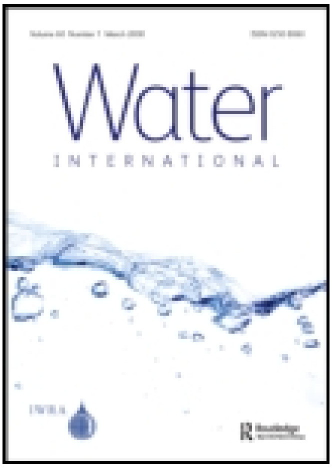

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Groundwater irrigation for smallholders in Sub-Saharan Africa - a synthesis of current knowledge to guide sustainable outcomes

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Groundwater irrigation for smallholders in Sub-Saharan Africa – a synthesis of current knowledge to guide sustainable outcomes

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Groundwater irrigation for smallholder farmers in Sub-Saharan Africa is growing in extent and importance. This growth is primarily driven spontaneously by the farmers themselves, spurred by improved access to low-cost technologies for pumps and drilling services as well as market opportunities for produce. This paper presents a review of the current status and knowledge of the prospects and constraints for sustainable and pro-poor groundwater irrigation in Sub-Saharan Africa. Further unlocking the potential of groundwater irrigation for smallholders will require better integrated approaches, simultaneously addressing groundwater-access constraints as well as enabling factors.

Keywords: groundwater; irrigation; smallholders; Sub-Saharan Africa; review

Introduction

Groundwater irrigation (GWI) is growing in extent and importance in arid and semi-arid areas of Sub-Saharan Africa (SSA) (Giordano, de Fraiture, Weight, & van der Bliek, 2012).[1] Groundwater responds to the demand of farmers for a reliable and flexible irrigation water supply. Also, better and more appropriate and cost-effective drilling and pump technologies, services and markets make it increasingly feasible. Giordano (2006) optimistically estimated the total groundwater-irrigated area in SSA to be 1–2 million ha. In Ethiopia, where development is presently promoted and is advancing rapidly with private as well as public funds, government statistics say that about 800,000 motor pumps were imported into the country between 2004 and 2010 (Namara, Gebregziabher, Giordano, & de Fraiture, 2013). Assuming that a quarter of these pumps went into GWI, each of them effectively irrigating 0.5 ha of cropland, this translates into about 100,000 ha of GWI land added over this period. Similar recent developments are seen in other parts of SSA. In Malawi, about half of the irrigated land (equivalent to about 20,000 ha) is serviced by lift irrigation (much of which is from groundwater), mostly using treadle pumps, with an increase observed over the last five to 10 years (Namara et al., 2013). In West Africa, it is now surmised that in Ghana, official figures for public irrigation schemes (mostly large-scale surface irrigation of 13,300 ha) have been surpassed several-fold by small-scale informal lift irrigation (approximately 190,000 ha), though official data are lacking (Namara et al., 2013).

Smallholders are poorer farmers, generally with landholdings that are smaller than 2 ha, privately owned, and under the complete control of the farmer (Abric et al., 2011).

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Smallholder GWI is increasingly promoted by governments, donors and NGOs (Abric et al., 2011; CAADP, 2009; Chokkakula and Giordano, 2013; Kay, 2001). Small-scale irrigation, including GWI, is the most rapidly expanding type of irrigation in Africa (Frenken, 2005). Smallholder GWI is seen as an important vehicle to promote (especially rural) poverty alleviation, food security (at various scales, from local to global) and land and labour productivity, as well as rural employment and general economic development and adaptation to increasing climate variability (Ngigi, 2009). Such strategies partly reflect the recognition that large-scale irrigation schemes (mostly from dams) have not created the expected benefits nor sufficiently targeted or benefited the poorest farmers (Abric et al., 2011; CAADP, 2009; Naugle & Sellen, 2006). Compared to surface water and communal irrigation schemes, GWI is believed to be more attractive to farmers due to the individual modes of uptake and operation (Abric et al., 2011; Naugle & Sellen, 2006). Current evidence shows that smallholders prefer GWI, whether subsidized or not (Abric et al., 2011; Giordano et al., 2012). Where they can find the means and finances, farmers often access groundwater to enhance their livelihoods, especially by moving from subsistence agriculture towards market-oriented farming (Dittoh, Awuni, & Akuriba, 2013; Shah, Verma, & Pavelic, 2013).

While the understanding of the potential and role of GWI for poverty alleviation and food production in SSA is rapidly increasing due to various recent larger regional research projects, research on GWI in SSA more generally has remained fragmented, anecdotal and focused on certain geographic regions or topics. There is a need for a broader, integrated and interdisciplinary approach to the research to ensure context-sensitive and evidence-based recommendations for future development. Furthermore, various development models, ranging from community-based deep groundwater schemes to individualistic shallow groundwater promotion, have been implemented, but with limited understanding of the relative impacts on poverty and food security of these interventions. There is a need for more evidence-based approaches to the support for GWI in SSA.

Hence, this article draws on the manuscripts submitted for this collection to frame the current narrative on GWI for smallholders in SSA and to review current knowledge in order to support such integrated and streamlined approaches. Its specific objectives are to update the estimate of the current extent of GWI in SSA, to classify SSA countries in terms of GWI potential based on multiple criteria, to propose a simple typology for GWI in SSA, to review knowledge on the socio-economic aspects and impacts of GWI, and to highlight constraints on further GWI development. It concludes with recommendations for supplementary research and critical issues for further supporting sustainable GWI development in SSA.

Current groundwater irrigation development in Sub-Saharan Africa

As noted by Giordano (2006) and Frenken (2005), official statistics on GWI, and particularly smallholder GWI, in SSA are imperfect and often not representative of the realities on the ground. This is partly because of methodological problems associated with the assessments (due to the inherent difficulty of discriminating the source of irrigation water, i.e. surface or groundwater, in public statistical databases or in remote-sensing approaches) and partly because of rapid changes, quickly outpacing the data. Hence, in order to get a more realistic estimate of GWI area, data from recent case studies as well as other recently reported data were used to supplement existing FAO-based compiled data (Siebert et al., 2010). This analysis shows that there are countries, like Malawi and Ethiopia, that have GWI areas well in excess of the data presented in Siebert et al. (2010) (Table 1) – in these

Table 1. Extent of groundwater irrigation in Sub-Saharan Africa (1000 ha).

