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Research paper

Can shallow groundwater sustain small-scale irrigated agriculture in sub-Saharan Africa? Evidence from N-W Ethiopia

John Gowing [a,*], David Walker [b,e], Geoff Parkin [b], Nathan Forsythe [b], Alemseged Tamiru Haile [c], Demis Alamirew Ayenew [d]

[a] School of Natural and Environmental Sciences, Newcastle University, Newcastle Upon Tyne, United Kingdom
[b] School of Engineering, Newcastle University, Newcastle Upon Tyne, United Kingdom
[c] International Water Management Institute, Addis Ababa, Ethiopia
[d] Geological Survey of Ethiopia, Addis Ababa, Ethiopia
[e] Faculty of Design, Kyushu University, Fukuoka, Japan

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ABSTRACT

We present an evidence-based approach to identify how best to support development of groundwater for small-scale irrigation in sub-Saharan Africa (SSA). We argue that it is important to focus this effort on shallow groundwater resources. We demonstrate and test this proposal at a case study site: Dangila woreda in the north-western highlands of Ethiopia. This site was selected to allow exploration of a shallow weathered volcanic regolith type aquifer formation which is found to the South of Lake Tana and also exists more extensively across Ethiopia. We believe lessons from this case study are transferable and there is a case for arguing that shallow groundwater represents a neglected opportunity for promoting sustainable small-scale irrigated agriculture in SSA.

In comparison with other global regions, the groundwater resources of SSA are among the least understood; borehole records and hydrogeological studies are lacking. Assessments of groundwater resources do exist, but they rely on remotely sensed data combined with modelling at national or regional scale, and they focus on deeper aquifers. There is a need for these broad evaluations to be supplemented by localised and detailed assessments. The case study here presents such an assessment in order to support analysis of strengths, weaknesses, opportunities and threats associated with developing small-scale irrigation utilising shallow groundwater.

A multimethod groundwater recharge assessment was conducted utilising formal and community-based monitoring, field investigation and existing published data. Water table recovery tests at existing hand dug wells confirm that well yields of 1 l/s are achievable at the end of the wet season when water would be available to support an additional irrigated crop. Hydraulic conductivity estimates ranged from 0.2 to 6.4 m/d in the dry season and from 2.8 to 22.3 m/day in the wet season. Specific yield estimations have a wider range though the mean value of 0.09 is as would be expected.

Records of groundwater levels and rainfall monitored by the local community for the period April 2014 to April 2018 show that all the wells maintained useable water levels beyond the end of the rainy season. An assessment of the hydrology of the Kilti catchment provided insights into groundwater availability within the wider area. The catchment receives about 1600 mm/year of rainfall, of which about 350 mm/year enters the groundwater as recharge, discharging to the river as baseflow with a similar amount of rapid runoff contributing to a total river flow of about 400 mm/year. The lowest value of baseflow is 82% of the mean baseflow, which suggests a degree of buffering and indicates that groundwater is available even in a very dry year.

We conclude that arguments previously put forward against the promotion of shallow groundwater use for agriculture in SSA appear exaggerated. Our analysis challenges the view that shallow aquifers are unproductive and that irrigation will have unacceptable impacts on wetlands and other groundwater-dependent ecosystems. We believe lessons from this case study are transferable, and there is a case for arguing that shallow groundwater represents a neglected opportunity for promoting sustainable small-scale irrigated agriculture in sub-Saharan Africa. It appears that factors other than the physical availability of groundwater control the 'triggering' of

* Corresponding author.
E-mail address: john.gowing@ncl.ac.uk (J. Gowing).

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development. Interventions to promote development of groundwater resources should recognise the importance of shallow aquifers.

1. Introduction

1.1. Context

There is abundant groundwater in Africa; more than 100 times the annual renewable freshwater resource and 20 times the amount of freshwater stored in lakes (MacDonald et al., 2012), but its productive use for irrigation in sub-Saharan Africa (SSA) remains low. Examining the evidence on use of groundwater for irrigation in SSA, Pavelic et al. (2013) argued for action to unlock its potential for improving livelihoods of smallholder farmers. However, there is a clear tendency for the discourse on groundwater development in SSA to focus on deep aquifers with high well yields (Korzenevica, 2019; van Koppen and Schreiner, 2018). In contrast, we examine here the opportunities and constraints to promote use of ***shallow*** groundwater for small-scale irrigation in SSA, drawing upon evidence from Ethiopia to demonstrate the case for action. The literature on groundwater in SSA considers 'shallow' groundwater as any aquifer up to 50 m or 60 m depth (Pavelic et al., 2012a), whereas much of the existing small-scale irrigation depends on a water-table depth less than 5 m. Because of power limits on water lifting (see supplementary material) and also because of available technology for well construction, we adopt a working definition of 'shallow' groundwater as <25 m depth.

Historically, groundwater exploitation has not been seen as an important component of water resources development in SSA (Braune and Xu, 2010). For most countries in SSA groundwater use represents <5% of national sustainable yield (Cobbing and Hiller, 2019). Its contribution to rural water supply is recognised, but groundwater has been seen more as a local resource, which supports domestic demand, rather than as a strategic resource which can support productive use and economic development. Arguments historically put forward against the promotion of groundwater use for agriculture in SSA include that aquifers are said to be low in transmissivity and that well yields are inadequate to support agricultural development at scales larger than garden irrigation (Wright, 1992; Chilton and Foster, 1995; MacDonald et al., 2012). It has also been argued that groundwater use for irrigation will have unacceptable impacts on wetlands and other groundwater-dependent ecosystems and on domestic supplies (Adams, 1993; Giordano and Villholth, 2007; MacDonald et al., 2009). These concerns represent perceived barriers to triggering a groundwater development revolution that will unlock SSA's potential (Cobbing and Hiller, 2019).

A review of the project portfolios of the World Bank and African Development Bank (Cobbing and Hiller, 2019) reveals the neglect of groundwater investment. However, the agenda has shifted, and groundwater irrigation (GWI) by smallholder farmers is increasingly being recognised by governments, donors and NGOs (Abric et al., 2011; CAADP , 2009; Chokkakula and Giordano, 2013). GWI is now seen as an important vehicle to promote poverty alleviation, food security, rural employment, market-oriented agriculture and climate change adaptation (Ngigi, 2009; Cobbing and Hiller, 2019). Groundwater resources are ideally suited to development of 'distributed irrigation systems' (Burney et al., 2013) in which farmers enjoy far greater autonomy and flexibility of water supply than is possible through canal systems. Survey evidence shows that smallholder farmers prefer GWI (Abric et al., 2011; Giordano et al., 2012; Villholth, 2013).

