SUSTAINABLE EXPANSION OF GROUNDWATER-BASED SOLAR WATER PUMPING FOR SMALLHOLDER FARMERS IN SUB-SAHARAN AFRICA

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EFFICIENCY FOR ACCESS COALITION

Drip irrigation solar pump,
Mahalankudza garden,
Zimbabwe

Photographer: David Brazier / IWMI

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ABBREVIATIONS

CCA	Climate Change Adaptation
CLASP	Collaborative Labelling and Appliance Standards Program
EUR	Euro
GAR	Groundwater abstracted relative to annually available replenishable resource
GW	Groundwater
IoT	Internet of Things
IPCC	Intergovernmental Panel on Climate Change
IWMI	International Water Management Institute
kW	Kilowatt
LEIA	Low Energy Inclusive Appliances (Programme)
mg/L	Milligrams per Litre
Mha	Million Hectares
NGO	Non-Governmental Organisation
PAYGo	Pay-As-You-Go
PGM	Participatory Groundwater Management
PV	Photovoltaic
RCP	Representative Concentration Pathway
ROI	Return On Investment
SMEs	Small and medium-sized enterprises
SDGs	Sustainable Development Goals
SWP	Solar Water Pump
USD	United States Dollar
Wp	Watt Peak

CONTEXT

This study was undertaken under the Low Energy Inclusive Appliances (LEIA) programme and delivers on the project titled: 'Environmental sustainability of solar water pumping in Sub-Saharan Africa'. It also contributes to the CGIAR Research Program on Water, Land and Ecosystems (WLE).

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About Efficiency for Access

Efficiency for Access is a global coalition working to promote high performing appliances that enable access to clean energy for the world's poorest people. It is a catalyst for change, accelerating the growth of off-grid appliance markets to boost incomes, reduce carbon emissions, improve quality of life and support sustainable development.

Efficiency for Access consists of 17 Donor Roundtable Members, 16 Programme Partners, and more than 30 Investor Network members.

Current Efficiency for Access Coalition members have programmes and initiatives spanning 44 countries and 22 key technologies. The Efficiency for Access Coalition is coordinated jointly by CLASP, an international appliance energy efficiency and market development specialist not for-profit organisation, and UK's Energy Saving Trust, which specialises in energy efficiency product verification, data and insight, advice and research.

The Low Energy Inclusive Appliances programme is Efficiency for Access' flagship initiative.

Solar water pumps (SWPs) are a clean, modern irrigation solution that have the potential to improve livelihoods and food security for smallholder farmers across Sub-Saharan Africa. As small-scale SWPs become more affordable, this market is poised for growth. This study was undertaken to assess the potential risks to groundwater availability over the next decade and makes recommendations on how national governments and key solar and agricultural industry stakeholders can maintain groundwater use within sustainable limits.

As less than 6% of Sub-Saharan Africa's farmland is irrigated, there is a tremendous need to accelerate SWP adoption for irrigated agriculture, which can help increase crop yields, diversification and incomes that can have transformative development potential for rural communities. To achieve this potential, groundwater resources need to be used effectively and managed sustainably. At this comparatively early stage of SWP development, it is timely to review the situation, assess the current risks and establish how these may change for a range of foreseeable projections of growth. The focus here on groundwater is consistent with our review of published SWP case study information from 20 Sub-Saharan African countries indicating groundwater to be the main water source for irrigated agriculture, animal husbandry and domestic uses.

Sub-Saharan Africa's groundwater resources are largely untapped. If harnessed effectively through SWP adoption, these resources could benefit millions of rural households.

Current rates of groundwater use are generally low with substantial scope to expand the use of this resource. However, the region's hydrogeological systems are complex, and this strongly affects the groundwater potential. In some hardrock aquifer settings, the quantity of water that can be abstracted from a borehole or well may be low (0.5 litre per second or less) and will have a direct effect on the area that can be irrigated and crop choices. The quality of groundwater is generally adequate for most uses.

Whilst the small-scale (<1kW) SWP market is still in its infancy, it is growing steadily due to declining capital costs and expansion into new territories.

Sub-Saharan Africa has enormous potential, with significant solar energy, agricultural land and groundwater resources that provide the biophysical building blocks for the adoption of solar water pumps tailored to rural households and smallholder farmers. However, the market environment in each country is evolving from very different baseline levels of market penetration and water demand. Conservative estimates suggest SWP sales of up to 10,000 units per year as reported during 2019 and 2020, with the majority of sales in East African countries such as Kenya and Uganda.

Projected growth in small-scale SWP systems has been assessed not to pose a major threat to groundwater availability over the short to medium term. However, if there is accelerated adoption in excess of the growth scenarios considered, then groundwater availability may become a challenge in locations of concentrated development.

Using projected growth rates ranging from 6% – 18% per year, together with conservatively high rates of groundwater pumping for irrigation, the maximum proportion of the available (replenished) groundwater resource abstracted by SWPs over the next decade is estimated to range from 0.4 to 0.6% for Sub-Saharan Africa as a whole. Corresponding values across the region range from <0.1% for Central Africa through to 1.6 to 2.1% for Southern Africa. Individual countries can typically sustain the installation of tens of thousands up to millions of additional SWPs without affecting the availability of groundwater supplies adversely. Larger countries, with higher recharge rates and lower levels of existing groundwater use, can support the highest number of new SWP installations. Over the longer term, the risks to groundwater availability could be higher than assessed here if SWP growth goes beyond current projections or if technological advancements enable more powerful small capacity pumps to enter the market. Isolated cases of groundwater resource over-exploitation are already occurring within the region; although these maybe unrelated to SWP use.

This report provides a set of recommendations that address challenges in groundwater development and management. These should be prioritised according to the risks to groundwater availability in different regions and countries and tailored to the diverse hydrogeological, climatic, and socioeconomic conditions in the region.

Recommendations broadly cover technical, capacity building, research, and policy related areas to support groundwater management over the short, medium, and long term. Examples of priority areas of action and available resources to assist implementation are also provided. The public sector can focus on areas such as resource assessments, monitoring resource conditions, integrated water resources planning and allocation, land use and borehole planning, and strengthening institutions and policy. The private sector can complement these efforts by focusing on areas such as filling data gaps, providing irrigation and borehole drilling information and services, improving product design, and educating water users.

Groundwater sustainability is thus an achievable goal in an environment of expanded solar water pump development if productive partnerships are created between public and private sector players.

Photography: Aggrico

1. Introduction

1.1 Background and context

SUB-SAHARAN AFRICA FACES MAJOR DEVELOPMENTAL CHALLENGES YET ITS VAST UNTAPPED SOLAR ENERGY RESOURCES OFFER SUBSTANTIAL POTENTIAL FOR POSITIVE CHANGE THROUGH THE USE OF SOLAR WATER PUMPS TO IMPROVE WATER ACCESS.

Despite significant improvements in social and economic development over recent decades, Sub-Saharan Africa remains home to hundreds of millions of people who still lack access to basic requirements for human development: clean water, nutritious food, and reliable electricity[1]. Only 24% of the region's population have access to safe drinking water, and 28% have basic sanitation facilities[2]. Only 4% of the region's arable land is irrigated, compared with a global average of around 20%[3]. Overall, water withdrawals are relatively low, amounting to just 4% of replenishable water supplies, compared to 13% globally. Water used in Sub-Saharan Africa generates only USD 6.7 per cubic metre in gross value added to the continent's economy; well below the global figure of USD 15.2 per cubic metre[4]. The region also has the world's lowest rate of electricity access at only 32% across rural areas (in 2018)[5]. However, Sub-Saharan Africa has amongst the highest levels of solar energy resources globally[1].

Donors, investors and governments are prioritising the deployment of solar-powered water pump technologies in rural communities.

Improved access to reliable and affordable electricity align with the United Nations Sustainable Development Goals (SDGs) relating to local development and human capital. A growing body of studies, policies and initiatives support the view that solar technologies have a critical role in advancing the United Nation's 2030 Agenda for Sustainable Development[6,7,8]. Solar water pumps (SWPs) offer a relatively new technology for Sub-Saharan Africa that can contribute towards cross-sectoral development in meeting the basic requirements for health and wellbeing by helping to progress no fewer than seven of the SDGs: SDG 1 (No Poverty); SDG 2 (Zero Hunger); SDG 3 (Good Health and Well-being); SDG 5 (Gender Equality); SDG 6 (Clean Water and Sanitation); SDG 7 (Affordable and Renewable Energy); and SDG 13 (Climate Action)[9].

Solar technologies are especially well-suited to water pumping since any electric pump can be powered by a solar array and hence, sized and operated according to the local availability of solar energy, land and water resources.

Substituting fuel-powered pumps with solar-powered pumps in turn offsets virtually all greenhouse gas emissions from pumping water. Being of relatively low cost, and suited to incremental development, SWPs may be successfully implemented in often remote villages to provide a reliable source of water and energy and thereby contribute positively towards rural electrification[10].

Africa's installed solar capacity has been increasing exponentially since about 2014 due to significant reductions in the cost of solar photovoltaic (PV) panels in recent years[11] (Figure 1.1).

Governments, with the support of donors and investors in many Sub-Saharan African countries are prioritising pro-poor approaches to ensure energy security through renewable technologies, particularly those harnessing solar PV technologies, with the aim of establishing sustainable food production and livelihoods[12]. A recent study by the Malabo Montpellier Panel – a group of agricultural experts guiding policy to accelerate progress towards food security and improved nutrition in Africa – stresses that "unlocking SSA's irrigation potential has to be a crucial component of strategies to improve farmers' resilience and livelihoods, and of meeting broader national and international food security and nutrition targets"[12]. Furthermore, solar technologies, including solar water pumps, represent an opportunity for progress toward climate goals expressed in the 2015 Paris Agreement and ratified by almost all Sub-Saharan African countries. Expanding smallholder irrigation affordably, effectively and sustainably using solar pump technologies would offer a powerful means of improving food security, addressing rural poverty and building resilience to climate-related uncertainties[13]. For example, SADC, through its Regional Strategic Action Plan (SADC RSAP) has committed to increase its irrigated area from 3.4 Mha to 10 Mha (i.e., 13% of the potential land available) in the coming years[14].

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1. IAE (International Energy Agency) (2019) Africa Energy Outlook 2019. World Energy Outlook Special Report. www.iea.org/africa2019

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3.Campbell B., Rijsberman F. and Smith M. (2019) Is solar irrigation set to take over Africa? https://ccafs.cgiar.org/blog/solar-irrigation-set-take-over-africa#.X5Amo9AzZPY

4.FAO (2018) Progress on Water-use Efficiency: Global baseline for SDG indicator 6.4.1. Food and Agricultural Organization of the United Nations and United Nations Water, Rome. http://www.fao.org/3/CA1588EN/ca1588en.pdf

5.World Bank, Sustainable Energy for All (SE4ALL) database: https://data.worldbank.org/indicator/EG.ELC.ACCS.RU.ZS?locations=ZG

6. Hartung H. and Pluschke L. (2018) The benefits and risks of solar-powered irrigation: A global overview. Food and Agriculture Organization of the United Nations, Rome. http://www.fao.org/documents/card/en/c/I9047EN/

7.Otoo M., Lefore N., Schmitter P., Barron J. and Gebregziabher G. (2018) Business model scenarios and suitability: Smallholder solar pump-based irrigation in Ethiopia. Agricultural Water Management – Making a Business Case for Smallholders. Colombo, Sri Lanka: International Water Management Institute (IWMI). 67p. (IWMI Research Report 172). doi: 10.5337/2018.207

8.IRENA (2015) Africa 2030: Roadmap for a Renewable Energy Future. The International Renewable Energy Agency, Abu Dhabi

9.Efficiency for Access Coalition (2019a) Solar Water Pump Outlook 2019: Global trends and market opportunities. Report prepared by CLASP / Energy Saving Trust / Dalberg, September 2019, 32p. https://efficiencyforaccess.org/publications/solar-water-pump-outlook-2019-global-trends-and-market-opportunities

10. Wazed S.M., Hughes B.R., O'Connor D. and Calautit J.K. (2018) A review of sustainable solar irrigation systems for Sub-Saharan Africa. Renewable and Sustainable Energy Reviews 81: 1206–1225

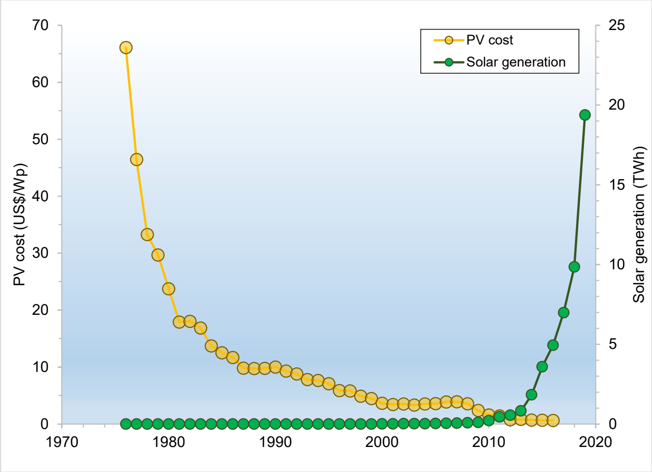
11.Costs declined by more than 80% between 2000 and 2012

12.Malabo Montpellier Panel (2018) Water-Wise: Smart Irrigation Strategies for Africa. https://www.ifpri.org/publication/water-wise-smart-irrigation-strategies-africa

13.Lefore N., Giordano M., Ringler C. and Barron J. (2019) Sustainable and equitable growth in farmer-led irrigation in sub-Saharan Africa: What will it take? Water Alternatives 12(1): 156-168

14.https://www.sadc.int/files/9914/6823/9107/SADC_Water_4th_Regional_Strategic_Action_Plan_English_version.pdf

Figure 1.1 Global solar panel prices and installed PV capacity in Africa
Source: https://ourworldindata.org/energy



The market for small-scale solar water pumps in Sub-Saharan Africa remains nascent, but is developing steadily.

There is broad consensus that the SWP market will expand steadily in many Sub-Saharan African countries over the coming decade. At the same time, some qualification on this growth is warranted under the current global scenario[15]. Solar water pumping provides rural households, including smallholder farmers, with a potentially cost-effective and sustainable source of energy to secure water supply, food production, sustain livelihoods, and build human resilience to climate risks. Sub-Saharan Africa's disproportionately high levels of food insecurity are due, in part, to uncertainty in rainfall patterns and lack of adaptive capacity due to limited irrigated agricultural land. Drought is endemic to much of the region, and climate change will further exacerbate the unreliability of growing seasons due to changes in rainfall patterns, variable temperatures and extremes in heat[16].

Sub-Saharan Africa's untapped groundwater resources potentially represent a major opportunity to enable more widespread SWP adoption but needs to go hand in hand with greater emphasis on groundwater governance.

It would appear that the majority of documented small-scale SWPs currently installed in Sub-Saharan Africa rely on shallow groundwater supplies[17], owing to the ubiquity of these resources.

There is consensus that Sub-Saharan Africa's groundwater resources are, on the whole, vastly underutilised, thereby providing considerable scope for expanding productive use through solar pumping if these resources were developed effectively and managed well[18,19,20,21]. Sub-Saharan Africa's groundwater reserves are estimated to be 20-fold greater than all surface water held above ground in lakes and reservoirs[22]. While all major freshwater resources have a role in providing domestic, livestock irrigation supplies, groundwater resources could be of critical importance to unlock the solar market in Sub-Saharan Africa and improve the welfare of small farm households.

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[15] Growth is expected to rebound following the easing of disruptions to manufacturing and trade caused by the current global COVID-19 pandemic and unfolding economic crisis that has stymied SDG progress

[16] IPCC (2014) Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [C.B. Field et al. (Eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 32p

[17] A key finding from Section 2 of this report

[18] Cobbing J. (2020) Groundwater and the discourse of shortage in Sub-Saharan Africa. Hydrogeology Journal 28: 1143–1154

[19] Xu Y., Seward P., Gaye C., Lin L. and Olago D.O. (2019) Groundwater in Sub-Saharan Africa. Hydrogeology Journal 27: 815–822

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[21] MacDonald A.M., Bonsor H.C., Dochartaigh B.É.Ó. and Taylor R.G. (2012) Quantitative maps of groundwater resources in Africa. Environmental Research Letters 7: 024009, 7p

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A scenario of significant expansion of groundwater use, even from a low baseline, could pose potential sustainability risks that warrants careful analysis. To reduce the risks, groundwater governance must be enhanced, taking account of pump market development.

Donors and other investors' interest and investment in SWP growth has received some scrutiny due to concerns associated with potentially unacceptable social and environmental impacts[23]. The problems associated with groundwater depletion in many regions of the world (including South Asia; Box 1.1) are well-known and well-documented[24]. There are, of course, potential concerns that Sub-Saharan Africa may be prone to similar issues in a scenario of rapid and uncontrolled expansion in groundwater use. Risks to groundwater resources could intensify if:

(a) technological advancements allow more powerful small pumps to enter the market – powered by solar as well as more conventional diesel or electric pumps – that may lead to significantly enhanced volumes of water pumped;

(b) large-scale government- or donor- driven efforts to promote SWPs eventuate in future growth beyond current projections;

(c) more severe and frequent occurrence of drought with significant impact on recharge of groundwater.

Further, solar pumps can operate for around 8 –12 hours of sunshine per day[25] (potentially longer with battery storage) at almost no marginal cost and can add to, or replace, diesel pumps that require costly fuel. Solar pumps can also, in theory, remain operational even when water is not needed or can be used to grow high water-demanding crops or expand land under irrigated agriculture[26]. There are few incentives for solar pump users to use their systems judiciously. Hence there is a risk that SWPs could lead to the depletion of shallow groundwater or a range of other impacts (Table 1.1).