Country	Siebert et al. (2010)			This study			Source for data on 'Area irrigated by groundwater-This study' (when different from Siebert et al. (2010)
	Total irrigated area[a]	Area irrigated by surface water	Area irrigated by groundwater	Total irrigated area	Area irrigated by surface water[b]	Area irrigated by groundwater	
Angola	35.0	28.0	7.0	35.0	28.0	7.0	
Benin	7.1	5.9	1.3	7.1	5.9	1.3	
Botswana	0.62	0.33	0.29	0.62	0.33	0.29	
Burkina Faso	25.0	22.0	3.0	52.0	22.0	30.0	Abric et al. (2011)
Burundi	21.4	21.4	0	21.4	21.4	0	
Cameroon	25.7	24.7	1.0	25.7	24.7	1.0	
Cape Verde	1.8	1.6	0.26	1.8	1.6	0.26	
Central African Republic	0.069	0.069	0	0.069	0.069	0	
Chad	26.2	21.0	5.2	26.2	21.0	5.2	
Comoros	0.085	0.082	0.033	0.085	0.082	0.033	
(Republic of the) Congo	0.22	0.22	0	0.22	0.22	0	
Côte d'Ivoire	66.9	66.9	0	66.9	66.9	0	
Dem. Republic of the Congo	6.8	6.8	0	6.8	6.8	0	
Djibouti	0.39	0	0.39	0.39	0	0.39	
Equatorial Guinea	0	0	0	0	0	0	
Eritrea	42.6	32.6	10.1	42.6	32.6	10.1	
Ethiopia	290.7	288.1	2.6	405.3	288.1	117.2	Namara et al. (2013)
Gabon	4.5	4.5	0	4.5	4.5	0	
Gambia	1.4	1.4	0.010	1.4	1.4	0.010	

(Continued)

Table 1. (Continued).

Country	Siebert et al. (2010) Total irrigated area[a]	Siebert et al. (2010) Area irrigated by surface water	Siebert et al. (2010) Area irrigated by groundwater	This study Total irrigated area	This study Area irrigated by surface water[b]	This study Area irrigated by groundwater	Source for data on 'Area irrigated by groundwater-This study' (when different from Siebert et al. (2010)
Ghana	54.7	42.7	12.0	228.7	42.7	186.0	Namara et al. (2013)
Guinea	94.9	94.5	0.46	94.9	94.5	0.46	
Guinea-Bissau	22.6	17.7	4.9	22.6	17.7	4.9	
Kenya	97.0	96.0	0.97	174.5	96.0	78.5	Mumma, Lane, Kairu, Tuinhof, & Hirji (2011)
Lesotho	0.067	0.0.17	0.050	0.067	0.017	0.050	
Liberia	2.1	2.1	0.011	2.1	2.1	0.011	
Madagascar	1080.7	1080.7	0	1080.7	1080.7	0	
Malawi	54.1	54.1	0.030	74.0	54.1	19.9	Namara et al. (2013)
Mali	176.8	176.1	0.75	181.1	176.1	5.0	Abric et al. (2011)
Mauritania	22.8	20.4	2.4	22.8	20.4	2.4	
Mauritius	20.8	15.6	5.2	20.8	15.6	5.2	
Mozambique	40.1	39.8	0.22	40.1	39.8	0.22	
Namibia	7.6	5.9	1.6	7.6	5.9	1.6	
Niger	65.6	64.4	1.2	80.5	64.4	16.2	Abric et al. (2011)
Nigeria	218.8	154.8	64.0	337.8	154.8	183.0	Abric et al. (2011)
Rwanda	8.5	8.4	0.085	8.5	8.4	0.085	
São Tomé and Príncipe	9.7	9.7	0	9.7	9.7	0	

(*Continued*)

Table 1. (Continued).

Country	Siebert et al. (2010)			This study			Source for data on 'Area irrigated by groundwater-This study' (when different from Siebert et al. (2010)
	Total irrigated area[a]	Area irrigated by surface water	Area irrigated by groundwater	Total irrigated area	Area irrigated by surface water[b]	Area irrigated by groundwater	
Senegal	69.0	62.1	6.9	69.0	62.1	6.9	
Seychelles	0.20	0.20	0	0.20	0.20	0	
Sierra Leone	10.0	9.9	0.15	10.0	9.9	0.15	
South Africa	1498.0	1370.7	127.3	1713.3	1370.7	342.7	Pietersen, Beekman, & Holland (2011)
Sudan (N&S)	800.0	770.3	29.7	800.0	770.3	29.7	
Swaziland	44.9	44.0	0.90	44.9	44.0	0.90	
Togo	6.3	6.2	0.046	6.3	6.2	0.046	
Uganda	5.9	5.8	0.059	5.9	5.8	0.059	
United Republic of Tanzania	189.0	171.6	17.5	189.0	171.6	17.5	
Zambia	155.9	149.3	6.6	253.0	149.3	103.8	Pavelic, Giordano, Keraita, Rao, & Ramesh (2012); Mayerhofer, Shamboko-Mbale, & Mweene (2010)
Zimbabwe	123.9	109.6	14.3	180.6	109.6	71.0	Pavelic, Giordano, et al. (2012)
Total	5, 436.6	5, 108.1	328.5	6, 356.9	5, 108.1	1, 248.8	
Groundwater as fraction of total			0.06			0.20	

[a]Siebert et al. (2010) statistics consider only two categories of water sources for irrigation: surface water and groundwater.
[b]The surface water irrigated area was kept constant from Siebert et al. (2010) estimate, assuming that GWI is the most significantly growing irrigation sector presently (Giordano et al., 2012).

cases by factors of 660 and 45, respectively. Similar but smaller underestimations were found for Ghana, Kenya, Niger and Zambia (Table 1). In all countries, values from recent field investigations, where available, were always higher than official statistics. This implies that similar tendencies can be expected for the remainder of the countries in SSA, and hence our data may still be underrepresenting the reality. General underestimation is likely even though some of the figures updated include irrigation categorized as smallholder "lift irrigation", which could also include irrigation from surface-water sources (in the case of Ethiopia, Ghana and Malawi) or "smallholder irrigation" (in Burkina Faso, Mali, Niger and Nigeria). The total figure for GWI area is 1,248,800 ha, representing 20% of the total irrigated area in SSA (Table 1), significantly higher than earlier estimates of 6% and 10% (Giordano, 2006; Siebert et al., 2010). According to this analysis, the total GW-irrigated area has almost quadrupled (from 328,500 ha). Assuming, alternatively, that one-third of the increase in countries with data for "lift irrigation" and one-fourth of the increase in countries with data for "smallholder irrigation" are attributable to GWI – and applying the average rate of increase from these countries (except two outliers) to the rest of the countries without updated information – yields a total GWI acreage of 1,222,200 ha, or 19% of the irrigated area. Though independent data are required to verify increases in individual countries from the second method, the data suggest a significant transition in irrigation preferences among farmers.