The global area equipped for irrigation has been estimated (Siebert et al., 2010) as 301 Mha, of which 38% depends on groundwater. In SSA the extent of GWI is much less, with only 6% of the irrigated area reported by Siebert et al. (2010) and 10% by Giordano (2006) to be supported by groundwater. However, a note of caution is necessary when considering official statistics because of problems of definition and invisibility of so-called 'informal irrigation' (Giordano, 2006; Frenken, 2005). Using evidence from various countries in SSA, Villholth (2013) revised this estimate to 20% of the total irrigated area. Notable examples of public sector initiatives exist, such as in the Fadama Development Programme in Nigeria (Abric et al., 2011), but it is important to recognise the dominance of the informal sector, which is characterised by autonomous farmer initiatives based upon the exploitation of shallow groundwater resources. Such initiatives receive little official recognition and support (Chokkakula and Giordano, 2013) and there is an urgent need to develop capacity for the state to function in a dual role as facilitator and regulator of GWI. We argue that it is important to focus this effort on ***shallow*** groundwater resources since it is shallow aquifers that are most likely to be accessible to poorer rural communities in SSA.

1.2. Shallow groundwater: the opportunity

In the past few decades in Asia, a paradigm shift has occurred in irrigation practice, such that 'distributed irrigation' using privately owned wells and small motorised pumps has expanded rapidly. This development has enabled smallholder farmers to diversify their farming systems and grow high-value crops for the market. There is growing, but patchy, evidence that a similar 'irrigation revolution' is happening in SSA (De Fraiture and Giordano, 2014; Dessalegn and Merrey, 2015; Cobbing and Hiller, 2019).

Irrigation does not currently play a major role in African agriculture; the area equipped for irrigation as a percentage of total cultivated land is 19.4% globally, but only 3.3% for SSA (Siebert et al., 2010), where agriculture remains almost entirely rainfed (You et al., 2010). There have been many assessments of the irrigation potential (eg. Frenken, 2005) and ambitious plans for its expansion, such as Commission for Africa (2005), which proposed doubling the area under irrigation. In reviewing the investment needs on behalf of the World Bank, You et al. (2010) examined biophysical and socio-economic factors affecting large and small-scale irrigation development. They found that small-scale irrigation offered far greater potential than large scale development, offering five times the expansion potential and double the estimated rate of economic return. GWI can make an important contribution to irrigation expansion in SSA provided that the focus is on technology that is appropriate for small-scale farmers. A focus on shallow groundwater offers this advantage in that technologies for well construction and for water lifting are accessible to these farmers (Amjath-Babu et al., 2016).

1.3. Shallow groundwater: anticipated constraints

Shallow groundwater is accessible to small-scale farmers with simple technologies for well construction and water lifting, and offers the best opportunity to develop low-cost GWI. However, it is important to consider constraints since shallow groundwater resources are likely to be vulnerable to over-exploitation and climatic variability. While the reported abundance of groundwater in SSA (MacDonald et al., 2012) is encouraging, renewability and accessibility issues need to be addressed (Edmunds, 2012). Villholth (2013) notes that sustainable development of groundwater use for irrigation is limited by "replenishment rates … extractability in some regions … and as a provider of environmental services", and argues that there is a need for understanding integrated groundwater and surface water systems at different scales".

Broad scale assessments of groundwater resource potential at national or continental scales (e.g. MacDonald et al., 2012) and at sub-national scales (e.g. Awulachew et al., 2010) provide an indication of the spatial extent and storage volume in aquifer formations, but an assessment of the resource potential is critically dependent on understanding groundwater dynamics. A recent review of groundwater conditions in 15 SSA countries concluded that "information on aquifer characteristics, groundwater recharge rates, flow regimes, quality controls and use is still rather patchy" (Pavelic et al., 2012b). There is widespread use of shallow groundwater for domestic supply in most SSA countries, and indigenous knowledge generally exists on the seasonal performance of wells during typical and drought years. However, this knowledge is localised, qualitative and unrecorded. In contrast, there is increasing availability of relevant global remote sensing data including topography, land cover, soil moisture and climate products providing broad scale information that can be used to estimate resource availability.

Broad scale quantitative mapping of groundwater potential for Africa was revisited by Altchenko and Villholth (2015) who considered the potential for sustainable GWI based on renewable groundwater resources with 0.5° spatial resolution. They adopted an approach based on conservative estimates of groundwater recharge and alternative scenarios for allocation of groundwater to satisfy environmental requirements. They concluded that throughout most of the Sahel and for the eastern tract of SSA from Ethiopia to Zimbabwe renewable groundwater is under-exploited, and in some countries is sufficient to irrigate all cropland. Any such assessment is subject to uncertainty and temporal variability of recharge estimates.

Due to the fragmented and localised nature of shallow groundwater resources (Pavelic et al., 2012a) their potential may be limited by available storage to a greater extent than in the case of extensive deep aquifer formations. As identified by Dessalegn and Merrey (2015), there is a need for these broad evaluations to be supplemented by "localised and detailed assessments". The case study presented here is an attempt to deliver such an assessment in order to support analysis of strengths, weaknesses, opportunities and threats (i.e. SWOT analysis), and to argue that shallow groundwater represents a neglected opportunity for promoting sustainable small-scale irrigated agriculture in sub-Saharan Africa.

2. Study area

The appropriate scale for the case study was considered to be a single administrative district (known in Ethiopia as a *woreda*) as this allowed consideration of both technical and socio-economic aspects of groundwater resource assessment and management. In view of the priority given to agricultural transformation in the area and availability of hydrogeological data, the Tana basin was selected as a suitable site for the pilot study. Several *woredas* in the basin were considered on the basis of their accessibility, the dominant farming system and their status within the agricultural growth strategy. Dangila *woreda* was selected as the case study site (Fig. 1).

Dangila *woreda* is situated in the north-western highlands with altitudes generally between 1850 m and 2350 m. Dangila town is situated along the Addis Ababa-Bahir Dar road at a distance of 60 km south west of Bahir Dar. Part of Dangila *woreda* drains north-east towards Gilgel Abay River and Lake Tana; the remaining area drains either west or south-west towards Beles River. Both of these are part of the Abay (Blue Nile) tributary of the River Nile. The climate is sub-tropical with annual rainfall around 1600 mm and the main rainy season (known as *Kiremt*) occurring in June–September.