Table 1.1. Potential environmental risks associated with uncontrolled growth of groundwater-based irrigation using small-scale solar water pumps

Quantity	**Quality and health**	**Environment**
• Unsustainable reduction of ground-water levels from shallow aquifers • Reduced environmental stream flows • Seawater intrusion (in coastal areas)	• Pollution of groundwater due to excessive applications of fertilisers and pesticides • Salinisation of irrigated soils • Unintended mobilisation of contaminants naturally present in aquifers	• Deterioration of environmental services in rivers, wetlands and floodplains

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[23] Efficiency for Access Coalition (2019b) Solar water pump technology roadmap. May 2019, 43p. https://efficiencyforaccess.org/publications/solar-water-pump-technology-roadmap

[24] Wada Y., van Beek L.P.H., van Kempen C.M., Reckman J.W.T.M., Vasak S. and Bierkens M.F.P. (2010) Global depletion of groundwater resources. Geophysical Research Letters 37, L20402. DOI: 10.1029/2010GL044571

https://www.sadc.int/files/9914/6823/9107/SADC_Water_4th_Regional_Strategic_Action_Plan_English_version.pdf

[25] CLASP (2019) Global LEAP Awards: 2019 Buyer's Guide for Solar Water Pumps. https://clasp.ngo/publications/2019-global-leap-awards-buyers-guide-for-solar-water-pumps

[26] Flammini A., Bracco S., Sims R., Cooke J. and Gomez San Juan M. (2019) Measuring impacts and enabling investments in energy-smart agrifood chains: findings from four country studies. FAO and GIZ

BOX 1.1


Photography: Aggrico

Lessons from groundwater depletion in South Asia for Sub-Saharan Africa

Per capita availability of groundwater in Sub-Saharan Africa is higher than most South Asian countries, although substantial variations exist across the region. However, the extent of groundwater use, particularly for irrigation, is many-fold lower than South Asia and scope for sustainable expansion exists provided these resources are effectively managed.

The need to improve Sub-Saharan Africa's groundwater management is also made clear by the isolated cases where resource exploitation is already occurring. Nairobi is a case in point in an urban context while examples due to intensive commercial agriculture include Kajiado District in Kenya and the Limpopo Basin karstic aquifers of South Africa.

South Asia is a region with rapidly growing populations and economies. It is also the biggest user of groundwater globally, accounting for nearly one-third of the groundwater abstracted globally and half the groundwater abstracted globally for irrigation. Since the advent of the Green Revolution in the 1960s, energy and pump subsidies stimulating groundwater irrigation has lifted hundreds of millions of people out of poverty. Groundwater is also critical to rural, urban, and industrial water supplies and remains essential for building climate resilience.

At the same time, intensive and largely unregulated pumping has threatened these benefits, as tens of millions of hectares of land have been affected by declining groundwater levels. In addition, groundwater contamination from constituents naturally present in groundwater such as arsenic, fluoride and salinity, as well as from sewage, industrial effluent and agricultural chemicals are further threatening the resource. This increases costs of access due to water treatment requirements and causes significant human health impacts.

Source: World Bank[27], Tuinhof et al. (2011)[28]

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[27] World Bank (2020) Managing Groundwater for Drought Resilience in South Asia. World Bank, Washington, DC

[28] Tuinhof A., Foster S., van Steenbergen F., Talbi A. and Wishart M. (2011) Appropriate groundwater management policy for Sub-Saharan Africa: In face of demographic pressure and climatic variability. GW-MATE Strategic Overview Series Number 5, 40p. https://openknowledge.worldbank.org/handle/10986/27363

1.2 Study objectives

This study presents a big-picture assessment of the potential risks to groundwater availability from small-scale SWP expansion over the next decade at the Sub-Saharan African and regional levels. It proposes a set of recommendations on how national governments can work with key solar and agricultural industry players to maintain groundwater use within sustainable limits.

With market penetration of SWPs in Sub-Saharan Africa still in its infancy but growing steadily, the timing appears opportune to: (1) review the state of affairs and determine the potential risks to groundwater that increasing rates of adoption of small-scale solar water pumping technology could affect over the next decade; and (2) propose measures to ensure that the expansion of small-scale SWP systems does not compromise groundwater sustainability[29]. Groundwater sustainability has been defined by the U.S. Geological Survey as "the development and use of groundwater resources to meet current and future beneficial uses without causing unacceptable environmental or socioeconomic consequences"[30].

The study involves a review of existing literature combined with analytical assessments that cover the following:

1. Insights from well-documented SWP case studies across Sub-Saharan Africa (Section 2)
2. SWP market trends and potential (Section 3)
3. Impacts of SWP growth on groundwater availability (Section 4)
4. Risk management framework for sustainable SWP expansion and sustainable groundwater use (Section 5)
5. Conclusions and recommendations (Section 6)

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[29] Omisore A.G. (2018) Attaining Sustainable Development Goals in sub-Saharan Africa: The need to address environmental challenges. Environmental Development 25: 138-145

[30] Alley W.M., Reilly T.E. and Franke O.L. (1999) Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186

Photography: Shell Foundation

Photography: Simusolar

2. Insights from solar water pumping case studies

A systematic and comprehensive review of 69 case studies of SWP systems applied to multiple uses from 20 Sub-Saharan African countries was carried out, which provided a robust dataset to gather key learnings. A summary of the key learning is given below, while a more detailed appraisal of the case studies is provided in Annex 1.

SWP systems perform better when a range of enabling conditions are addressed which rely on inputs from a range of different actors. The conditions that facilitate better SWP uptake include financing mechanisms such as PAYGo to reduce the upfront costs of SWPs, building female farmers' capacity to grow existing, high value crops and marketing, farmer awareness and technical training (installation, maintenance), and recognition of reduced labour expenses (Table 2.1a). Implementation falls within the responsibility of the users (primarily farmers), governments and the private sector. Opportunities for promoting more sustainable groundwater use rely on the use of tools and technologies such as water accounting models, hydro-meteorology networks, low-capacity pumps, and irrigated area mapping to match water supply with demand (Table 2.1b). This is facilitated by a range of different actors including end-users, governments, private sector. There was an absence of detailed and systematic studies to demonstrate the impacts of the different factors on SWP performance and water use.

Table 2.1a. Lessons for enhancing effective SWP adoption arranged according to various enabling conditions
The number of reviewed cases identified are given in rectangular brackets: ' [ ] '.

Factor	Examples from the cases	Participating actors
Availability and use of water	•High borehole yield, physical water availability [4] •Storing of water and energy to secure water availability during pump inactivity or when there is less sunshine [19]	Farmers
Access to agricultural value chains	•High value crops (e.g., vegetables), secured access to markets, seeds, and agro-chemicals for pest management, and reduced post-harvest losses [2] •Reduced labour [12] •Improved health, education, and poverty alleviation [11]	Farmers, government, private sector
Access to SWP supply chains and markets	•Blending of solar distribution with financing–developed markets, including equipment installation and after-sales services in sales for SWP [3] •Metrics to assess SWP equipment quality [2]	Private sector, government, farmers
Availability of end-user financing	•High diesel/fuel price encouraging farmers to move to SWP [14] •Mobile financing, secured incentivising micro-finance intermediaries in remote markets [5] •Innovative business models by SWP distributors/ manufacturers are key in promoting the adoption of SWPs, e.g., PAYGo systems, appliance financing, willingness to invest by farmers [3] •Security of SWPs from theft [2] •Reduced SWP upfront costs [5]	Private sector, government, farmers
Awareness-raising, technical assistance and capacity building	•Customised training for women e.g., on high value crops, markets, etc. [11] •Using drip to grow crops compared to sprinkler and drip-irrigation to increasing yield with less water [2] •Raising awareness & technical training (installation, maintenance) [11] •Electing of community committee to oversee SWP operations [3]	Women and other farmers, government

Table 2.1b. Lessons for sustainable groundwater use at the individual SWP scale arranged according to various enabling conditions. The number of reviewed cases identified are given in rectangular brackets: ‘ [ ] ’.

Factor	Example from cases	Participating actors
Availability and use of water	•Pumping rates set to less than borehole yield to ensure sustainable pumping [19] •Use of storage to provide water buffer during cloudy periods to ensure water availability throughout the day [22] •Alignment between power and pump requirements for adequate solar water pumping [6] •Using drip irrigation to grow crops as opposed to sprinklers and furrow irrigation for increasing yield with less water [2] •Operating small SWPs throughout the day for low-yielding and shallow aquifers rather than high discharge diesel pumps [3] •Water accounting, hydro-met networks, irrigated area mapping [35]	Government, private sector, farmers
Availability of end-user financing	•Monthly or seasonal price or volume-based PAYGo [7] •Farmers/users pump less, so that they pay less especially when they do not have money to meet their pay-as-you-go obligations [3]	Private sector, government
Supportive policies	•Secured access to water resource rights to ensure access to bank financing [4] •Synergies between water-energy-food development policies, green bonds to fund projects with a positive environmental and/or climate benefit such as SWPs, borehole registration/drilling to keep record of abstraction points and borehole yield [2]	Government, private sector, NGOs
Awareness-raising, technical assistance and capacity building	•Awareness on available SWP products to ensure farmers choose appropriately to match water availability [4] •Digital advisory services on sustainable water extraction to reach larger numbers of farmers [4] •Metrics to measure the monetary (income) and non-monetary benefits (nutrition) and return on investments from SWP for farmers to provide evidence of success to funders and adopters [25]	Private sector, government, farmers

3. Irrigation trends and market potential

3.1 Irrigation trends and potential

SUB-SAHARAN AFRICA IS CHARACTERISED BY A LOW PROPORTION OF IRRIGATION DEVELOPMENT RELATIVE TO OTHER REGIONS.

Only 4-6% of Sub-Saharan Africa's arable land is irrigated, compared to 35% in Asia and 15% in Latin America[31] (Figure 3.1a). Furthermore, the area equipped for irrigation grew by just 1.5% between 1990 and 2015[12]. Despite slow growth, irrigation remains vital for food security in the region. Approximately 78% of Sub-Saharan Africa's large- and small-scale irrigation schemes use surface water, while only 20% use groundwater resources[32] (Figure 3.1b). This last figure may be an underestimate, as groundwater use is often significantly under-reported[33].

Over the past two decades, there has been a trend to move away from medium- and large- scale irrigation schemes towards small-scale irrigation development, operated by individuals or small groups, in a process known as 'farmer-led irrigation'[13, 34,35].

Nowadays, over 80% of irrigated land in Sub-Saharan Africa is comprised of small-scale, farmer-led irrigation systems. Groundwater also has a rapidly expanding role in small-scale irrigation across much of Sub-Saharan Africa and can be the main water source as indicated in Section 2 (but with notable exceptions for areas where reliable surface water is available).

Previous studies reveal high potential for expanding irrigated agriculture with groundwater supplies across Sub-Saharan Africa.

The first study, which did not specifically focus on SWPs, considered the available replenishable groundwater resources in relation to irrigation demands for a range of crop types. It estimated that the area of cropland irrigable with groundwater across Sub-Saharan Africa can be expanded by between 27 Mha and 64 Mha depending on the proportion of groundwater allocated for environmental services, or the equivalent of 13 to 30% of available cropland[36]. This groundwater irrigation potential may be met through a mix of small and larger scale developments. The groundwater irrigation potential (Figure 3.2) is distributed by regions as follows: West Africa (22%); East Africa (30%); Southern Africa (<1%); and Central Africa (48%).

The second study relied on a cost-comparison analysis that benchmarked the cost-effectiveness of water pumping systems powered by solar PV with conventional diesel pumping system in groundwater-fed irrigation under a range of scenarios[37]. The analysis showed that, from a financial viewpoint, the attractiveness of solar PV over diesel pumps is sensitive to farmer's crop choice, future diesel fuel price and solar PV installation cost. In many contexts, solar energy can serve as a more economical substitute for diesel energy to support the development of groundwater irrigation. For example, in maize cultivation, in a reference scenario with an escalation rate of future diesel fuel price of 2% and solar PV pumping system installed cost of USD 2.5 per Wp, solar irrigation is a more cost-effective option compared to diesel irrigation on more than 85% of cropland in Southern Africa, 65% of cropland in Central Africa and about 40% and 30% of cropland in West and East Africa, respectively. These percentages increase to approximately 90% and 80% in Southern and Central Africa and 60% in both West and East Africa if an installed cost for solar PV system of USD 2 per Wp is assumed. In East Africa, the adoption potential of solar irrigation is concentrated in South Sudan, Eritrea, Somalia, and Tanzania. Drip-irrigated tomatoes, onions, chickpeas and beans have similar life cycle costs compared to growing these crops in flood-irrigated scenarios. Understanding the opportunities, constraints and distribution of the emerging SWP market is key to promoting sustainable groundwater use.

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[31] IAASTD (International Assessment of Agricultural Knowledge, Science and Technology for Development) (2009) Sub-Saharan Africa (SSA) Report. Edited by B.D. McIntyre etal. https://www.globalagriculture.org/fileadmin/files/weltagrarbericht/IAASTDBerichte/SubglobalReportSubSaharanAfrica.pdf

[32] Relatively low use of groundwater reported within the irrigation sector as a whole should be differentiated from findings given in Section A1.1 that the majority of SWP cases are reliant on groundwater

[33] Giordano M. (2006) Agricultural groundwater use and rural livelihoods in Sub-Saharan Africa: A first cut assessment. Hydrogeology Journal 14(3): 310-318

[34] Shah T., Namara R. and Abhishek Rajan A. (2020) Accelerating irrigation expansion in Sub-Saharan Africa: Policy lessons from the global revolution in farmer-led smallholder irrigation. World Bank Washington, DC. https://www.iwmi.cgiar.org/Publications/Other/Reports/accelerating-irrigation-expansion-in-sub-saharan-africa.pdf

[35] Wiggins S. and Lankford B. (2019) Farmer-led irrigation in sub-Saharan Africa: synthesis of current understandings. London: Evidence & Policy Group of the DFID-ESRC Growth Research Programme,Overseas Development Institute

[36] Altchenko Y. and Villholth K.G. (2015) Mapping irrigation potential from renewable groundwater in Africa – a quantitative hydrological approach. Hydrol. Earth Syst. Sci. 19: 1055–1067

[37] Xie H., Ringler C. and Hossain Mondal M.A. (2021) Solar or diesel: A comparison of costs for groundwater-fed irrigation in Sub-Saharan Africa under two energy solutions. Earth's Future, 9, e2020EF001611. https://doi.org/10.1029/2020EF001611

Figure 3.1. Area equipped for irrigation expressed as a percentage of the total area (left) and area irrigated with groundwater expressed as a percentage of the total area equipped for irrigation (right)[38]

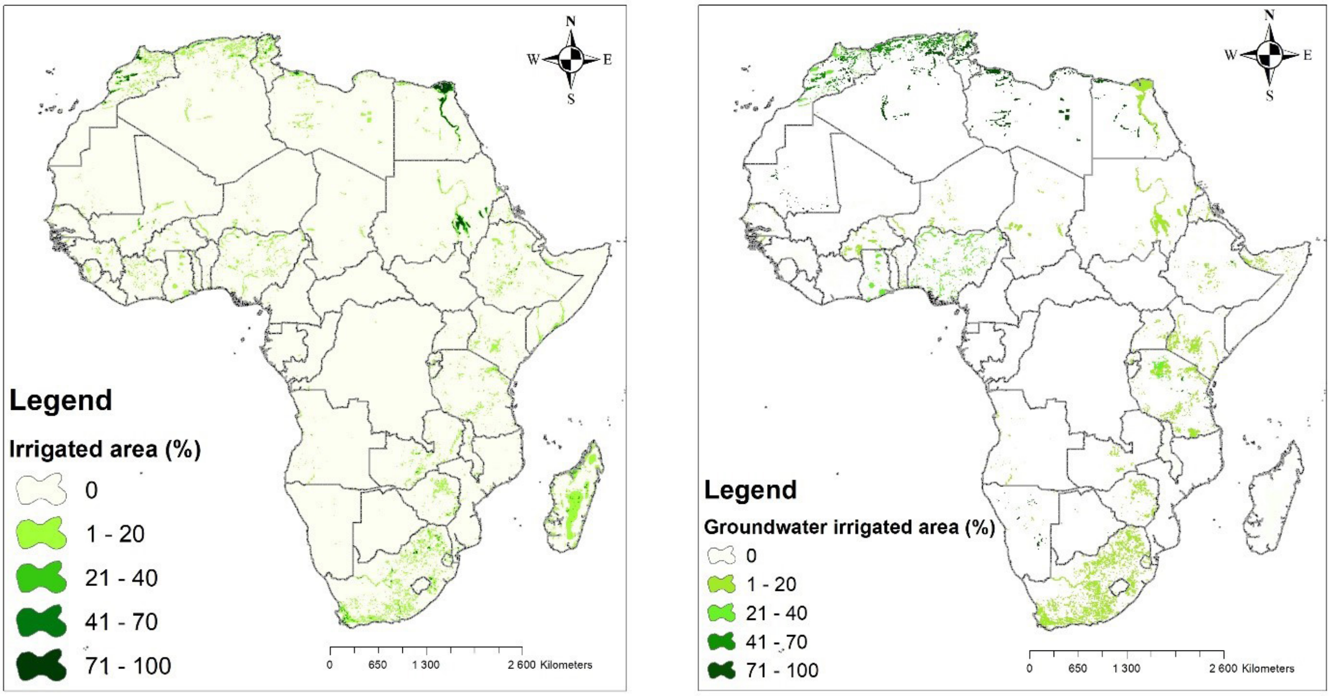
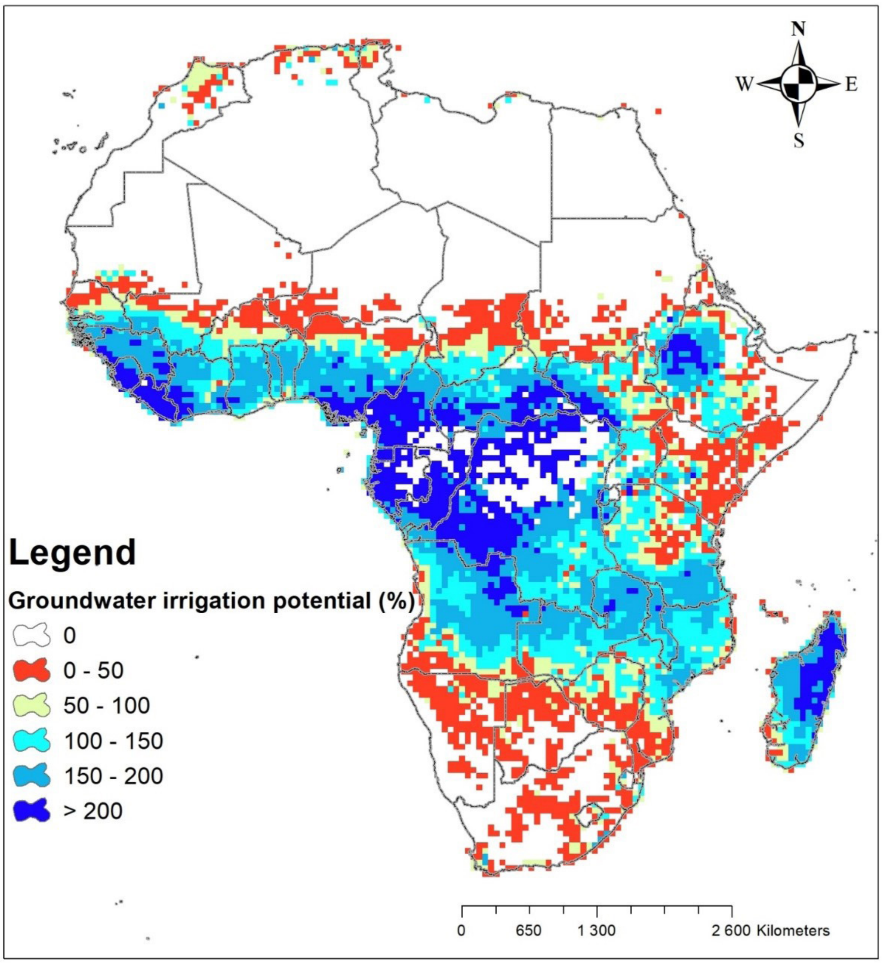


