Properties of shallow thin regolith aquifers in sub-Saharan Africa: a case study from northwest Ethiopia

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Abstract

Pumping tests have been successfully conducted on shallow hand-dug wells in two areas of northwest Ethiopia. The drawdown and recovery data were analysed separately providing consistent results confirming suitability of methods. Hydraulic conductivity estimates ranged from 0.2 to 6.4 m/d (mean = 2.3 m/d, median = 1.6 m/d) in the dry season and ranged from 2.8 to 22.3 m/d (mean = 9.7 m/d, median = 6.5 m/d) in the wet season when the water-table was higher. This difference indicates the importance of excavating wells as deeply as possible to increase the likelihood of intercepting more transmissive (water-bearing) layers. Specific yield estimations have a wider range (0.00001 to 0.32) and are more uncertain though the mean of 0.09 (median of 0.08) is reasonable. Estimates of well yield average 0.5 l/s though this increases to >1 l/s in the wet season; giving opmitism that small-scale irrigation is achievable, therefore, potentially reducing the reliance on rain fed agriculture. These results from weathered basalt regolith add to the sparse available data on shallow groundwater resources in sub-Saharan Africa. Consistency of results from nearby and distant wells indicates homogeneity of shallow aquifer materials giving a high transferability of findings to other areas of Ethiopia. This knowledge of aquifer properties facilitates modelling for estimating impacts of climate variability and change, and for developing sustainable management strategies for shallow groundwater resources.

Introduction

It is well discussed that the hydrogeology of sub-Saharan Africa is poorly understood, particularly regarding shallow groundwater resources (Calow et al., 2009, MacDonald et al., 2009, Robins et al., 2006), even though such resources sustain the majority of the continent's population (Lapworth et al., 2013). A knowledge of aquifer properties allows for calculations and models to assess groundwater recharge, abstraction potential, contamination risk, impacts of future climate variability, and management strategies. However, few data are available on shallow aquifer properties for this region (Bonsor et al., 2014).

The most useful shallow aquifer properties are; hydraulic conductivity (K) – the ease by which water moves through an aquifer, specific yield (S_y) – the volume of water that drains from the aquifer per unit surface area of aquifer per unit decline of the water table (the drainable porosity), and well yield – the rate at which water can be abstracted from a well.

As part of an ongoing project assessing the vulnerability of shallow aquifers in sub-Saharan Africa, pumping tests were first conducted during a field visit to Ethiopia in March/April 2015, timed to coincide with the end of the dry season and period of greatest water scarcity. Further testing was undertaken during a second field visit in October/November 2015 at the end of the wet season. In order to estimate hydraulic conductivity, specific yield and well yield, tests were conducted on hand-dug wells in two locations within the Amhara region (Figure 1). Both drawdown (the drop in water level within the well caused by pumping) and recovery (the increase in water level back to pre-test level following cessation of pumping) were monitored then analysed using alternative methods.

Testing Locations

Seven wells were tested within Dangila *woreda* (Figure 1), benefiting from and enhancing relationships established by a community-based monitoring programme which has been ongoing since March 2014 (Walker et al., 2016). A further well was tested in Robit-Bata *kebele*, 80 km northeast of Dangila *woreda*, close to the city of Bahir Dar.

All of the wells tested were located within weathered basalt regolith above variously massive, vesicular and/or fractured basalt. Tested wells ranged in depth from 3.55 to 10.09 metres below ground level (mbgl) with (often irregular) diameters of around a metre ($\pm$0.2 m). Wells are excavated by hand with picks and shovels until the solid geology is hit. Therefore, water column height is considered the saturated thickness of the aquifer and in the tested wells ranges from 0.54 to 3.85 m in the dry season and 1.99 to 6.34 m in the wet season. These ranges of well geometries and water depths are typical of hand-dug wells in the areas. Wells were selected to cover a range of topographies from floodplains, to valley slopes, to higher elevations, in an area of moderate relief within the Ethiopian Highlands.