The total population of Dangila *woreda* is estimated at about 200,000 people in an area of about 800 km^2. Crop–livestock mixed subsistence farming is the primary source of livelihood. According to a recent survey (Belay and Bewket, 2013) approximately 14% of cropland is irrigated. This compares with estimates for Ethiopia as a whole of 1.8% by Siebert et al. (2010) and 2.5% by Altchenko and Villholth (2015). Irrigation is mainly by means of shared gravity diversions from seasonal and

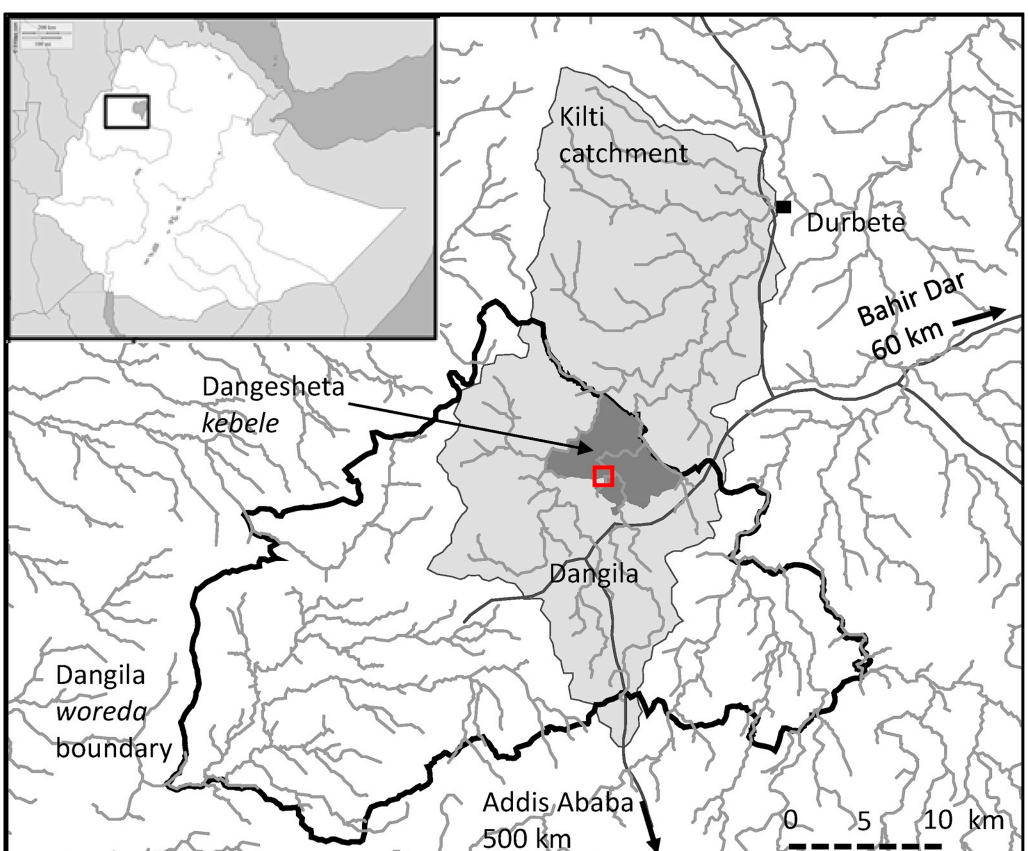

Fig. 1. Case study site: Dangila *woreda* in Amhara region, Ethiopia. The red box gives the location of Fig. 2 map.

perennial streams, though there are some reports of water lifting. There are many shallow (up to 15 m) dug wells throughout the *woreda*, but they are used primarily for domestic supply with only small pockets of garden irrigation. There are some deeper drilled wells fitted with hand-pumps and some springs have been developed for community water supply.

Ethiopia's hydrogeology is complex. Basement aquifers, volcanic aquifers and Mesozoic sediment aquifers are most extensive, but these are generally poor aquifers and consequently, Quaternary alluvial and regolith aquifers are more important. The geology is often highly varied and, due to tectonic movement, areas with very shallow groundwater can occur alongside rift areas with very deep groundwater. Kebede (2013) mapped the extent of alluvio-lacustrine sediments in Ethiopia covering around 25% of the total land area. The alluvial deposits are of two types: (1) extensive alluvial plains and (2) more localised strips of land and river beds along rivers and streams occurring in most places both in the highlands and in the lowlands.

Existing mapping of shallow aquifers shows an extensive area of shallow regoliths to the south of Lake Tana. The study site was selected to allow its exploration as a representative of the extensive shallow aquifer formations.

At the case study site the geology consists of predominantly Quaternary basalt and trachyte above Eocene Oligocene basalts and trachyte: the ages of these formations are taken from the 1:2,000,000 scale Geological Map of Ethiopia (Tefera et al., 1996). Outcrops are visible in river beds and occasionally on steeper slopes and in a few man-made excavations. The basalts are variously massive, fractured and vesicular with variations occurring over short distances. Above the solid geology lies weathered basalt regolith, itself overlain by red soils (nitisols). The red soils become more lithic and clayey with depth, grading into the regolith usually with no obvious boundary. The regolith becomes greyer and stronger and has to be chiselled as it deepens, though it is still quite friable. The most friable regolith is the result of weathering of scoriaceous basalt.

The superficial materials underlying the floodplains are darker in colour, with deep and wide desiccation cracks suggesting a high clay content (vertisols), though occasionally containing fluvial sands and gravels. The depth to the top of the solid geology is highly variable. Wells are typically excavated until further excavation becomes impossible, therefore the location of the rock-head can be inferred from well depth. The rivers have often incised to the level of the rock-head, where solid basalt forms the river bed with banks of only 1–3 m in height.

3. Assessment of the shallow groundwater resource

3.1. Methodology

3.1.1. Hydrogeological assessment

Hydrogeological assessments of the Dangila case study site were conducted between October 2013 and February 2017. The pre-existing geological map was reinterpreted on the basis of observation of surface features combined with sampling from dug wells and springs. Evaluation of the controlling factors for groundwater movement and storage, and identification of geological structures (faults, lineaments, joints) and their role to control flow direction in relation to the direction of major and minor structures was evidenced by measurement or estimation of spring discharge, estimation of dug well yield based on users' information, and measurement of some stream flows. Rivers were surveyed in order to accurately locate (using GPS) perennial and seasonal reaches, and water depth, channel incision and bank width was measured while geology of the river banks and river bed was recorded. Transects were surveyed to validate assessments of land-use and vegetation type using Google-Earth imagery; this was found to be satisfactory for the purpose of assigning land-use and vegetation type categories.

Well tests were conducted on seven selected dug wells in order to estimate aquifer hydraulic conductivity and specific yield. Tests were repeated in March (dry season) and October (wet season) of 2015. Drawdown and recovery were analysed separately, applying the Moench (1985) and Barker and Herbert (1989) methods, respectively. Details of the tests and analyses are presented in Walker (2016).