Figure 3.2 Groundwater irrigation potential in Africa expressed as the percentage of the area irrigated with groundwater

Source: Altchenko and Villholth[36]



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[38] Siebert S., Henrich V., Frenken K.andBurke J.(2013) Global Map of Irrigation Areas version 5. Rheinische Friedrich-Wilhelms-University, Bonn, Germany / Food and Agriculture Organization of the United Nations, Rome, Italy

3.2 Opportunities and constraints in the emerging SWP market

PRIVATE SECTOR COMPANIES AND INVESTORS PLAY A LARGE ROLE IN ENHANCING THE AFFORDABILITY AND ADOPTION OF SWPS.

SWP systems are a small but growing portion of the solar industry. SWPs are increasingly available in Sub-Saharan Africa's markets, driven to a large extent by early-stage, Sub-Saharan Africa-based companies developing and/or distributing off-grid solar technology and supported by distributors to reach geographically-dispersed customers[9,39]. These early-stage companies are leading the market for small-scale (<1kW) SWPs appropriate for smallholder farmers. Advances in solar-powered technologies and, to some extent, in financing ecosystems are helping to reduce upfront costs resulting in an increasing number of affordable pumps entering the market tailored to small-scale use with improved system capacity and efficiency[25].

The business case for SWPs geared towards irrigation mainly relies on favourable returns on investment (ROIs), which vary significantly across countries and for the specific crops grown.

In theory, SWP applications generate a good ROI and thus can be applied effectively in irrigated agriculture as well as livestock watering and domestic supply[39]. With costs for solar PV cells falling significantly over the past decade, the capital costs for small-scale SWP systems on the market range from approximately USD 400 to 2,000[23,39] although this may vary significantly across the region depending on transportation and import costs. Although the equivalent cost for a diesel pump is substantially less at around USD 200, high fuel costs mean that solar water pumps achieve lower life-cycle costs, with calculated payback times for solar applied to high-valued crops in Kenya as low as 12 to 18 months[9,39]. The calculated benefits to smallholder farmers due to increased yield from irrigation vary by crop, with higher ROIs generally reported for crops with shorter growing seasons enabling an increased number of harvests annually. For example, over two years, the ROI for solar water pumps range from 150 to 250% for horticulture farmers using 75-370W pumps[39]. In practice, the economic feasibility of SWPs for individual farmers depends on a large number of factors such as the depth to groundwater levels, solar pump type and sizing, land size, productivity gains, fuel cost savings and the seasonality/volatility of the crops grown. Modelling of the economics of SWPs for all three countries indicates that the payback time is generally less than one year[39].

Overcoming existing technical, financial, institutional and awareness related constraints is crucial to ensuring the viable adoption and expansion of SWPs.

Even when ROI is high, there are a range of technical and financial barriers that need to be overcome. A recent study by the International Finance Corporation assessed the viability of SWP for irrigation in three African countries: Kenya in the east; the Ivory Coast in the west; and Zimbabwe in the south[39]. In Kenya, uptake is growing rapidly; specialist providers/distributors and larger manufacturers are starting to enter the Sub-Saharan Africa market using Kenya as an entry point, and diffusion is already evident in neighbouring countries such as Uganda. In the Ivory Coast, the market penetration of SWPs remains very low to date, reportedly due to climate patterns and the market environment which makes water pump sales difficult for applications other than horticulture[40]. In Zimbabwe, SWPs are available, but adoption is limited. There are several distributors targeting smallholders, but affordability is a major constraint due to the limited opportunities for end-user financing of solar technologies and irrigation more generally.

Hence, the African SWP market is challenged by a number of constraints, which include weak SWP supply chains and services, inadequate financing mechanisms and financing ecosystems, complex technology and the high cost of drilling services (Box 3.1). The high costs of drilling boreholes and wells tends to prohibit the expansion of groundwater resources. It has also sparked innovation within the NGO sector to find effective and scalable lower-cost manual methods of construction of wells in countries such as Uganda[41] and Ethiopia .

Additionally, in many Sub-Saharan African countries, smallholder farmers are less familiar with the benefits that may emerge from SWP technologies, and how to incorporate irrigation technologies into farming[9,23]. A high proportion of Sub-Saharan African farmers operate with low levels of mechanisation at subsistence levels or sell limited quantities of produce to local markets, typically via informal traders. In the absence of direct subsidies and low smallholder farmer incomes characterising the region, the lack of affordability is an important market constraint in expanding SWP use[39]. Asset financing is rarely available in many situations and micro-finance institutions generally do not provide lending for irrigation equipment[43]. Furthermore, upfront payment and regular repayments can be unaffordable for smallholder farmers whose low incomes mean that they are unable to invest in assets that would otherwise enhance their productivity[44].

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39. International Finance Corporation (IFC) (2019) The market opportunity for productive use leveraging solar energy (PULSE) in Sub-Saharan Africa. https://www.lightingglobal.org/resource/pulse-market-opportunity/

40.This claim may be questioned given that the situation in Ivory Coast is not substantially different to that of other West African countries (e.g., Togo and Benin) where SWP sales are growing

41. https://www.practica.org/projects/low-cost-drilling-malawi/

42.http://www.huismanfoundation.nl/index.php?id=68

43.Merrey D.J. and Lefore N. (2018) Improving the availability and effectiveness of rural and "Micro" finance for small-scale irrigation in Sub-Saharan Africa: a review of lessons learned. Colombo, Sri Lanka: International Water Management Institute (IWMI). 46p. (IWMI Working Paper 185)

44.Gassner A., Harris D., Mausch K., Terheggen A., Lopes C., Finlayson R.F. and Dobie P. (2019) Poverty eradication and food security through agriculture in Africa: Rethinking objectives and entry points.

BOX 3.1

The high cost of borehole drilling

Small SWPs typically access shallow aquifers at depths of up to around 50 metres, but generally considerably less. However, there is interest in accessing deeper aquifers – typically up to around 100 metres deep – with higher and more reliable supplies than shallower aquifers. This is made difficult due to the prohibitively high cost of borehole drilling and energy needs for deep water pumping. Unit costs for boreholes in Sub-Saharan Africa typically ranged anywhere from USD 6,000 to 23,000 within individual countries and are considerably more expensive compared to Latin America or South Asia. The reasons for this are varied and include:

- small economies of scale with restricted competition within the sparse market
- high site set up / pack up costs due to the vast area covered, often with poor transport infrastructure
- low standards of service provision amongst drilling and pumping contractors
- high duties and taxes on imported drilling equipment, with limited manufacturing of spare parts;

Despite tentative forecasts that drilling costs could be reducing with higher competition, upgraded machinery and capacity-building within the industry, borehole installation remains far beyond the reach of most smallholders. Furthermore, the dearth of reliable information on aquifer characteristics leads to high uncertainty in aquifer potential and risk for smallholder farmers to invest in borehole drilling.

Overview of drilling costs of boreholes (BHs) in 10 Sub-Saharan African Countries

Country	BH Depth (metre)	BH Yield (m^3/hour)	Total costs (USD)
Burkina Faso	60 (± 6)	5 (± 4)	12,549 (± 1,631)
Ethiopia	100 (± 50)	5 (± 3)	23,268 (± 6,980)
Ghana	52 (± 30)	25 (± 18)	9,465 (± 2,389)
Kenya	80 (± 49)	5 (± 3)	20,906 (± 5,226)
Mali	100 (± 50)	6 (± 2)	15,462 (± 3,247)
Tanzania	75 (± 33)	11 (± 7)	16,540 (± 5,789)
Zambia	60 (± 24)	15 (± 4)	6,028 (± 1,507)
Niger	50 (± 40)	-	12,194 (± 4,878)
Nigeria	50(± 10)	1.5 (± 0.8)	6,241 (±1,248)
Mozambique	41(± 10)	5 (± 2)	8,672 (± 2,081)
Uganda	65 (± 20)	6 (± 2.4)	10,476 (± 2,095)

Source: Braune and Adams (2013)[45] ; Xenarios and Pavelic (2013) [46]

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[45] Braune E. and Adams S. (2013) Groundwater Governance: A Global Framework for Action (2011-2014). Regional Diagnosis for the Sub-Saharan Africa Region. Regional Diagnostic Report, Sub-Saharan Africa Region, 57p

[46] Xenarios S. and Pavelic P. (2013) Assessing and forecasting groundwater development costs in Sub-Saharan Africa. Water SA 39(4):529-537, doi: http://dx.doi.org/10.4314/wsa.v39i4.12

THERE ARE EMERGING OPPORTUNITIES TO OVERCOME ENTRENCHED FINANCIAL CONSTRAINTS TO SWP ADOPTION.

There is a clear need for innovative financing models that can address financial constraints to SWP adoption[7]. Private sector driven PAYGo models allow users to pay in smaller affordable instalments, and they are for households that otherwise would not be able to meet the high upfront costs. These business models, which combine mobile payment with decentralised power generation, are considerably advanced in several Sub-Saharan African markets. Across Sub-Saharan Africa, PAYGo sales represented over 70% of sales in the last 12 months of reporting prior to COVID-19[47]. Government or donor-driven targeted subsidies provide another channel to expand the market further[39]. New approaches are being tested to find solutions to promote gender equity in credit scoring for private sector financing (Box 3.2).

Harnessing market intelligence[48] may help overcome affordability constraints and facilitate scaling up. The Feed the Future Innovation Lab for Small-Scale Irrigation (ILSSI) project is an example of current efforts to identify and overcome systemic barriers to upscaling small-scale irrigation, including the testing of innovative finance modalities with solar companies to reduce barriers to access in several East and West African countries[49]. Efforts are also underway to accurately match specific SWP technologies with potential customers (i.e., farmers) and cropping systems in Kenya using GIS-based modelling approaches of varying scales and sophistication[50,51].

BOX 3.2

Promoting gender equity in private sector financing

Solar water pumping can bring significant benefits to women and help promote gender equity. Both women and men farmers tend to prefer SWPs compared to other water-lifting technologies due to the cost and/or labour savings offered. At the same time, there are entrenched barriers that could hinder adoption by particular social groups. Women in Sub-Saharan Africa make up around half of the agricultural labour force, yet gender-based constraints to financial resources (i.e., access to credit and formal banking, resource ownership) affect their ability to invest in solar pumping technologies for agriculture. Women also tend to lack information about using agricultural technologies when compared to men.

A recent assessment shows that credit scorecards used by distributors offering financial services use resource ownership and income as criteria to assess the potential of its clients, which marginalises most women as they are resource-poor. Furthermore, the income assessment does not account for on- and off- farm income related to activities that women undertake in the household such as firewood gathering/sales, charcoal production, basket weaving, handicrafts, and snail gathering/breeding. Including these income generating activities would help better estimate the purchasing power of women farmers.

Other ways to promote gender equity include tackling issues around financial management and literacy, social capital and access to infrastructure and extension services and storage facilities. Contractual features should include financial and non-financial indicators such as social capital and potential for future income. This would lead to customised contracts for individual- or group- based financing, thereby allowing women to pool their resources.

Source: Innovation Laboratory for Small Scale Irrigation[48]

47.Xenarios S. and Pavelic P. (2013) Assessing and forecasting groundwater development costs in Sub-Saharan Africa. Water SA 39(4):529-537, doi: http://dx.doi.org/10.4314/wsa.v39i4.12

48.GOGLA (2020a) Global Off-Grid Solar Market Report: Semi-Annual Sales and Impact Data. July - December 2019, Public Report. https://www.gogla.org/sites/default/files/resource_docs/global_off-grid_solar_market_report_h1_2019.pdf

49. Typically defined as the data collected by or for a company concerning a specific market it seeks to enter for the purpose of making investment-related decisions
https://ilssi.iwmi.org/

50.Factor[e] Ventures (2018) Solar water pump market sizing methods. Accelerating access to energy. www.factore.com

51. RTLAB personal communication

3.3 SWP sales trends and projections

RELEVANT MARKET RESEARCH WITH PARTICULAR EMPHASIS ON MICRO- TO SMALL- SCALE (50W TO 1KW) SOLAR PUMPS THAT CAN BE DEPLOYED BY SMALL FARM HOUSEHOLDS ARE DRAWN UPON HERE TO ESTABLISH SWP SALES TRENDS AND PROJECTIONS.

Seven studies of relevance have been identified and all but one were conducted over the past two years. This reflects growing interest in how solar technologies can help end-users achieve water and food security and enhance livelihoods for off-grid households (Annex 2). GOGLA has presented information on SWP sales in the past four bi-yearly reports[52]. GOGLA's reports showed that SWP sales for Sub-Saharan Africa have ranged from 2,900 to 4,900 units over the first three reporting periods to December 2019. Over the fourth reporting period for the first-half of 2020, total sales for Sub-Saharan Africa were just 2,700 units. This signals a significant decline in growth of SWPs due to COVID-19, with a rebound unlikely over the short term. These figures illustrate the modest level of sales to date and vulnerability of the market. The data reported by GOGLA only captures a proportion of actual sales by GOGLA-affiliated companies[53], noting that strict rule applied to reporting[54]. The market share represented by GOGLA affiliates is not yet well known due to insufficient data from the solar providers. Estimates of GOGLA's market share for all off-grid solar pico and solar home systems range from 7 to 97% of total sales across eight Sub-Saharan Africa countries, with the market share specific to SWPs somewhat more ambiguous[52].

Efficiency for Access' 2019 publication 'Solar Water Pump Outlook 2019: Global Trends and Market Opportunities'[9] provides valuable market demand estimates across countries and regions. It reveals that the current (2018) addressable market for small SWPs in Sub-Saharan Africa is around 0.7 million households and valued at USD 0.5 billion[55]. Over the next decade to 2030, SWPs have the potential to reach up to 2.8 million households at a value of approximately USD 1.6 billion.

GOGLA sales data up to the end of 2019 suggested that around 86% of sales activity takes place in East Africa consistent with documented case studies in Section 2, with only 14% in West Africa and no sales captured in either Central and Southern Africa[47].

The largest markets for SWPs were Kenya, Uganda, Senegal and Zimbabwe,[56] which collectively accounted for around 70% of total sales. At the moment, GOGLA does not report SWP sales for Nigeria although the country is reported to account for half of Sub-Saharan Africa's market[57].

Information provided by some of the leading companies in the SWP market also indicated that East Africa accounted for around 77% of the market, with West Africa making up the difference. Sub-Saharan African solar companies continue to expand into new territories. Futurepump[58], for example, currently distributes its low-cost solar water pumps for irrigating small farms (<1 ha) to 19 countries globally, mostly in Africa; up from just one country in 2015/16 with a total of > 8,000 pumps sold to date.

Sales of SWPs for irrigation in Ethiopia[59] reportedly increased by 20.3% in the previous three years[60]. However, it is important to note that this is starting from a very low base and largely driven by donor and NGO investments. That study also highlights that projecting from solar pump sales alone could be insufficient given the large potential to replace larger proportions of existing diesel-powered water pumps with solar if policy environments in specific countries were to shift in favour of solar technologies. In the four states of Ethiopia studied, there were reported to be around 157,000 motorised pumps installed.

