



Research paper

## Groundwater and welfare: A conceptual framework applied to coastal Kenya

Jacob Katuva<sup>a,\*</sup>, Rob Hope<sup>a</sup>, Tim Foster<sup>b</sup>, Johanna Koehler<sup>a</sup>, Patrick Thomson<sup>a</sup>

<sup>a</sup> School of Geography and the Environment, Oxford University, UK

<sup>b</sup> Institute for Sustainable Futures, University of Technology Sydney, 235 Jones Street, Ultimo, NSW, 2007, Australia



### ARTICLE INFO

#### Keywords:

Groundwater  
Water services  
Welfare  
Kenya

### ABSTRACT

The links between groundwater and welfare are highly contested, unclear and confounded by political, environmental and economic factors. The lack of understanding of these links has wider implication on policies and strategies aimed at accelerating the sustainable development goals of safely-managed drinking water services and eradicating poverty. This study provides empirical evidence of the existing links between groundwater and poverty using welfare metrics versus productive uses of water, groundwater table depth, drinking water services and groundwater dependency with data obtained from a household socio-economic survey (n = 3349), a water audit of water infrastructure (n = 570) and volumetric usage from water data transmitters (n = 300). Results show that the bottom welfare households are characterized by greater dependency on shallow groundwater, less acceptable drinking water services by taste, reliability, affordability or accessibility but not quantity. Productive use of groundwater for livestock accrues to the middle welfare quintiles with the bottom and top welfare quintiles by choice or exclusion having little engagement. Groundwater productive uses, services and characteristics explain at least 17% of the variation in a households' welfare with productive uses particularly benefiting female headed households. These findings suggest that ancillary investments to improve affordability and reliability of rural water services will be needed to enhance welfare of the poor who depend on groundwater systems. Further, such knowledge of the relationships between water and welfare can support the formulation of policies and strategies aimed at poverty reduction, inclusive growth and access to safe water for all.

### 1. Introduction

Groundwater plays an important role in human welfare, particularly for vulnerable and marginalized populations in rural Africa and Asia (Moench, 2002; Mukherji, 2005; Calow et al., 2010). However, the relationship between groundwater and human welfare lacks conceptual clarity due to identification and measurement problems. Identification issues concern how people use different water resources (surface water, rainwater or vended water) at different times for domestic (bathing, cooking, drinking, laundry or washing) and productive (livestock, agriculture, enterprise) purposes. Measurement issues revolve around availability of acceptable data on the timing, type and volume of water usage and the associated linkages to welfare. Welfare may be a broader conceptualization of the well-being, capabilities and functioning of individuals, households or communities which go beyond income or expenditure analysis, providing one aspect of multi-dimensional poverty (Sen, 1976; Dasgupta, 2001; Alkire and Foster, 2011; Ravallion, 2011).

While a large number of rural Africans depend on groundwater sources from millions of handpumps (RWSN, 2009b; Macarthur, 2015), the dynamics between groundwater resource availability and quality, reliability and affordability of the water services, management of the infrastructure and varying uses of water confound the potential of groundwater (water services) for livelihood improvement (Foster, 2013; Bartram et al., 2014; Fisher et al., 2015; Thomas, 2017). Understanding groundwater and welfare is thus of increasing importance for progress towards the Sustainable Development Goals targets, including poverty, gender inequality, water, climate, hunger, health, work and growth, and sustainable cities and communities. With the unsatisfactory progress from the Millennium Development Goals era, Africa remains a region of concern and priority as it lags behind the rest of the world.

While groundwater resources in Africa are estimated to be two orders of magnitude greater in terms of storage compared to annual, renewable surface water resources (MacDonald et al., 2012; Taylor et al., 2012; Lapworth et al., 2017), the high-yielding aquifers (>20 l/s) often do not

\* Corresponding author. School of Geography and the Environment, Oxford University, Dyson Perrins Building, South Parks Road, Oxford, OX1 3QY, UK.  
E-mail addresses: [jacob.katuva@ouce.ox.ac.uk](mailto:jacob.katuva@ouce.ox.ac.uk), [jacob.katuva@gmail.com](mailto:jacob.katuva@gmail.com) (J. Katuva).

coincide with human demand. Shallow and limited aquifer systems (<80 m; < 5 l/s) are the primary resource for some 200 million rural Africans who tend to be poor (Macdonald et al., 2009; Foster and Garduño, 2013; Baguma et al., 2017). Despite examples of geogenic contamination from arsenic, fluoride and iron in particular environments (Smedley and Kinniburgh, 2013; Edmunds et al., 2015), groundwater quality is generally considered of good quality (Giordano, 2009), particularly in relation to organic contamination in shallow wells or surface exposed to human or animal pollution (Hunter et al., 2010; Prüss-Ustün et al., 2014). While this provides an opportunity to unlock the potential of groundwater for the poor, the widespread gaps in scientific understanding on the extent, nature and variability in groundwater (Fan et al., 2013) and the systematic data deficit reflects the uncertainty in understanding groundwater and welfare interactions and impacts.

The broad assumptions that access to groundwater may improve health, reduce collection time for women and girls, promote small-scale agriculture, such as food gardens or livestock, or other micro-enterprises (Haller et al., 2007; Hunter et al., 2010; Namara et al., 2010; Prüss-Ustün et al., 2014) may not align well with the evidence on the functionality, availability or allocation of handpumps in rural African communities. Furthermore, there exists a scarcity of high quality studies that have examined how domestic and productive uses of groundwater shape welfare for growth and development in Africa (Baguma et al., 2017). This paper aims to contribute to advancing the conceptual understanding of groundwater and welfare in three dimensions. First, a conceptual framework identifies the salient components and interactions between water resources, including groundwater, and their association with domestic and productive water uses, which in turn influences different welfare outcomes and impacts. Second, we test this framework in coastal Kenya drawing upon interdisciplinary data from over 3349 households and measured handpump usage using ‘smart handpump’ technology (Thomson, Hope and Foster, 2012a). Third, we map and model these relationships to estimate the share of household welfare associated with groundwater and its spatial distribution in a study area of some 2000 km<sup>2</sup>. The following section introduces the conceptual framework followed by the methodology and study site. Section four presents the results followed by a discussion of the three

major findings followed by a conclusion.

## 2. Groundwater and welfare

In this section, we outline a conceptual framework of groundwater and welfare. The framework has four dimensions in a schematic of the dynamic and multiple feedback loops between: (1) water resources, (2) drinking water systems, (3) productive water systems, and (4) welfare status. The framing is devised in the context of the systems which are found in large parts of rural Africa and Asia (Fig. 1).

The water resources’ dimension recognizes the major flows or stocks available to people in terms of rainwater, surface water (rivers, streams, springs), soil moisture and groundwater. The partitioning of these resources over space and time will naturally vary and be influenced by hydro-climatic variability and shocks, legal and policy frameworks, the political economy of allocation, and regulation and enforcement systems. Hydro-climatic variability across Africa is illustrated by the East African Paradox where modelling projections of rainfall patterns are not consistent with observed data, particularly in the long rains season (March, April, May), which has implications for the vulnerability and exposure of millions of people and their livelihood systems in the future. Equally, the disproportionate influence of El Niño events on groundwater recharge in the short rains season (October, November, December) illustrate the spatial and temporal importance of extremes to guide policy and planning on groundwater management (Taylor et al., 2012, 2013; Rowell et al., 2015; Lyon and Vigaud, 2017). Existing legal and policy frameworks for groundwater management are constrained by the significant gaps in Africa’s hydro-meteorological and groundwater monitoring systems (Mumma et al., 2011; Comte et al., 2016). In turn, the political economy of allocating groundwater for competing users is challenged by scientific uncertainty and water-based interest groups claiming historical rights or new claims with short-term demands potentially not consistent with long-term resource sustainability (Burke and Moench, 2000; Llamas and Martínez-Santos, 2005; Hope and Rouse, 2013). Regulatory and enforcement systems are another critical but often constrained institutional response to dealing with scientific uncertainty and significant monitoring gaps to provide the checks and balances to manage groundwater sustainably. While recognizing the

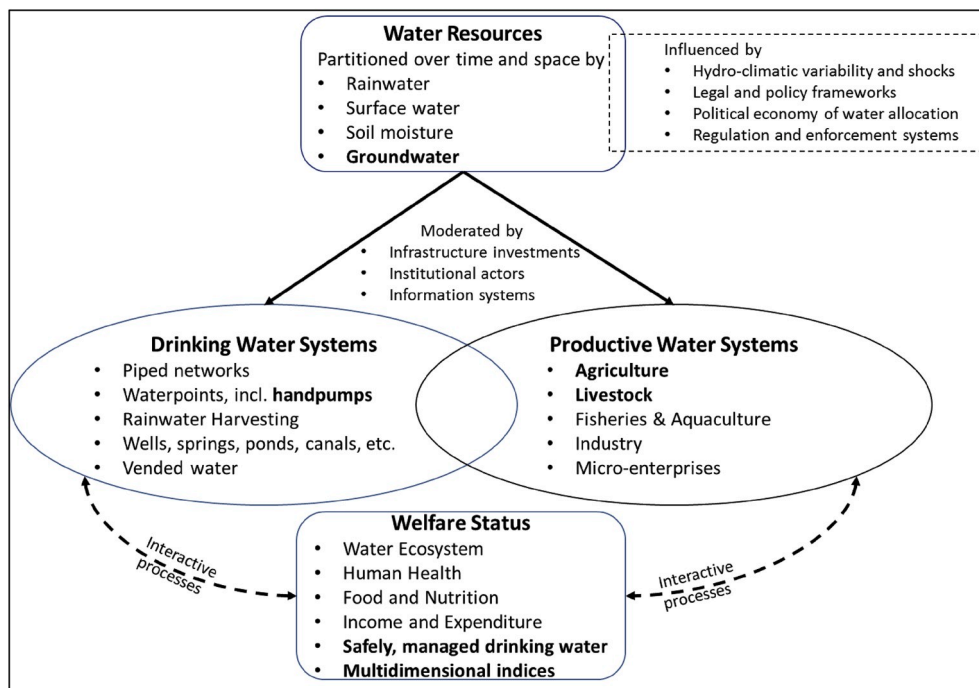


Fig. 1. Groundwater and welfare conceptual framework.

importance and relevance of all these dimensions, here we will focus only on the groundwater resource in a rural Kenyan context.