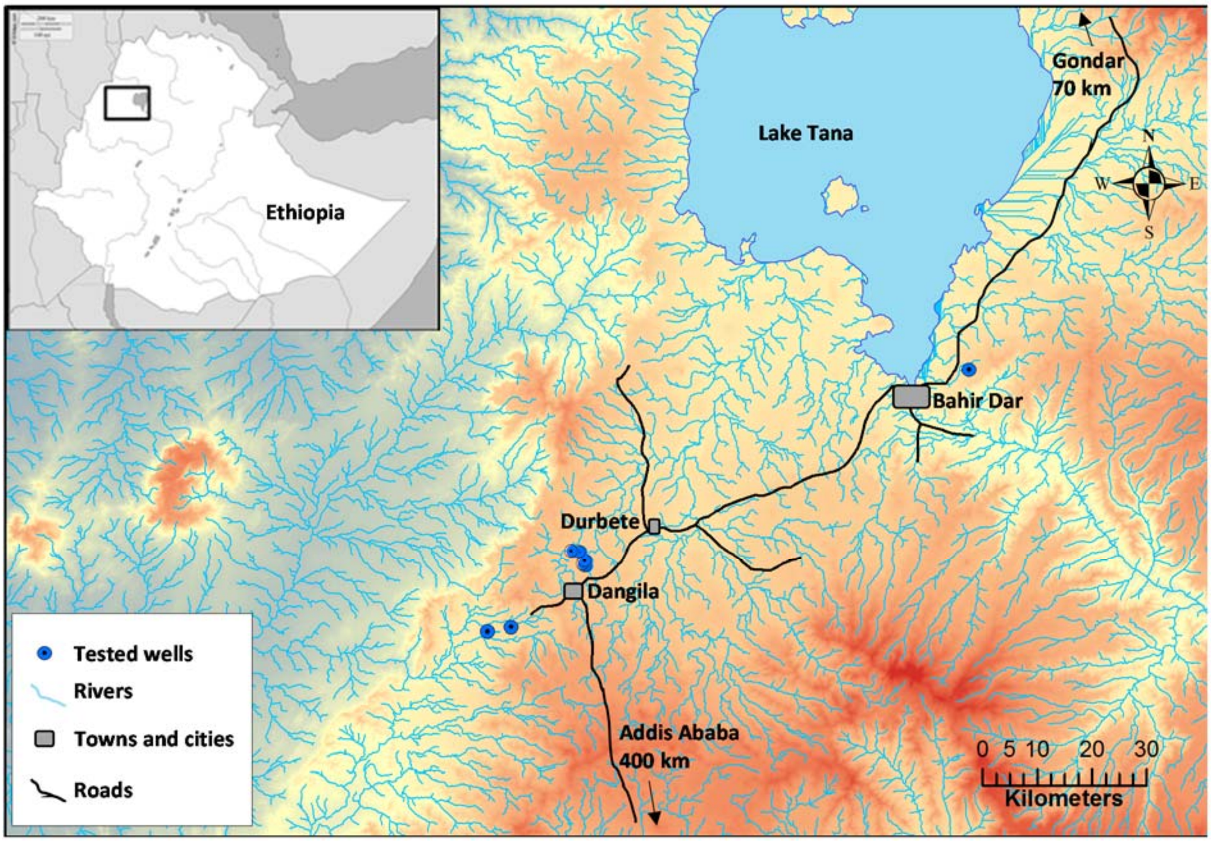

Figure 1. Geographical distribution of testing locations

Testing Methodology

Motor pumps were not available, therefore, water was removed from wells using manual methods. Water-lifting incorporated a rope and bucket; the bucket being a modified HDPE water container. At least two people were involved in water-lifting (Figure 2) which helped to maintain a largely constant discharge rate.

A pressure transducer measuring every two seconds was placed in the well prior to starting a test and water levels were also manually measured using a dip-meter. The volume of the emptying water container was measured in addition to well diameter and depth. The number of buckets abstracted per minute was monitored to calculate the pumping rate. The pumping rate varied between wells from 2 litres/minute to 15 litres/minute (with one exception) dependent on the size of the container and the depth to the water table; the smallest container and deepest water table giving the slowest pumping rate. The test in Robit-Bata *kebele* had a pumping rate of 30 litres/minute being the only tested well with a pulley and double bucket system which leads to much more efficient water lifting.

