreau, G., Todd, M., Shamsudduha, M., Villholth, K., MacDonald, A., Scanlon, B., Kotchoni, D., Vouillamoz, J., Lawson, F., Adjomayi, P., Kashaigili, J., Seddon, D., Sorensen, J., Ebrahim, G., Owor, M., Nyenje, P., Nazoumou, Y., Goni, I., Ousmane, B., Sibanda, T., Ascott, M., Macdonald, D., Agyekum, W., Koussoubé, Y., Wanke, H., Kim, H., Wada, Y., Lo, M., Oki, T., Kukuric, N., (2019) 'Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa', *Nature 2019* 572(7768): 230–4 <https://doi.org/10.1038/s41586-019-1441-7>.

Daly, S., Lowe, J., Hornsby, G., Harris, A.(2021) 'Multiple water source use in low- and middle-income countries: a systematic review', *Journal of Water and Health*, 19(3): 370–92 <https://doi.org/10.2166/wh.2021.205>.

DuChanois, R., Liddle, E., Fenner, R., Jeuland, M., Evans, B., Cumming, O., Zaman, R., Mujica-Pereira, A., Ross, I., Gribble, M., Brown, J. (2019) 'Factors associated with water service continuity for the rural populations of Bangladesh, Pakistan, Ethiopia, and Mozambique', *Environmental Science & Technology* 53: 31 <https://doi.org/10.1021/acs.est.8b07173>.

Edwards, C. (2011) 'Cost-effectiveness analysis in practice', in J. Cameron et al. (eds), *Valuing Water, Valuing Livelihoods*, Chapter 10, pg. 181-190. London: IWA Publishing.

Copyright

Elliott, M., Foster, T., MacDonald, M., Harris, A., Schwab, K., Hadwen, W. (2019) 'Addressing how multiple household water sources and uses build water resilience and support sustainable development', *npj Clean Water* 2(1): 1–5 <https://doi.org/10.1038/s41545-019-0031-4>.

Fischer, E.M. and Knutti, R. (2016) 'Observed heavy precipitation increase confirms theory and early models', *Nature Climate Change* 6(11): 986–91 <https://doi.org/10.1038/nclimate3110>.

Foster, T. (2013) 'Predictors of sustainability for community-managed handpumps in sub-Saharan Africa: evidence from Liberia, Sierra Leone, and Uganda', *Environmental Science and Technology* 47(21): 12037–46 <https://doi.org/10.1021/ES402086N>.

Foster, T. (2017) 'A critical mass analysis of community-based financing of water services in rural Kenya', *Water Resources and Rural Development* 10: 1–13 <https://doi.org/10.1016/J.WRR.2017.04.003>.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J. (2015) 'The climate hazards infrared precipitation with stations: a new environmental record for monitoring extremes', *Scientific Data* 2(1): 1–21 <https://doi.org/10.1038/sdata.2015.66>.

Garrone, P., Grilli, L. and Marzano, R. (2019) 'Price elasticity of water demand considering scarcity and attitudes', *Utilities Policy* 59: 100927 <https://doi.org/10.1016/J.JUP.2019.100927>.

Gross, E. and Elshiewy, O. (2019) 'Choice and quantity demand for improved and unimproved public water sources in rural areas: evidence from Benin', *Journal of Rural Studies* 69: 186–94 <https://doi.org/10.1016/J.JRURSTUD.2019.02.021>.

Hamilton, K., Reyneke, B., Waso, M., Clements, T., Ndlovu, T., Khan, W., DiGiovanni, K., Rakestraw, E., Montalto, F., Haas, C., Ahmed, W. (2019) 'A global review of the microbiological quality and potential health risks associated with roof-harvested rainwater tanks', *npj Clean Water* 2(1): 1–18 <https://doi.org/10.1038/s41545-019-0030-5>.

Hope, R. and Ballon, P. (2019) 'Global water policy and local payment choices in rural Africa', *npj Clean Water* 2: 21 <https://doi.org/10.1038/s41545-019-0045-y>.

Hope, R., Thomson, P., Koehler, J., Foster, T. (2020) 'Rethinking the economics of rural water in Africa', *Oxford Review of Economic Policy* 36(1): 171–90 <https://doi.org/10.1093/oxrep/grz036>.

Hopkins, O., Lauria, D., Kold, A. (2004) 'Demand-based planning of rural water systems in developing countries', *Journal of Water Resources and Planning* 130(1): 44–52 <https://doi.org/10.1061/ASCE0733-94962004130:144>.

Hoque, S.F. and Hope, R. (2018) 'The water diary method – proof-of-concept and policy implications for monitoring water use behaviour in rural Kenya', *Water Policy* 20(4): 725–43 <https://doi.org/10.2166/WP.2018.179>.