Water resources provide stock or flows of water for drinking water systems and productive water systems moderated by infrastructure investments, institutional actors and information systems. Drinking water systems include a portfolio of technologies with our focus explicitly interested in handpumps, which we discuss further below. This does not exclude the wider array of piped networks, kiosks, vended water or self-supply sources but proposes a parsimonious approach for testing the framework below. Productive water systems may share the same infrastructure for small-scale agriculture, livestock or micro-enterprises as domestic water though in bulk water demands for fisheries, industry or commercial agriculture rely on separate infrastructure investments. Infrastructure investments may be financed in multiple ways with differing risks and returns partitioning the level and mix of public or private finance. At one level, self-supply of domestic water may be a function of private investment in labour and some materials. Alternatively, large industrial water demands may require hundreds of thousands of dollars of investment capital geared to the expected returns of the productive activity over years or possibly decades. New financing instruments consider social and private investment returns with impact investing or green bonds providing favorable forms of finance which blend both capital returns as well as social returns, such as benefits to women, children or protecting environmental flows or groundwater quality (Trémolet et al., 2010; Trémolet, 2011) Explicit in this new water financial architecture is that performance-based metrics and monitoring systems are required to document and validate the societal or private returns. This reflects the progress in water information systems from remote sensing, mobile-based technology or digital monitoring surveillance (Hutchings et al., 2012; Thomson, Hope and Foster, 2012b). Here, we consider ‘smart handpumps’ (Thomson, Hope and Foster, 2012a) which use mobile-enabled data transmitter to send data automatically on hourly usage. The institutional actors for these wider water systems is extensive across irrigation, utility, industrial or

community typologies (Molle and Mollinga, 2003; Ostrom, 2009; Koehler et al., 2015). Here, we consider community water management as one sub-component of this wider institutional system.

Finally, welfare status incorporates both environmental concerns of ecosystem health and status along with multi-dimensional welfare concerns including income and expenditure, health, food and nutrition, as well as the performance of indicators of safely managed drinking water services. The latter provide the focus in our analysis covering the quantity, quality, reliability and accessibility of handpumps for different social groups.

### 3. Methodology

#### 3.1. Study site

The study site is located in Kwale County, Kenya, south of Mombasa and adjacent to northern Tanzania (Fig. 2). The coastal climate has a bi-modal rainfall pattern with an average annual precipitation of 1200 mm with inter-annual and spatial variability. The coastal lowland is the wettest with the climate getting drier to the west (inland) and north. The average annual temperatures are above 28 °C (GOK, 1985). The County has a population of over 810,000 people most of whom live in rural areas (82%) with over 70% living below the poverty line of less than USD \$1.25 a day (KNBS, 2006). The study area covers 2156 km<sup>2</sup> in Lunga Lungu, Msambweni and Matuga sub-Counties with around 300,000 residents (KNBS, 2010). This area includes the international tourism destination of Diani beach. Since 2013, the pace of environmental, economic, social and political change has increased with the establishment of two new and major economic activities in the area. Kwale International Sugarcane Company Limited (KISCOL) has been progressively rehabilitating 5500 ha of sub-surface irrigated sugarcane including the commissioning of its own sugar mill in 2015. Adjacent to the plantations is the country’s newest and largest mining operation (Kwale Mineral Sands Project). The mine, operated by Base Titanium

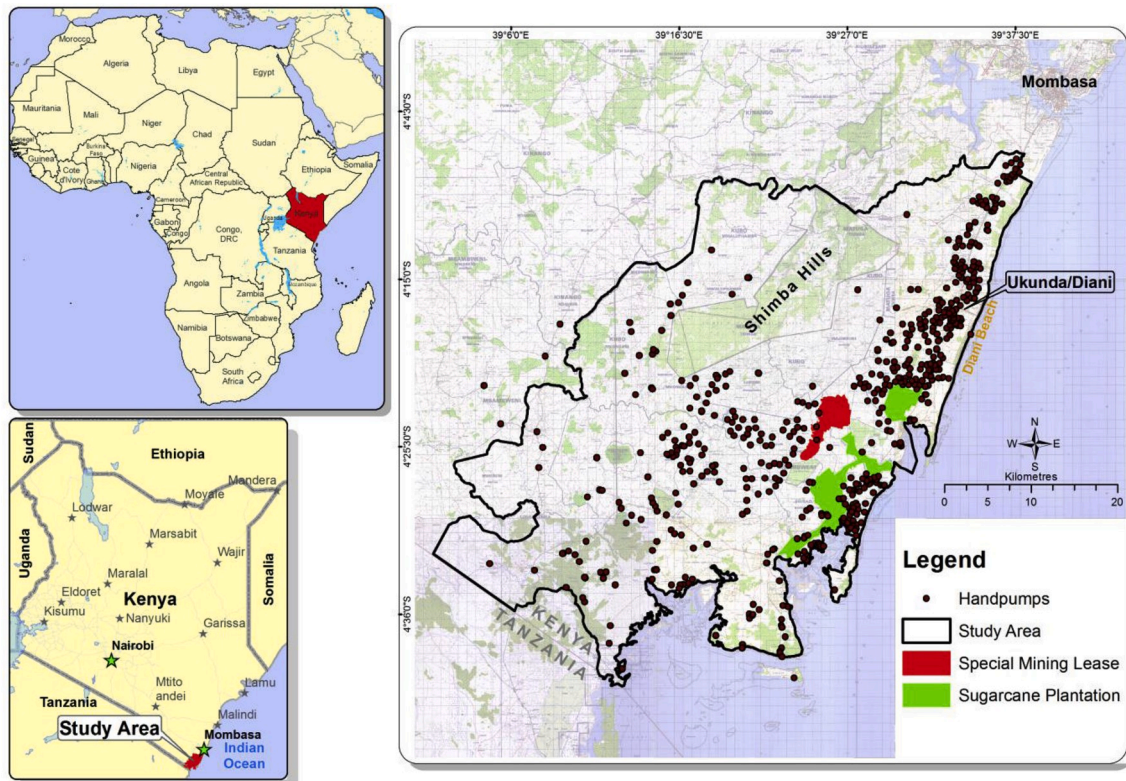


Fig. 2. Map of study area.



Ltd., is currently projected to export 6.5 m tonnes of titanium ore by 2028 from Likoni port, some 30 km north of the mine site. Scattered around the mine site and sugarcane plantation are around 300 handpumps (generally 5 m–30 m in depth) providing drinking water to communities, schools and health centres.

### 3.2. Sampling frame

In August 2013, a waterpoint survey identified 574 handpumps (all Afridevs) of which 45% were non-functioning (Foster and Hope, 2016). A sample of 531 handpump locations was used as a sampling frame for a household survey in 2013/14. A separate water quality assessment was conducted on the functioning handpumps documenting physical water quality parameters such as pH, electrical conductivity and temperature. GSM-enabled transmitters were installed on the 300 operational handpumps to transmit and record daily pumping to estimate water usage and functionality (Thomson, Hope and Foster, 2012a). At each of the 531 handpumps, a stratified random sample of households which currently or previously used the handpump was produced, yielding 3500 survey participants that reduced to 3349 after data cleaning. A pilot survey was conducted with 19 enumerators recruited from communities across the study area who administered the survey in local languages (Swahili, 53.8%; Digo, 42.6%; Duruma, 2.1%; other, 1.5%). The main survey entailed a range of themes including demographic, socio-economic status of household (here including livelihood, concerns and subjective welfare), household health status, water sources, waterpoint management, water payments, water resources management, governance and political engagement. All the households surveyed were geo-referenced for mapping purposes.

Ethical permission to conduct this survey was provided by the University of Oxford's Central University Research Ethics Committee and research permission granted by the Government of Kenya's National Council of Science and Technology, Kenya (NCST/RCD/17/013/132, September 2013). All interviews were voluntary with informed consent procedures observed in the local language. Data have been anonymised and stored in encrypted files.

### 3.3. Data analysis

The household survey identified six major water sources used by households, these included; handpumps ( $n = 2126$ ), protected wells ( $n = 94$ ), boreholes with submersible pumps ( $n = 170$ ), piped sources ( $n = 331$ ), unprotected wells ( $n = 339$ ) and surface water sources ( $n = 231$ ). This analysis largely focused on the handpumps (groundwater sources) as they were the dominant water supply and we had estimates of volumetric abstraction from the GSM-enabled transmitters. A multidimensional welfare index was constructed using 29 indicators drawn from household composition, dwelling characteristics, asset ownership, sanitation and health, and drinking water variables. The weights used to compute the welfare index were generated from principal component analysis (Falkingham and Namazie, 2002; Filmer and Pritchett, 2001; Gwatkin et al., 2007; Vyas and Kumaranayake, 2006). The welfare index ranged between 0 and 1 where households scoring higher values were relatively well off compared to those scoring values close to zero. We divided the welfare index into five levels with equal range, i.e., welfare index ranging from 0 to 0.2 (Q1), 0.2 to 0.4 (Q2), 0.4 to 0.6 (Q3), 0.6 to 0.8 (Q4) and 0.8 to 1.0 (Q5). Each level comprised of a wealth group which we refer to as 'welfare quintile 1' to 'welfare quintile 5'. Households were then categorized into the five wealth groups depending on their welfare index scores to identify household distribution across 'welfare space'. This classification was used to reflect the dimensions of welfare space and associated share of households falling into each welfare quintile.