Water was abstracted until the well water column was reduced by at least 10 %. The necessary time to remove the entire well volume or to reach steady-state conditions with the equipment available would have been excessive and extremely labour-intensive. More importantly, given that the first field visit took place during the period of greatest water scarcity, it would have been unethical to attempt to reduce the water level in the wells to near empty. In order not to waste water, all containers that each household possessed were filled during pumping tests and further water was used for backyard irrigation and for watering livestock. The recovery of the water level was monitored with no additional abstraction.

Figure 2. Photographs of pumping tests

Test Analysis

Selecting analysis methods was not straightforward. The shallow aquifer here may be unconfined, however, a low-permeability though leaky clay-rich layer is commonly observed in weathered igneous regolith profiles above more permeable material which hosts the aquifer (Sharp, 2014, Taylor and Eggleton, 2001). In addition, it is suspected that fractures in the underlying solid geology are influential. There is further uncertainty over whether the wells are fully-penetrating; wells are generally excavated until solid geology is hit though they may be partially penetrating if a boulder was struck (such boulders are commonly observed in regolith stream bank sections) or where water-tables are shallow (i.e. on floodplains).

The Moench (1985) method was selected because it considers leaky aquifers and large-diameter wells, i.e. well bore storage is included, and is straightforward to use on AquiferWin32 software. The method requires: well geometry, aquifer thickness, pumping rate, and a time-series of drawdown. Given that the period of pumping was quite short and did not reach steady state, only a small portion of curve was available for matching to provide values for hydraulic conductivity and specific yield. Therefore, there is a potential error on the results though it is likely to be less than the natural variation of the aquifer material. However, the specific yield values resulting from this method were often considered impossibly low ($< \sim 1 \times 10^{-6}$), as they are computed from early time data which is considered in pumping test analysis to be the least reliable, and have not been included when calculating averages (Table 1).

Recovery data was analysed using nomograms presented by Barker and Herbert (1989) to facilitate application of the solution of Papadopulos and Cooper (1967) to recovery tests on large-diameter wells. The method requires: well geometry, pumping rate and period, drawdown at the end of pumping, and time taken for 25 %, 50 % or 75 % recovery, and provides values for transmissivity (T) (the rate at which water flows horizontally through an aquifer; T = K multiplied by aquifer saturated thickness) and specific yield. Values for hydraulic conductivity were derived by dividing the transmissivity by the measured saturated thickness.

Potential well yield is considered to be the maximum continuous abstraction, i.e. pumped to steady state, that a well could be subjected to without drying out. In this case, "drying out" is considered to be a water depth of 0.3 m which is the minimum depth from which water could be abstracted using bucket and rope methods or without excessive sediment intake in a motor pump. Well yield (Q) was calculated with the application of the Thiem (1906) equation:

$$Q = \frac{K(H^2 - h^2)}{C\log(R/r)}$$

Hydraulic conductivity (K) was taken from the pumping test analyses, saturated thickness (H) and well radius (r) were as measured prior to testing, water depth (h) was fixed at 0.3 m, C is a constant equal to 0.733, and the radius of the cone of depression (R) was varied from 5-20 m.

Results

Given the uncertainties over well and aquifer geometry, hydraulic conductivity and specific yield results are sufficiently similar from the drawdown and recovery analyses to indicate suitability of methods (Table 1). The largest differences in properties between testing methods are within the natural variation of the aquifer materials.

Table 1. Aquifer properties determined by pumping tests; K = hydraulic conductivity and S_y = specific yield. The S_y results in italics are considered unreliable (see text) and were not used to calculate averages.

		No. of tests	**K (m/d)**	**S_y**	**Well yield (l/s)**
End of dry season	***Dangila***				
	Drawdown	5	0.7 – 5.3	0.03 – 0.12	0.001 – 0.32
	Recovery	5	0.2 – 6.4	0.00001 – 0.32	
	Robit-Bata				
	Drawdown	1	0.4	-	0.03 – 0.25
	Recovery	1	1.8	0.029	
End of wet season	***Dangila***				
	Drawdown	5	2.8 – 6.8	*$7.8 \times 10^{-7} – 3.6 \times 10^{-6}$*	0.21 – 3.5
	Recovery	5	6.2 – 22.3	0.05 – 0.10	

Significantly, the result from Robit-Bata is consistent with those from Dangila confirming field observations of the similarity of the regolith of both areas. This outcome suggests that conclusions reached on the hydrogeology may be transferrable to other shallow aquifers above basalt bedrock throughout Ethiopia. Continuing research is required to determine if findings on the shallow aquifer in this region are potentially transferrable across a wider area as studies have shown that regolith has hydrogeologically similar characteristics across a variety of rock types (Jones, 1985).