3.1.2. Groundwater recharge assessment

A multimethod groundwater recharge assessment was conducted utilising formal and community-based hydrometeorological monitoring data, field investigation data and existing published data. The methods were applied at local scale in the case of water table fluctuation methods, to catchment scale with water balance methods, and up to regional scale with consideration of published national and continental-scale recharge maps. Unsaturated zone methods were applied, such as soil moisture balance, in addition to saturated zone methods, such as chloride mass balance, methods that consider only surface water, e.g. baseflow separation, and methods considering all zones, e.g. physically based modelling. For further information see Walker et al. (2019).

3.1.3. Hydrometeorological assessment

Time series data were available from the national hydrometric network for the Kilti river gauge at Durbete (Fig. 1), and for rainfall and potential evapotranspiration from a meteorological station near Dangila town. A 7-year period of daily data from January 1997 to December 2003 was chosen for which almost complete data were available. The daily rainfall amounts were compared against data from the Tropical Rainfall Monitoring Mission (TRMM), to determine if they are likely to be representative of the spatial average over the catchment area.

The river flow data were processed to identify baseflow using a standard flow separation method (Tallaksen and van Lanen, 2004). Various other methods exist for flow separation, but this provided a consistent approach to estimate the seasonal contribution from groundwater to the river flow during years with different meteorological conditions.

3.1.4. Community-based mapping and monitoring

Following selection of the Dangesheta *kebele* (sub-district) as the focus site, gender-separated focus groups delivered a participatory mapping exercise of available local water resources and areas of land used for pastoral and crop agriculture, followed by a broader discussion of existing understanding of the hydrological system, current water use, and constraints and aspirations for agricultural development. Subsequently, a small sub-group of the participants assisted in identifying appropriate sites on two of the main river systems for monitoring river levels, as well as sites for monitoring rainfall and groundwater levels. Two standard river staff gauges were installed by the community, a suitable site was identified for installation of a non-recording (manual) rain gauge and 5 shallow hand-dug wells were selected to be monitored using a dipmeter.

These activities were carried out by members of the community, from whom observers were selected by the community to take daily readings. A workshop was then held to demonstrate the equipment and its use to a mixed gender and age group audience. The installations and training were carried out in February 2014, and daily monitoring has continued without interruption and is still continuing up to and beyond the time of writing. This close engagement with the community has ensured that the equipment has been protected as there is a sense of ownership by the community. Data derived from the monitoring has been tested for its reliability (Walker et al., 2016) and fed back to the community in order to ensure there is motivation for continued monitoring through demonstrating the usefulness of this level of quantitative understanding.

3.2. Results of resource assessment

3.2.1. Hydrogeological assessments

Previous hydrogeological investigations (Kebede et al., 2005) have focussed on deeper aquifers and reported well depths of 30–100 m. Here the focus is on the shallow aquifer. Water-table depth is seen to be controlled by topography and regolith thickness with clear seasonal variations. Near the end of the dry season in March/April within the floodplains, where the solid geology is at a depth of 3–4 m, the water-table lies at around 2.5–3.5 m. The water-table can often be seen as a seepage face at this depth within river bank regolith sections. However, on the larger and steeper slopes where rock-head is around 15 m deep the water-table is at a depth of around 12–15 m.

Despite the shallow aquifer being considered to be the weathered basalt regolith and alluvial materials above the solid geology, it is possible that fractures within the solid geology are influential to the hydrogeological regime. Heterogeneities within the regolith, such as the clay content and the fractured or vesicular nature of the pre-weathered rock, determine the productivity of a well, though this is very difficult to estimate prior to excavation. Fissure flow in the immediately underlying basalt is not observed and is likely to be very restricted, as any fractures are probably filled with weathered material with the same properties as the overlying materials.

Hydraulic conductivity estimates obtained from well tests ranged from 0.2 to 6.4 m/d in the dry season and from 2.8 to 22.3 m/day in the wet season; indicating that more transmissive layers occur higher in the aquifer that are intercepted when saturated thickness is greater (Walker, 2016). Specific yield estimations have a wider range and are more uncertain though the mean value of 0.09 is as would be expected (Walker, 2018). A summary of the results is presented in Table 1. They confirm that well yields of 1 l/s are achievable at the end of the wet season when irrigation water would be required for an additional irrigated crop. Analysis presented as supplementary material shows that this target well yield is sufficient to irrigate a plot size of 1 ha if pumping is continuous at times of peak demand.

Following field investigations and community workshops, it became evident that topography has a significant influence on well locations and most likely also on well yields, more so than the nature of the underlying parent geology. Lowland areas comprising expansive floodplains and low relief topography have greater yield, though floodplains have reduced storage as the regolith aquifer is thin. Conversely, higher ground, such as near catchment boundaries, has a thick regolith aquifer but drainage occurs soon into the dry season and measured yields are low.

The locations of the five wells and the rain gauge monitored by the Dangesheta community are shown in Fig. 2, against the background of a Google Earth satellite image. It is clearly evident that these wells follow the general pattern of being mostly close to the edge of the floodplains, where they remain accessible for the whole year, but are downslope from the higher ground which provides recharge.

3.2.2. Groundwater recharge assessment

The multimethod recharge assessment resulted in a wide range of groundwater recharge estimates. This can be explained by differences in what the calculated "recharge" actually represents for particular methods, and the spatial and temporal scales that the method considers, as discussed by Walker et al (2019). The best estimate of annual recharge for Dangila *woreda* is in the range 280–430 mm (see Walker et al., 2019). Water table fluctuation methods gave higher results, confirming that monitoring wells situated at the base of hillslopes receive lateral as well as vertical recharge.

Table 1
Aquifer properties determined by well tests using methods of Moench (1985) and Barker and Herbert (1989): hydraulic conductivity (K); specific yield (S_Y).

	Dry season		Wet season		S_Y
	K (m/d)	Yield (l/s)	K (m/d)	Yield (l/s)	
Mean	2.3	0.07	9.7	1.2	0.08
Median	1.6	0.03	6.5	1.0	0.09
St Dev	1.95	0.08	7.19	0.83	0.079

3.2.3. Community-based mapping and monitoring

Records of groundwater levels and rainfall monitored by the local community for the period April 2014 to April 2018 are shown in Fig. 3. These show that only one of the wells (MW1) dries out completely early in the dry season. Three of the wells (MW2, MW3 and MW5) show similar behaviour, draining exponentially through most of the dry season, with small but non-zero depths of water present throughout the season. Water depths in well MW4 remain high through most of the dry season, before falling sharply in April/May. These data do, however, show that all the wells maintained useable water levels into at least the end of December, and in some cases for considerably longer.