We further categorized the households into three groups by a simplified typology of three economic geographies in the area: (1) the southern, coastal belt with people living within a 5 km strip of the sea

(52% of the sample), whose main economic activity is fishing; (2) inland and more remote areas below the Shimba Hills and away from the coastal margin (38% of the sample), where the main economic activity is farming; and (3) the small town of Ukunda/Diani which largely serves the tourism industry along Diani beach (10% of the sample). A spatial welfare map was developed using Kolmogorov Wiener prediction method (also known as kriging) to provide spatial welfare predictions (Webster and Oliver, 2007). This map was later used to evaluate spatial welfare patterns around waterpoints and estimate the generalised welfare indexes of households associated with each handpump through resampling the spatial welfare patterns to 1 km grid cells using the bilinear interpolation technique in geo-statistics. The result from this process was the associated mean welfare index for every handpump based on a 1 km spatial resolution. The spatial resolution of 1 km was chosen taking into consideration the computed distance at which spatial autocorrelation becomes more pronounced, this was determined to be 7.6 km from the Moran's I statistic (Legendre and Legendre, 1998; Overmars et al., 2003; Getis, 2007). Given that the spatial resolution ought to be smaller than 7.6 km while at the same time large enough to ensure that majority of the cells had at least one household represented, a 1 km spatial resolution was selected.

Monthly data on volumetric usage of groundwater from each handpump was obtained from the waterpoint data transmitters which were installed on 300 handpumps while electrical conductivity data was collected using handheld EC/pH/temperature testers. The electrical conductivity variable was re-defined as binary with cut off threshold value set at 1500  $\mu\text{S}/\text{cm}$ . This threshold value was based on the Drinking Water Standards that recommend a threshold value of 1500  $\mu\text{S}/\text{cm}$  (WHO, 2011). Data on static groundwater depth level (referred to as water rest level not influenced by abstraction or recharge) was obtained from the drilling records kept at the County government's offices. The records were part of a major Swedish Development Agency (Sida) and the World Bank drilling programme in the mid and late 1980s which was one of the first installations of Afridev handpumps in Africa. Records included data on location (name), borehole depth, casing diameter, static (rest) water level, temperature, EC and yield (liters per hour). We then had to match these handpumps records to our own records using a number of parameters like name of borehole, location on map, administrative unit, and borehole completion record numbers. We matched about 333 handpumps which had static groundwater depth level data to our database. Data on groundwater productive uses such as livestock watering and crop irrigation as well as information on whether the households had access to sufficient, affordable, reliable, safe, good quality water (in terms of perceived taste) and distance to the groundwater source was obtained from the 2014 household socio-economic survey data.

## 4. Results

### 4.1. Descriptive statistics

Table 1 below shows the fraction of households associated with different variables and disaggregated by sex of respondent and household head. Examining household drinking water profiles reveals handpumps are used for drinking water by two in three households with one in five households also using handpumps for livestock watering. Household perceptions of the satisfaction with drinking water services declines from physical proximity (58%) to water quality (taste at 40%, safety at 39%), and from reliability (31%) to affordability (12%). Groundwater from handpumps was six times more likely to provide households with drinking water compared to piped water networks though one in four households stated that groundwater was the only water supply. About one in ten households depended on piped water sources which reflected the limited infrastructure found in Ukunda/Diani and Tiwi (North of Ukunda) areas (Fig. 2). We found no differences in comparing scores of the female-headed households with the

**Table 1**  
Profile of groundwater use and drinking water services by disaggregated household data (n = 3349).

	Explanatory Variables	All Households (n = 3291)	By sex of respondent		By female-headed household (n = 516)
			Male (n = 1101)	Female (n = 2190)	
			Mean	Mean	
Main drinking water source	Handpump	0.65	0.63	0.65	0.67
	Piped	0.10	0.10	0.10	0.08
	Protected well	0.03	0.03	0.03	0.03
	Submersible pump	0.05	0.05	0.05	0.03
	Surface water	0.07	0.09	0.06	0.09
	Unprotected well	0.10	0.11	0.10	0.10
	Use handpump for Irrigation	0.05	0.06	0.05	0.07
	Use handpump for Livestock	0.17	0.14	0.18	0.18
	Own Livestock	0.21	0.22	0.20	0.22
	Electrical Conductivity (<1500 µS/cm)	0.83	0.84	0.83	0.79
% of households stating drinking water is ...	Affordable	0.12	0.10	0.13	0.10
	Reliable	0.31	0.31	0.31	0.30
	Safe to drink	0.39	0.36	0.40	0.36
	Taste (good)	0.40	0.35	0.42	0.38
	Close (distance to water source)	0.58	0.52	0.61	0.60
	Groundwater is the only source	0.26	0.28	0.24	0.28

This table only shows the binary variables. Rounding means all totals may not sum to 100%. Female-headed households are defined by 'no male adult living in the household'.

wider sample (t-test, all values >0.10, not reported) despite the descriptive data indicating higher surface water use, greater dependency on groundwater and lower affordability score.

#### 4.2. Welfare distribution

The distribution of households, that depended on groundwater sources through handpumps, by the redefined welfare quintiles in the data analysis section approximated a normal distribution with a third of households in the fourth and fifth welfare quintiles while two in every five households were observed in the first and second welfare quintiles (Fig. 3a). The spatial welfare map identified the majority of higher welfare households located in the Ukunda/Diani area while another cluster was observed to reside inland and south of the Shimba Hills National Reserve in Lukore and Mangawani locations (Fig. 3b). Along the coastline but south of the Ukunda/Diani area were found households with lower welfare indexes.

#### 4.3. Groundwater and productive uses

Here, and following, we assess the intensity of welfare in each welfare quintile by counting the sub-sample of households that reported using, for example, groundwater for livestock watering in each welfare quintile as the numerator divided by the total number of households using groundwater sources which are handpumps (n = 2125) in each welfare quintile. The results show that the use of groundwater for livestock watering varied distinctively across the welfare quintiles. The top two welfare quintiles had almost a third of the households using groundwater for livestock watering (Fig. 4a). In contrast, the bottom two welfare quintiles were half as likely as the top two quintiles to water their livestock using groundwater albeit about a third of the households in these welfare quintiles owned livestock. While fewer households in Kwale County chose to irrigate from groundwater (5%), we observed variability in irrigation practices across the welfare quintiles with the top welfare quintiles being almost twice as likely to irrigate compared to the bottom two welfare quintiles (Fig. 4b). As such, groundwater for livestock watering appeared a potential strategy to benefit lower welfare groups though it will benefit few, about one in ten households in the bottom quintile.

#### 4.4. Groundwater depth and welfare

Results indicate increasing welfare is associated with increasing depth to groundwater (Fig. 5). The data do not provide a means to determine causality and it is plausible that higher welfare households have been able to invest in deeper and more secure groundwater sources. Other confound factors maybe geography related in that households living further inland practice farming and tend to be wealthier but the groundwater sources are deeper, deeper boreholes have a higher failure rate which may impose a higher financial burden on the less wealthier households depending on the deeper boreholes and vice versa. The median depth provided a linear profile of greater welfare with deeper boreholes. A bivariate and ahistorical correlation test suggests there is a significant relationship ( $r = 0.542$ ,  $n = 332$ ,  $p < 0.001$ ). Despite the uncertainty over the historical or political processes, the data showed higher welfare households gained access to deeper boreholes though how this process occurred is not known. What is more certain is that lowest welfare group rely on shallower groundwater (6 m–14 m deep) which may be more vulnerable to natural or human-related contamination.

#### 4.5. Groundwater and drinking water services

Access to affordable, safe and reliable drinking water roughly doubled if a household was in the top rather than lowest welfare quintile; this relationship did not apply to proximity (Fig. 6). We observed a gradual increase of the fraction of households who found groundwater sources affordable in each welfare quintile. Households in the top welfare quintiles were twice as likely to have access to affordable groundwater sources. A similar pattern held for reliability, safety but not proximity where the difference between low and high welfare access was relatively minimal, and overall higher in terms of access across the five categories evaluated.

Electrical conductivity (EC) was lower than the recommended threshold for the majority of households across all the welfare quintiles (Fig. 7a). However, the perception of taste suggested about three in every five households had access to drinking water sources with unsatisfactory taste (Fig. 7b). About one in every five households in the first to fourth welfare quintile depended on groundwater sources as the only source for drinking water while the top welfare group had about nine in ten households depending on other sources of water (Fig. 7c). Given that the denominator was the number of households using