Hunter, P.R., Zmirou-Navier, D. and Hartemann, P. (2009) 'Estimating the impact on health of poor reliability of drinking water interventions in developing countries', *Science of The Total Environment* 407(8): 2621–4 <https://doi.org/10.1016/J.SCITOTENV.2009.01.018>.

Hutton, G. (2006) *Economic and Health Effects of Increasing Coverage of Low Cost Water and Sanitation Interventions* (No. HDOCPA-2006-33) [online], New York: Human Development Report Office (HDRO), United Nations Development Programme (UNDP) <https://EconPapers.repec.org/RePEc:hdr:hdocpa:hdocpa-2006-33> [accessed 14 July 2021].

Ingram, W. and Memon, F.A. (2020) 'Rural water collection patterns: combining smart meter data with user experiences in Tanzania', *Water* 12(4): 1164 <https://doi.org/10.3390/W12041164>.

Copyright

Ingram, W. and Memon, F.A. (2021) 'Measuring seasonal reductions in water collection from piped systems in rural sub-Saharan Africa using novel pre-payment "smart meters"', in *The Virtual Conference of AQUA≈360: Water for All - Emerging Issues and Innovations*, Exeter, UK.

Jackson, L., Finney, D., Kendon, E., Marsham, J., Parker, D., Stratton, R., Tomassini, L., Tucker, S. (2020) 'The effect of explicit convection on couplings between rainfall, humidity, and ascent over Africa under climate change', *Journal of Climate* 33(19): 8315–37 <https://doi.org/10.1175/JCLI-D-19-0322.1>.

Katuva, J., Hope, R., Foster, T., Koehler, J., Thomson, P.(2020) 'Groundwater and welfare: a conceptual framework applied to coastal Kenya', *Groundwater for Sustainable Development* 10: 100314 <https://doi.org/10.1016/J.GSD.2019.100314>.

Kelly, E., Shields, K., Cronk, R., Lee, K., Behnke, N., Klug, T., Bartram, J. (2018) 'Seasonality, water use and community management of water systems in rural settings: qualitative evidence from Ghana, Kenya, and Zambia', *Science of The Total Environment* 628–9: 715–21 <https://doi.org/10.1016/J.SCITOTENV.2018.02.045>.

Kendon, E., Stratton, R., Tucker, S., Marsham, J., Berthou, S., Rowell, D., Senior, C.(2019) 'Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale', *Nature Communications* 10(1): 1–14 <https://doi.org/10.1038/s41467-019-09776-9>.

Komakech, H.C., Kwezi, L. and Ali, M. (2020) 'Why prepaid technologies are not a panacea for inclusive and sustainable rural water services in Tanzania?', *Water Policy* 22(5): 925–42 <https://doi.org/10.2166/WP.2020.070>.

Kraay, A., Man, O., Levy, M., Levy, K., Ionides, E., Eisenberg, J.(2020) 'Understanding the impact of rainfall on diarrhea: testing the concentration-dilution hypothesis using a systematic review and meta-analysis', *Environmental Health Perspectives* 128(12): 126001 <https://doi.org/10.1289/EHP6181>.

Kulinkina, A., Kosinski, K., Liss, A., Adjei, M., Ayamgah, G., Webb, P., Gute, D., Plummer, J., Naumova, E.(2016) 'Piped water consumption in Ghana: a case study of temporal and spatial patterns of clean water demand relative to alternative water sources in rural small towns', *Science of The Total Environment* 559: 291–301 <https://doi.org/10.1016/J.SCITOTENV.2016.03.148>.

Lapworth, D., Macdonald, A., Tijani, M., Darling, W., Gooddy, D., Bonsor, H., Araguás-Araguás, L. (2013) 'Residence times of shallow groundwater in West Africa: implications for hydrogeology and resilience to future changes in climate', *Hydrogeology Journal* 21(3): 673–86 <https://doi.org/10.1007/s10040-012-0925-4>.

Lawrence, A., Macdonald, D., Howard, A., Barrett, M., Pedley, S., Ahmed, K., Nalubega, M. (2001) *Guidelines for assessing the risk to groundwater from on-site sanitation CR/01/142*. British Geological Survey. Keyworth, UK.

Maidment, R., Grimes, D., Black, E., Tarnavsky, E., Young, M., Greatrex, H., Allan, R., Stein, T., Nkonde, E., Senkunda, S., Alcántara, E.(2017) 'A new, long-term daily satellite-based rainfall dataset for operational monitoring in Africa', *Scientific Data* 4(1): 1–19 <https://doi.org/10.1038/sdata.2017.63>.

McMullen, J.S. and Bergman, B.J. (2018) 'The promise and problems of price subsidization in social entrepreneurship', *Business Horizons* 61(4): 609–21 <https://doi.org/10.1016/J.BUSHOR.2018.03.009>.