The potential of groundwater irrigation in Sub-Saharan Africa

Despite recent expansion, irrigation in SSA (irrespective of source) is limited, compared to most other regions of the world. Only 3.3% of arable land (approximately 6 million ha) is irrigated, compared to 37% in Asia (Siebert et al., 2010). Hence, there is ample room for expanding areas under irrigation (Foster & Briceño-Garmendia, 2010). You et al. (2010) estimated the potential contribution from small-scale irrigation (e.g. ponds, small reservoirs, rainwater harvesting, and groundwater) in Africa to be anywhere from 0.3 to 16 million ha, based on a distributed multi-criteria analysis. They also found that the internal rate of return on investment in small-scale irrigation was significantly higher than for large-scale (dam-based) irrigation schemes (You et al., 2010). They did not estimate the specific contribution of groundwater. Only recently has dedicated research addressed this resource, mostly in terms of its physical limits. Pavelic, Smakhtin, Favreau, and Villholth (2012) developed a simple catchment water balance–based method for estimating allocation limits to GWI (translated also into GWI areas depending on crop water requirements) as residuals of annual groundwater recharge after accounting for existing demands, including domestic, livestock, industrial and environmental. They applied this approach to two catchments in Sahelian West Africa with good data to illustrate the considerable scope for further GWI development in these areas (Pavelic, Smakhtin, et al., 2012). A subsequent application at the national scale for 13 countries in SSA illustrated that all countries have variable but significant potential for GWI expansion, in total an area of 13 million ha, potentially serving 26 million additional smallholder households (Pavelic, Villholth, Smakhtin, Shu, & Rebelo, 2013). Hence, groundwater may not restrict development in these countries, at least in the short term.[2] This is encouraging and warrants further investigations into best options and locations, while not neglecting local conditions and impacts that may differ from the national results.

To further refine assessments, mapping of relative development potential at distributed sub-national scales has been attempted in Ethiopia (Awulachew, Erkossa, & Namara, 2010; Santini, Peiser, & Faurès, 2012) and Ghana (Evans, Giordano, & Clayton, 2012; Forkuor, Pavelic, Asare, & Obuobie, 2013; Gumma & Pavelic, 2012). The three Ghana studies adopt a hydrogeological, a hydrogeophysical, and a biophysical suitability approach, respectively. Even granting that the objective of Forkuor et al. (2013) was broader, on the potential for adoption of small motor pumps (including for surface-water pumping), the three studies arrive at inconsistent and sometimes diverging results, illustrating the complexities of data availability, interpretation, mapping and verification of results. Still, it highlights the need to combine and integrate socio-economic approaches, such as market options, infrastructure and livelihoods options, into the more typical hydrogeological and geophysical studies.

Table 2 gives key figures relevant for GWI development in 14 selected SSA countries. These figures relate to economic growth, poverty (here "hunger index" [von Grebmer et al., 2012] as a proxy for the need for increased food productivity), current irrigation development, groundwater resources availability and accessibility, cost of development, and a couple of infrastructure parameters that reflect the degree of rural development ("Share of population without access to electricity" and "Proportion of good rural road networks"). A first observation is that all countries except South Africa have low shares of irrigated land.

For a simple multiple objective analysis, the countries can be grouped into four overall groups with respect to GWI development potential and scope. The first are relatively arid countries with low resource endowments, where only localized GWI development may make sense (Kenya and South Africa). The slightly more GW-affluent countries (Mali, Niger and Tanzania), though semi-arid, have zones of various extents where (further) GWI may be feasible and desirable, considering poverty levels. The next group contains more promising countries: Burkina Faso, Ethiopia, Ghana, Malawi, Mozambique, Nigeria and Zambia. These are low-income countries (perhaps excepting Ghana and Nigeria) with rapid current GWI development yet with untapped physical potential. In accordance, some of these countries exhibit low and falling prices of GWI development (Xenarios & Pavelic, 2011). In the last category are Rwanda and Uganda, countries with relatively low aridity (NB: high aridity index), signifying less need (under present population and climate conditions) for irrigation and hence little documented development of GWI (Table 1). Most of the remaining countries in SSA probably fall into one of these four categories. Table 2 further shows that the 14 countries vary significantly in electrification rates and proportion of good rural networks, factors that could significantly influence GWI uptake, making simple generalizations or recommendations based on constraints inappropriate. As an example, Ghana generally has both good roads and relatively good electrification. Mozambique is quite the opposite. Burkina Faso has good roads but poor electrification, while nearby Nigeria has good electrification but poor roads. Constraints to GWI development will be discussed later in this paper.

Groundwater irrigation typology

While the focus in this paper is on GWI for smallholders, groundwater is accessed through diverse schemes, varying by scale, funding source, ownership of land and resources, type and depth of groundwater utilized, crops grown, degree of market orientation and systems used to extract the groundwater. A simple typology that encompasses the most prominent forms of GWI in SSA is suggested in Table 3, which distinguishes between two overall parameters: depth of the groundwater utilized and funding source. According to this classification, which may not be exclusive or exhaustive, smallholder schemes fall under Types 2, 3 and 4. Type 1 represents larger-scale (>100 ha), mechanized, often export-oriented crop

Table 2. Key figures related to groundwater irrigation in selected countries in SSA.