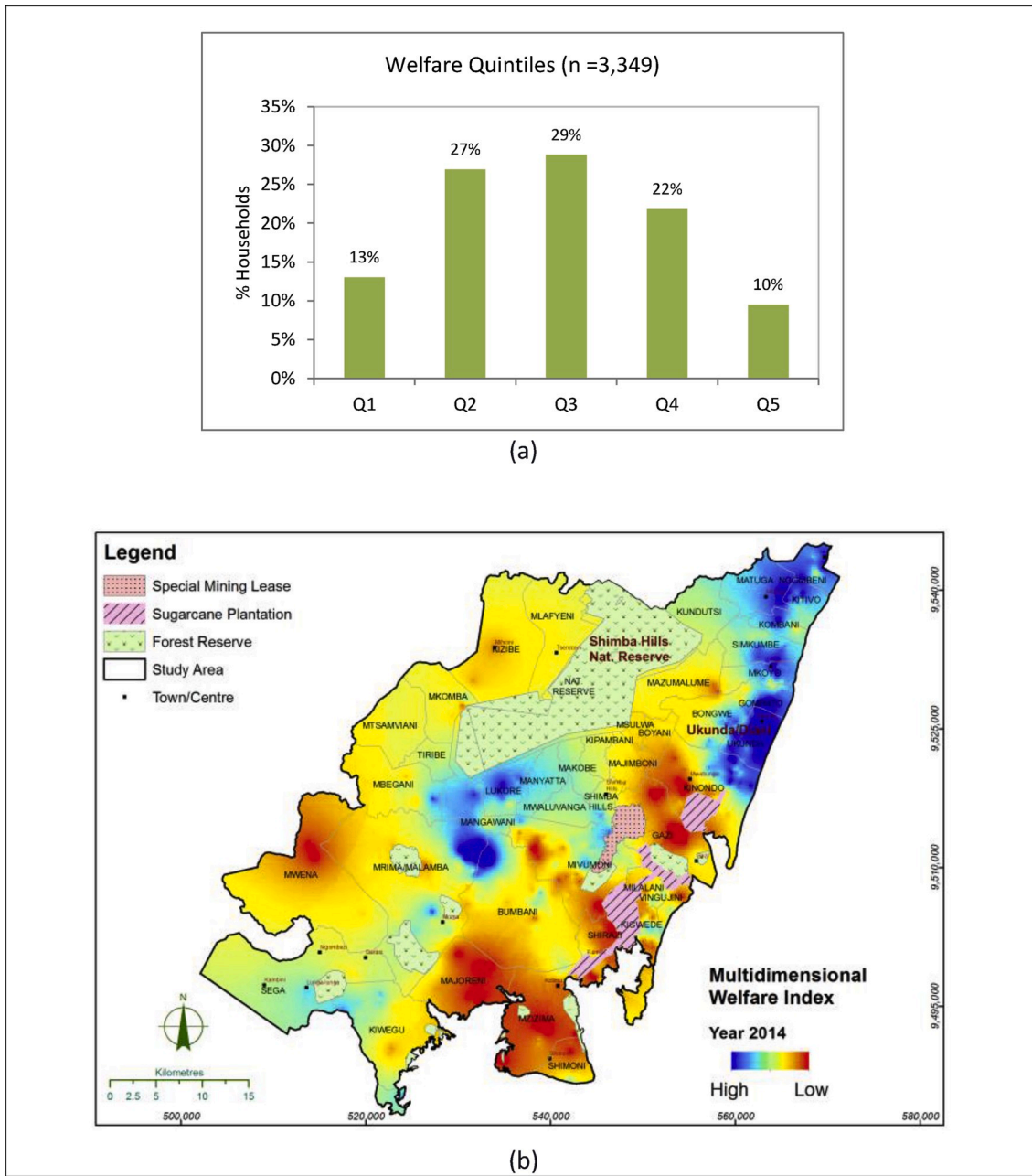


Fig. 3. (a) Welfare Quintiles (b) spatial representation of welfare in 2014.

groundwater sources extracted via a handpump, the intensity of handpump usage was expected to mimic the welfare profile across all the quintiles. Handpump usage was therefore observed to be higher among households in the third welfare quintile, 29%, while one in ten households used handpumps as the main drinking water sources in the bottom and top welfare quintile (Fig. 7d).

4.6. Groundwater usage and welfare

Groundwater usage was assessed using estimated volumetric data from the water data transmitters. We plotted usage against welfare quintiles which were estimated from the re-sampled spatial welfare maps at 1 km spatial resolution. Fig. 8 shows a box plot of monthly total volume of groundwater abstracted from the handpumps and welfare quintiles for 2014. There was variation on monthly volume abstracted across all the welfare quintiles with a median value of around 50,000

litres per month with the upper quartile range for the second and third welfare quintiles around three times the median.

Mapping abstraction rates from the handpumps revealed no clear pattern (Fig. 9). Further analysis may later consider seasonal patterns to understand peak demand and also the issue of attribution between drinking water and livestock water demands over space and time.

4.7. Estimating the share of groundwater towards household welfare

In theory, the share of a household’s welfare to groundwater may be modelled by regressing a range of groundwater-related variables independent to the welfare index comprising here of common consumables such as tea, flour, cooking oil, soap and dwelling condition by floor, wall and roof. Available data focus on the unique availability of handpump usage, groundwater quality and groundwater usage. We acknowledge the absence of broader and widely recognized indicators of welfare,

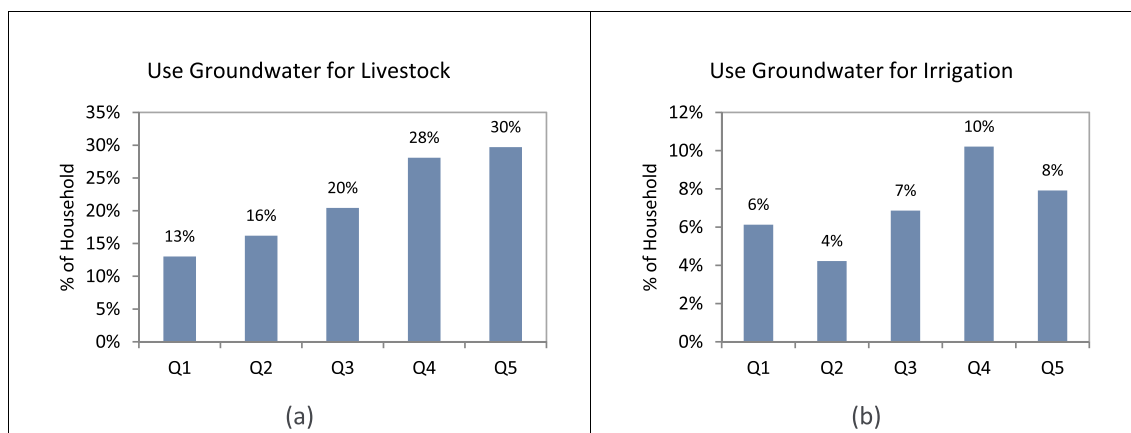


Fig. 4. Share of households in welfare quintiles using groundwater for (a) livestock watering and (b) irrigation.

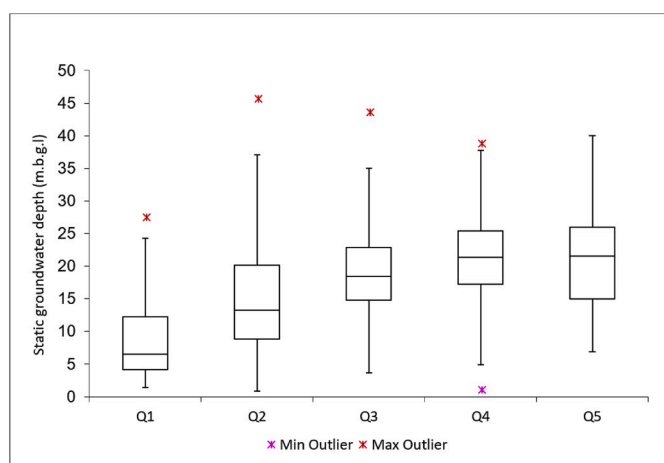


Fig. 5. Box plot of groundwater table depth vs welfare quintiles ( $r = 0.542$ ,  $n = 332$ ,  $p < 0.001$ ).

including education, health, employment and qualitative measures of equality and capabilities. The analytical challenge of reconciling appropriate temporal and scalar dimensions by broader welfare indicators across individual, household and community limit the utility of a more ambitious but less tractable estimation procedure of welfare. Here, we tackle a more constrained and simple relationship with data sources of suitable temporal and spatial coherence. The estimation is multidimensional by design and a multivariable regression (an extension of simple linear regression) procedure is chosen. The model reported in Table 2 provides a general estimation for all households (Model I), male respondents (Model II), female respondents (Model III) and female-headed households (Model IV) with a statistically significant fit ( $F = 32.625$ ,  $p < 0.001$ ).

The results indicate about 17 per cent of the variation in a households' welfare was explained by the groundwater covariates. Running the model for disaggregated samples yielded similar results for female headed households (19%), male respondents (20%) and female respondents (17%). All the models were significant ( $p < 0.01$ ).

From Model I (all households), all explanatory variables except 'affordability' and 'only source' were significant. Positive and significant include productive groundwater uses along with water quality (EC) and volumetric usage. Shallower groundwater and living in coastal or inland zones were negative (associated with low welfare) and significant compared to those living in Ukunda/Diani area.

For Models II and III, we observed similarities for drinking water variables but a divergence for productive uses and the water rest level.

Female respondents differed to male respondents in positive and significant coefficients for productive uses compared to male respondents who record positive but non-significant estimates.

In Model IV, the female-headed households' positive and significant coefficients to welfare are perceived water safety (not EC) and volumetric usage with productive uses of groundwater large and significant predictors of welfare. Shallower groundwater differed from female respondents but accorded with the full sample and male respondents as being negative and significant.

## 5. Discussion

Four findings emerge from the results to contribute to the wider scholarship around groundwater and welfare in rural Africa and the global drive to achieve 'safely-managed drinking water' under the Sustainable Development Goals' target 6.1 (UNICEF/WHO, 2017). First, groundwater depth is related with welfare in two overlapping domains: (a) increasing welfare is strongly associated with deeper groundwater usage, and (b) shallower groundwater dependency has a negative and significant relationship with household welfare. Second, productive uses of groundwater is a positive, significant and comparable determinant of household welfare alongside drinking water services. Third, across four drinking water services' indicators only proximity to a handpump is welfare-neutral with evidence that lower welfare groups have less affordable, safe or reliable drinking water services. Fourth, gendered-differences emerge in women's different use of groundwater to men with equity implications as revealed by the sub-sample of female-headed households.

An intuitive relationship emerges between increasing welfare and access to deeper groundwater supplies. The likelihood that higher welfare groups all stumble upon deeper groundwater as lower groundwater users opt for shallower groundwater seems implausible. While there is no evidence of the causality or socio-political or economic processes that result in this finding, it is consistent with strands of literature on 'elite capture' in relation to rural water infrastructure (Bardhan and Mookherjee, 2006; Geen et al., 2016) and the development economics' hypothesis of 'poverty traps' (Barrett and Swallow, 2006; Carter and Barrett, 2006; Banerjee and Duflo, 2011; Barrett and Carter, 2013). Evidence here suggest ancillary infrastructure to support drinking and productive uses of groundwater need to focus on drilling deeper and resilient boreholes to buffer populations during droughts and dry seasons. This builds on recent work on sustainable groundwater development policies that supports standardization of borehole drilling and self-supply with emphasis on institutional practices taking the lead on regulating stakeholders to adopt sustainable groundwater development approaches that will impact livelihoods positively while improving rural water services delivery (RWSN, 2009a, 2010).