3.2.4. Hydrometeorological assessments

An assessment of the hydrology of the Kilti catchment (Fig. 1) for the period 1997–2003 provides insights into groundwater availability within the wider catchment area. Rainfall data for this period was compared with a longer record (1993–2014) of monthly rainfall in order to allow an assessment of whether it reflected a sufficiently wide range of conditions. It was found that 1999, 2000 and 1997 represent wet years (96%, 86% and 73% probability of non-exceedance respectively), while 2002 and 2003 represent dry years (9% and 14% probability of non-exceedance respectively) and 1998 represents an average year (40% probability of non-exceedance). The data for 1997–2003 therefore provide an adequate representation of longer term variability.

Annual water balance components for the Kilti catchment are summarised in Table 2 and shown in Fig. 4. The catchment receives about 1600 mm/year of rainfall, of which about 350 mm/year enters the groundwater as recharge. Discharge to the river as baseflow, about 200 mm/year, is less than actual recharge. This indicates that losses occur from the groundwater reservoir following recharge. These losses can be explained (Walker et al., 2019) as a combination of evapotranspiration from the saturated zone, which would be expected given the very shallow wet season water table, and seepage into the deeper aquifer.

It can be seen that the wettest year (rainfall 1960 mm) yields 12.8% baseflow, whereas the driest year (rainfall 1350 mm) yields 15.8% baseflow. The lowest value of baseflow is 82% of the mean baseflow which suggests a degree of buffering and indicates that groundwater is available even in a very dry year.

Mean monthly water balance components for the period 1997–2003 are summarised in Table 3 and shown in Fig. 5. Storage change is negative during the dry season and positive during the wet season. It should be noted that apparently high negative changes in storage are attributable to the use of potential evapotranspiration rather than actual evapotranspiration. It is possible that the rainfall totals from Dangila underestimate rainfall totals in the higher ground (for which we have no data). The shape of the annual Kilti hydrograph follows that of the annual precipitation cycle. It can be seen that baseflow does not begin to recover until June, thus indicating that groundwater recharge during *Belg* season (early 'small' wet season) is minimal. However, there is evidence of baseflow persistence beyond the cessation of *Kiremt* season (main wet season). Mean baseflows for 1997–2003 at the end of the months of September to December are estimated as 8.8, 5.3, 2.1 and 0.93 m^3/s respectively, following an exponential decline indicative of natural drainage of groundwater within the catchment. During the driest year of 2002 with rainfall probability of non-exceedence of only 9% based on the long-term data, the baseflow at the end of December remained at 0.52 m^3/s, representing 43% of the mean value for that date, indicating that groundwater remains available at this time even during dry years.

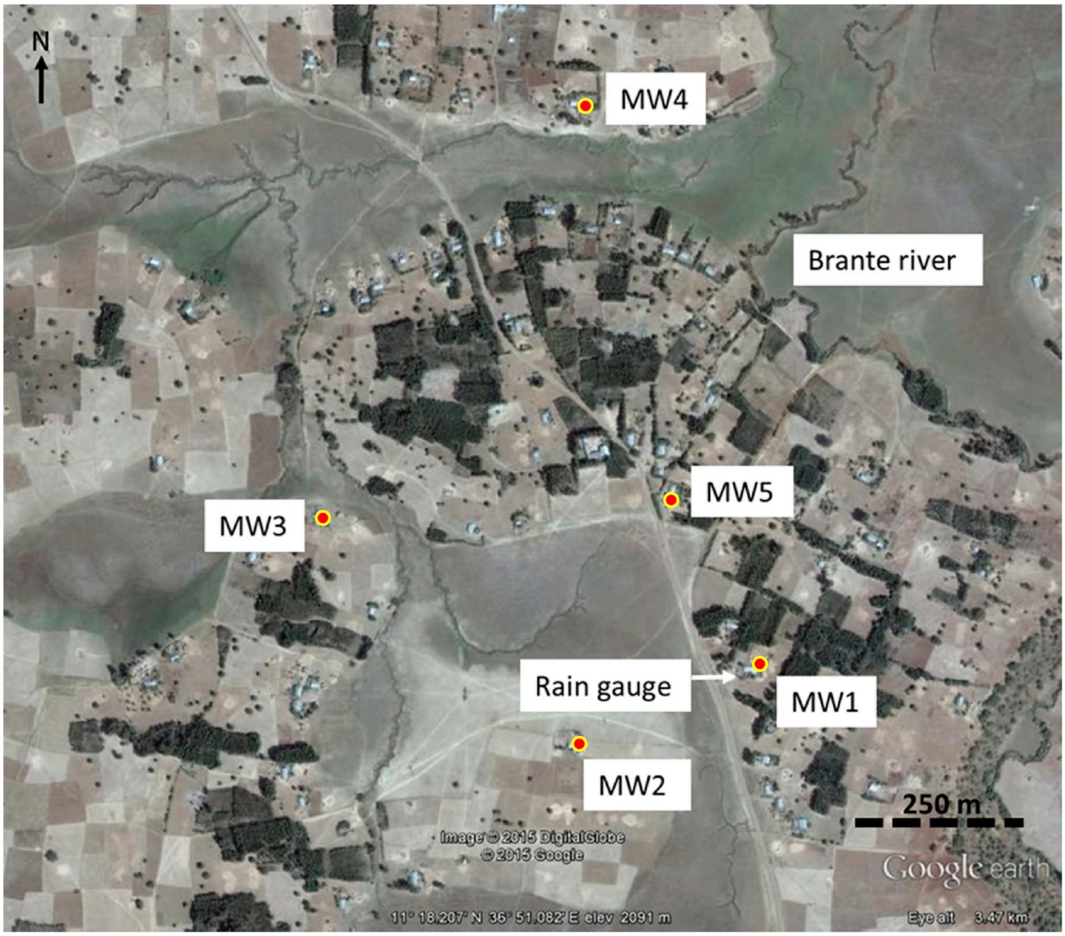

Fig. 2. Locations of community monitoring wells and rain gauge. (Image source: Google earth; Imagery ©2015 DigitalGlobe).