Country	Country-level GDP[a] (US$/capita)	Hunger index[b] (% decrease, 1990 – 2012)	Aridity index[c]	Non-irrigated arable land[d], Mha	% of arable land irrigated (SW+GW)[d]	GW irrigated land[e], 1000 ha	GW renewable resource[d], km^3/yr, (m^3/yr/cap.)	Share of land w. sufficient aquifer yield[f], %	Cost of drilling[g]: Per well, US$ (depth of wells)	Cost of drilling[g]: Per m, US$	Share of pop. w/o electricity access[h]	Proportion of good rural road network[i], %
Burkina Faso	663	17.2 (26.8)	0.38	5.9	0.42	30.0	9.5 (543)	100	10,000–20,000 (40–60m)	166–500	90	63
Ethiopia	359	28.7 (32.0)	0.45	13.7	2.1	117.2	20.0 (231)	95	8,000–26,700 (60–100 m)	136–258	85	33
Ghana	1528	8.9 (58.4)	0.73	4.3	1.2	186.0	26.3 (1030)	79	6000 (60 m)	100	46	51
Kenya	850	19.3 (6.8)	0.34	5.3	1.8	78.5	3.5 (82)	96	8,400–21,000 (700–300 m)	70–120	85	49
Malawi	350	16.7 (42.8)	0.69	3.5	1.5	19.9	2.5 (157)	100	5000 (50 m)	100	91	41
Mali	668	16.2 (41.7)	0.15	6.2	2.8	5.0	20.0 (1226)	94	14,260–36,800 (30–58m)	320–641	83	–
Mozambique	582	23.3 (34.4)	0.58	5.0	0.79	0.22	17.0 (695)	94	4,900–7,900 (31–55m)	136–166	88	18

(Continued)

Table 2. (Continued).

Country	Country-level GDP[a] (US$/capita)	Hunger index[b] (% decrease, 1990 – 2012)	Aridity index[c]	Non-irrigated arable land[d], Mha	% of arable land irrigated (SW+GW)[d]	GW irrigated land[e], 1000 ha	GW renewable resource[d], km^3/yr, (m^3/yr/cap.)	Share of land w. sufficient aquifer yield[f], %	Cost of drilling[g]: Per well, US$ (depth of wells)	Cost of drilling[g]: Per m, US$	Share of pop. w/o electricity access[h]	Proportion of good rural road network[i], %
Niger	399	22.3 (38.7)	0.06	14.9	0.44	16.2	2.5 (150)	92	–	157–503	91	31
Nigeria	1490	15.7 (34.9)	0.66	33.7	0.64	183.0	87.0 (522)	52	3,300–13,000 (50 m)	66–260	53	14
Rwanda	605	19.7 (30.1)	0.77	1.3	0.65	0.085	7.0 (621)	100	–	–	95	0
South Africa	8066	5.8 (15.9)	0.33	12.9	10.4	342.7	4.8 (95)	92	2,618–4,761 (50–200 m)	13–95	25	31
Tanzania	553	19.3 (16.8)	0.61	9.8	1.9	17.5	30.0 (630)	64	5,000–13,500 (50–100m)	100–193	89	31
Uganda	477	16.1 (13.9)	0.70	6.6	0.09	0.059	29.0 (814)	35	11,000	183	91	0
Zambia	1413	23.3 (6.0)	0.59	3.2	4.7	103.8	47.0 (3385)	93	2,600–55,000 (30–120m)	86–458	81	16

[a]GDP: Gross Domestic Product. Wikidepia (2013).
[b]von Grebmer et al. (2012).
[c]Global Potential Evapotranspiration (Global-PET) and Aridity Index (Global-Aridity). CGIAR-CSI (2009). AI < 0.65: Arid/semi-arid areas with high aridity.
[d]FAO (2013).
[e]This study, see Table 1.
[f]Assuming an aquifer (well) yield of 0.5 l/s as a lower threshold for feasible smallholder irrigation (Pavelic et al., 2013; MacDonald, Bonsor, Dochartaigh, & Taylor, 2012).
[g]Pavelic, Giordano, et al. (2012a). These figures pertain to deep wells (most likely motorized drilling). Shallow manual well drilling will be cheaper (Abric et al., 2011).
[h]UNDP-WHO (2009).
[i]Foster and Briceño-Garmendia (2010).

Table 3. Typology of GWI systems.

<table>
<tr><td colspan="2"></td><td colspan="3">Depth of wells[a]</td></tr>
<tr><td colspan="2"></td><td colspan="2">Deep</td><td>Shallow</td></tr>
<tr><td rowspan="4">Funding source</td><td rowspan="2">Private[b]</td><td colspan="2">1. Commercial, larger-cale, mechanized, export-oriented</td><td>2. Informal, small-scale, farmer-driven</td></tr>
<tr><td>Examples:</td><td>Flower farms in Ethiopia, Center-pivot grain farms in Zambia</td><td>Vegetable growing schemes in Northeast Ghana</td></tr>
<tr><td rowspan="2">Public[c]</td><td colspan="2">3. Deep systems, subsidized</td><td>4. Shallow systems, subsidized</td></tr>
<tr><td>Examples:</td><td>Public schemes in Raya-Kobo in Ethiopia</td><td>Fadama systems in Nigeria</td></tr>
</table>

[a]Somewhat arbitrarily, the following distinction has been made: Deep wells are >20 m deep (typically drilled wells), shallow wells <20 m deep (typically dug wells).
[b]Investment derived from the farmers themselves.
[c]Investment is derived from external sources, like the public sector, NGOs, international donors, etc.

production, such as flower farms in Ethiopia (Pavelic, Giordano, Keraita, Rao, & Ramesh, 2012), grain producers in the outskirts of Lusaka, Zambia (Mayerhofer, Shamboko-Mbale, & Mweene, 2010), and similar systems in Zimbabwe and South Africa (Masiyandima & Giordano, 2007; Pietersen, Beekman, & Holland, 2011). Type 2 is characterized by private development of shallow groundwater by the farmers themselves, usually individually or in small groups, typically using rudimentary wells and extraction means, like ropes and buckets or human- or animal-operated mechanical pumps. With low capital investments, these systems, exemplified by the floodplain and valley-bottom systems of the Upper East Region of Ghana (Dittoh et al., 2013; Namara et al., 2011), are financed by the farmers themselves. Type 3 is deep-well public systems supported by government, donors or non-governmental organizations (NGOs) for groups of farmers, as seen in the Raya-Kobo Valley in Ethiopia (Ayenew, GebreEgziabher, Kebede, & Mamo, 2013; Gebregziabher, Yirga, & Namara, 2013) and Maunganidze in Zimbabwe (IFAD, 2007). Finally, Type 4 is exemplified by shallow well smallholder schemes subsidized with irrigation structures and input from the public sector, donors and NGOs, such as the *fadama*[3] systems in Nigeria, supported since the 1990s mostly by the World Bank (Abric et al., 2011; Nkonya, Phillip, Mogues, Pender, & Kato, 2010). Key figures for some smallholder schemes are given in Table 4. These will be further discussed in the remainder of this paper.

Agronomic and socio-economic aspects and impacts of GWI

Numerous studies indicate that farmers favour GWI, as the resource is always available and they have autonomy over its control. This leads to lowered risk in investments for other inputs (seeds, fertilizers and energy), which in turn leads to intensification, diversification,

Table 4. Data from irrigation cases, including GWI, in SSA, with focus on smallholder systems.