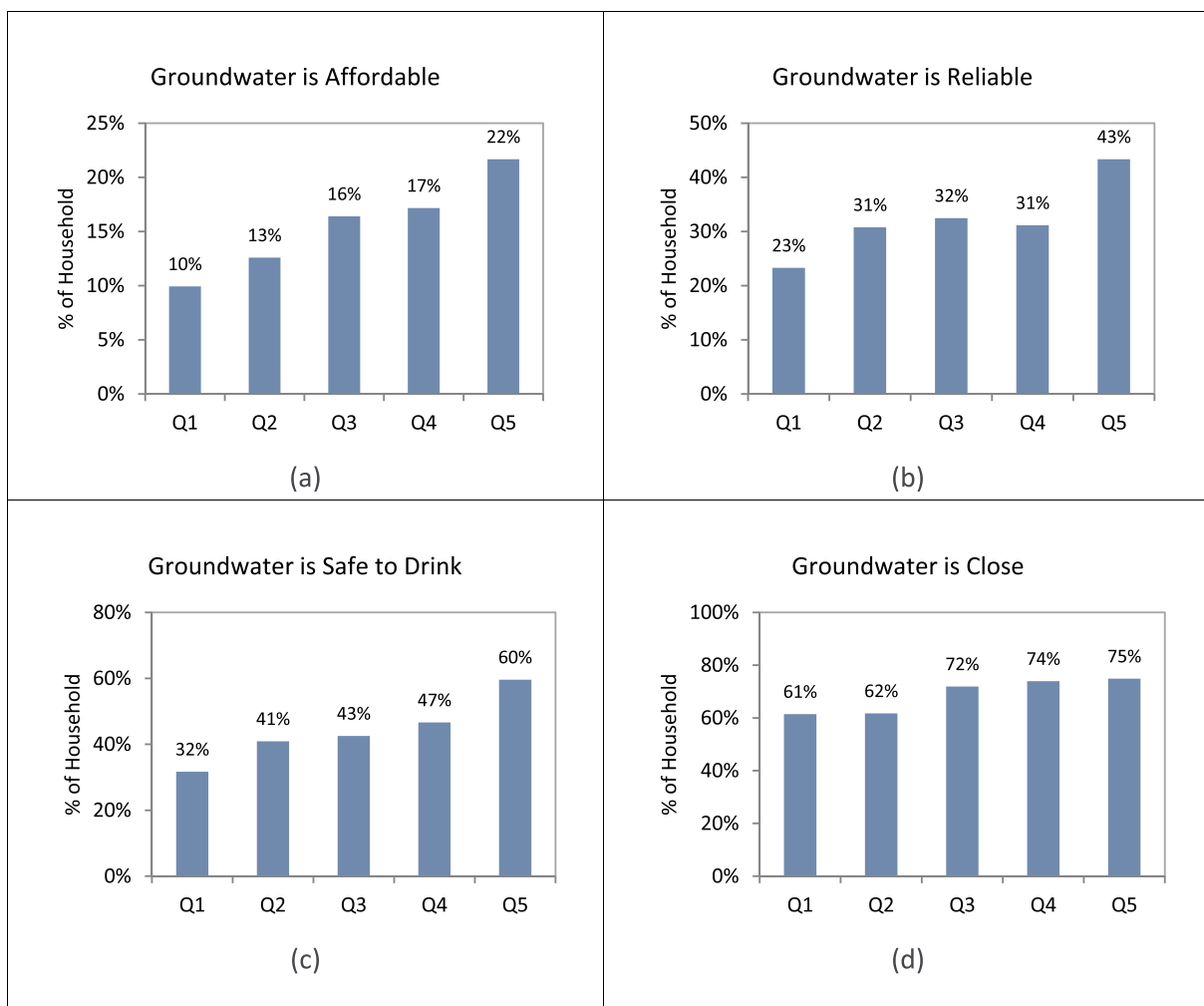


Fig. 6. Drinking Water Services vs Welfare Quintiles.

Multiple use systems for rural water have been documented in many countries recognizing that both productive water infrastructure, such as irrigation systems, or drinking water systems, such as piped networks or pumped systems, are commonly used by both groups (Meinzen-Dick and Van Der Hoek, 2001; Renwick, 2001; Koppen et al., 2006; Smits et al., 2010). Often dubbed as the ‘water pays for water’ hypothesis the approach has gained salience from the potential financial sustainability for productive uses to increase both the value and financial resources to manage the system, though the literature shows limited evidence of this in practice. Wider evidence points to the potential conflict over limited water during times of drought when waterpoints may be heavily over-subscribed (Thomson et al., 2019). While these conditions rarely manifest in our study area, a simplistic reading would belie the potential challenges as well as opportunities from multiple water uses. The findings do underline the positive relationship between livestock watering and small-scale irrigation with welfare, particularly for women. While irrigation from groundwater is extremely limited in both potential yield from handpumps (circa 1 m<sup>3</sup> per hour) and current practices (5% of sample households), livestock is more widespread (21%) with widespread use of handpumps for watering at some point during the year. Again, women seem to be engaged in, or more familiar, with this activity than men. As a coefficient in household welfare, livestock watering from groundwater is high, particularly for female-headed households who represent a social group of concern.

The welfare composition of satisfaction with current drinking water services reveals a regressive pattern of higher welfare households with

affordable, safe and reliable water. Only proximity to the handpump is welfare-neutral in the sense that there is relatively limited difference between welfare quintiles and that this indicator is the highest of the four in terms of coverage. These findings broadly accord with the disaggregated data analysis by the global Joint Monitoring Program (WHO and UNICEF, 2017) which highlight similar inequalities in global reporting. Our findings imply that while implementation activities are doing relatively well in locating waterpoints near everyone, the services delivered are unsatisfactory. In many ways this is symptomatic of the Millennium Development Goal (MDG) era of infrastructure provision without ancillary investments in institutions to manage, maintain and regulate services in rural areas. While the data may be read in different ways it would be consistent to think of unaffordable water leading to lower welfare groups using less safe and potentially less reliable sources. The increasing recognition that universal drinking water security may not be consistent with financial sustainability is emerging as a defining challenge of the Sustainable Development Goals where the ambition for safely managed drinking water requires monitoring of services with disaggregated data of vulnerable populations to help identify and inform improved policy and practice (Thomson and Koehler, 2016). The implication for future policy and practice is that investments in safely managed drinking water require greater institutional oversight and regulation if the benefits are to be shared by lower welfare groups.

Gendered inequalities are an increasingly key component of national and global measuring distributional impacts of services for the poor. The well-rehearsed role of African women in rural water management and



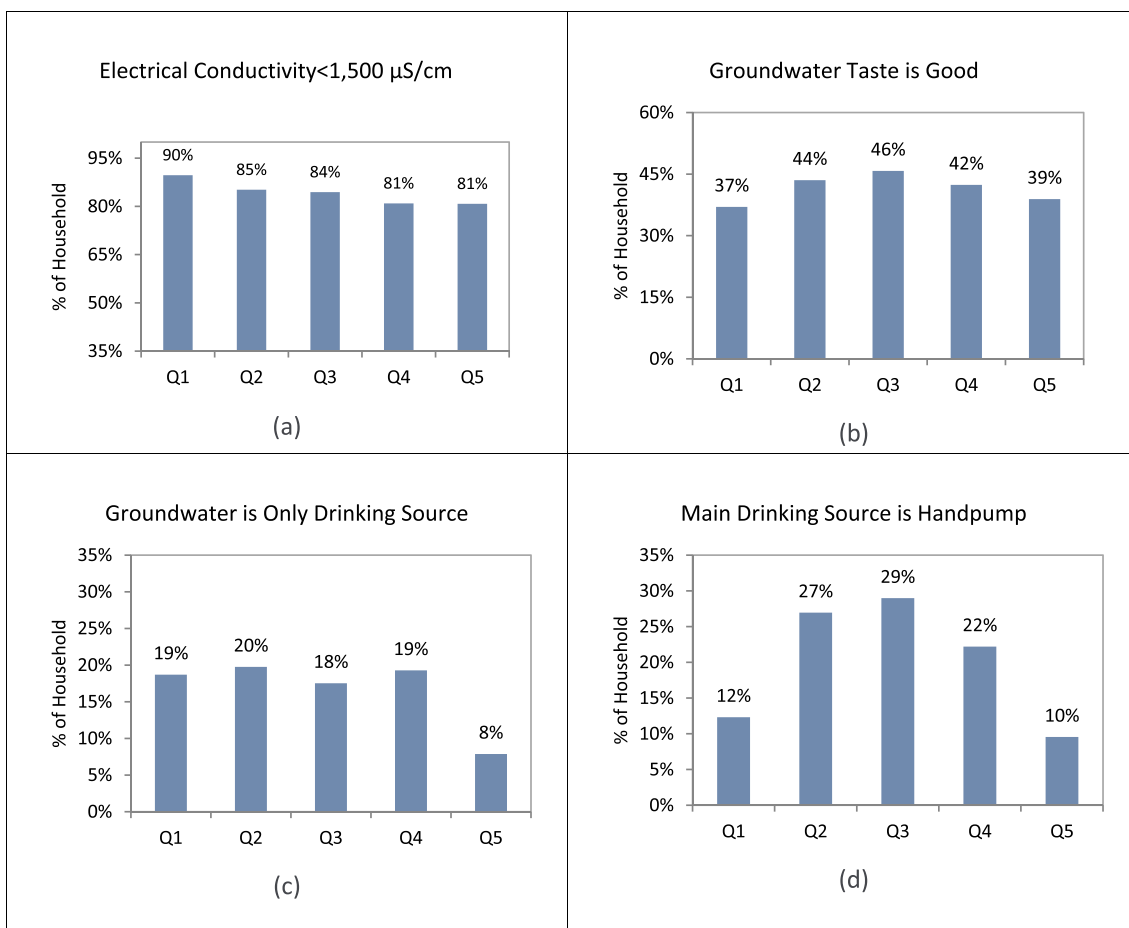


Fig. 7. Groundwater quality and dependency by welfare quintiles.