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[52] GOGLA (2020b) Global Off-Grid Solar Market Report: Semi-Annual Sales and Impact Data. January - June 2020, Public Report (Table 5; page 111) https://www.gogla.org/sites/default/files/resource_docs/global_off_grid_solar_market_report_h1_2020.pdf

[53] Affiliates include GOGLA members and appliance companies associated with the Global LEAP Awards or Low Energy Inclusive Appliances (LEIA) programme

[54] GOGLA only report data where there are three or more separate manufacturers

[55] Assumptions made in defining the addressable market are given in Table 4.1

[56] Zimbabwe is tabled within East Africa by GOGLA, although it lies within the UN Subregion of Southern Africa

[57] Foster R. and Cota A. (2014) Solar water pumping advances and comparative economics. Energy Procedia 57: 1431 – 1436

[58] https://futurepump.com/

[59] No sales are captured by GOGLA affiliate companies for Ethiopia, however it is the third-largest market in SSA of one major solar company

[60] GIZ (Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH) (2020) Solar irrigation market analysis in Ethiopia. GIZ Energy Programme Ethiopia

3.4 Scenarios for projected sales

WE HAVE DEFINED SEVERAL ALTERNATIVE GROWTH SCENARIOS THAT ACCOUNT FOR KNOWN UNCERTAINTIES AND PROVIDE A PLAUSIBLE SET OF SWP SALES PROJECTIONS FOR THE NEXT DECADE.

The information presented in the earlier sections of this report illustrates that a promising market exists in Sub-Saharan Africa with reasonable prospects for growth in the solar water pump market. However, the specific trajectories of growth across countries are uncertain. Contributing factors include rates of progress on solar technology advancement, access to end-user financing, irrigation and agricultural market development, government policies and borehole drilling technologies and financing. SWP growth in the coming years may depend on how quickly Sub-Saharan Africa can recover from the COVID-19 pandemic, which is negatively affecting the labour market, start-ups and SMEs. The pandemic is also contributing to higher levels of poverty and inequality and is likely to reverse several years of development progress[61].

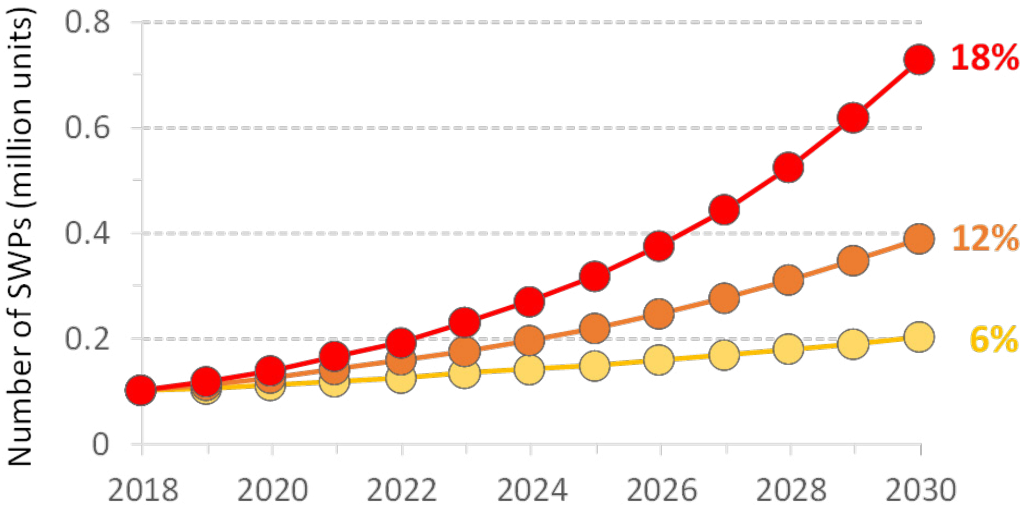
To address the lack of data on the small scale SWP market and the highly uncertain future market, a set of alternative scenarios of market projections for SWP sales are defined based, in part, on the Solar Water Pump Outlook and PULSE studies[9,39] which, together, provide the best available SWP market information for the whole of Sub-Saharan Africa. Based on the projections, it is estimated that the total serviceable market will grow by around 12% per year to 2030. This will be driven by the combined effects of rising income levels, growing rural population and electrification rates, and an estimated reduction in end prices of between 10 to 15%.

For this study, three market growth scenarios are given based on a growth of 12% (base case), along with 6% and 18%. Values of up to 18% growth have also been analysed to account for the unaccounted sales data and possible acceleration in sales due to unforeseen developments, such as new technologies, policies, donor investments etc. A more conservative growth rate of 6% is included in the event that the depression due to COVID-19 persists and markets fail to rebound for several years at least.

The total number of installed small SWP systems is assumed to be 100,000 given that GOGLA sales over the past two years have been less than 20,000 (although they do not represent the entire market). Thus, the total of 700,000 SWP systems previously reported[9,39] have been significantly downscaled as they reflect the addressable 'unrealised' market and not actual sales. Downscaling Sub-Saharan Africa-level estimates of resource impacts to regional and country levels are based on semi-annual sales data for SWPs from the GOGLA affiliated companies[47,52] supplemented by country-level market sales information from major SWP manufacturers in the region.

For the lowest-growth scenario of 6%, an additional 100,000 smallholder farmer households could have access to SWP systems within a decade, whilst for the highest-growth scenario of 18% there would be an additional 630,000 households (Figure 3.3). These figures are the equivalent to around 0.1% to 0.7% of Sub-Saharan Africa's 95 million households.

Figure 3.3 Projected SWP growth curves to 2030 for three assumed growth rates. SWP projections all start from a 2018 baseline of 0.1 million units and reach 0.20, 0.39 and 0.73 million units for growth rates of 6, 12 and 18% respectively.



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61. Cilliers J., Oosthuizen M., Kwasi S., Alexander K., Pooe T.K., Yeboua K. and Moyer J.D. (2020) Impact of COVID-19 in Africa: A scenario analysis to 2030. Institute for Security Studies Report. https://issafrica.org/research/africa-report/impact-of-covid-19-in-africa-a-scenario-analysis-to-2030

4. The potential for SWP expansion using groundwater resources

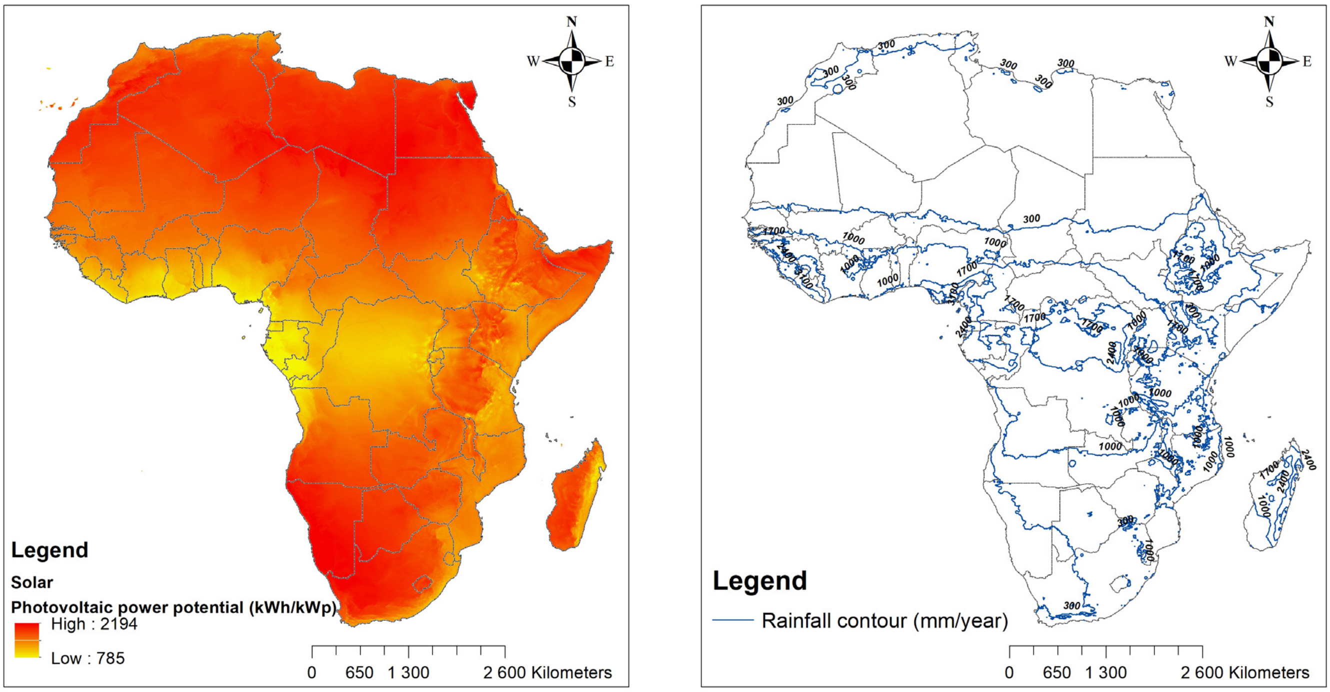
4.1. Review of solar resources

Sub-Saharan Africa is well-equipped with solar energy resources, although this varies across the region's diverse geographic areas and climatic zones.

The Sub-Saharan African region features 21 of the 70 countries best equipped with conditions for solar PV countries in the world, where average daily output exceeds 4.5 kilowatt hours per installed kilowatt of capacity (kWh/kWp)[62].Countries that lie in the wet-humid zone have the lowest solar potential while countries with higher and lower latitudes including Niger, Sudan, South Africa and Namibia have the highest potential for solar development (Figure 4.1). Solar PV potential across most regions in Sub-Saharan Africa falls within the 'high' range of 1,500-2,500 kWh/m^2/yr (GHI)[63], with parts of West and Central Africa being 'suitable' (1,000-1,500 kWh/m^2/yr (GHI)) and smaller parts of East Africa having 'excellent suitability' (2,500-3,000 kWh/m^2/yr (GHI)) based on solar irradiation and PV technology GIS suitability classification.[64] This abundant solar energy means that even remote rural areas will be able to access reliable electricity.

Climate change assessments forecast that by the end of this century solar energy will fall across Africa by 4% on average due mainly to a decline in solar irradiation and increase in temperature[65].

Figure 4.1. Maps showing solar PV (left) and rainfall (right) for Africa
Source: Global Solar Atlas[66]



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[62] Note that kWh/m2/yr (GHI) = kilowatt hour per square metre per year. GHI = Global horizontal irradiation (a solar irradiation measure selected to best approximate PV cell output)

[63] Hermann S., Miketa A. and Fichaux N. (2014) Estimating the renewable energy potential in Africa. IRENA-KTH Working Paper, International Renewable Energy Agency, Abu Dhabi. https://www.irena.org/publications/2014/Aug/Estimating-the-Renewable-Energy-Potential-in-Africa-A-GIS-based-approach

[64] Bichet A., Hingray B., Evin G., Diedhiou A., Kebe C.M.F. and Anquetin S. (2019) Potential impact of climate change on solar resource in Africa for photovoltaic energy: analyses from CORDEX-AFRICA climate experiments.

[65] Environ. Res. Lett. 14 124039 https://doi.org/10.1088/1748-9326/ab500a

[66] https://globalsolaratlas.info/download/sub-saharan-africa

4.2 Review of groundwater resources

Groundwater is generally plentiful and of good quality throughout Sub-Saharan Africa. It is relied on to meet the daily needs of over 100 million people for domestic, watering livestock and small-scale irrigation.

Groundwater occurrence and availability is strongly dependent upon the region's hydrogeological environment. Four main aquifer types are found: (i) weathered basement rocks, which extend over 40% of Sub-Saharan Africa's territory; (ii) consolidated sedimentary rocks (32%); (iii) unconsolidated sediments (22%); and (iv) volcanic rocks (6%). Boreholes and wells in weathered basement typically have yield flows of 0.5-1.0 litre per second. Yields from other aquifer types tend to be higher – up to 5 litres per second or more in unconsolidated and some consolidated aquifers. Recharge is a critical element of sustainable groundwater development. Groundwater recharge rates across the regions vary from <1 mm per year in arid settings through >500 mm per year in the tropics. Although Sub-Saharan Africa's distribution of renewable groundwater resources are highly skewed towards the wetter equatorial areas of West, Central and East Africa, groundwater development is most concentrated in the drier regions with precipitation rates of <1,000 mm per year and where surface water storage opportunities are limited. The quality of groundwater is generally of adequate physical, chemical and microbial quality for most uses, yet specific issues do arise for specific parameters in particular settings. Health risks are largely associated with elevated concentrations of arsenic and fluoride, or deficient concentrations of iodine. In some locations, levels of total dissolved solids (i.e. salinity) in groundwater are too high for drinking and irrigation. Elevated nitrate concentrations derived from sewage waste or fertilisers can also be problematic in some cases. A more detailed account of the groundwater resources of the region is given in Annex 3.

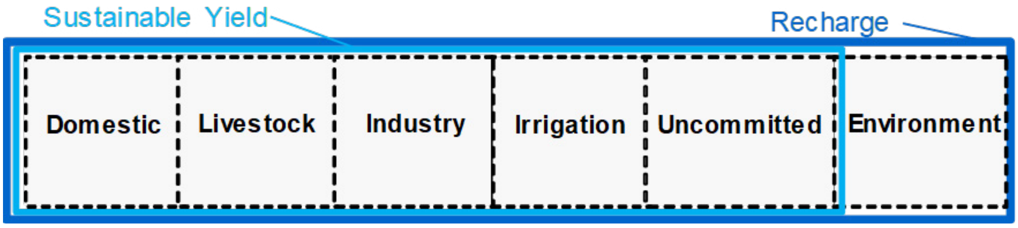
4.3 Impacts of SWP expansion on groundwater availability

4.3.1 Principles and approach

Planning for the sustainable expansion of groundwater through the deployment of SWPs or use of other water lifting technologies depends upon ensuring that development is constrained to within the limits of the resource. These limits need to be defined.

Only a fraction of the vast quantities of groundwater held in storage is available for sustainable development[21]. As highlighted in Section 4.1, aquifer systems in Sub-Saharan Africa are actively replenished by rainfall (primarily) in a process known as groundwater recharge. This means that, establishing the resource availability for SWP growth relies on knowledge of the uncommitted reserves within the aquifers of any given geographic area of interest, taking into account current and future anthropogenic uses, and the environmental flow requirements (Figure 4.2). The uncommitted stocks potentially available for future development should be sufficient to take into account the additional uncertainty brought about by climate change (Box 4.1). The widely-accepted concept of 'sustainable yield'[67] defines the groundwater volume that can be abstracted from any given aquifer without unacceptable negative impacts. Sustainable yield requires considerable scientific data and analysis to determine[21] and may change over time due to climate change and other anthropogenic factors. In the Sahel, for example, recharge to groundwater has increased significantly due to heavy downpours that result in flooding compounded by widespread land clearing of deep-rooted trees and replacement with shallow-rooted crops that allow a higher proportion of rainfall to infiltrate to aquifers on decadal time scales[68].

Figure 4.2. Replenishable groundwater storage of an aquifer partitioned into the various components. The recharge and the sustainable yield components are indicated. The uncommitted reserves are available for growth and other future human use.
Source: Adapted from Pavelic et al. (2013)[69]



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[67] A working definition of the sustainable yield used here is 'the already committed storage that serves existing uses as well as the uncommitted groundwater storage, less the component that provides environmental services', as indicated in Figure 4.4. Estimates of sustainable yield are generally arrived at through the evaluation of the aquifer's physical properties, boundary conditions, recharge rates, groundwater use, and often incorporating numerical groundwater modelling techniques. Throughout most of SSA, the data needed to establish the development potential of groundwater with high certainty is limited

[68] Leduc C., Favreau G. and Schroeter P. (2001) Long-term rise in a Sahelian water-table: the Continental Terminal in South-West Niger. Journal of Hydrology 243: 43-54

[69] Pavelic P., Villholth K.G., Shu Y., Rebelo L-M. and Smakhtin V. (2013) Smallholder groundwater irrigation in sub-Saharan Africa: country-level estimates of development potential. Water International 38(4): 392-407

BOX 4.1

Climate change impacts on groundwater resilience

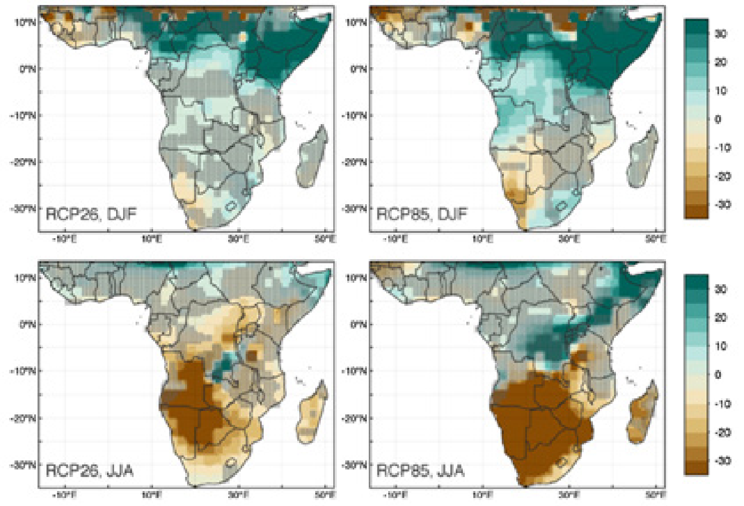
Climate change is having pronounced and deleterious effects on both natural and human systems throughout Sub-Saharan Africa. The most recent IPCC assessment report shows warming across the region (particularly in the inland subtropics); frequent occurrence of extreme heat events; increasing aridity; and changes in rainfall — with a particularly pronounced rainfall decline in Southern Africa and an increase in East Africa from the middle of this century. Under a high-emission scenario, the region could also experience as much as one metre in rising sea-levels by the end of this century leading to salinisation of coastal aquifers[16].

Climate change modifies both rainfall and evaporation, affecting the hydrologic balance and irrigation requirements across areas and regions. Groundwater systems are specifically affected through their replenishment by recharge and in changing patterns of groundwater use. Increasing frequency and intensity of droughts is associated with increased groundwater withdrawals whilst changing rainfall patterns may affect the replenishment of aquifers. The consequences in more arid, groundwater-dependent parts of Sub-Saharan Africa could be severe, with potential for diminished groundwater storage and enhanced water scarcity[70]. Drought typically affects supplies from open wells (and springs) far more severely than deeper boreholes[71].