Country, region	Irrigation started	Plot size per HH[a] (ha)	GW depth, well type	Combined w. rainfed?	Lifting device, irrigation device	Crops, GWI season	GWI practitioners	Land tenure	GWI type (cf. Table 3)	GWI dev. stage[b]	Farming w. highest productivity[c]	External financial support	Reference
Ethiopia Raya-Kobo Valley	>1995	~ 0.25	Deep, wells (60-170 m)	Yes	Elec. pumps, furrow/ buckets/ sprin-kler	Onion/ tomato/ pepper Dry season	Smallholder farmers	Lease/ share cropping/ own	3	2	Motor pump irrigation from GW	Partly gov't/ NGOs	Gebregziabher et al. (2013); Ayenew et al. (2013); Abate (2006)
Ghana Upper East Region	1890's	0.01–0.21	Shallow, dugouts/ HDWs[d]	Yes	Rope and buckets	Tomato/ onion/ pepper Dry season	Mostly women and youth	Lease	2	1	Bucket irrigators from GW	Limited	Obuobie, Ofori, Agodzo, & Okrah (2013); Namara et al. (2013); Dittoh et al. (2013)
Niger Niamay Capital District	>1990	0.13	Deep + shallow, various	Yes	Hand/ foot pumps, buckets	Onion/ tomato/ cabbage Dry season	2/3 women	Individual/ collec-tive	2	1	GW irrigation	Partly gov't/ NGOs	Torou et al., 2013
Nigeria Northern Nigeria	>1993	0.5–1.0	Shallow, bore-holes	Yes	Motor pumps, flooding	Onion, cabbage, pepper, tomatoes All year	Smallholder farmers	Individual/ lease	4	2-3	GW irrigation	World Bank/ Gov't	Abric et al. (2011); Nkonya et al. (2010); Dabi (no year)

[a]HH: Household; [b]GWI development stage acc. to Deb Roy and Shah (2003). 1 signifies early stages of groundwater development while 4 indicates mature and over-development of groundwater; [c]Gross revenue per ha; [d]HDW: Hand-dug well.

higher and more stable outputs, and higher productivity and net incomes (per area under cultivation and per labour input) as compared to rainfed or surface-water systems (for SSA, see Shah et al., 2013; Dittoh et al., 2013).

GWI is almost exclusively utilized in high-value horticulture production for market (mostly vegetables and to a smaller degree fruits, flowers, herbs, etc.), and rarely for staple and non-food crops. This reflects the higher production costs, including labour, of GWI, increasing market demands for horticulture crops, higher suitability of smaller irrigated and intensively managed plots, and greater willingness of farmers to risk pursuing higher-value crops. Contrary to common arguments for increasing irrigation in SSA, smallholder GWI does not appear to be converting rainfed staple crops (i.e. grain) to being irrigated, even on a supplementary basis (Shah et al., 2013). What is observed generally is that groundwater supports dry-season irrigation on separate (often much smaller) dedicated plots, for garden-style crop production. Often, rainfed cropping and the irrigated gardens coexist and combine to serve the livelihood strategies of the farmer households (Dittoh et al., 2013) by addressing their needs for a more diversified and nutritious diet. Often, women take a primary role in irrigated gardening while men focus on rainfed (Namara et al., 2013; Shah et al., 2013; van Koppen, Hope, & Colenbrander, 2013). Livestock, often partly dependent on groundwater for their drinking water and fodder production, also forms an important source of income, food and wealth security for many of the smallholder systems observed, depending on factors such as climate, population density, traditional production systems, land tenure, soils and culture.

In the Upper East Region of Ghana, Dittoh et al. (2013) found that farmers using groundwater by manual means obtained at least 20% higher net revenues per area irrigated than those using pumps or surface water (Table 4). Similarly, Kamwamba (2012) found that value added per area for GWI (pump or manual) was at least twice that of other irrigation systems in Malawi. It also provided the largest value added per labourer. Kamwamba-Mtethiwa, Namara, de Fraiture, Mangisoni, and Owusu (2012) found that treadle-pump users using shallow groundwater or surface water in Malawi were better off than non-adopters. Ajayi and Nwalieji (2010) found a significant increase in the number of farmers in higher income brackets upon adoption of vegetable production as a result of the *fadama* interventions in Nigeria. Abate (2006) found similar but less well-documented results in the deep-well irrigation schemes in the Kobo Valley in Ethiopia. However, for various reasons, crop productivity from GWI (Abric et al., 2011) still lags behind international benchmark standards FAOSTAT (2013).

GWI may not unilaterally alleviate poverty for the poorest segment of farmers. While Namara et al. (2011) found that small farmers in Ghana significantly improved their livelihoods through access to GWI – and local rural societies were stabilized through reduced distress migration due to increased livelihoods and employment opportunities – in a later study, they found that direct GWI benefits in other areas mostly accrued to the wealthier farmers (Namara et al., 2013). Although treadle pumps support irrigation livelihoods, they do not significantly alleviate labour for lifting water (Kamwamba, 2012), nor are they commonly available to the poorest or to women (Adeoti, Barry, Namara, Kamara, & Titiati, 2007; Kamwamba-Mtethiwa et al., 2012). Most studies focusing on distributional impacts of irrigation development, including GWI, find that farmers adopting motor-pump irrigation are better off than exclusively rainfed farmers or adopters of other types of irrigation (Kamwamba, 2012; Namara et al., 2013; Shah et al., 2013). However, such studies fail to account for *ex ante* differences between groups, and hence they are inconclusive as to whether the uptake of GWI alleviates poverty or simply maintains or aggravates existing wealth disparity (Kamwamba-Mtethiwa et al., 2012).