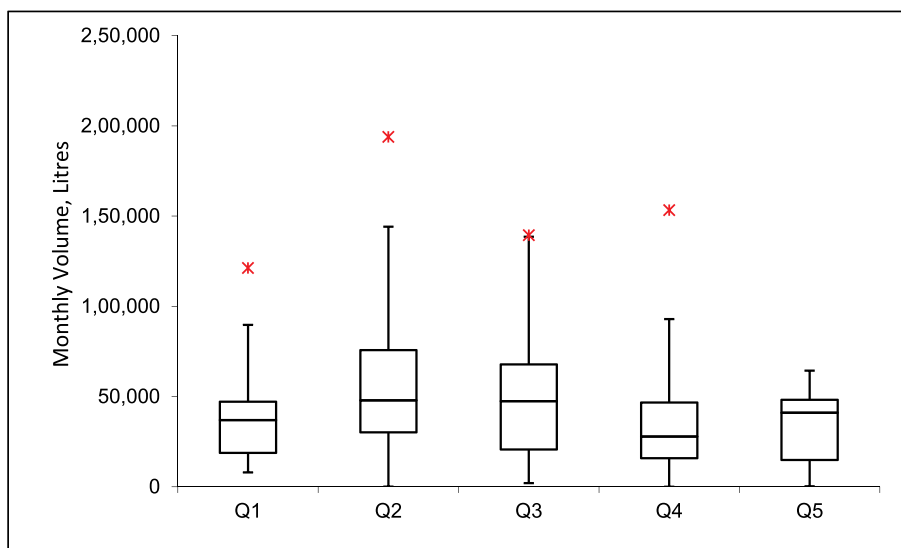


Fig. 8. Groundwater dependency and Welfare.

collection (Thompson et al., 2001; Hope, 2006) is reinforced by our findings with a concern on the potential marginalisation of female-headed households. It is noteworthy that perceived water safety is the only service indicator of significance to female headed households' welfare of the four drinking water indicators. While proximity and reliability are positive they are not significant for welfare suggesting

a unique and singular prioritization compared to other households. Equally, the significance of productive uses of groundwater for household welfare is noted indicating potentially welfare-enhancing measures to support women who may be situated in inland areas where farming systems are more prominent than fishery-based systems along the coast. The social practices which moderate and reproduce these outcomes, in

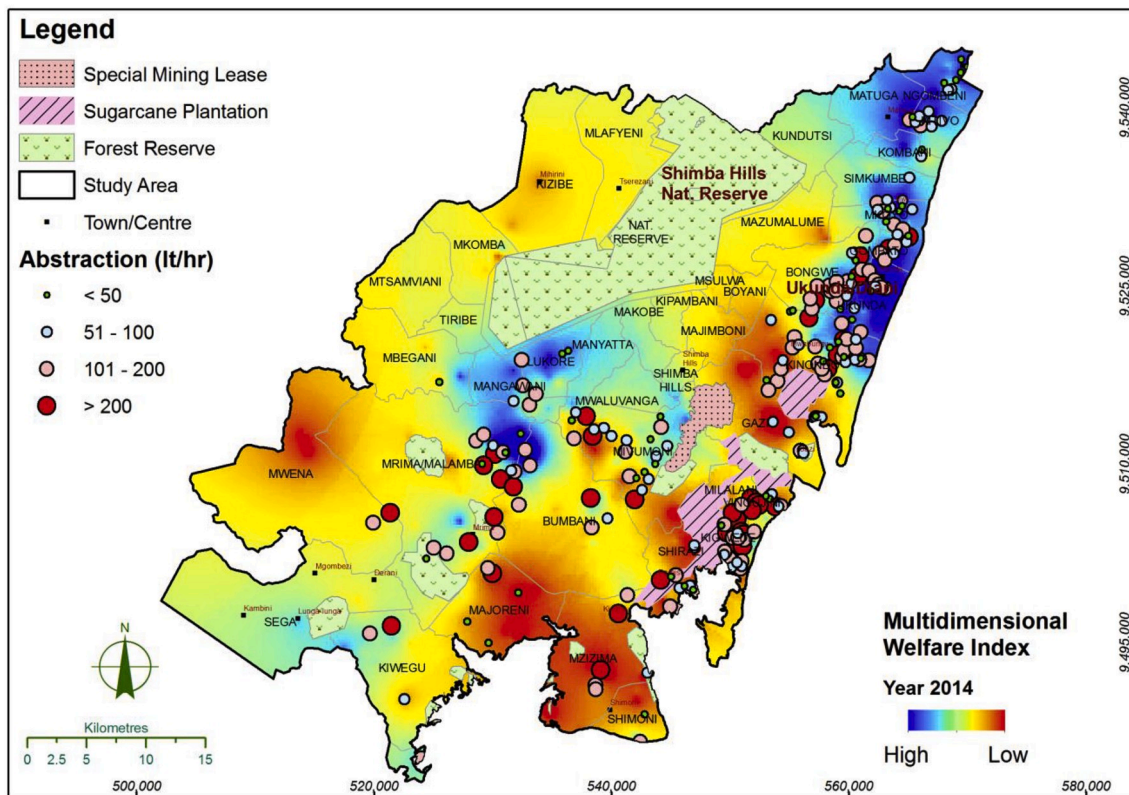


Fig. 9. Groundwater abstraction by handpumps and welfare in 2014.

Table 2  
Multivariable regression of household welfare on groundwater usage and dependency.

	Explanatory Variables	Model I All Households (n = 2007)		Model II Male Respondents (n = 653)		Model III Female Respondents (n = 1353)		Model IV Female Headed (n = 322)	
		Coeff.	t-value	Coeff.	t-value	Coeff.	t-value	Coeff.	t-value
Safely managed drinking water	(Constant)	0.453	14.126	0.422	8.163	0.465	11.325	0.333	3.769
	Affordable	0.017	1.265	0.032	1.342	0.011	0.667	0.019	0.534
	Safe (to drink)	0.039***	4.129	0.046***	2.797	0.039***	3.340	0.042*	1.719
	Reliable	0.033***	3.329	0.048***	2.828	0.029**	2.358	0.038	1.461
	Close (distance to water source)	0.053***	5.031	0.079***	4.342	0.043***	3.268	0.026	0.951
Productive Uses	Groundwater only source	-0.003	-0.261	0.015	0.708	-0.013	-0.870	-0.006	-0.193
	Irrigation	0.056***	2.940	0.048	1.587	0.057**	2.293	0.089**	2.044
	Livestock	0.047***	3.982	0.029	1.306	0.056***	3.984	0.079***	2.584
Usage	household reported Volume collected per day	0.001***	9.582	0.001***	6.808	0.001***	6.741	0.001***	4.494
Household Location (Reference location is Ukunda)	Coastal	-0.072***	-4.131	-0.081***	-2.587	-0.067***	-3.206	-0.018	-0.335
	Inland	-0.054***	-2.995	-0.053*	-1.676	-0.053**	-2.462	0.021	0.385
Water rest level of boreholes (Reference depth is > 21.9 m)	depth between 0 and 3.8 m	-0.146***	-4.637	-0.099*	-1.771	-0.164***	-4.251	-0.160*	-1.686
	depth between 3.8 and 7.6 m	-0.173***	-7.186	-0.171***	-4.394	-0.176***	-5.713	-0.172***	-2.964
	depth between 7.6 and 15 m	-0.097***	-4.714	-0.045	-1.422	-0.122***	-4.536	-0.082	-1.633
	depth between 15 and 17.3 m	-0.104***	-4.812	-0.127***	-3.757	-0.095***	-3.370	-0.111**	-2.053
	depth between 17.3 and 21.9 m	-0.017	-0.729	0.000	-0.004	-0.026	-0.880	-0.012	-0.227
Quality	Electrical Conductivity	0.000***	3.353	0.000*	1.746	0.000***	3.189	0.000	1.372
	R <sup>2</sup>	0.17		0.20		0.17		0.19	

\*Significant at 10%, \*\*Significant at 5%, \*\*\*Significant at 1%. Coeff. = Unstandardized Coefficients. Sample sizes changed due to missing data on either one of the explanatory variables.

rural settings, is not well-understood or adequately addressed by this research. However, the findings point to the need to better understand and recognize how groundwater provision to vulnerable groups may buffer, exclude or lift people out of poverty across welfare dimensions. The redistributive practices of access to groundwater, particularly in times of high demand or drought, is being documented in Kenya (Foster and Hope, 2016, 2017) underlining local control and management which may, or may not, be equitable and sustainable. What our findings

point to is the potential of groundwater to support productive practices but these largely accrue to higher welfare groups, potentially excluding others, due to the inability to purchase livestock or limited access to groundwater. While this is beyond the scope of this study, it is an important and weakly understood area for further analysis. This should go beyond simple binary gendered differences and be centred more broadly on processes of social accumulation, exclusion or loss, which better capture welfare transitions rather than imposing a politically, or

donor, favoured social group which potentially misses people of greater but hidden vulnerabilities (Narayan et al., 2000; Hulme and Shepherd, 2003; Mehta and Shah, 2003).

## 6. Study limitations

We acknowledge at least five limitations to the study. First, the observed groundwater use data from the waterpoint data transmitters provide a major but singular source of groundwater for households. Others include open, dug wells at the household or in the community, and some springs in the Shimba Hills (inland zone). We also emphasize that the 'litres per month' metric is a proxy and embeds livestock and minor agricultural water use; we have no plausible methodology to differentiating these variable uses of the handpump without heroic assumptions. Second, the usage provides unique hourly records over a year, but this period is not claimed to be representative of the variable climate but had an average rainfall of 1862 mm which is above the long term mean of 1300 mm. The application of the framework in a more arid environment will likely provide further insights in a more stressed hydrological system. Third, poverty is multidimensional with groundwater as one component of wider health, welfare and economic impacts for different user groups. Ancillary investments in health, education, energy or other sectors need to be examined to have a fuller understanding of the socio-ecological nature of the extent to which groundwater interacts with poverty pathways for different welfare groups over space and time. Fourth, we recognize the uneven nature of spatial resolution of the households across the study area, this has implications on the artificial nature of the welfare predictions although we control for this through geostatistical modelling creating heat maps. Fifth, the household survey was conducted between November 2013 and January 2014 which is during the short rains and beginning of the dry season in East Africa.