Studies conducted to establish the effects of climate change on groundwater systems are challenged by multiple, interacting factors and changing baseline conditions. For example, the frequency and intensity of rainfall is as important as rainfall magnitude, particularly across the drylands.[72] It is likely that the impacts on groundwater will vary across climatic zones and according to aquifer types. It is almost certain that reliance on groundwater systems to meet growing water demands will be increasingly important with climate change. Increasing reliance on groundwater as an important climate change adaptation measure means that the energy access stakeholder community must urgently prioritise groundwater management. At the same time, the overall impact of climate change on Africa's groundwater resources is uncertain. It is conceivable that climate change could be overshadowed by impacts from non-climatic drivers such as population growth, growing urbanisation, increased reliance on irrigation to meet growing food demand and land use change. In effect, climate change combined with excessive groundwater development could compromise the resilience of groundwater resources and require greater investments in interventions and tools to strengthen groundwater management[73].

Mean percentage change in precipitation during summer (DJF, top row) and winter (JJA, bottom row) for RCP2.6 (left) and RCP8.5 (right) over the period 2071–2099 relative to 1951–1980

Source: Serdeczny et al. (2017)[74]



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70. Taylor R.G., Koussis A.D. and Tindimugaya C. (2009) Groundwater and climate in Africa—a review. Hydrological Sciences J. 54(4): 655-664

71. MacAllister D.J., MacDonald A.M., Kebede S. et al. (2020) Comparative performance of rural water supplies during drought. Nat. Commun. 11, 1099

72. Cuthbert M.O., Taylor R.G., Favreau G., et al. (2019) Observed controls on resilience of groundwater to climate variability in sub-Saharan Africa. Nature 572: 230-234. https://doi.org/10.1038/s41586-019-1441-7

73. Villholth K.G., Tøttrup C., Stendel M. and Maherry A. (2013) Integrated mapping of groundwater drought risk in the Southern African Development Community (SADC) region. Hydrogeology Journal 21: 863–885

74. Serdeczny O., Adams S., Baarsch F., Coumou D., Robinson A., Hare W., Schaeffer M., Perrette M. and Reinhardt J. (2017) Climate change impacts in Sub-Saharan Africa: from physical changes to their social repercussions. Regional Environmental Change 17(6): 1585-1600

A water balance procedure[75] is applied here to estimate the effects of small-scale SWP growth for irrigation on groundwater resource availability. Water use is prioritised for irrigation as rates of abstraction generally far exceed other productive uses.

The procedure applied here builds upon earlier studies that have established the groundwater irrigation potential from uncommitted reserves more generally[36,70]. The region is characterised by a scarcity of groundwater data, which includes limited information on rates of abstraction from SWP systems (as highlighted in Section 2 and Annex 1). Therefore, to apply the groundwater balance approach, estimates of groundwater pumping were initially made with three candidate methods based upon: (i) borehole yield[76]; (ii) pump capacity[77]; and (iii) gross irrigation water demand[78]. Ranges in volumetric pumping rate for each candidate method under specific conditions are indicated in Table 4.1. They effectively relate to different physical factors that may affect groundwater pumping. Taken together, they help to establish whether the limits for groundwater pumping are associated with the aquifer, solar pump, or irrigation water demand. The main points gleaned from Table 4.1 are as follows:

- In hydrogeological settings of low aquifer productivity considered here, the borehole yield (i.e., method i) may be a limiting factor for water supply delivery, except in cases where irrigated areas or pump capacities are extremely low;

- In all areas, the solar pump capacity (method ii) can be a constraint, particularly where borehole yield or irrigation demand is sufficiently high; and

- For irrigated areas of around 0.5– 1.0 ha or more, the pump capacity can be a constraint in meeting the high demand for irrigation water (method iii), and in some cases the borehole capacity can also be constraint in areas with low yielding aquifers.

Given the strong linkages between the methods, two were selected to estimate groundwater abstraction at the regional and country scales: pump capacity (method ii) and irrigation demand (method iii). Together, they provide realistic supply- and demand- based upper-bound estimates of abstraction, which can help avoid potentially underestimating the risk in situations of high uncertainty. Method (i) was not used as the upper limit was comparable to that of method (ii). For method (ii), solar pumps were assumed to operate at the upper limit of the low-flow range (29 m^3 per solar day). For method (iii) the irrigated area was assumed to be 0.5 hectares growing vegetables per the conditions outlined in Table 4.1.

For the calculation of water demand, six (i.e., 3×2) scenarios were defined that incorporate the three growth rates: 6, 12 and 18% introduced in Section 3 and the two methods of abstraction as given above. Rates of groundwater abstracted by new SWPs relative to the annually available replenishable resource[79] were estimated by building upon a previous GIS-based, groundwater balance assessment for the whole of Sub-Saharan Africa[36].

Two key outputs from that study were used for methods (ii) and (iii), namely, the annually available groundwater resources and the area potentially irrigable by groundwater respectively. The case in which 50% of the replenishable resource is set aside to meet environmental flow requirements is used here. This figure comes from earlier research[70] and is higher than the 30% identified as the global-average environmental requirement[80]. Margin is provided for increased future demand from irrigation and other uses and allow for potential uncertainties due to climate change.

Table 4.1. Volumetric pumping rates per SWP unit for the three candidate methods

Method	Volumetric pumping rates (m^3/year)	Reference
Borehole yield 1 (method i)	1,050 – 10,500	McDonald et al. (2012)
Pump capacity 2 (method ii)	730 – 10,600	CLASP (2019)
Irrigation demand 3 (method iii)	3,520 – 35,200	Altchenko and Villholth (2015)

1. considers the typical range of borehole yields of 0.1-1 litres/second for the weathered basement aquifers which are a major aquifer type in East and West Africa. Each borehole or well is assumed to pump for 8 hours each day.
2. based on daily pump discharges over a 'solar day' for small solar pumps for subsurface applications with low flow (2-29 m3/solar day) taken from the Global LEAP Awards 2019 Buyer's Guide for Solar Water Pumps (CLASP 2019)
3. based on vegetables which have highest water demand (up to 1,100 mm over the notional 6-month dry season). Irrigation efficiency is assumed to be 80%. Supplemental irrigation during the notional 6-month wet season is assumed to be 20% of the dry season water demand. Irrigated areas range from 0.2 - 2 ha (upper limit of this range based on 80% of Africa's farm sizes are 2 ha or less as noted by the Efficiency for Access Coalition 2019b)

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[75] A water balance calculates all the inputs to and all the outputs from the groundwater system. In simple form, the inputs come from recharge and outputs form pumping

[76] Broadly defined as the highest rate of pumping from a borehole that can be sustained

[77] The flow rate through a water pump at its designed conditions

[78] The rate of water to be pumped for irrigation to meet crop water needs and any water losses (i.e., gross irrigation demand)

[79] Referred to as 'GAR' in this report and expressed as a percentage

[80] Sood A., Smakhtin V., Eriyagama N., Villholth K.G., Liyanage N., Wada Y., Ebrahim G. and Dickens C. (2017) Global environmental flow information for the sustainable development goals. Colombo, Sri Lanka: International Water Management Institute (IWMI). 37p. (IWMI Research Report 168). doi: 10.5337/2017.201

4.3.2 Results at the regional and country levels

Outputs from the water balance procedure offer a preliminary estimate of the likely impacts of the three scenarios of SWP growth. By establishing the level of risk of groundwater depletion over a specific time-frame, the appropriate management response(s) can be determined.

At the Sub-Saharan Africa scale, the estimated volumes of abstraction at the 2030 level of SWP growth range from 1.1 to 6.7 km^3 per year according to method (ii), and from 0.8 to 5.2 km^3 per year for method (iii) (Table 4.2).Both estimation methods indicate GARs of <1% for all growth rates. A high degree of aggregation at the Sub-Saharan Africa scale masks regional differences. For the 18% growth scenario, GARs range from <0.1% for Central Africa due to the low SWP market share and high irrigation potential, up to 2.1% for Southern Africa with a similar market share, but limited

For East Africa, with the greatest share of the SWP market (75% of sales assumed), GARs for highest growth are up to 1.5%; with West Africa up to 0.5%, probably due to the proportionately lower market share (20% of sales).

These findings suggest that SWP markets are too small to pose a serious and widespread threat to groundwater availability over the short to medium term. The overall risks from groundwater depletion in countries and regions with less uncommitted recharge or high rates of SWP growth could be higher in the long-term in the event that current conditions change due to factors detailed in Section 1.1.

Table 4.2. Volumes of available replenishable groundwater resource withdrawn annually by small-scale SWPs in 2030 for the three growth scenarios

Method	**(ii)[2]**			**(iii)[3]**		
Growth	**6%**	**12%**	**18%**	**6%**	**12%**	**18%**
Region[1]	SWP volumes withdrawn (km^3/yr)					
East Africa	0.8	2.3	5.0	0.6	1.8	3.9
West Africa	0.2	0.6	1.3	0.2	0.5	1.0
Central Africa	<0.1	0.1	0.2	<0.1	0.1	0.2
Southern Africa	<0.1	<0.1	0.1	<0.1	< 0.1	0.1
Sub-Saharan Africa	**1.1**	**3.1**	**6.7**	**0.8**	**2.4**	**5.2**

1. assumed distribution of pump sales by region: East Africa: 75%; West Africa: 20%; Central Africa: 3%; Southern Africa: 2%
2. pumps are assumed to operate at the upper limit of the low-flow range (29 m3/solar day) throughout the entire year
3. refer to footnote 3 in Table 4.1

Table 4.3. Percent of the groundwater resource withdrawn annually relative to annually available replenishable resource (GAR) by small-scale SWPs in 2030 based on methods (ii) and (iii) for the three growth scenarios

Method	**(ii)[2]**			**(iii)[3]**		
Growth	**6%**	**12%**	**18%**	**6%**	**12%**	**18%**
Region[1]	SWP volumes withdrawn (km^3/yr)					
East Africa	0.2	0.7	1.5	0.2	0.5	1.1
West Africa	0.1	0.2	0.5	0.1	0.2	0.4
Central Africa	<0.1	<0.1	<0.1	<0.1	< 0.1	<0.1
Southern Africa	0.3	1.0	2.1	0.3	0.7	1.6
Sub-Saharan Africa	**0.1**	**0.3**	**0.6**	**0.1**	**0.2**	**0.4**

1. assumed distribution of pump sales by region: East Africa: 75%; West Africa: 20%; Central Africa: 3%; Southern Africa: 2%
2. pumps are assumed to operate at the upper limit of the low-flow range (29 m3/solar day) throughout the entire year
3. each SWP unit is assumed to irrigate 0.5 ha of vegetables as per the conditions indicated in Table 4.1

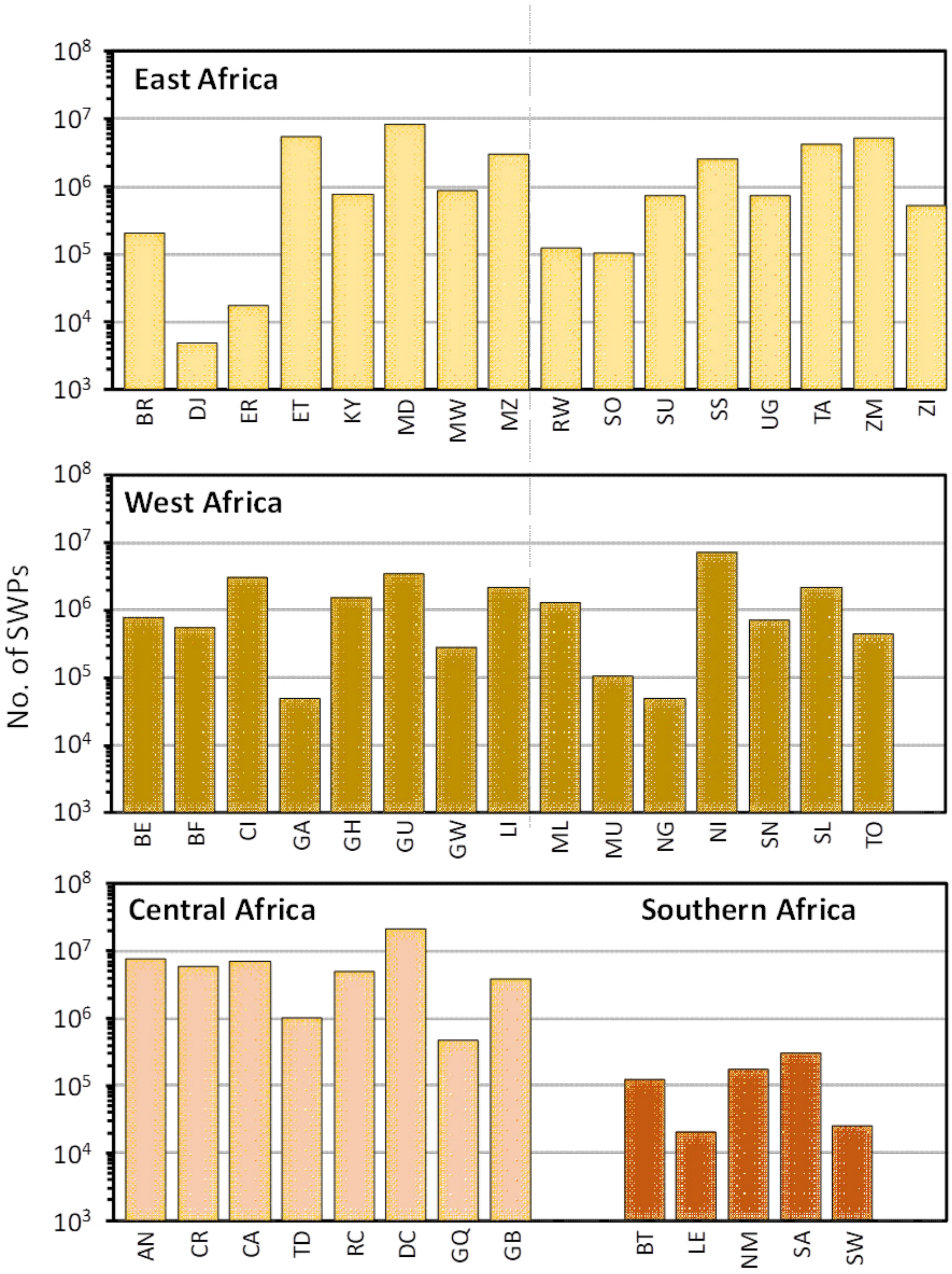
A further scenario involving the allocation of all available groundwater resources to SWP expansion provides an upper limit estimate of the scale of SWP development that can be sustained.

Based on method (ii), individual countries in the region have groundwater resources to potentially support in the order of tens of thousands through to millions of units, although higher and lower cases are calculated for specific countries (Figure 4.3). Larger countries, with high recharge rates and lower proportion of existing groundwater use have highest potential.

The available groundwater resources in Kenya, for example, may potentially support in the order of 750,000 units; a value that lies within the medium to high range in the distribution owing to its large internally generated groundwater resources but curtailed somewhat by the relatively high level of committed groundwater use. SWP development potential for Southern African countries is lower than other regions, consistent with findings at the regional level. The highest sales projections to 2030 account for 14% of the upper limit of SWP development in East Africa, 0.4% for Central Africa, 21% for Southern Africa and 5% for West Africa.

These findings generally align with other studies that identify a large potential for increased groundwater development in Sub-Saharan Africa[36,70]. The hydrogeological context will be an important consideration for realising this potential. Countries with a high proportion of low yielding aquifers (e.g., weather basement rocks in Malawi, Uganda and elsewhere) are likely to face constraints in the scale of individual SWP systems possible. To put these results into perspective further, it worthwhile to note that as countries and regions develop surface water systems and deeper aquifers, the potential for small scale SWP from shallow groundwater may change depending on the impacts of surface water and deep groundwater development.

Figure 4.3. Maximum number of SWP units that could potentially be installed in each country based on the current available resource limits (for method ii)



The analytical results from this study are based on best estimates and thus have associated uncertainty. However, they are sufficient to give a broad indication of the likely impacts on groundwater resources. Further work is needed to refine groundwater use for different SWP applications and to better establish groundwater recharge.

Box 4.2 highlights research currently underway to estimate the magnitude and patterns of groundwater abstraction from small SWPs in Kenya. Studies such as this are instrumental for improved resource impact assessments in future. As more data is collected on how SWPs are actually used, greater clarity will emerge on the risks and potentially also how they can be mitigated. It should be noted that the pilot analysis presented in Box 4.2 does not account for groundwater demand from larger solar pumps (>1kW) and the expectation of continued growth in diesel pumps under specific contexts[37].