Women farmers, either as sole heads of households or as married companions to their husbands, participate in and derive benefit from groundwater irrigation (van Koppen et al., 2013). Limited results suggest that GWI may suit well the roles and capabilities of women. However, while preliminary findings suggest that GWI is also benefiting women, they also suggest that women are disadvantaged due to the lack of secure land tenure, as traditionally they have no right of land inheritance (van Koppen et al., 2013; Torou et al., 2013). Hence they are limited in obtaining loans (Wahaj, Hartl, Lubbock, Cleveringa, & Nepveu, 2007) and thereby acquiring irrigation equipment. This may partly explain why female-headed households have smaller plots irrigated by groundwater and tend to use manual methods for lifting water (Kamwamba, 2012; Namara et al., 2013; Shah et al., 2013; van Koppen et al., 2013). Also, female farmers may have less labour available than men, due to the generally smaller size of female-headed households (Naugle & Sellen, 2006; van Koppen et al., 2013). Traditional "women's" chores such as fetching water and firewood further reduce the time that can be devoted to other activities (Coulter, Kebede, & Zeleke, 2010). Hence, gender-related factors may cause GWI to underperform its expected potentials. These findings point to the need to consider gender and distributional aspects in order to understand statistics of GWI adoption rates and poverty impacts, and to derive appropriate and acceptable recommendations for further support in order to increase equality in access to water, land, credit and technology. Preliminary research indicates that where women farmers are favoured in grant and credit schemes, positive outcomes are achieved for the overall communities (van Koppen et al., 2013).

Constraints to further groundwater irrigation development

In analyzing the constraints facing poor farmers in increasing productivity from groundwater-irrigated crop production in SSA, one may distinguish between direct factors that are specific to accessing groundwater and ones that are indirect and linked to common constraints faced by farmers, such as knowledge and markets for purchasing inputs and selling outputs. Villholth, Ganeshamoorthy, Rundblad, and Knudsen (2013) proposed such a generalized framework, essentially building on a value-chain concept, in which GWI is seen as an input to individual food-crop value chains as well as the outcome of its own value chain.

Direct constraints refer to accessing groundwater by means of wells and lifting devices. The techniques used depend on groundwater and hydrogeological conditions. For shallow, high-yielding aquifers, very simple technologies can be applied, such as manual digging and human lifting of water. In this case, the primary constraint is the availability of labour. Deeper drilling and various types of mechanized pumps may be more common as they become available or necessary due to groundwater-level decline. In this phase or in areas with deeper groundwater, a major constraint for small farmers is access to mechanized technologies.

Pumps

Although no data exist on the distribution and prevalence of the various types of pumps at the regional level, preliminary research indicates that most smallholder GWI in SSA at present is done with manual lifting and small pumps using diesel or petrol (Abric et al., 2011). In Malawi, motorized pumping is used on 2800 ha, while treadle pumps (driven by human foot power) contribute to 13,000 ha (Namara et al., 2013). In a larger survey in two of the nine regions in Ethiopia, Namara et al. (2013) found that 31% of farmers used water-lifting devices. Of these, 84% used buckets, while 16% used motor pumps. The major advantage of motorized pumps is their considerably greater capacity to lift water, making it possible to expand irrigated surface areas. Their major disadvantages include higher capital and recurrent costs (for fuel and maintenance) (Perry, 1997). Namara et al. (2013) found diesel to be the energy source most used for motor pumps in Ethiopia, followed by petrol and then electricity, reflecting the unit cost and availability of these sources in the rural areas. Pump prices range from USD60 to USD360 for human-powered pumps and from USD80 to more than USD2000 for motorized pumps (3–5 hp) (Abric et al., 2011). Pumps are increasingly imported from South-East and East Asia (China and India), displacing Europe and Japan (Perry, 1997), which are higher-cost sources (Abric et al., 2011; Colenbrander & van Koppen, 2013).

Pump rental markets have emerged among smallholders (Namara et al., 2013), but groundwater sales by well owners to non-owners, as reported in parts of India (Mukherji, 2004), have not been documented in SSA, presumably because of lower population and irrigation intensity.

The pump supply chains are underdeveloped and unsustaianable in a variety of ways. The provision of sales and services is concentrated in urban areas (Colenbrander & van Koppen, 2013); spare-part availability is unreliable; quality control is limited; and supply diminishes or breaks down altogether after supportive external project interventions end (Abric et al., 2011). Large travel distances present farmers with high transaction costs in acquiring pumps (Takeshima, Adeoti, & Salau, 2009).

Wells

Well construction can be classified into three types: manual digging (superficial water only), manual drilling (mostly shallow wells, less than about 20 m and through unconsolidated materials) and motorized drilling (mostly deep drilling and through harder formations), with costs increasing from the rudimentary to the more advanced technologies. Abric et al. (2011) show prices for low-cost shallow manual drilling in West Africa as approximately one-tenth of prices given for deep wells (Table 2). Hence, manual drilling has been promoted and adopted widely in West Africa as a suitable approach for smallholder irrigation (Abric et al., 2011). UNICEF and International Development Enterprises have produced maps of appropriate areas for manual drilling (IDE, 2013; UNICEF, Practica, & and Enterprise Works, 2011).

Credit and capital

Capital is the largest constraint faced by poor farmers in SSA in accessing new technology. Farmers can draw from their own savings, borrow from family, use remittances or sales of farm proceeds, go to private money lenders, obtain loans from formal credit institutions, or benefit from different subsidy or donation models. Subsidies have been broadly used for pumps, wells, fertilizers, energy and other inputs (e.g. Abric et al., 2011), theoretically increasing the chance of favouring the poorest. Unfortunately, they often do not (Wiggins & Leturque, 2010). Also, subsidies tend to distort the market and to generate a culture of dependency (Naugle & Sellen, 2006). They also undermine policies of water and energy demand management (Rosegrant & Perez, 1997). Treadle pumps tend not to be used as efficiently when subsidized as they are when purchased with farmers' own funds (Abric et al., 2011). Where subsidies are used, they need to be "smart": targeted to those who need them; limited in time; and designed to enhance rather than supplant commercial production and distribution (Wiggins & Leturque, 2010). Furthermore, ensuring a degree of consistency and transparency in subsidy schemes across various initiatives and programmes is critical to their success (Abate, 2006; Abric et al., 2011).

Direct grants or subsidies for GWI development have been applied in Ethiopia (Gebregziabher et al., 2013), Zimbabwe (deep wells) (IFAD, 2007) and Nigeria (shallow wells) (Abric et al., 2011), among others. Though the public investments are viable over the service life of the projects, outsourcing, especially for deep well interventions, is costly and not economically sustainable for the public sector (Gebregziabher et al., 2013). It is estimated that the total investment costs of the *fadama* systems in Nigeria have been USD1650/ha (Abric et al., 2011), just less than a suggested optimal upper limit for capital investment in small-scale irrigation of USD2000/ha (Foster & Briceño-Garmendia, 2010), while capital costs (including power transmission lines and concrete distribution canals) of USD10,940/ha for deep-well systems were found in Zimbabwe (IFAD, 2007), and USD4900/ha (including electric power and powerhouse and installation for drip and sprinkler systems) in Ethiopia (Gebregziabher et al., 2013). Gebregziabher et al. (2013) propose a cost-sharing mechanism through long-term pay-back to the government from the smallholder farmers to sustain financial viability. No experience with such recovery schemes yet exists.