## 7. Conclusion

Unlocking the potential of groundwater for the poor has emerged as a global science and policy puzzle. Increasingly unpredictable climate futures, a data deficit in groundwater resource monitoring and unregulated growth in industrial, agricultural and municipal demand for water is placing groundwater under unprecedented stress. In the absence of a plausible theoretical understanding of groundwater and welfare interactions and impacts it is likely that vulnerable and marginalized groups may be excluded from potential developmental pathways as groundwater resources are captured by competing and more powerful users. In coastal Kenya we find evidence that the conceptual framing of groundwater and welfare helps understand part of this dynamic and context-specific puzzle. Welfare-enhancing approaches emerge both in terms of the type and depth of groundwater infrastructure with different domestic and productive uses of groundwater with alternative welfare outcomes for different social groups. The contribution of groundwater to household welfare represents a minor but important component worthy of greater political action and oversight. With advances in groundwater monitoring systems, new streams of data can be marshalled with historical sources to close information asymmetry gaps and guide political action to support welfare-enhancing interventions which work for the poor and support sustainable groundwater management.

## Acknowledgments

This research was supported by Base Titanium, NERC, ESRC and DFID via the Gro for Good project (UPGro Consortium Grant: NE/M008894/1), ESRC-DFID Joint Fund for Poverty Alleviation Research: New Mobile Citizens and Waterpoint Sustainability in Rural Africa - ES/J018120/1.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gsd.2019.100314>.

## References

- Alkire, S., Foster, J., 2011. Counting and multidimensional poverty measurement. *J. Public Econ.* 95 (7–8), 476–487. <https://doi.org/10.1016/j.jpubeco.2010.11.006>. Elsevier B.V.
- Baguma, A., et al., 2017. Groundwater and poverty in sub-Saharan Africa: a short investigation highlighting outstanding knowledge gaps. [https://opus.lib.uts.edu.au/bitstream/10453/104407/1/groundwater-and-poverty-report\\_0003.pdf](https://opus.lib.uts.edu.au/bitstream/10453/104407/1/groundwater-and-poverty-report_0003.pdf).
- Banerjee, A., Duflo, E., 2011. *Poor Economics: A Radical Rethinking of the Way to Fight Global Poverty*.
- Bardhan, P., Mookherjee, D., 2006. Pro-poor targeting and accountability of local governments in West Bengal. *J. Dev. Econ.* 79 (2), 303–327. <https://doi.org/10.1016/j.jdeveco.2006.01.004>.
- Barrett, C.B., Carter, M.R., 2013. The economics of poverty traps and persistent poverty: empirical and policy implications. *J. Dev. Stud.* 49 (7), 976–990. <https://doi.org/10.1080/00220388.2013.785527>.
- Barrett, C.B., Swallow, B.M., 2006. Fractal poverty traps. *World Dev.* 34 (1), 1–15. <https://doi.org/10.1016/j.worlddev.2005.06.008>.
- Bartram, J., et al., 2014. Global monitoring of water supply and sanitation: history, methods and future challenges. *Int. J. Environ. Res. Public Health* 11 (8), 8137–8165. <https://doi.org/10.3390/ijerph110808137>.
- Burke, J.J., Moench, M.H., 2000. *Groundwater and Society: Resources, Tensions and Opportunities*. Department. United Nations Department of Economic and Social Affairs, New York, NY.
- Calow, R.C., et al., 2010. Ground water security and drought in Africa: linking availability, access, and demand. *Gr. Water* 48 (2), 246–256. <https://doi.org/10.1111/j.1745-6584.2009.00558.x>.
- Carter, M.R., Barrett, C.B., 2006. The economics of poverty traps and persistent poverty: an asset-based approach. *J. Dev. Stud.* 42 (2), 178–199. <https://doi.org/10.1080/00220380500405261>.
- Comte, J.C., et al., 2016. Challenges in groundwater resource management in coastal aquifers of East Africa: investigations and lessons learnt in the Comoros Islands, Kenya and Tanzania. *J. Hydrol.: Reg. Stud.* <https://doi.org/10.1016/j.ejrh.2015.12.065>.
- Dasgupta, P., 2001. *Human Well-Being and the Natural Environment*. OUP Oxford (Oxford scholarship online). <https://books.google.co.uk/books?id=OuMTDAAAQBAJ>.
- Edmunds, W.M., Ahmed, K.M., Whitehead, P.G., 2015. A review of arsenic and its impacts in groundwater of the Ganges–Brahmaputra–Meghna delta, Bangladesh. *Environ. Sci. Process. Impacts* 17, 1032–1046. <https://doi.org/10.1039/c4em00673a>.
- Falkingham, J., Namazie, C., 2002. Measuring health and poverty: a review of approaches to identifying the poor. Available at: <http://eprints.soton.ac.uk/35016/>.
- Fan, Y., Li, H., Miguez-Macho, G., 2013. Global patterns of groundwater table depth. *Science* 339 (6122), 940–943. <https://doi.org/10.1126/science.1229881>.
- Filmer, D., Pritchett, L.H., 2001. Estimating wealth effects without expenditure data — or Tears: an application to educational enrollments in States of India. *Demography* 38 (1), 115–132. <https://doi.org/10.1353/dem.2001.0003>.
- Fisher, M.B., et al., 2015. Understanding handpump sustainability: determinants of rural water source functionality in the Greater Afram Plains region of Ghana. *Water Resour. Res.* 51 (10), 8431–8449. <https://doi.org/10.1002/2014WR016770>.
- Foster, T., 2013. Predictors of sustainability for community-managed handpumps in sub-Saharan Africa: evidence from Liberia, Sierra Leone, and Uganda. *Environ. Sci. Technol.* 47 (21), 12037–12046. <https://doi.org/10.1021/es402086n>.
- Foster, S., Garduño, H., 2013. Groundwater-resource governance: are governments and stakeholders responding to the challenge? *Hydrogeol. J.* 21 (2), 317–320. <https://doi.org/10.1007/s10040-012-0904-9>.
- Foster, T., Hope, R., 2016. A multi-decadal and social-ecological systems analysis of community waterpoint payment behaviours in rural Kenya. *Elsevier Ltd J. Rural Stud.* 61, 1–31. <https://doi.org/10.1017/CBO9781107415324.004>, 0.
- Foster, T., Hope, R., 2017. Evaluating waterpoint sustainability and access implications of revenue collection approaches in rural Kenya. *Water Resour. Res.* 53, 1–18. <https://doi.org/10.1002/2016WR019634>.
- Geen, A. van, et al., 2016. Inequitable allocation of deep community wells for reducing arsenic exposure in Bangladesh. *J. Water, Sanit. Hyg. Dev.* 6 (1), 142–150. <https://doi.org/10.2166/washdev.2015.115>.
- Getis, A., 2007. Reflections on spatial autocorrelation. *Reg. Sci. Urban Econ.* 37 (4), 491–496. <https://doi.org/10.1016/j.regsciurbeco.2007.04.005>.
- Giordano, M., 2009. Global groundwater? issues and solutions. *Annu. Rev. Environ. Resour.* 34 (June), 153–178. <https://doi.org/10.1146/annurev.enviro.030308.100251>.
- GOK, 1985. *Kwale District Environmental Assessment Report*. National Environmental Secretariat, Ministry of Environment and Natural Resources.
- Gwatkin, D., et al., 2007. *Socio-Economic Differences in Health, Nutrition, and Population* (April).
- Haller, L., Hutton, G., Bartram, J., 2007. Estimating the costs and health benefits of water and sanitation improvements at global level. *J. Water Health* 5 (4), 467–480. <https://doi.org/10.2166/wh.2007.008>.