BOX 4.2

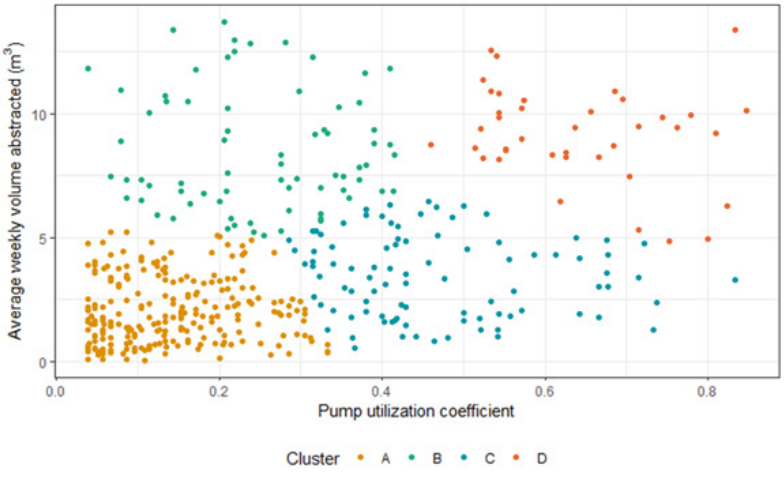
Pilot analysis of big data from smart solar pumps to understand water use behaviour and shallow water regimes

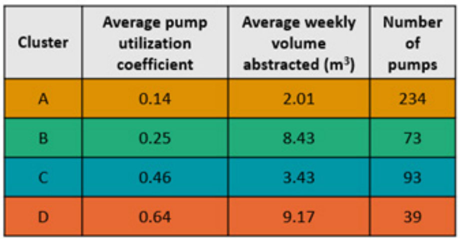
4IR technologies[81] can be implemented to better understand smallholder solar pump use across Africa and Asia. Futurepump, a private sector solar pump manufacturer, has incorporated Internet of Things (IoT) technology into its product. The IoT ecosystem is a collection of devices (sensors, controllers, antennae) that collect data and upload it to servers (i.e., the cloud). This data can then be analysed to inform decisions, develop applications, create user interfaces, etc. Futurepump's solar pumps upload minute-resolution data to a server using data loggers, creating a detailed and innovative database. This database consists of over 5,000 pumps across Africa and Asia and includes voltage, current, and rotation-per-minute readings of the pumps, providing an opportunity to analyse shallow water regimes in ways that have not been done before. Through a public-private partnership, the IoT capabilities of Futurepump's solar pumps are used to provide live and accessible data on groundwater use, estimate groundwater abstraction, and better understand patterns in solar pump use.

A methodological approach is piloted for approximately 400 solar pumps in Kenya for May 2019 to April 2021 to better understand patterns in solar pump use. These solar pumps use a mix of water sources and are used for a variety of purposes, such as irrigation, livestock watering, and domestic uses. To understand if solar pumps in Kenya are used in similar ways, pumps are grouped by similarity in volume abstracted and utilisation (i.e., the pump utilisation coefficient is calculated by looking at the number of weeks used over the duration of the study period). Groups are created using cluster analysis, an unsupervised machine learning technique. The figure and table below illustrate the four types of behaviour found, ranging from infrequent pump utilisation and low average weekly abstraction to greater pump utilisation and higher weekly abstraction. Further analysis is possible to identify if there are temporal and/or geographic patterns amongst the four groups. Using forecasting, a machine learning method, the amount of water the average pump within a group will abstract can be predicted. This work provides insight into patterns in solar pump use and quantifies the volumes abstracted, which can be used to identify areas of high usage. Such data-based solutions can help energy access stakeholders to monitor shallow water regimes with limited on-the-ground instrumentation, demonstrating the benefits of 4IR technologies in the water sector.

Pump clusters based on pump utilisation and average weekly volume abstracted (m^3) for May 2019 to April 2021. Each point represents a pump.

Source: Source: International Water Management Institute and Futurepump[82]





Cluster	Average pump utilization coefficient	Average weekly volume abstracted (m^3)	Number of pumps
A	0.14	2.01	234
B	0.25	8.43	73
C	0.46	3.43	93
D	0.64	9.17	39

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[81] 4IR = fourth industrial revolution technologies as explained in: https://www.weforum.org/agenda/2016/01/the-fourth-industrial-revolution-what-it-means-and-how-to-respond/

[82] von Gnechten R., Schmitter P., Parriott E. and Mallet H. (in preparation) Utilizing IoT equipped solar pumps to understand and forecast water abstracted in Kenya and Uganda

Photography: Simusolar

5. A risk management framework for sustainable groundwater use

THE FINDINGS FROM SECTION 4 SHOW THAT GROUNDWATER DEPLETION IS UNLIKELY TO POSE A MAJOR RISK IN THE SHORT TO MEDIUM TERM. HOWEVER, IN A HIGH SWP GROWTH SCENARIO IT COULD BECOME A MORE SERIOUS ISSUE IN SPECIFIC REGIONS AND COUNTRIES, PARTICULARLY OVER THE LONGER TERM. THUS A CLEAR APPROACH TO RISK MANAGEMENT IS NEEDED THAT IS COMMENSURATE WITH THE RISKS.

5.1 Linkages between SWP expansion and groundwater use

Planning for scenarios of expanded groundwater use can be assisted by conceptualising the evolving trends in groundwater use in relation to the aquifer's sustainable yield.

From a conceptual point of view, it is convenient to distinguish between a number of stages of groundwater stress that could evolve over time, beginning with existing low levels of stress and moving towards emerging, advanced and ultimately unsustainable levels of stress which would occur if the sustainable yield of the aquifer were exceeded (Figure 5.1). The analysis presented in Section 4 suggests a situation that may shift over the decade from generally low stress towards emerging stress in the most severe case[83].

Widespread groundwater pumping by small-scale SWPs at unsustainable levels is unlikely to emerge over the coming decade. Whether groundwater resources become severely stressed in the long term depends on the level of growth as well as the hydrogeological characteristics. In general, aquifers that are composed of hard rock and situated in arid areas have low storage capacity and low recharge, making them particularly vulnerable and less resilient to climatic shocks from prolonged droughts. Such areas include western Namibia and much of Zimbabwe for example. Aquifers composed of sedimentary material and situated in higher rainfall areas are less vulnerable and more resilient. Such areas include western Angola and northern Tanzania.

5.2 Risk management framework

A risk management framework is developed that draws upon key insights from earlier sections of this report to help define the enabling conditions needed to ensure groundwater is used sustainably in a context of more widespread small-scale SWP adoption. Following a risk-based approach implies that investments to strengthen groundwater governance are commensurate with the costs and benefits of management activities and interventions.

The framework recognises the inter-linkages and co-dependencies between SWP expansion/adoption and groundwater resource management (Figure 5.2). The trends and potential of the SWP market dictate the level of risk to groundwater resources. Market forces also strongly influence the SWP operating environment which include choices in crop type, irrigation practices, and others that affect water use and groundwater resource availability. Concentrated or excessive levels of SWP development may heighten the risk of local or more widespread groundwater depletion. The framework seeks to avoid overexploitation of groundwater by improving the enabling conditions for solar water pumps and for more effective groundwater management.

The framework indicates that a number of important factors need to be taken into account to enhance the enabling environment and ensure that SWP systems are adopted to deliver effective and ongoing benefits across the farmer/household scale as well as the system scales. Access to safe and reliable groundwater supplies near a proposed intervention is a vital prerequisite for successful implementation. Other critical factors include access to finance, access to markets to sell produce, supply chains to buy and repair SWP equipment and farmer knowledge in irrigated agriculture (crop choice, seeds, fertiliser, etc.).

From a groundwater management perspective, the framework illustrates that groundwater is a historically neglected and misunderstood resource owing, in part, to its hidden nature. Groundwater management could be strengthened by addressing a set of priority areas that cover technical, institutional, financial and regulatory aspects[28,45]. They include strengthening the understanding about groundwater resources at the field level; establishing groundwater monitoring networks and overcoming capacity constraints. It is also important to strengthen the legal and regulatory environment to support the effective implementation of management measures, which could include enhancing water use efficiency and best agricultural practices, promoting local participation, developing business models that put a financial value on solar energy generation to encourage water conservation, and protecting and enhancing groundwater recharge.

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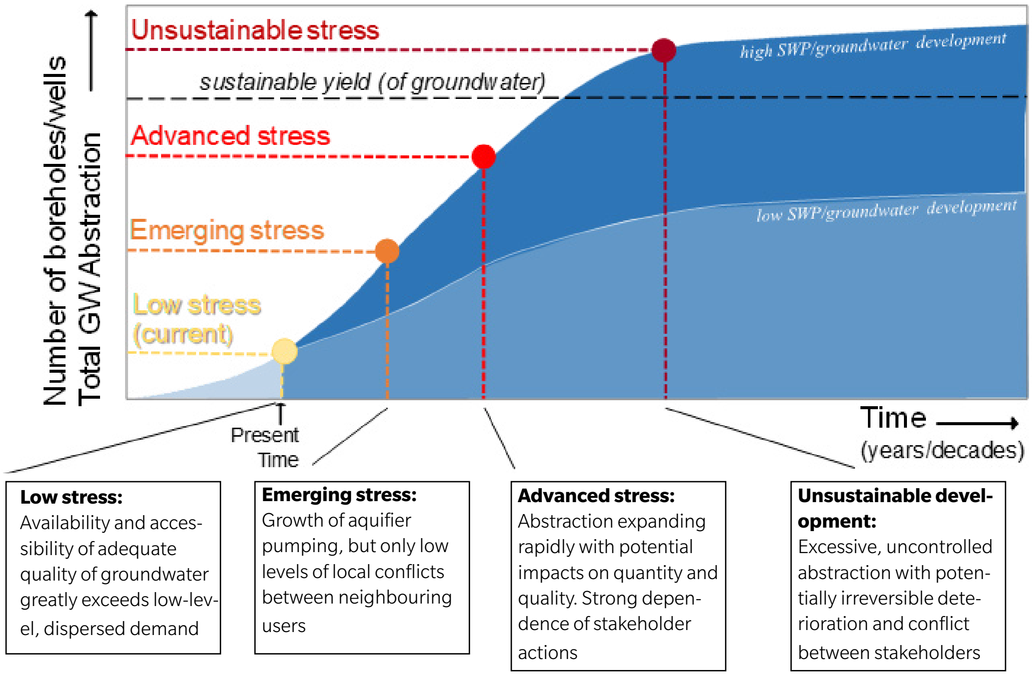
[83] Unfortunately, it is not possible to plot where specific countries or regions presently lie on Fig. 5.1 owing to lack of available data on existing groundwater use

Figure 5.1. Pathways for developing groundwater under high and low growth scenarios and associated impacts on groundwater stress.

Source: adapted from Tuinhof et al. (2006)[84]



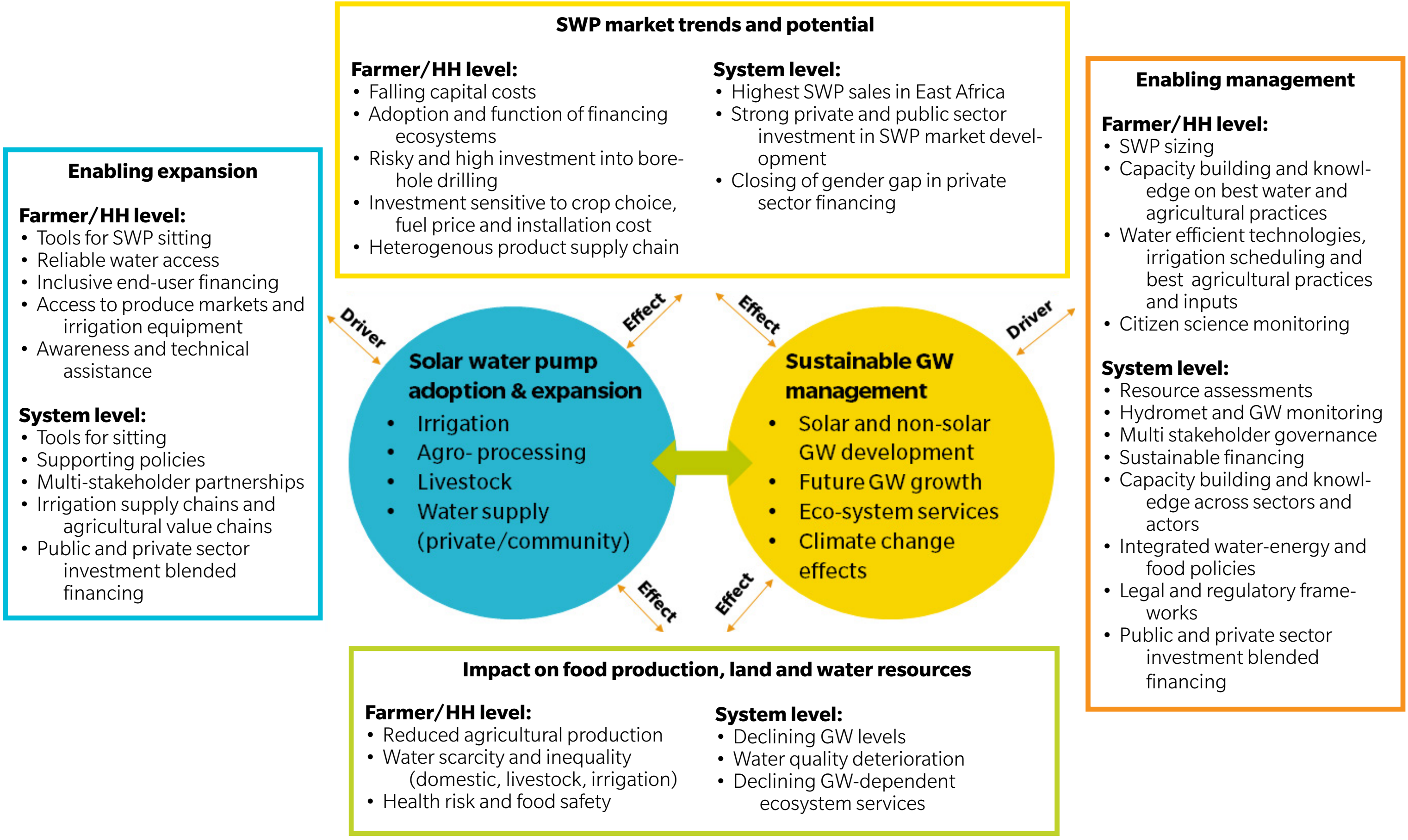
Low stress: Availability and accessibility of adequate quality of groundwater greatly exceeds low-level, dispersed demand

Emerging stress: Growth of aquifier pumping, but only low levels of local conflicts between neighbouring users

Advanced stress: Abstraction expanding rapidly with potential impacts on quantity and quality. Strong dependence of stakeholder actions

Unsustainable development: Excessive, uncontrolled abstraction with potentially irreversible deterioration and conflict between stakeholders

Figure 5.2. Risk management framework for sustainable solar water pumping and groundwater management, taking account of the inter-linkages and co-dependencies between SWP adoption/expansion and groundwater resource management and the associated enabling conditions at the local and system levels.



SWP market trends and potential

Farmer/HH level:
- Falling capital costs
- Adoption and function of financing ecosystems
- Risky and high investment into borehole drilling
- Investment sensitive to crop choice, fuel price and installation cost
- Heterogenous product supply chain

System level:
- Highest SWP sales in East Africa
- Strong private and public sector investment in SWP market development
- Closing of gender gap in private sector financing

Enabling expansion

Farmer/HH level:
- Tools for SWP sitting
- Reliable water access
- Inclusive end-user financing
- Access to produce markets and irrigation equipment
- Awareness and technical assistance

System level:
- Tools for sitting
- Supporting policies
- Multi-stakeholder partnerships
- Irrigation supply chains and agricultural value chains
- Public and private sector investment blended financing

Solar water pump adoption & expansion
- Irrigation
- Agro- processing
- Livestock
- Water supply (private/community)

Sustainable GW management
- Solar and non-solar GW development
- Future GW growth
- Eco-system services
- Climate change effects

Enabling management

Farmer/HH level:
- SWP sizing
- Capacity building and knowledge on best water and agricultural practices
- Water efficient technologies, irrigation scheduling and best agricultural practices and inputs
- Citizen science monitoring

System level:
- Resource assessments
- Hydromet and GW monitoring
- Multi stakeholder governance
- Sustainable financing
- Capacity building and knowledge across sectors and actors
- Integrated water-energy and food policies
- Legal and regulatory frameworks
- Public and private sector investment blended financing

Impact on food production, land and water resources

Farmer/HH level:
- Reduced agricultural production
- Water scarcity and inequality (domestic, livestock, irrigation)
- Health risk and food safety

System level:
- Declining GW levels
- Water quality deterioration
- Declining GW-dependent ecosystem services

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84. Tuinhof A., Dumars C., Foster S., Kemper K., Garduño H. and Nanni M. (2006) Groundwater resource management: An introduction to its scope and practice. GW•Mate Briefing Note Series, No. 1, Washington, D.C.: World Bank Group http://documents.worldbank.org/curated/en/287291468322748277/Groundwater-resource-management-an-introduction-to-its-scope-and-practice


Photography: Shell Foundation

6. Conclusions and Recommendations

6.1. Conclusions

This study has assessed that that SWP markets in Sub-Saharan Africa are likely too small to pose a serious and widespread threat to groundwater availability over the short to medium term. However, there is also considerable regional variation in groundwater use owing to heterogeneity in markets and groundwater resources. If the assumptions on market distribution implicit in the analysis are accurate then Southern Africa, as well as countries with high anticipated rates of SWP growth, would have higher potential for groundwater stress. Further, the overall risks to groundwater could be higher in the long-term in the event that the current conditions change as a result of factors such as:

(a) Technological advancements that allow more powerful small capacity pumps to enter the market and may lead to significantly enhanced volumes of water pumped;

(b) Large-scale government- or donor- driven efforts to promote SWPs eventuate in future growth beyond current projections;

(c) More severe and frequent occurrence of drought with significant impact on groundwater recharge.

The key findings from this study are nuanced around two key messages:

1) Given the low aggregated risk to groundwater depletion over most of Sub-Saharan Africa over the next decade, there is vast potential to support sustainable expansion of small SWPs;

2) In some regions or countries (e.g., Southern Africa), the potential impacts on local groundwater availability pose a higher risk.

Efforts to ensure sustainable groundwater management need to be commensurate with the risk of groundwater depletion and hence cannot be broadly generalised.

Sustainable groundwater use requires a long-term holistic perspective to identify trends in resource conditions; and institute effective systems of management to avoid unsustainable levels of use. It also requires an approach locally tailored to the specific resource setting as characterised by the diverse hydrogeological, climatic and socioeconomic conditions across the vast regions of Sub-Saharan Africa.