McNicholl, D., Hope, R., Money, A., Lane, A., Armstrong, A., van der Wilk, N., Dupuis, M., Harvey, A., Nyaga, C., Womble, S., Favre, D., Allen, J., Katuva, J., Barbotte, T., Buhungiro, E., Thomson, P., Koehler, J. (2019) *Performance-based Funding for Reliable Rural Water Services in Africa*, Uptime Consortium, Working Paper 1. https://www.smithschool.ox.ac.uk/research/water/publications/Performance-based_funding_for_reliable_rural_water_services.pdf

Copyright

Nauges, C. and van den Berg, C. (2008) 'Demand for piped and non-piped water supply services: evidence from southwest Sri Lanka', *Environmental and Resource Economics* 42(4): 535–49 <https://doi.org/10.1007/S10640-008-9222-Z>.

Nauges, C. and Whittington, D. (2010) 'Estimation of water demand in developing countries: an overview', *The World Bank Research Observer* 25(2): 263–94 <https://doi.org/10.1093/WBRO/LKP016>.

Nauges, C. and Whittington, D. (2017) 'Evaluating the performance of alternative municipal water tariff designs: quantifying the tradeoffs between equity, economic efficiency, and cost recovery', *World Development* 91: 125–43 <https://doi.org/10.1016/j.worlddev.2016.10.014>.

Null, C., Kremer, M., Miguel, E., Hombrados, J., Meeks, R., Zwane, A.(2012) *Willingness to Pay for Cleaner Water in Less Developed Countries: Systematic Review of Experimental Evidence*. International Initiative for Impact Evaluation (3ie), Systematic Review 006. Washington D.C.

Nyaga, C. (2019) *A Water Infrastructure Audit of Kitui County*. USAID/SWS; University of Oxford, Rural Focus, University of Colorado.

Odhiambo, C. and Almedom, A. (1994) 'The rationality factor: choosing water sources according to water uses', *Waterlines* 13(2): 28-31. <doi:10.3362/0262-8104.1994.044>

Parker, A., Youlten, R., Dillon, M., Nussbaumer, T., Carter, R., Tyrrel, S., Webster, J. (2010) 'An assessment of microbiological water quality of six water source categories in north-east Uganda', *Journal of Water and Health* 8(3): 550–60 <https://doi.org/10.2166/WH.2010.128>.

Prüss-Ustün, A., Wolf, J., Bartram, J., Clasen, T., Cumming, O., Freeman, M., Gordon, B., Hunter, P., Medlicott, K., Johnston, R. (2019) 'Burden of disease from inadequate water, sanitation and hygiene for selected adverse health outcomes: an updated analysis with a focus on low- and middle-income countries', *International Journal of Hygiene and Environmental Health* 222(5): 765–77 <https://doi.org/10.1016/j.ijheh.2019.05.004>.

Rietveld, P., Rouwendal, J. and Zwart, B. (2000) 'Block rate pricing of water in Indonesia: an analysis of welfare effects', *Bulletin of Indonesian Economic Studies* 36(3): 73–92 <https://doi.org/10.1080/00074910012331338983>.

Risebro, H. and Hunter, P.R. (2011) 'Estimating health impacts of interventions with a focus on small scale drinking water interventions', in J. Cameron et al. (eds), *Valuing Water, Valuing Livelihoods*, Chapter 9, pg. 167-180. London: IWA Publishing.

Rogers, P., de Silva, R. and Bhatia, R. (2002) 'Water is an economic good: how to use prices to promote equity, efficiency, and sustainability', *Water Policy* 4: 1–17.

Skofronick-Jackson, G., Kirschbaum, D., Petersen, W., Huffman, G., Kidd, C., Stocker, E., Kakar, R. (2018) 'The Global Precipitation Measurement (GPM) mission's scientific achievements and societal contributions: reviewing four years of advanced rain and snow observations', *Quarterly Journal of the Royal Meteorological Society* 144: 27–48 <https://doi.org/10.1002/qj.3313>.

Thiam, S., Diène, A., Sy, I., Winkler, M., Schindler, C., Ndione, J., Faye, O., Vounatsou, P., Utzinger, J., Cissé, G. (2017) 'Association between childhood diarrhoeal incidence and climatic factors in urban and rural settings in the health district of Mbour, Senegal', *International Journal of Environmental Research and Public Health* 14(9): 1049 <https://doi.org/10.3390/IJERPH14091049>.

Thomas, E., Needoba, J., Kaberia, D., Butterworth, J., Adams, E., Oduor, P., Macharia, D., Mitheu, F., Mugo, R., Nagel, C. (2019) 'Quantifying increased groundwater demand from prolonged drought in the East African Rift Valley', *Science of The Total Environment* 666: 1265–72 <https://doi.org/10.1016/J.SCITOTENV.2019.02.206>.