- Hope, R.A., 2006. Evaluating water policy scenarios against the priorities of the rural poor. *World Dev.* 34 (1), 167–179. <https://doi.org/10.1016/j.worlddev.2005.07.014>.
- Hope, R., Rouse, M., 2013. Risks and responses to universal drinking water security. *Philos. Trans. R. Soc. A* (371) <https://doi.org/10.1098/rsta.2012.0417>.
- Hulme, D., Shepherd, A., 2003. Conceptualizing chronic poverty. *World Dev.* 31 (3), 403–423. [https://doi.org/10.1016/S0305-750X\(02\)00222-X](https://doi.org/10.1016/S0305-750X(02)00222-X).
- Hunter, P.R., MacDonald, A.M., Carter, R.C., 2010. Water supply and health. *PLoS Med.* 7 (11) <https://doi.org/10.1371/journal.pmed.1000361>.
- Hutchings, M.T., et al., 2012. In: Ross, N., Luu, P., Oakland, C.A. (Eds.), mWASH: Mobile Phone Applications for the Water, Sanitation, and Hygiene Sector. Available at: <https://www.pacinst.org/wp-content/uploads/2014/04/mwash.pdf>. (Accessed 29 January 2018).
- KNBS, 2006. Kenya Integrated Household Budget Survey (KIHBS) 2005/06. Government of Kenya: Kenya National Bureau of Statistics, Nairobi, Kenya.
- KNBS, 2010. The 2009 Kenya Population and Housing Census - Population Distribution by Age, Sex and Administrative Units. Government of Kenya: Kenya National Bureau of Statistics. Available at: [http://www.knbs.or.ke/index.php?option=com\\_phocadownload&view=category&id=109:population-and-housing-census-2009&Itemid=599](http://www.knbs.or.ke/index.php?option=com_phocadownload&view=category&id=109:population-and-housing-census-2009&Itemid=599).
- Koehler, J., Thomson, P., Hope, R., 2015. Pump-priming payments for sustainable water services in Rural Africa. *World Dev.* 74, 397–411. <https://doi.org/10.1016/j.worlddev.2015.05.020>. Elsevier Ltd.
- Koppen, B. van, Moriarty, P., Boelee, E., 2006. Multiple-Use Water Services to Advance the Millennium Development Goals. Colombo, Sri Lanka.
- Lapworth, D.J., et al., 2017. Urban groundwater quality in sub-Saharan Africa: current status and implications for water security and public health. *Hydrogeol. J.* 1–24. <https://doi.org/10.1007/s10040-016-1516-6>.
- Legendre, P., Legendre, L., 1998. Numerical Ecology. Second Eng. (Developments in Environmental Modelling), Second Eng. Elsevier Science B.V, Amsterdam. <https://doi.org/10.1017/CBO9781107415324.004>.
- Llamas, M., Martínez-Santos, P., 2005. Intensive groundwater use: silent revolution and potential source of social conflicts. Ed. *J. Water Resour.* 337–341. Available at: [http://ascelibrary.org/doi/pdf/10.1061/\(ASCE\)0733-9496\(2005\)131:5\(337\)](http://ascelibrary.org/doi/pdf/10.1061/(ASCE)0733-9496(2005)131:5(337)).
- Lyon, B., Vigaud, N., 2017. Unraveling East Africa's climate paradox. In: Wang, S.-Y.S., et al. (Eds.), *Climate Extremes: Patterns and Mechanisms*. John Wiley & Sons Inc, Hoboken, NJ, USA. <https://doi.org/10.1002/9781119068020.ch16>.
- Macarthur, J., 2015. Handpump Standardisation in Sub-saharan Africa. 2015–1. Rural Water Supply Network.
- Macdonald, A.M., et al., 2009. What impact will climate change have on rural groundwater supplies in Africa? *Hydrol. Sci. J. des Sci. Hydrol.* 54 (4). Available at: <http://www.tandfonline.com/doi/pdf/10.1623/hysj.54.4.690?needAccess=true>. (Accessed 20 January 2018).
- MacDonald, A.M., et al., 2012. Quantitative maps of groundwater resources in Africa. *Environ. Res. Lett.* 7 (2), 7. <https://doi.org/10.1088/1748-9326/7/2/024009>.
- Mehta, A.K., Shah, A., 2003. Chronic poverty in India: incidence, causes and policies. *World Dev.* 31 (3), 491–511. [https://doi.org/10.1016/S0305-750X\(02\)00212-7](https://doi.org/10.1016/S0305-750X(02)00212-7).
- Meinzen-Dick, R.S., Van Der Hoek, W., 2001. Multiple uses of water in irrigated areas. *Irrig. Drain. Syst.* 15 (2), 93–98. <https://doi.org/10.1023/A:1012931726639>.
- Moench, M., 2002. Water and the potential for social instability: livelihoods, migration and the building of society. *Nat. Resour. Forum* 26 (3), 195–204. <https://doi.org/10.1111/0165-0203.00021>.
- Molle, F., Mollinga, P., 2003. Water poverty indicators: conceptual problems and policy issues. *Water Policy* 5 (5–6), 529–544.
- Mukherji, A., 2005. Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. *Hydrogeol. J.* 14 (3), 392–406. <https://doi.org/10.1007/s10040-005-0007-y>.
- Mumma, A., et al., 2011. *Kenya Groundwater Governance, Water Papers*. Water Partnership Program. The World Bank, Washington D.C.
- Namara, R.E., et al., 2010. Agricultural water management and poverty linkages. *Agric. Water Manag.* 97, 520–527. <https://doi.org/10.1016/j.agwat.2009.05.007>.
- Narayan, D., et al., 2000. Can Anyone Hear Us? Voices from 47 Countries, World Development Bank. World Development Bank, Washington DC.
- Ostrom, E., 2009. A general framework for analyzing sustainability of social-ecological systems. *Science* (New York, N.Y.) 325 (5939), 419–422. <https://doi.org/10.1126/science.1172133>.
- Overmars, K.P., De Koning, G.H.J., Veldkamp, A., 2003. Spatial autocorrelation in multi-scale land use models. *Ecol. Model.* 164 (2–3), 257–270. [https://doi.org/10.1016/S0304-3800\(03\)00070-X](https://doi.org/10.1016/S0304-3800(03)00070-X).
- Prüss-Ustün, A., et al., 2014. Burden of disease from inadequate water, sanitation and hygiene in low- and middle-income settings: a retrospective analysis of data from 145 countries. *Trop. Med. Int. Health* 19 (8), 894–905. <https://doi.org/10.1111/tmi.12329>.
- Ravallion, M., 2011. On multidimensional indices of poverty. *J. Econ. Inequal.* 9 (2), 235–248. <https://doi.org/10.1007/s10888-011-9173-4>.
- Renwick, M.E., 2001. Valuing water in a multiple-use system: irrigated agriculture and reservoir fisheries. *Irrig. Drain. Syst.* 15 (2), 149–171. <https://doi.org/10.1023/A:1012950912505>.
- Rowell, D.P., et al., 2015. Reconciling past and future rainfall trends over East Africa. *J. Clim.* 28 (24), 9768–9788. <https://doi.org/10.1175/JCLI-D-15-0140.1>.
- RWSN, 2009. An introduction to self supply: putting the user first. Available at: [http://www.wsp.org/sites/wsp.org/files/publications/Af\\_SelfSupply\\_1.pdf](http://www.wsp.org/sites/wsp.org/files/publications/Af_SelfSupply_1.pdf). (Accessed 24 June 2018).
- RWSN, 2009. Handpump data, selected countries in sub-saharan Africa. Available at: [http://www.rural-water-supply.net/\\_resources/documents/default/203.pdf](http://www.rural-water-supply.net/_resources/documents/default/203.pdf). (Accessed 13 November 2018).
- RWSN, 2010. Code of practice for cost effective boreholes. Available at: [https://www.unicef.org/wash/files/Code\\_of\\_Practice\\_FINAL.pdf](https://www.unicef.org/wash/files/Code_of_Practice_FINAL.pdf). (Accessed 1 July 2018).
- Sen, A., 1976. Poverty: an ordinal approach to measurement. *Econometrica* 44 (2), 219–231. <https://doi.org/10.2307/1912718>.
- Smedley, P.L., Kinniburgh, D.G., 2013. In: Selinus, J.A., Alloway, O., Centeno, B., Finkelman, S., R B Fuge, R., Lindh, P.L. (Eds.), *Arsenic in Groundwater and the Environment*. Second, Essentials of Medical Geology, Second. Springer. Available at: [http://nora.nerc.ac.uk/id/eprint/502491/1/SmedleyMedicalGeology\\_Arsenic2013.pdf](http://nora.nerc.ac.uk/id/eprint/502491/1/SmedleyMedicalGeology_Arsenic2013.pdf). (Accessed 20 January 2018).
- Smits, S., et al., 2010. Multiple-use services as an alternative to rural water supply services: a characterisation of the approach. *Water Altern.* 3 (1), 102–121 doi: Cited By (since 1996) 1\nExport Date 9 July 2012\nSource Scopus.
- Taylor, R.G., et al., 2012. Evidence of the dependence of groundwater resources on extreme rainfall in East Africa. *Nat. Climate Change* 3 (4), 374–378. <https://doi.org/10.1038/nclimate1731>. Nature Publishing Group.
- Taylor, R.G., et al., 2013. Ground water and climate change. *Nat. Clim. Chang.* 3 (November), 322–329. <https://doi.org/10.1038/nclimate1744>.
- Thomas, E.A., 2017. Beyond broken pumps and promises: rethinking intent and impact in environmental health. *Elsevier Ltd Energy Res. Soc. Sci.* 25, 33–36. <https://doi.org/10.1016/j.erss.2016.12.006>, 2017.
- Thompson, J., et al., 2001. Drawers of Water II - 30 Years of Change in Domestic Water Use & Environmental Health in East Africa. International Institute for Environment and Development. International Institute for Environment and Development 3 Endsleigh Street, London WC1H 0DD, United Kingdom. <https://doi.org/10.3362/0262-8104.2003.039>.
- Thomson, Patrick, Koehler, Johanna, 2016. Performance-oriented monitoring for the water SDG – challenges, tensions and opportunities. In: *Aquatic Procedia*, vol. 6. Stockholm International Water Institute: Elsevier B.V., pp. 87–95. <https://doi.org/10.1016/j.aqpro.2016.06.010>
- Thomson, P., Hope, R., Foster, T., 2012. GSM-enabled remote monitoring of rural handpumps: a proof-of-concept study. *J. Hydroinf.* 14 (4), 829. <https://doi.org/10.2166/hydro.2012.183>.
- Thomson, P., Hope, R., Foster, T., 2012. Is silence golden? Of mobiles, monitoring, and rural water supplies. *Waterlines* 31 (4). <https://doi.org/10.3362/1756-3488.2012.031>.
- Thomson, P., et al., 2019. Rainfall and groundwater use in rural Kenya. *Sci. Total Environ.* 649, 722–730. <https://doi.org/10.1016/j.scitotenv.2018.08.330>.
- Trémolet, S., 2011. Identifying the potential for results-based financing for sanitation scaling up rural sanitation water and sanitation program: working paper. Available at: <https://www.issuelab.org/resources/14575/14575.pdf>. (Accessed 28 January 2018).
- Trémolet, S., Kolsky, P., Perez, E., 2010. Financing on-site sanitation for the poor A six country comparative review and analysis. Washington DC. Available at: [http://www.wsp.org/sites/wsp.org/files/publications/financing\\_analysis.pdf](http://www.wsp.org/sites/wsp.org/files/publications/financing_analysis.pdf). (Accessed 28 January 2018).
- Vyas, S., Kumaranayake, L., 2006. Constructing socio-economic status indices: how to use principal components analysis. *Health Policy Plan.* 21 (6), 459–468. <https://doi.org/10.1093/heapol/czl029>.
- Webster, R., Oliver, M.A., 2007. In: Senn, S., Scott, M., Barnett, V. (Eds.), *Geostatistics for Environmental Scientists Statistics in Practice*, second ed. John Wiley & Sons, Ltd, The Atrium, West Sussex, England.
- WHO, 2011. Guidelines for Drinking-Water Quality, fourth ed. WHO Press, World Health Organization, Geneva, Switzerland. [https://doi.org/10.1016/S1462-0758\(00\)00006-6](https://doi.org/10.1016/S1462-0758(00)00006-6). WHO chronicle. Fourth Ed.
- WHO and UNICEF, 2017. *Progress on Drinking Water, Sanitation and Hygiene: 2017 Update and SDG Baselines*. World Health Organization (WHO) and the United Nations Children's Fund (UNICEF), Geneva, 2017. Licence: CC BY-NC-SA 3.0 IGO.