The mean dry season hydraulic conductivity values derived from all wells using analysis of both drawdown and recovery data is 2.3 m/d with a median of 1.6 m/d, a range of 0.2 to 6.4 m/d and a standard deviation of 1.95. The mean wet season hydraulic conductivity is 9.7 m/d with a median of 6.5 m/d, a range of 2.8 to 22.3 m/d and a standard deviation of 7.19. This disparity between seasons is not only of transmissivity but hydraulic conductivity, therefore, is not explained by greater saturated thickness. Layers of higher hydraulic conductivity must exist within the higher water column during the wet season. The implication of this finding is significant; not only would wells excavated more deeply below the water-table have higher well bore storage, but they are more likely to intercept more transmissive (water-bearing) layers providing greater yield. Estimates of well yield are generally >1 l/s in the wet season when the water column is high though this may drop an order of magnitude during the dry season.

The hydraulic conductivity results are comparable to studies of regolith elsewhere in Africa: Olaniyan et al. (2010) report a range of 0.30 to 9.36 m/d (average: 2.13 m/d) from a study in Nigeria, Taylor and Howard (1998) report a range of 0.3 to 3.0 m/d in Uganda, while 0.05 to 1.5 m/d is reported by Chilton and Smith-Carington (1984) in Malawi. A textbook range for weathered igneous regolith presented by Taylor and Eggleton (2001) is 0.09 to 1.7 m/d.

It is well reported that there are few data on specific yield of regolith, or indeed any, aquifers in Africa (MacDonald et al., 2012). From all seasons and locations the specific yield range of 0.00001 to 0.32 and mean of 0.09 (median of 0.08 and standard deviation of 0.079) is similar to the wide range quoted by Jones (1985) of 0.00001 to 0.1 for Central Africa and higher than the 0.003 reported by Taylor et al. (2010). Bahir Dar University laboratory assessment of density, porosity and field capacity of five bulk samples enabled estimation of a specific yield range of 0.052 to 0.219 for weathered basalt regolith from Robit-Bata *kebele* (D. L. Yilak, personal communication, March 2015). A textbook range for specific yield of regolith presented by Fetter (2001) is 0.15 to 0.3.

Conclusions

Pumping tests conducted on hand-dug wells in northwest Ethiopia provide mean hydraulic conductivity values of 2.3 m/d in the dry season and 9.7 m/d in the wet season (median = 1.6 and 6.5 m/d), and a mean specific yield value of 0.09 (median = 0.08). These values contribute to the extremely sparse data available in published literature for shallow regolith aquifers in sub-Saharan Africa. Calculations of well yield (average = 0.5 l/s) indicate that penetrating a substantial saturated thickness of aquifer (>3 m below water-table) to maximise water column height is as important for achieving desirable yield as locating areas of high hydraulic conductivity. A well or borehole fitted with a handpump must be able to sustain a supply of >0.1 l/s (preferably 0.3 l/s) to supply a community (MacDonald et al., 2012). Irrigation demand depends on crop type and local environmental conditions, though these are less significant when considering general feasibility. For the range of crops and conditions likely to be encountered at the study site and the short distance of delivery from well to crop, daily water use can be calculated as approximately 1 l/s/ha. Given this calculated irrigation requirement, the well yield estimations give some optimism that small scale irrigation, in addition to the existing community supply, is achievable from hand dug wells in shallow regolith aquifers. Further research is required to determine the transferability of findings, though similarities in results from wells some distance apart and with published results suggest the findings may be transferable to other areas of shallow weathered regolith aquifers across sub-Saharan Africa and certainly to shallow weathered basalt regolith aquifers within Ethiopia. Knowledge of aquifer parameters is vital in constructing models for simulation of climate change impacts and in developing management strategies for sustainable development of shallow groundwater resources.

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