Copyright

Thomson, P. (2018) ‘Only rapid handpump repairs reduce diarrhoea morbidity: evidence from Kenya’, presentation at *UNC Water and Health 2018* [Preprint] < https://www.antenna.ch/wp-content/uploads/2021/12/From-Emergency-to-Development-Autonomous-Chlorine-Production-for-Water-Utilities-in-Conflict-Regions-Insights-from-Ukraine.pdf >.

Thomson, P., Bradley, D., Katilu, A., Katuva, J., Lanzoni, M., Koehler, J., Hope, R. (2019) ‘Rainfall and groundwater use in rural Kenya’, *Science of The Total Environment* 649: 722–30 <https://doi.org/10.1016/J.SCITOTENV.2018.08.330>.

Troeger, C., Forouzanfar, M., Rao, P., Khalil, I., Brown, A., Reiner, R., Fullman, N., Thompson, R., Abajobir, A., Ahmed, M., Alemayohu, M., Alvis-Guzman, N., Amare, A., Antonio, C., Asayesh, H., Avokpaho, E., Awasthi, A., Bacha, U., Barac, A., Betsue, B., Beyene, A., Boneya, D., Malta, D., Dandona, L., Dandona, R., Dubey, M., Eshrati, B., Fitchett, J., Gebrehiwot, T., Hailu, G., Horino, M., Hotez, P., Jibat, T., Jonas, J., Kasaeian, A., Kissoon, N., Kotloff, K., Koyanagi, A., Kumar, G., Rai, R., Lal, A., El, Razek., H, Mengistie, M., Moe, C., Patton, G., Platts-Mills, J., Qorbani, M., Ram, U., Roba, H., Sanabria, J., Sartorius, B., Sawhney, M., Shigematsu, M., Sreeramareddy, C., Swaminathan, S., Tedla, B., Jagiellonian, R., Ukwaja, K., Werdecker, A., Widdowson, M., Yonemoto, N., El Sayed Zaki M., Lim, S., Naghavi, M., Vos, T., Hay, S., Murray, C., Mokdad, A. (2017) ‘Estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the Global Burden of Disease Study 2015’, *The Lancet Infectious Diseases* 17(9): 909–48 <https://doi.org/10.1016/S1473-3099(17)30276-1>.

Turman-Bryant, N., Nagel, C., Stover, L., Muragijimana, C., Thomas, E. (2019) ‘Improved drought resilience through continuous water service monitoring and specialized institutions: a longitudinal analysis of water service delivery across motorized boreholes in northern Kenya’, *Sustainability* 11: 3046 <https://doi.org/10.3390/SU11113046>.

Waddington, H. and Snilstveit, B. (2009) ‘Effectiveness and sustainability of water, sanitation, and hygiene interventions in combating diarrhoea’, *Journal of Development Effectiveness* 1(3): 295–335 <https://doi.org/10.1080/19439340903141175>.

Wagner, J., Cook, J. and Kimuyu, P. (2019) ‘Household demand for water in rural Kenya’, *Environmental and Resource Economics* 74(4): 1563–84 <https://doi.org/10.1007/S10640-019-00380-5>.

Whittington, D., Jeuland, M., Barker, K., Yuen, Y. (2012) ‘Setting priorities, targeting subsidies among water, sanitation, and preventive health interventions in developing countries’, *World Development* 40(8): 1546–68 <https://doi.org/10.1016/J.WORLDDEV.2012.03.004>.

Winpenny, J. (2011) *Financing for Water and Sanitation: A Primer for Practitioners and Students in Developing Countries*, EU Initiative Finance Working Group. https://www.gwp.org/globalassets/global/toolbox/references/financing-for-water-and-sanitation-euwi-fwg-2011.pdf

Wolf, J., Hunter, P., Freeman, M., Cumming, O., Clasen, T., Bartram, J., Higgins, J., Johnston, R., Medlicott, K., Boisson, S., Prüss-Ustün, A. (2018) ‘Impact of drinking water, sanitation and handwashing with soap on childhood diarrhoeal disease: updated meta-analysis and meta-regression’, *Tropical Medicine & International Health* 23(5): 508–25 <https://doi.org/10.1111/TMI.13051>.

World Bank Water Demand Team (1993) ‘The demand for water in rural areas: determinants and policy implications’, *The World Bank Research Observer* 8(1): 47–70 <https://doi.org/10.4324/9781351159289-30>.

World Health Organization (2018) *Global Health Estimates 2016: Disease Burden by Cause, Age, Sex, by Country and by Region, 2000–2016*, WHO, Geneva.

Zekri, S. and Dinar, A. (2003) ‘Welfare consequences of water supply alternatives in rural Tunisia’, *Agricultural Economics* 28(1): 1–12 <https://doi.org/10.1111/J.1574-0862.2003.TB00130.X>.

Copyright