Loans from formal credit institutions are often out of reach of farmers, both physically, as these facilities are not present in the rural areas, and financially, due to high interest rates and farmers' lack of collateral (Chokkakula and Giordano, 2013). There is a large potential for micro-finance schemes that specifically target rural households for irrigation investments (Chokkakula and Giordano, 2013; Colenbrander & van Koppen, 2013); yet little attention has been paid to supporting GWI. Present impediments include lack of diffusion of micro-finance to rural areas and lack of knowledge of GWI technologies by lenders (Colenbrander & van Koppen, 2013). Ideally, micro-finance would be designed to break the persistent land-tenure constraints that disadvantage small farmers, especially women, in getting access to credit. Also, tax and duty exemptions on imported pumps for smallholders could improve their availability (Colenbrander & van Koppen, 2013; Giordano et al., 2012)

Energy

Energy for mechanized groundwater pumping typically comes from fossil fuels or electricity. Electrical pumping has lower running costs and is cleaner (Pavelic, Giordano et al., 2012), but it is constrained by low rural electrification rates, which average about 12% in SSA (Table 2) (Energy for Development and Poverty Reduction, 2013). Naturally, groundwater use and irrigation tend to increase with rural electrification, as seen in South Africa, Kenya and Ethiopia (Pavelic, Giordano et al., 2012). Similarly, mechanized GWI was significantly promoted by public fuel subsidies in Nigeria, lowering the cost of fuel to one-half to one-third that of neighbouring countries (Abric et al., 2011). Promoting rural electrification, combined with rational supply and pricing policies, is an efficient way of promoting GWI development. While individual metering of use entails excessive transaction costs, alternative approaches of flat-rate tariffs for individuals or groups of users, combined with restriction and separation of power for irrigation (Pietersen et al., 2011) would show promise in the SSA context. The current prospects for using alternative energy sources like biofuels and solar power for irrigation are limited but should be further explored (Abric et al., 2011; Burney, Woltering, Burke, Naylor, & Pasternak, 2010).

Land tenure

Insecure land tenure is consistently mentioned as a constraint to the further development of small-scale irrigation (CAADP, 2009; Namara et al., 2011; Shah et al., 2013). But this issue is not easy to address, as tenure is highly complex and diverse across the settings, with local arrangements often bound to traditional and informal regulations. Land tenure rights are often highly skewed towards the wealthier farmers. Where much of the land is rented or under communal tenure, smallholder insecurity hampers irrigation expansion (IFAD, 2007). Recent large land acquisitions by foreign investors tend to support large-scale farming, and so are also affecting smallholders' access to cultivated land or water (Allan, Keulertz, Sojamo, & Warner, 2012).

Markets for produce

To be profitable, GWI must be used for cash crops. Cash crops need markets. Those in turn necessitate a demand for the crops, proximity to outlets, reliable road infrastructure, and options for selling the crops at favourable prices. Generally, increasing urbanization and diversified diets, general economic development, and increasing means for and interest in processed food have increased the demand for vegetables and fruit in SSA (Perry, 1997). Limited road networks, especially in the rural areas (Foster and Briceño-Garmendia (2010) (Table 2), restrict accessibility to markets, except for increasing peri-urban agriculture (FAO, 2011). Because they lack storage facilities and telecommunication capabilities, smallholder farmers often find themselves trapped in inferior negotiating positions and selling at low prices to middlemen at times of oversupply (Chokkakula and Giordano, 2013; Villholth, Ganeshamoorthy et al., 2013). The proliferation of mobile phones is quickly remedying the telecommunication and information barriers in many areas (How we made it in Africa, 2012).

Groundwater resources: availability, assessment and impacts

Groundwater resources are generally plentiful in SSA (MacDonald et al., 2012) and still developed to a smaller extent, traditionally, and most critically for rural domestic water supply (Carter & Beven, 2008). However, their sustainable exploitation is limited by replenishment rates (even more than by storage capacity), extractability in some regions, and groundwater's role in the hydrological cycle and as a provider of environmental services (Colvin, Le Maitre, Saayman, & Hughes, 2007). Hence, with the ongoing rapid expansion of groundwater use for irrigated agriculture and emerging evidence of resource degradation in groundwater-dependent agricultural areas (Hagos, Ayenew, Mamo, & Ade, 2013; Ngigi, 2009; Pietersen et al., 2011), it is imperative that environmental sustainability issues are critically examined and accounted for in the planning, development and management of GWI.

Much smallholder GWI in SSA, especially when fully farmer-driven, occurs on an opportunistic, unregulated basis, with little regard to the resource endowment. Even in larger government and donor-driven development, either little prior comprehensive assessment of the groundwater resource potential is carried out (Abric et al., 2011) or significant uncertainty in estimates prevails (Gebregziabher et al., 2013). In a few cases, an emerging broader conceptual, qualitative and quantitative understanding of the groundwater systems is accompanying development, for example in Ghana (Obuobie, Ofori, Agodzo, & Okrah, 2013), Niger (Favreau et al., 2009) and Ethiopia (Ayenew et al., 2013). Hence, dedicated and integrated studies are required to comprehend the circulation patterns of groundwater at various scales as well as the possible impacts of development and factors such as climate change and land use modifications that affect the resource base (Taylor et al., 2010; Villholth Tøttrup, Stendel, & Maherry, 2013). While development of the knowledge base and of the resource run in parallel for GWI, the knowledge generated does not necessarily feed into planning and is mostly unrelated to investigations of socio-economic aspects, missing the wider issues of integrated sustainability (Silliman, Hamlin, Crane, & Boukari, 2008).

The negative impacts of groundwater development on agriculture include depletion and degradation of the resource as well as potential social conflicts. In arid and semi-arid areas, salt accumulated in upper soils due to evapotranspiration on previously uncultivated land may generate transitory salt leaching and soil and groundwater contamination upon clearing and irrigation (Favreau, Seidel, Leduc, Marlin, & Mariotti, 2004). The major issue in most cases, however, relates to overdrafting of groundwater, leading to continuous lowering of the groundwater level and increasing costs of exploitation (Abric et al., 2011), as well as potential effects on groundwater-dependent surface water bodies (Hagos et al., 2013). Conflicts with non-farmers and with those drawing their drinking water from the same resource, especially during drought, are likely (Coulter et al., 2010, Hagos et al., 2013).