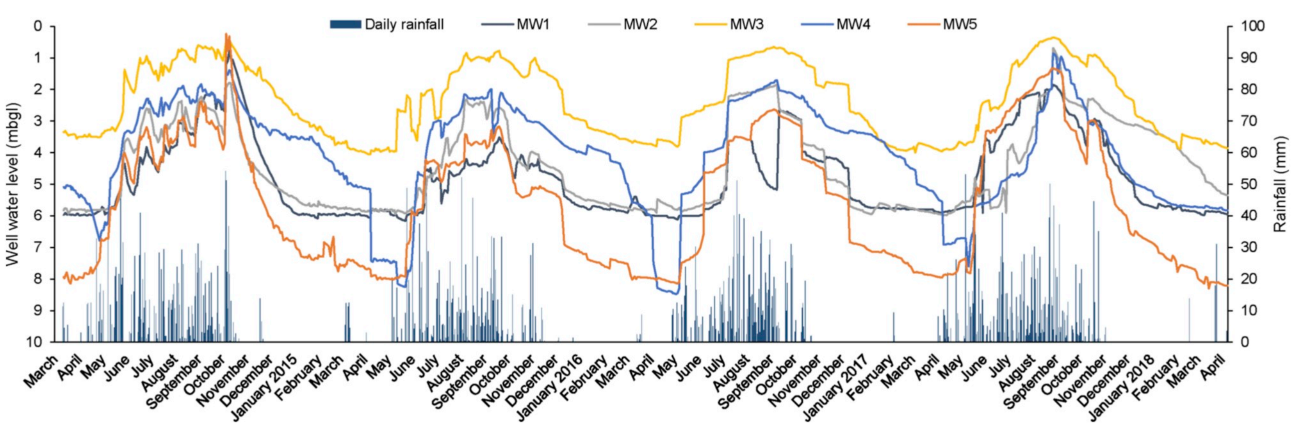

Fig. 3. Daily community observed rainfall and groundwater level data for 2014–18 (well depths are: MW1 6.0 m; MW2 6.9 m; MW3 4.2 m; MW4 9.2 m; MW5 8.4 m).

Table 2
Annual water balance data for 1997–2003 (mm).

	1997	1998	1999	2000	2001	2002	2003	Mean
Rainfall	1667	1555	1959	1896	1411	1350	1369	1601
Potential Evapotranspiration	1451	1425	1417	1416	1405	1415	1422	1422
Discharge	395	368	481	544	324	358	388	408
Baseflow	208	210	252	259	179	213	175	214
Change in storage	−179	−238	−61	−64	−318	−423	−441	−229

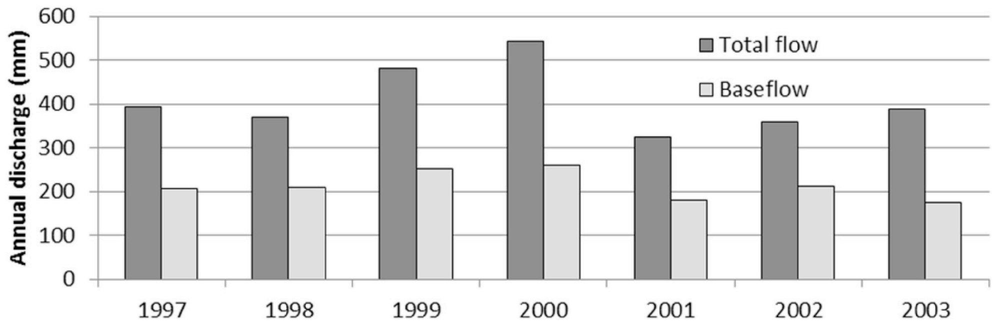

Fig. 4. Annual river discharge and baseflow for the Kilti catchment (1997–2003).

Table 3
Mean monthly water balance data for 1997–2003 (mm/day).

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Rainfall	0.01	0.06	0.46	1.00	4.76	8.38	10.84	11.06	7.79	5.02	1.39	0.07	4.26
Potential Evaporation	3.51	3.99	4.42	4.75	4.42	3.99	3.42	3.27	3.73	4.02	3.80	3.42	3.89
Discharge	0.11	0.06	0.03	0.03	0.12	0.85	2.75	4.14	2.73	1.67	0.61	0.20	1.12
Baseflow	0.09	0.05	0.02	0.01	0.03	0.21	1.12	2.08	1.74	1.00	0.44	0.18	0.58
Change in storage	−3.61	−3.99	−3.97	−3.78	0.22	3.54	4.67	3.65	1.33	−0.67	−3.02	−3.55	−0.75

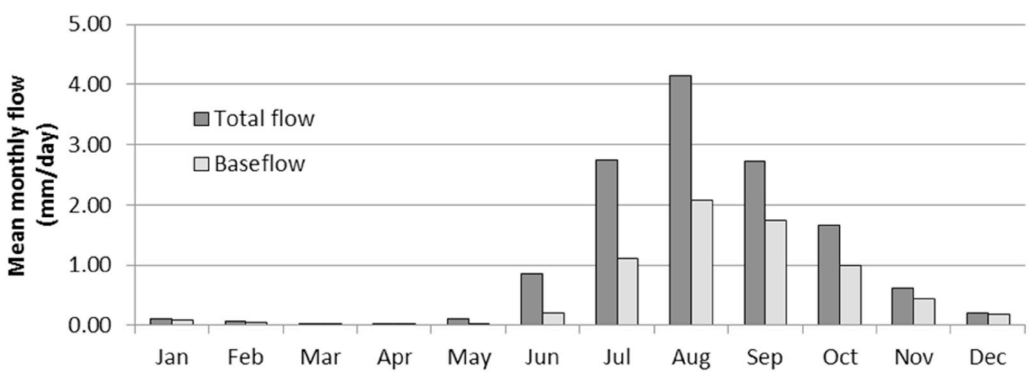

Fig. 5. Mean monthly river discharge and baseflow for the Kilti catchment (1997–2003).

4. Discussion

4.1. Insights gained from the case study

There is an expanding literature on smallholder groundwater irrigation in SSA (Giordano, 2006; Giordano and Villholth, 2007; Siebert et al., 2010; Pavelic et al., 2013; Villholth, 2013; Altchenko and Villholth, 2015). Previous studies have estimated the extent of groundwater irrigation potential across SSA, and most recently, Altchenko and Villholth (2015) identified the scope for developing small-scale GWI. They concluded that the semi-arid Sahel and East Africa regions offer appreciable potential. In Ethiopia, their estimate of sustainable GWI potential based on renewable groundwater was in the range 1.8×10^6 to 4.3×10^6 ha (depending on provision for environmental requirements). The focus has generally been on assessing potential at country level, and there is a need for these broad evaluations to be supplemented by "localised and detailed assessments".

The case study presented here for Dangila *woreda* in Ethiopia is an attempt to deliver such an assessment in order to support a wider analysis of strengths, weaknesses, opportunities and threats (i.e. SWOT analysis). As with the study of Fogera *woreda*, presented by Dessalegn and Merrey (2015), useful insights into the wider issues are revealed by the localised case study approach.