6.2. Recommendations and available resources

In this section, four key recommendations are proposed that describe strategic actions needed to help ensure sustainable management of groundwater in an environment characterised by variable solar water pump expansion and contrasting risks across countries and regions. They cover:

1) Groundwater resource assessments and data collection

2) Capacity building and awareness raising

3) Research for development

4) Policy and regulatory aspects

The first three recommendations focus on technical, capacity and research related areas and provide options and guidance to support groundwater management over the short and medium term. The final recommendation focuses on institutions and policy and requires a longer-term outlook, as it relies on inputs from the other recommendations and would likely be most relevant where a substantial risk to resource sustainability prevails. Each of the recommendations should be prioritised according to the anticipated risks in different regions and countries.

The recommendations recognise the unique but overlapping roles of different stakeholder groups. In a broad sense, the public sector would focus on areas such as resource assessments, monitoring resource conditions, integrated water resources planning and allocation, land use and borehole planning, and strengthening institutions and policy. The private sector, on the other hand, would play a key role in areas such as filling data gaps and providing irrigation and borehole drilling information and services. This stakeholder group could also help introduce smart financing (e.g., promote solar subsidies linked to use of water efficient technologies, smart irrigation scheduling) and use of technological innovations (e.g., remote monitoring, intelligent pumps with automatic switch-off systems etc.).

6.2.1 Prioritised investments in groundwater resource assessments and long-term data collection

Groundwater resource management could be greatly enhanced if the sustainable development potential of groundwater is known and groundwater monitoring networks are put in place. Data and maps at the sub-national and local scales remain scattered or non-existent for the most part. In complex hydrogeological settings that are typical of large parts of Sub-Saharan Africa, enhancing the availability of reliable local information increases the success rate of borehole and well construction, which is particularly important as borehole drilling can be a major capital cost for new SWP investments. The PRACTICA Foundation's recently published Drillers' Toolbox provides an example of practical measures to reduce drilling risk which has begun to be applied in several African and Asian countries . The toolbox captures and collates a range of hydrogeological datasets such as geophysics, drilling and pumping test data in easily accessible digital format.

Groundwater monitoring networks and associated information management systems are absent or inadequate in most countries. Uganda is one exception where groundwater level monitoring systems have been in operation for decades. Groundwater quantity and quality monitoring information is the most reliable way to track changes in the resource base and provide clear evidence to support resource management related decision making. There is strong potential for the private sector to stimulate sustainable development using emerging technologies (e.g., 4IR; Box 4.2) in collaboration with the public sector given the lack of available public funding put towards resource monitoring.

Examples of priority areas:

- Improve groundwater resource assessments in areas of high groundwater potential within countries that have experienced or anticipate highest growth in SWP development. Countries with high SWP sales such as Kenya, Uganda, Senegal and Zimbabwe could be the focus to begin this process. Government efforts could be directed towards comprehensive mapping at the national scale to first identify aquifers likely to have high development prospects where this is not already known.

- Responsible actors in the water resource sector (resource managers, river basin authorities etc.) should establish dedicated observation well networks in priority areas to monitor groundwater quantity and quality, as well as to monitor groundwater abstraction from boreholes and wells used for productive purposes. Information and data need to be made openly accessible to all stakeholders. Access to stable financing is a critical consideration in setting up and maintaining hydrological networks to ensure continuity of data collection over the long term.

- Governments can work together with solar networks and the private sector to track latest developments in the SWP market and identify whether expansion could negatively affect groundwater availability using the types of methods employed in this study or similar.

- Donors are encouraged to incorporate water accounting as part of a mandatory environmental sustainability framework to guide national governments in planning of major SWP investment programs.

- Private solar, agriculture and food sector players could have an important role in filling data gaps on SWP expansion, groundwater levels, irrigated area expansion and water use.

6.2.2 Capacity building and awareness raising within the solar pump, groundwater and agricultural sectors

Capacity within the groundwater sector remains limited, particularly at the local level. Technical assistance and specialised training can help build required skills. Capacity development tends to be an evolving process that requires twin focus on individuals in enhancing skills and knowledge and institutions, in addressing higher-level attributes such as leadership, knowledge, accountability etc.

Farmers experienced in rainfed agriculture often lack skills and knowledge to do well in irrigated agriculture. Information presented in Section 2 and Annex 1 showed that male and female farmers implementing SWPs need practical training on how to grow high value crops and market their produce. They should also acquire technical skills in solar installation, maintenance and the efficient use of water.

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85. https://via.farm/

86. https://www.practica.org/digital-tools-for-groundwater-development/

87. Pavelic P., Giordano M., Keraita B., Ramesh V. and Rao T. [Eds.] (2012) Groundwater availability and use in Sub-Saharan Africa: a review of 15 countries. Colombo, Sri Lanka: International Water Management Institute (IWMI), 274p, doi: 10.5337/2012.213

88. http://africangroundwater.com/

89. https://www.rural-water-supply.net/en/

Capacity building would be best served by focusing on adding value to established initiatives, which helps leverage the synergies and increase potential for impact. Existing regional level groundwater networks are already in place that could potentially be built upon, and in some cases require enhanced focus on solar water pumping. The African Groundwater Network (AGW-Net) , for example, was established to raise awareness of groundwater's potential and support capacity building within the sector, and has prepared high quality groundwater materials that are being used in training courses. The Rural Water Supply Network (RWSN), with its strong focus on improving water services across rural Sub-Saharan Africa, has a thematic area on sustainable groundwater development, and has produced manuals on best practices in groundwater. RWSN also runs regular training courses and webinars and supports a mentoring program for young professionals. The Water and Energy for Food (WE4F) programme, which aims to increase food production along the value chain through a more sustainable and efficient usage of water and energy, hosts a 'Toolbox on Solar Powered Irrigation Systems' which contains useful and up to date information and guidance on water management and range of other topics (Box 6.1). Tools for siting SWP's accounting for water access and other critical factors based on best available information can help ensure that SWP systems are adopted to deliver effective and ongoing benefits across scales[90] (Box 6.2).

Examples of priority areas

- Groundwater specialists could provide training to water authorities, water user groups and other relevant local institutions on the fundamentals of groundwater and on how to monitor groundwater resources effectively.

- Solar networks could facilitate training of local field-level actors such as SWP companies, farmers and other water users, agricultural extension officers on best operating practices for SWPs to encourage sustainable development outcomes. Experience in best practices in design, installation and operations & maintenance for environmental sustainability (e.g., drip irrigation or other methods to conserve water) are available for the Kenyan context that could be adapted and applied more widely[91].

- Policy makers within the agricultural, food and solar sectors can play a leading role in monitoring of crop and water productivity to improve efficient water use in irrigated agriculture further. This could lead to the introduction of water indicators into GAP[92] certification and SDG reporting while providing digital extension services to farmers on best irrigation and agricultural practices.

- Solar networks could foster innovation and the development of technologies, which enhances water use in agriculture through better scheduling, climate advisory services and efficient application through smart financing or voucher subsidies linked to SWP financing ecosystem.

- Encourage major government and non-government players in the groundwater, solar pump and related sectors to become aware of sustainability and incorporate it into policies, planning and action. Information from groundwater monitoring could be validated and disseminated as information products tailored to stakeholders at all levels.

- The public and private sectors could work together to introduce large scale awareness or investment programmes (e.g., water stewardship, 2030 Water Resources Group[93]) and sustainable financing to increase storage and recharge in areas with extensive SWP development or low yielding aquifers. They could inform water users of the benefits of improved water use practices and learn from their experiences and challenges.

- Donors, governments and the private sector are encouraged to support a culture of innovation and cooperation to bridge the private/NGO sector and research sector divide, leveraging efforts underway in engineering-related aspects of SWPs. For example, establishing scholarships and/or awards that provide junior/early career researchers and practitioners opportunities to pursue and embrace innovation in technological, institutional or other fields of relevance. Investment of this nature could contribute positively towards addressing resource sustainability issues and create new skills to strengthen longer term prospects within the SWP sector.

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90. Schmitter P., Kibret K.S., Lefore N. and Barron J. (2018) Suitability mapping framework for solar photovoltaic pumps for smallholder farmers in sub-Saharan Africa. Applied Geography 94: 41–57

91. EED Advisory Ltd. (2018) Evaluation of the sustainability of solar powered water supply systems in Kenya. https://www.rural-water-supply.net/en/resources/details/820

92. GAP = Good Agricultural Practices. An overview is available at: http://www.fao.org/tempref/GI/Reserved/FTP_FaoRlc/old/foro/bpa/pdf/good.pdf

93. https://www.2030wrg.org/

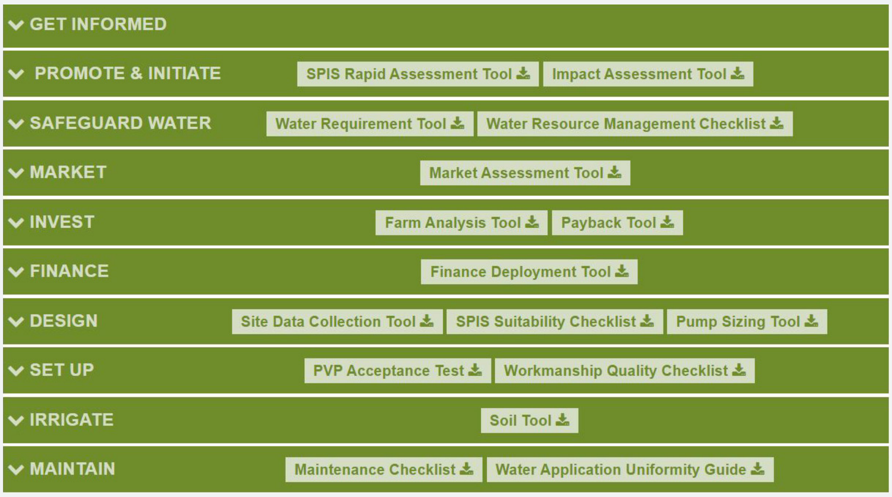
BOX 6.1

Toolbox on Solar Powered Irrigation Systems – Safeguarding Water Resources

The Toolbox on Solar Powered Irrigation Systems provides broad hands-on learning to SWP users, advisors and others through informative modules and user-friendly software tools. The Safeguard Water module in the toolbox introduces groundwater concepts and the principles of sustainable water management. It also provides the means for estimating crop water requirements. Furthermore, it reviews the risks and impacts related to an overdraft of groundwater resources. The expectation is to sensitise the planner and the future SWP user of towards responsible and sustainable use of water sources and encourage information sharing with neighbouring farmers or other water users. Finally, this module provides practical guidance for the integration of water management into the planning and operation of SWPs and is available as a downloadable app for mobile devices[94].

Contents of the Toolbox

Source: Energypedia - Toolbox on Solar Powered Irrigations Systems[95]



GET INFORMED	
PROMOTE & INITIATE	SPIS Rapid Assessment Tool Impact Assessment Tool
SAFEGUARD WATER	Water Requirement Tool Water Resource Management Checklist
MARKET	Market Assessment Tool
INVEST	Farm Analysis Tool Payback Tool
FINANCE	Finance Deployment Tool
DESIGN	Site Data Collection Tool SPIS Suitability Checklist Pump Sizing Tool
SET UP	PVP Acceptance Test Workmanship Quality Checklist
IRRIGATE	Soil Tool
MAINTAIN	Maintenance Checklist Water Application Uniformity Guide

BOX 6.2

Solar suitability assessment tool for Africa

An online solar irrigation suitability-mapping framework has been developed using a GIS-based Multi-Criteria Evaluation approach, building upon earlier work of a similar nature covering Ethiopia[91]. This interactive tool is intended to help users identify suitable areas for solar-based irrigation depending on water sources and pump characteristics. The suitability scale consists of five classes; least suitable (0-30% probability), less suitable (30-60% probability), moderately suitable (60-75% probability), suitable (75-90% probability) and highly suitable (90-100% probability) for solar-powered irrigation. Mapping is based on different water resources: surface water, groundwater or both surface and groundwater at various groundwater depths (0-7 m, 7-25 m, 25-50 m, 50–100 m, 100-250 m and greater than 250 m). Environmental water requirements and the solar vs. diesel affordability[37] are also considered in the suitability assessment. This platform can help investors and governments in Africa in planning and sustainable implementation of solar-powered irrigation.

User interface for the tool

Source: International Water Management Institute[96]

(All area outputs are calculated in km²)

Calculation	
Location	Ghana
Source	GW/SW
Depth	0-250m
Least Suitable	0
Less Suitable	0
Moderately Suitable	5555
Suitable	85741
Highly Suitable	170

○ Select all

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94. https://play.google.com/store/apps/details?id=com.giz.investpaybacktool
95. https://energypedia.info/wiki/Toolbox_on_SPIS
96. http://sip.africa.iwmi.org/

6.2.3 Targeted efforts in research for development

This study has highlighted major gaps in scientific knowledge and data across the region. In broad terms, the research community should strive for impact-oriented, multidisciplinary research that directly addresses the most pressing issues of widespread concern in relation to groundwater-based SWP development and resource management. Wherever possible, cross-cutting issues such as gender equality, social inclusion, climate change and ecosystem services should be incorporated. To aid the take-up of research findings, the research would need to be conducted in close partnership with the public and private sectors. Furthermore, given the multiple benefits of SWPs to the agricultural, energy and WASH sectors, it will be important to pursue research to stimulate sustainable expansion that targets both productive and non-productive use. This will help ensure water security for the most vulnerable and resource-poor farmers while harnessing economic benefits from solar powered irrigated agriculture.

The case studies reviewed in this study showed that a holistic and systemic approach to assess socio-economic, agricultural and environmental impacts of SWP use is lacking. Specific research is needed to build the knowledge base for the sustainable growth of small-scale SWPs and support its evaluation across the SDGs. Spinoffs would also emerge from building capacity for participants who have recently entered or are new to the solar energy and aligned sectors. Potential areas of research are illustrated by the examples below.

Examples of priority areas

- Improved estimation methods and datasets on individual and collective rates of groundwater abstraction for multiple uses from small-scale SWP systems in contrasting settings and types of solar pump applications: Data from SWPs would need to be assessed with abstraction data from non-solar sources and integrated through modelling approaches such as hydrologic or water accounting models to make the assessments relevant to the larger spatial and temporal scales that would be useful for management. Successful research could, for example, support future planning and advisory services targeted to different water users in a changing climatic environment (i.e., increase in the frequency of drought or wet years).

- Understand the operational behaviour and priorities of SWP users and the factors that affect the extent of daily, seasonal and annual use of SWPs, so that strategies to improve water use can be formulated.

- Establish more reliable estimates of long term groundwater recharge at country and regional scales.

- Characterise the reliability of major aquifer types to deliver operational water needs of SWP systems for different applications to reduce the financial risks of SWP implementation in new areas.

- Assessments of water quality for specific constituents such as agro-chemicals (nitrate, pesticides), salinity, fluoride and microbial pathogens, amongst others, that may present health or environmental hazards and potentially constrain SWP development.

- Identify and test new ways to use the energy generated during inactive (non-irrigation) days to improve economic performance of SWP systems and potentially bring about water savings and diversified income. Testing could also be extended to cover alternative drought resilient or high value crops, irrigation methods and practices, and marketing methods.

- Explore the potential for technical innovations that may support sustainable management. For example, 'intelligent' pumps are beginning to enter the market that have flow control devices that enable the pump down to be switched off remotely. This can save water, labour and prevent pumps from being damaged by dewatering[97].

6.2.4 Strengthen policy and regulatory frameworks

Common pool resources such as groundwater tend to require specific management, recognising that groundwater is mostly accessed by individual users. Controlling groundwater abstraction and its potential impacts is made difficult as regulations, even where they exist, are not consistently enforced[45]. Over the longer term, legal and regulatory approaches may need to be strengthened (e.g., to ensure customary laws and practices are recognised, water is used efficiently, and minimum separation distances between boreholes/wells are identified and adhered to).

In keeping with a risk-based approach, governments from across the region need to monitor the evolving nexus between water and energy carefully. Doing so helps understand how the falling costs of generating solar energy and improvements in pumping technologies, business models and financing mechanisms are going to play out on patterns of SWP adoption and thus on sustainability. One of the most difficult challenges that policy makers may face is finding the right balance between enabling SWP expansion for poverty alleviation and socioeconomic development whilst disabling inappropriate or excessive expansion to ensure sustainability goals are achieved.

[97] https://product-selection.grundfos.com/za/categories/pump-systems/solar-water-pumping-systems?tab=categories

The costs of preventative policies and measures are likely to be significantly lower than any remedial actions needed. The SWP case study review identified an example of good practices from Kenya, where boreholes must be registered so that government authorities can keep track of abstraction points and the yields from boreholes.

Examples of priority areas

- New policies need to be defined and promoted that are inclusive of SWP applications reliant on groundwater supplies. This effectively means incorporating solar pumping into groundwater, (irrigated) agriculture and energy policies and strategies with a strong emphasis on sustainability and water conservation. As SWP expansion evolves, resource agencies need to establish effective methods to regulate groundwater use, and avoid potential conflicts amongst water users by taking preventative steps, whilst making best use of available groundwater monitoring information.

- Given the high potential identified for SWP expansion, there is clear scope for including SWPs in new national irrigation development strategies. High level policy dialogues could be held to allow experts from the solar industry and academia to bring sustainable development related issues to the attention of decision makers at the highest political levels.

- New policies that cater for smallholder farmers to overcome barriers to access loans, drill wells and invest in irrigation.

- The private sector could champion the adoption of best practices in the standardisation of designs, operation and scaling. In particular, solar service providers promote more standardised adoption SWP system designs, communicating to water users the benefits of more efficient use to reduce operational risks from drying-out of boreholes and wells.

- The stocks and status of groundwater resources need to be integrated effectively within natural resources and agricultural development planning which would likely require coordination amongst relevant agencies within the water resources, energy and agriculture sectors. Co-design integrated water management plans across these sectors will be key to stimulate improved water use and collective management of surface water and groundwater resources.