Often, the source of the water used for irrigation is unclear. In the primary phases of development and for rudimentary systems, groundwater is often drawn from shallow aquifers, many of which (as with the *fadama* systems) are in direct connection with surface-water systems. Hence, there is a need to recognize the complementarity of these resources, their interconnectedness, and the scope for planned conjunctive use, to increase water use efficiency, mitigate undesirable fluctuations in water supply, and control shallow water-table levels and soil salinity (Evans & Evans, 2012, Foster & van Steenbergen, 2011). This may to some extent already be ongoing in an unplanned manner, as farmers with access to motorized pumps find themselves enabled to access multiple water sources in an opportunistic manner. The importance of such access transcends groundwater, empowering farmers to extend their domain of water control. However, issues of well siting (Carter, Chilton, Danert, & Olschewski, 2010; MacDonald, Davies, & Dochartaigh, 2001), drilling technologies (Abric et al., 2011) and maintenance of wells and pumps (Furey & Danert, 2012) are particular to GWI in SSA and still cause concerns for overall sustainability.

Policy and institutional aspects of groundwater irrigation

International and regional development policies increasingly favour smallholder GWI (Abric et al., 2011; CAADP, 2009), but these are not reflected in national policies and institutions. Ethiopia does have significant, almost unrealistically optimistic, plans to expand groundwater development, including for irrigation (Ministry of Water Resources, 2011), but, as in many countries, institutional capacities are insufficient and roles are unclear. Often, GWI falls between the mandates of the agricultural and WASH (water, sanitation and hygiene) sectors. In addition, irrigation planning continues to favour large-scale public surface water schemes, or (e.g. in Ethiopia) community-based government-driven groundwater development (CAADP, 2009; Chokkakula and Giordano, 2013). Farmer-driven smallholder GWI receives little recognition or support. Chokkakula and Giordano (2013) argue that an excessive focus on regulation under the guise of integrated water resources management (IWRM) is at fault. Whatever the current paradigm, the real culprit is more likely inertia in irrigation development strategies and planning, reflecting vested professional and bureaucratic interests. Smallholder GWI development will require policy makers to recognize that the state can be a facilitator of individual initiative as well as a regulator.

Discussion and conclusions

Sub-Saharan Africa is finally catching up with GWI development after lagging behind other developing economies (Shah, Burke, & Villholth, 2007). The estimated expansion of 248,800 ha to 1,177,000 ha over a 7-year period corresponds to growth rates in India in the beginning of the 1960s (Narayanamoorthy, 2010). Concurrently, a wealth of knowledge has been generated over the last decade through the dedicated research reviewed in this paper. Groundwater irrigation is very popular among farmers, and may presently be expanding at a higher rate than other types of irrigation (Frenken, 2005). Hence, smallholder GWI may well be a suitable and socio-economically acceptable alternative and supplement to large-scale surface water irrigation. However, a number of issues remain to be resolved:

- Getting a better understanding of the extent and depth of the benefits and the socio-economic context and variable forms under which smallholder GWI exists across SSA
- Understanding the residual potential for GWI as a resource while avoiding negative environmental impacts from increased use
- Developing better ways to mainstream GWI development through well-targeted, integrated, informed and feasible interventions
- Building the human and institutional capacity to manage groundwater and GWI at various levels

Presently, the high economic barriers faced by smallholder farmers imply that (1) the poorest farmers are unlikely to initially adopt and directly benefit from GWI;[4] and therefore that (2) increased attention must be devoted to credit and financing schemes that lower this barrier, especially for women and marginalized groups, who constitute a significant proportion of farmers.

Further promotion of smallholder GWI requires the consideration of various models of support, as indicated in Table 3, while taking into account resource conditions and financing options. There is a trade-off between the shallow, informal systems (Types 2 and 4) and the deep, more formal systems (Types 1 and 3). The deeper systems tend to provide more secure and perennial water availability, but require larger initial investments, higher maintenance and stricter farmer organization to deal with water sharing (the latter particularly for Type 3). The public sector also tends to have better control of implementation, farmer training, and monitoring of deep systems, whilst farmer-driven informal systems tend to be spontaneous, autonomous and still largely unrecognized by the public sector.

Whether support comes in the form of direct investment in deep wells or indirect subsidies to farmers for shallow ones, the reviewed research uniformly affirms the fundamental nature of supplemental support to enabling factors, such as energy, credits or subsidies for agricultural inputs, infrastructure for transport and markets, and extension services on cropping, irrigation, marketing and groundwater management (Lipton, Litchfield, & Faurès, 2003; Nkonya et al., 2010). One notable success story was an EU-funded project in Zimbabwe, where farmers risked investing in inputs to obtain higher yields and achieved a 265% increase in farm income due to the provision of an assured market by NGO-established grower associations and of reliable groundwater supplies (IFAD, 2007).

Ensuring community engagement, preferably empowerment, and local management of land and water resources should not be neglected. Despite GWI being primarily a private enterprise that benefits farmers individually, long-term viability often hinges on joint beneficiary action in areas such as management of land and water, marketing of produce, and negotiation for grants and policy change. Hence, building on existing organizations such as farmer groups or farmers' cooperatives may be more feasible for irrigation and groundwater management than the conventionally prescribed water user associations (Ghazouani, Molle, & Rap, 2012). Further, basic farmer education repeatedly emerges as influential for greater adoption and better outcomes of GWI (Burney & Naylor, 2012).

In sum, governments have to realize their dual role as facilitator as well as regulator in the development of GWI in SSA and this across relevant sectors. Understanding the groundwater resources and its users and managing them, require up-front attention and integration into policy and decision making. This becomes the more critical as larger shares of groundwater are being appropriated for agriculture.

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Notes

1. Sub-Saharan Africa is defined to include all of Africa with the exception of the North African countries of Algeria, Egypt, Libya, Morocco and Tunisia.
2. Population increases, welfare increases and climate change impacts have not been accounted for.
3. *Fadama* refers to the low-lying areas in Nigeria, where groundwater is shallow and in direct connection with surface-water systems that are flooded or waterlogged part of the year (Tarhule & Woo, 1997).
4. However, general agricultural development may still have an overall positive poverty alleviation impact, through for instance reduced food prices and increased labour options for the poorest (Lipton et al., 2003).

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