This detailed case study has explored the feasibility of exploiting shallow groundwater for small-scale irrigation over a range of rainfall conditions. We have shown that variability of rainfall (9%–96% probability of non-exceedance) does not translate into equivalent variability in groundwater levels and baseflow. Recharge quantities are high enough to create a productive shallow groundwater resource capable of supporting small-scale irrigation. Groundwater levels observed in most shallow wells persist into the dry season to at least the end of December and generally into February, indicating that water is potentially available for irrigation use during the period after the cessation of the wet season (typically mid October). Catchment baseflows also persist to at least the end of December, even during dry years, indicating that groundwater is available more widely across the catchment during this period.

Well tests indicate that shallow wells (<25 m) can support abstraction rates of 3.6 m^3/hr, which are sufficient to support small-scale irrigation (see supplementary material) at the end of the *Kiremt* wet season from October to December. A single well can support irrigated cropping on a plot up to 1 ha using technology for well construction and water lifting that is accessible to small-scale farmers. In general, it will be necessary to avoid the second part of the dry season when groundwater levels have generally declined through natural drainage, and which may be required to support other environmental requirements.

A conservative approach to extrapolation, which considers only the geology that characterises the shallow aquifer at the case study site (ie.

weathered regolith above Cenozoic volcanics), provides an indication of the wider relevance of insights gained from this case study. Around 40% of Ethiopia is underlain by Cenozoic volcanic rocks (Prave et al., 2016), and similar geology exists along the East African Rift from Eritrea to Malawi and in unconnected areas such as western Cameroon/eastern Nigeria and southwest Sudan. Additional evidence comes from Kebede (2013) who estimates that shallow unconsolidated aquifer types exist across 25% of Ethiopia. In addition, ATA (2019) estimated that active shallow aquifers in the Tana – Beles and Tarmaber – Maychew basins cover 27,080 km^2 (83.5% of total area) and 9070 km^2 (69.8% of total area) respectively. The localised assessment reported here supports broad evaluations of groundwater potential for irrigation (Siebert et al., 2010; Altchenko and Villholth, 2015). However, sustainability of small-scale shallow groundwater-based irrigation (SGWI) is determined by socioeconomic and institutional factors as well as technical considerations. While the focus of this investigation has been on technical dimensions of sustainability, SGWI, like any other type of irrigation development, should be seen as a socio-technical problem (Dessalegn and Merrey, 2015).

4.2. Socioeconomic and institutional considerations

Some insight into the important role of non-technical considerations is revealed through consideration of the literature on rural water supply (RWS), where much of the effort in SSA has been devoted to developing shallow groundwater resources for hand-pumped water points. Whaley and Cleaver (2017) argue that the drive to develop rural water supplies under the impetus of various international initiatives favoured a focus on achieving targets for coverage with considerations of sustainability taking second place. The sustainability concern was transposed into a policy of promoting community-based management (CBM), whereby a local level organisation was charged with the responsibility for delivering it. In principle, CBM creates a relationship between the water point and its users (ie. between the technology and its users). The high failure rate of newly installed water points is evidence of poor performance of the CBM paradigm, which has been explained by the concept of 'functionality'. As noted by Whaley and Cleaver (2017), "it is not only the functionality of the physical infrastructure that it of concern, but also the functionality of the community organisation charged with managing it". The lesson for SGWI would appear to be that it is important to establish an effective arrangement for CBM, but this can be problematic.

Within the CBM model (whether for RWS or for SGWI) the local organisation is responsible for operation and management of the technical infrastructure. These roles involve activities such as: devising rules for access and use; enforcing these rules; maintaining shared physical infrastructure; collecting financial contributions for these works. There is an obvious connection here also to the extensive literature on performance of farmer-managed canal-based irrigation (Veldwisch et al., 2019; Haileslassie et al., 2016; Senanayake et al., 2015). Whaley and Cleaver (2017), as with other critiques of the CBM model, identify concerns around (i) neglect of local institutions and power relations, (ii) broader governance issues, and (iii) the socio-technical interface. Whaley et al. (2019), based on a survey of 600 sites in SSA, concluded that the evidence does not support the CBM paradigm for RWS. The scope of the investigation reported here did not permit a full exploration of these issues as they relate to SGWI, but some insights can be identified.

Firstly, it should be recognised that the small-scale SGWI technology under investigation differs from the RWS hand-pump technology (and canal-based irrigation) in that SGWI technology is privately owned. SGWI is an example of a 'distributed irrigation system' (Burney et al., 2013) in which users enjoy far greater autonomy than is possible through canal systems or public water points. In this case, CBM is limited to devising rules for access and use, and enforcing these rules. Secondly, the adoption of a participatory approach to resource mapping and monitoring (citizen science) at the case study site was seen as the entry-point for developing a localised approach to resource governance. Alley et al. (2016) note that, "groundwater governance is inadequate in most, if not all, countries" and they attribute this in part to the 'invisibility' of the resource. Transparency of groundwater information, through effective monitoring, is a key aspect of good governance, as with all CBM for natural resource management (Cox et al., 2010). The lessons for SGWI would appear to be that CBM must exist within a clear governance framework, and that a citizen science approach is necessary to address the resource visibility challenge.

A different, but equally informative, perspective on the important role of non-technical considerations is offered by Cobbing and Hiller (2019), who argue that these 'secondary' factors "appear to be the predominant barrier to triggering SSA's groundwater development revolution". In other words, the absence of the necessary enabling environment and predominance of limiting conditions is seen as the explanation for SSA lagging behind other global regions in developing its groundwater resources. The discourse on semi-anarchic, unmanaged over-abstraction, that has followed the boom phase of groundwater development in South Asia, China and parts of USA, has influenced attitudes towards investment in groundwater-based development in SSA and added to the already considerable inertia. Cobbing and Hiller (2019) challenge this thinking, and conclude that there is a need to choose "between the current situation in which little groundwater is being used and therefore it is not significantly contributing to economic development, and future groundwater development where only partial control may be possible". We can consider this challenge, and evaluate the role of SGWI in the format of a SWOT analysis.

4.3. SWOT analysis of SGWI

Previously published SWOT analyses for development of shallow groundwater resources focus on the issue of water quality and pollution (eg. Kallioras et al., 2010). Here we propose an analysis derived from the case study which focuses on socio-technical issues affecting use of the groundwater resource for small-scale irrigation in SSA.

(i) Strengths (ie. intrinsic characteristics that provide an advantage)
- Groundwater is available beyond the end of the rainy season, allowing small-scale farmers to extend their cropping season;
- Reliable access to sufficient groundwater for irrigation permits farmers to adopt market-oriented horticultural crops;
- Access to shallow groundwater is achievable by individual farmers using available technology for well construction and water lifting;
- SGWI is suited to autonomous development by individual farmers, with requirement for collective action limited to resource management.

(ii) Weaknesses (ie. intrinsic characteristics that represent disadvantages)
- Lack of data (groundwater levels, spring flow, rainfall) creates a problem for assessing resource potential and managing resource use;
- Lack of hydrogeological mapping (for shallow aquifers in particular) creates a problem for identifying suitable sites where SGWI can be developed successfully;
- Shallow aquifers are vulnerable to over-exploitation, and management by existing formal institutions is beyond their capability;
- Adoption of SGWI is restricted by energy constraint on water lifting technology (see Supplementary Material).

(iii) Opportunities (ie. extrinsic factors that could be exploited to advantage)
- Use of shallow groundwater resources can unlock potential for growth in irrigated agriculture provided that good market access exists;

- SGWI represents an attractive agri-technology innovation that is accessible to individual farmers provided that an appropriate enabling environment exists;
- Existing community-based watershed management initiatives demonstrate successful participatory resource management, and provide an entry-point for developing SGWI;
- Solar power has become a mature and affordable technology option for groundwater pumping thus alleviating the energy constraint.

(iv) Threats (ie. extrinsic factors that could represent disadvantages)

- Climate change (and/or land use change) may impact adversely on groundwater recharge and reduce reliability of shallow groundwater resource;
- Competition from other water uses (domestic supply, abstraction from deep aquifers, run-of-river irrigation) may lead to disputes over resource allocation;
- Market failure may limit availability of appropriate water-lifting technology unless action is taken to stimulate the market;
- Weak governance arrangements for groundwater resources may contribute to vulnerability unless 'functional' community-based institutions can be enabled.

The SGWI model for small-scale irrigation development has discernible strengths in both technical and social dimensions. Combining SWOT features into a response matrix (Table 4) indicates a feasible way forward for developing SGWI for a range of scenarios likely to be encountered at any potential site. Scenario A represents the most favourable case where shallow groundwater is available at a site with good market access and capacity exists for effective community-based resource management. Autonomous development of SGWI by individual farmers should be actively promoted and the required response is to target actions towards the enabling environment for SGWI. This requires (i) alleviating the market failure in providing appropriate water-lifting technology and (ii) adopting a groundwater governance framework that permits participatory resource management at local community scale.

Other scenarios represent cases where intrinsic weaknesses or external threats are more evident. In scenario B, capacity for community management exists at a site with good market access, but knowledge of the shallow groundwater resource is inadequate. The required response is to promote a citizen science approach to data collection in order to gain better understanding of the opportunity. In scenario C, shallow groundwater is available but competition from other water uses (domestic supply, abstraction from deep aquifers, run-of-river irrigation) may lead to disputes over resource allocation. This may represent a severe challenge for community-based management, requiring additional support to enable engagement with wider governance arrangements. In scenario D, the shallow groundwater resource does not allow sustainable exploitation and SGWI should not be promoted. Improved mapping of shallow aquifers is required to identify sites more likely to be suitable for development.

Table 4
Summary of responses (actions) identified from SWOT analysis of SGWI.

Extrinsic factors	Opportunities	Scenario A: Shallow groundwater is available and capacity exists for effective community-based management *Response = Exploit:* Target actions towards enabling environment for SGWI	Scenario B: Enabling environment supports SGWI and capacity for community management exists but resource knowledge is weak *Response = Search:* Promote citizen science approach to data collection
	Threats	Scenario C: Shallow groundwater is available but is vulnerable to over-exploitation *Response = Confront:* Target actions towards enabling community-based management	Scenario D: Shallow groundwater resource does not allow sustainable exploitation *Response = Avoid:* Provide mapping and typology of shallow aquifers suitable for development
		Strengths	Weaknesses
		Intrinsic factors	

5. Conclusion

Shallow groundwater resources represent a neglected opportunity for sustainable intensification of small-scale agriculture in Ethiopia, and the analysis presented here informs the debate about irrigation policy across SSA. This case study approach adds detail to the existing broad scale assessments of groundwater resource potential at national and sub-national scales. A conservative approach to extrapolation, which considers only the geology that characterises the shallow aquifer at the case study site, provides an indication of the wider relevance of insights gained from this case study.

Strengths are that shallow groundwater (<25 m depth) is accessible to small-scale farmers and permits farmers to adopt market-oriented horticultural crops. SGWI allows development of 'distributed irrigation systems' in which farmers enjoy far greater autonomy than is possible through canal systems. SGWI can be developed quickly with minimal infrastructure investment provided that appropriate water-lifting technology is made available to farmers (see supplementary material). Weaknesses exist in that current information on shallow aquifers is inadequate, but concerns over low aquifer transmissivity, low well yields, aquifer vulnerability and resource conflict appear to be exaggerated. Weak governance arrangements for groundwater resources contribute to vulnerability, but the localised nature of shallow aquifers is ideally suited to an approach based around participatory resource management by local communities.

Community based monitoring has been shown to be valuable in providing the data required for resource management (Walker et al., 2016). There is widespread use of shallow groundwater for domestic supply in most SSA countries, and indigenous knowledge generally exists on the seasonal performance of wells during typical and drought years. This knowledge is localised, qualitative and unrecorded, but it provides an entry-point for a participatory approach. At the same time, this citizen science approach can also provide an entry-point for introducing devolved governance of the shallow groundwater resource. Experience of community-based management of RWS indicates the importance of socioeconomic and institutional factors in determining functionality. The participatory citizen science approach, as adopted for this case study, delivers the information needed to overcome the problem of resource invisibility.

We propose an approach to developing irrigation from shallow groundwater in SSA with a focus on community-led adaptive resource management. This is based on four responses:

- a bottom-up approach with close engagement between local communities and professionals is necessary for development of shallow groundwater resources for small-scale irrigation;
- the opportunities for distributed irrigation using privately owned wells (as previously occurred in Asia) requires attention to the enabling environment, in particular provision of small motorised pumps;
- an adaptive approach to integrated management of groundwater and surface water resources is necessary for long-term sustainability, and this requires a citizen science approach to hydrological monitoring at the local scale;
- existing hydrogeological data for shallow aquifers should be used to target action for promoting bottom-up community based initiatives.

There is a need for further action-research at this scale in places like Dangila *woreda* to develop capacity for the state to function in a dual role as facilitator and regulator of irrigation from shallow groundwater.

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Appendix A. Supplementary data

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