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Annex 1. In-depth assessment of the solar water pumping case studies

A1.1 Overview of the SWP case studies

A systematic and comprehensive review of 69 case studies of SWP systems applied to multiple uses from 20 Sub-Saharan African countries was carried out, which provide a robust dataset to gather key learnings.

The information presented in this section was obtained from various scientific publications, project reports and academic theses, as well as information received from solar companies and government agencies that create and implement solar water pumping systems. The review focused on the current solar water pumping landscape including the funding models, energy sources and field sizes. The dataset was examined to identify the key lessons for SWP performance and water use. A listing of all the indicators used to collect data is given in Table A1.1. Case studies were selected for review if the basic technical details of the SWP system had been provided and the operation monitored for at least one complete season. The review covered a combination of farmer-led investments (using smaller pumps, < 1kW), community (small to medium pumps, < 3kW) and donor funded solar water pump systems. The main quantitative findings of the review are presented in Figure A1.1 a-e.

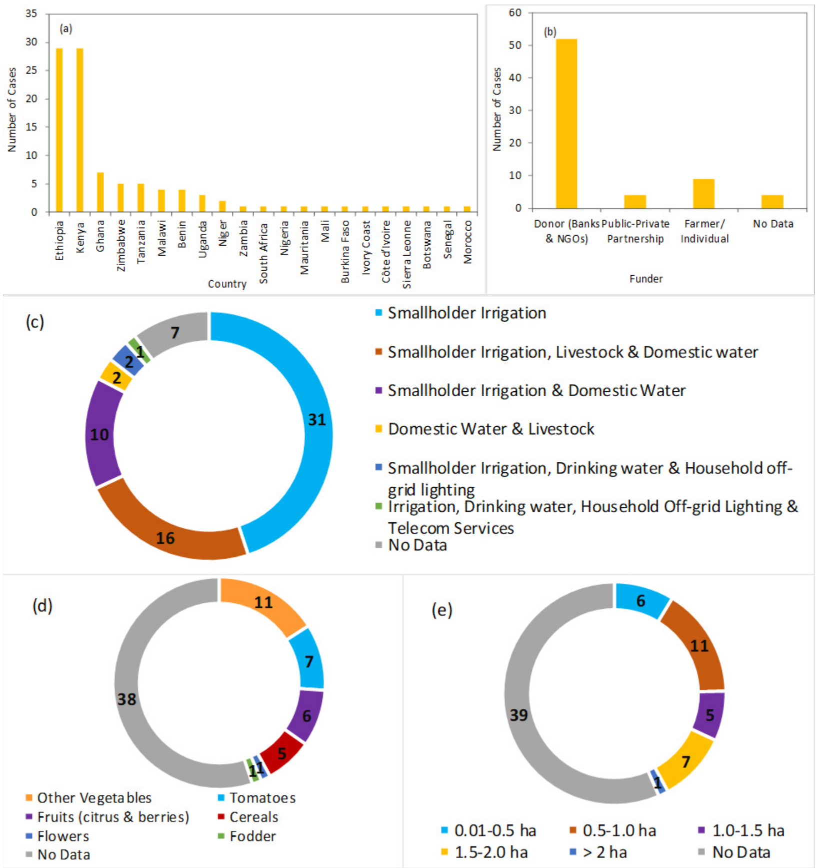
By far, the largest number of cases were identified in East Africa. Ethiopia [29][98] and Kenya [24] have the highest number of documented case studies compared to other Sub-Saharan African countries (Fig. 2.1a). The number of case studies reported by year were 2008 [2], 2010 [1], 2014 [1], 2015 [3], 2016 [6], 2017 [2], 2018 [14], 2019 [5], and 2020 [35]. This suggests a growing level of interest given that almost 80% were reported over the past three years (2018–2020). Multilateral banks and donors funded 51 SWP cases, while nine cases saw individual farmers invest in SWPs using alternative financing models such as Pay-As-You-Go (PAYGo). Four cases reported loans under public-private partnership financial models (Fig. A1.1b). Blending these financial mechanisms could be attractive for smallholder farm households in different contexts.

The SWP case studies were further analysed according to the reported energy sources. As expected, the majority of cases [59] utilised only solar power, whilst the remainder [10] used hybrid energy sources that combined solar with fuel (diesel or petrol), mechanical and electricity from the grid. Most solar powered systems were used for irrigation [31]. Multiple uses were equally common [27] and involved smallholder irrigation/livestock/domestic water [16], smallholder irrigation/domestic water [10], and irrigation/drinking water/household off-grid lighting and telecommunication services [1] (Fig. A1c).

SWP configurations included:

- direct pumping for irrigation and household use;
- pumping to a storage and then to the point of use;
- multiple-use system for other on-farm activities;
- pump feeding excess solar into the mini-grids to generate income and hybrid systems with multiple sources of energy such as fuel (diesel & petrol) pump and electricity grid.

The majority of cases relied solely on groundwater [51], with the remainder relying on combined use of groundwater and surface water[99] [9] or only surface water [1]. For groundwater-based systems, the depths of boreholes and wells ranged from seven to 47 metres deep, indicating the aquifer depths that are generally accessed. The most common crops irrigated were vegetables (particularly tomatoes) due to their high economic value that is key to ensuring the financial viability of SWPs, reducing the payback time on the investment (Fig. A1.1d). Smallholder SWP systems used for irrigation were almost entirely applied to market-oriented crops such as horticulture with limited application for staple crops such as grains, tubers or non-food crops such as cotton. Irrigated field sizes with less than 0.5 ha were reported in 6 cases, 0.5 to 1.0 ha in 11 cases and for 1.5 to 2.0 ha in seven cases (Fig. A1.1e), while other cases did not report on the field size. It was noted that field sizes of 1.0 ha or less are more affordable to equip with solar pumps, storage and irrigation kits such as drip and more amenable to the low discharge solar irrigation pumping systems in Sub-Saharan Africa. However, crop type and field application method require consideration. All cases reported on dry season irrigation and no mention was made of supplemental irrigation during the rainy season, however this may have been a neglected aspect.



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[98] Note that the number of cases identified are indicated in rectangular brackets in the text

[99] The source of water was noted to change over time depending on water availability

Table A1.1. List of parameters extracted from the field solar pumping case studies

Reference
Year
Country
Region
National location
Coordinates
Funder of study/ Capital costs
Implementer
Manufacturer
Energy Source: Solar or solar and fuel (diesel or petrol, electricity)
Pump model name/size /ID
Pumping head (m)
Water source: Groundwater, surface water
Type of pump
Pump Size
Aquifer type
Well type/depth (m)
Depth to groundwater (m)
Aquifer productivity (l/s)
Borehole yield
Recommended design yield (70% of tested yield)
Flow rate from Pump (L/min)
Total solar power (KW)
Power required by motor (KW)
Adequacy of power provided versus power required by motor
Water use per day, month, year?
Level of use of the system compared to capacity
Application of solar system: Smallholder irrigation, livestock, domestic water, industry, household off-grid lighting
Irrigation method: Drip, hydroponic, sprinkler, basin- flood, furrow, hand watering
Tank/torage Yes/No (size)
Tank stand height (m)
Irrigated area per farmer (Ha) or total for group of farmers
Crop (cereals, legumes, vegetables, tubers), trees, livestock
Population/farmers serviced
Market access: Road network, population, transport, refrigerated storage
Level (frequency) of maintenance/ cost per month or year
Reported return on investment (actual)
Factors affecting adaption/adoption constraints
Methods: Field observation or modelling
Reported Success (Yes/No)
Nature/indicator of success/ indicator of Impact
Reported value of success
Business models: Financial model used to finance the solar system
Investment required for scaling from public and or private
Policies and regulations
Lessons learned
Additional information

A1.2 Key lessons from case studies for SWP and groundwater management

SWP systems accelerated sector growth has been enabled by conditions that rely on inputs from a range of different actors.It is likely that the conditions that facilitated better uptake included financing mechanisms such as PAYGo to reduce the upfront costs of SWPs, building female farmers' capacity to grow existing high value crops and marketing, farmer awareness and technical training (installation, maintenance), and reduced labour expenses (Table A1.1a). The enabling of these conditions is the responsibility of the users (primarily farmers), governments and the private sector as indicated in the table.

Sustainable pumping at the individual SWP system level is promoted by a range of enabling conditions that rely on inputs from different actors. Opportunities for promoting more sustainable groundwater use at the SWP level rely on the use of tools and technologies such as water accounting models, hydro-meteorology networks, low-capacity pumps, and irrigated area mapping to match water supply with demand (Table A1.1b). This is facilitated by a range of different actors including end-users, governments, private sector. There was an absence of detailed and systematic studies to demonstrate the impacts of the different factors on SWP performance and water use.

A1.3 References for case studies

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Annex 2. Summary of market sales and projections

Approach and Assumptions	Main Findings
Study: GIZ (2020)	
Provides sales projections for Ethiopia for different scenarios to address perceived gaps in SWP demand forecasting	• Scenario 1 involves replacing the existing fuel based pumps in the four regional states – it would nominally require 156,609 SWP units. The capital investment costs would be between EUR 238 million and 1,071 million. By 2025, with 10% growth of fuel pumps converted to solar would require 481,512 units. • Scenario 2 involves installing solar pumps for irrigating plots of lands - demand would reach 940 units per annum by 2025 given a growth rate 20.3% per annum over past 3 years. • Scenario 3 involves trends in marketed solar pumps – it would require 16.8 million solar pumps at an investment cost of EUR 25.536 billion in SWPs and EUR 1.965 billion for the construction of manually drilled boreholes based on developing all the land assessed to be suitable for solar irrigation across the country
Study: GOGLA (2020a); GOGLA (2020b) [100]	
• SWP sales information is based on semi-annual evaluations from GOGLA 'affiliate companies' • Sales estimates are for pumps <3 kW in size • Regional data is openly accessible whereas data for any country is only provided in aggregated form if three or more affiliates report sales data to ensure confidentiality procedures are followed • The market share of the affiliates (in terms of all solar appliances) ranges from 97% in Rwanda to 14% in Niger	• Over the first 3 semi-annual reporting periods SWP sales for Sub-Saharan Africa have ranged from 2,900 to 4,900 units, with the strongest being the reported period of July to December 2019 (prior to COVID-19) • The dominant market share is held by East Africa (4,200 units from five reported countries), follow by West Africa (700 from three reported countries), Central Africa (0 from two reported countries) and Southern Africa (0 from one reported country) • The 4th period reported for Jan. to Jun. 2020 signalled a half in growth of SWPs due to COVID-19. Sales for Sub-Saharan Africa were 2,700 units
Study: Efficiency for Access Coalition (2019b)	
The study focuses on off-grid SWPs for smallholder farmers at the Sub-Saharan Africa-level and focuses on: • small (75–370W) pumps at an assumed SWP price of USD 650 per unit and conservatively assuming a 1% annual reduction in price over time • the 'addressable' market – accounting for farming households who have clear need for a solar water pump and can afford one, assuming access to finance over 36 months, with 10% upfront payment • off-grid and weak-grid farming households who have access to a water source are included whereas subsistence farmers are not due to absence of a reliable agricultural income source	• The market potential in Sub-Saharan Africa is projected to grow from 0.7 million household (currently) to 2.8 million households by 2030 • The value of the SWP market over this period will grow from USD 0.5 to 1.6 billion
Study: Detollenaere et al. (2019)[101]	
• This report analyses ten key national markets as well as trends, opportunities and business models	• Findings show that Botswana, Mauritius, Rwanda and South Africa are among the markets with the highest potential for solar PV. Ghana, Kenya and others closely follow • Most markets should be worthy of examination by investors • Political instability remains a major roadblock to untapping the potential for PV development for some countries
Study: IFC (2019)[42]	
The focus is on the solar irrigation market (and other solar applications) in three focal countries with contrasting contexts: Kenya in the east; Ivory Coast in the west; and Zimbabwe in the south.	• Kenya – SWP uptake is growing rapidly; specialist providers / distributors and (now) larger manufacturers are starting to enter the market using Kenya as an entry point • Ivory Coast – SWP penetration remains very low to date; climate patterns and the market environment makes water pump sales difficult for applications other than horticulture • Zimbabwe – SWPs are available but uptake is limited; there are several distributors targeting smallholders, but the major constraint is the affordability

Table continues onto next page

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[100] GOGLA only report data where there are three or more separate manufacturers

[101] Detollenaere A., Puddu S., Masson G., Wedepohl D. and Tepper M. (2019) Solarize Africa Market Report, German Solar Association –BSW-Solar, May 2019. http://becquerelinstitute.org/wp-content/uploads/2019/05/Solarize-Africa-Market-Report.pdf

Approach and Assumptions	Main Findings
Study: Factor[e] Ventures (2018)	
• Presents a GIS-based (visual/quantitative) approach for establishing the potential for solar pump sales, addressing the accurate customer identification as a key market barrier • Approach is applied to Kenya using data on climate, groundwater level, crop production and crop prices • Customers identified can be, at a high level, matched with a solar pump off the market	Not applicable (methodological note only)
Study: Foster and Cota (2014)	
Presents a review of the African SWP market during its emerging phase	• SWP sales can be segregated into irrigation and community water supplies. For Kenya and Ghana the splits are 50:50 and 60:40 for the two applications respectively • Nigeria accounts for half of Africa's SWP sales • Sales account for only a few hundred units per annum per country at the time of the study (an order of magnitude lower than the most recent figures)

Annex 3. Overview of Sub-Saharan Africa's groundwater resources

A3.1 Water quantity

Access to water sources across rural Sub-Saharan Africa has typically depended on groundwater supplies delivered through shallow, hand-dug wells or hand-pump equipped boreholes.

Over 100 million people, including rural populations throughout Africause groundwater for domestic supplies, watering livestock and small-scale irrigation[102]. Groundwater dependency by communities in arid and semi-arid areas is estimated to be as high as 75% or more[102]. Key priorities from a groundwater focus for Sub-Saharan Africa countries continued to be: (i) improving rural water supply and sanitation; and (ii) expanding irrigated agriculture production for s subsistence and commercial purposes[84].

Groundwater occurrence and availability in Sub-Saharan Africa is strongly dependent upon the region's hydrogeological environment[21].

Four main aquifer types underpin Sub-Saharan Africa's regions: (i) weathered basement rocks, which extend over 40% of the land mass; (ii) consolidated sedimentary rocks (32%); (iii) unconsolidated sediments (22%); and (iv) volcanic rocks (6%) (Figure A3.1)[107,108,103].

- **Weathered basement rocks** – These rocks comprise complex crystalline igneous and metamorphic rocks with low storativityand poor permeability. This aquifer type covers much of West Africa, Uganda and Tanzania in East Africa, Malawi in Southern Africa, much of Zimbabwe, northern Mozambique and northern South Africa. Groundwater productivity for these aquifers is highest where there has been extensive weathering of the parent rock, or where fractured/fissured zones are present.
- **Consolidated sedimentary rocks** – These rocks rangefrom highly productive sandstone and limestone through to low yielding mudstone. They are distributed across most of South Africa, Botswana, southern Angola, eastern Namibia, eastern Democratic Republic of Congo, north-west Zimbabwe, eastern Ethiopia and Somalia.
- **Unconsolidated sediments** – These rocks range in composition from highly productive coarse gravel and sand to silt to low productive clays, and are found along major and minor rivers and in coastal areas. These aquifers occur in southern Mozambique, central Democratic Republic of Congo, and across much of the Sahel.
- **Volcanic rocks** – These rocks are found to a limited extent mainly in the Ethiopian and Kenyan highlands and Southern Africa. They can be important groundwater resources, but productivity is highly variable due to their geological complexity, which is associated with fracture anddyke features.

Boreholes and wells in weathered basement typically have yield flows of 0.5-1.0 litre per second. Yields from other aquifer types tend to be higher –up to 5 litres per second or more is common in unconsolidated and some consolidated aquifers[108]. It is challenging to sustain rates of groundwater pumping over the extended dry season months in hardrock aquifers due to their low storage capacity.

102. Adelana S.M.A. and MacDonald A.M. [Editors] (2008) Applied Groundwater Research in Africa. IAH Selected Papers on Hydrogeology, CRC Press, Volume 13, 518p.
103. Braune E. and Xu Y. (2010) The role of ground water in Sub-Saharan Africa. Ground Water48(2): 229–238.
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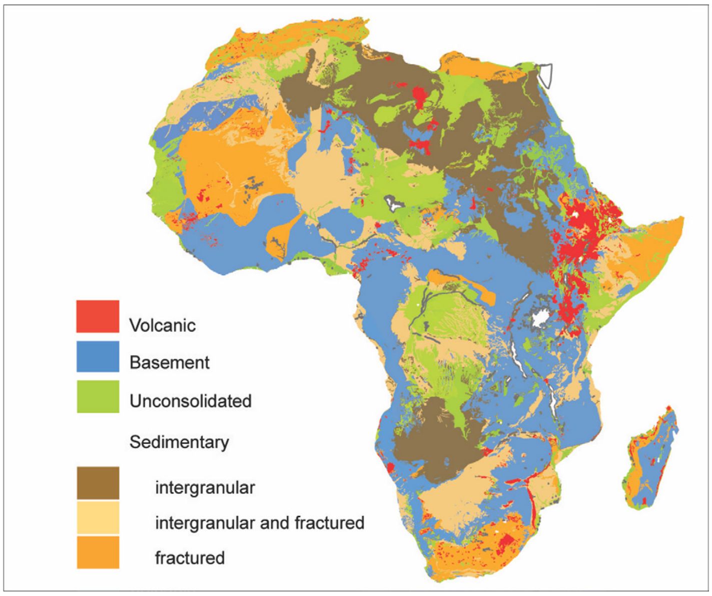
Figure A3.1. Hydrogeology of Africa[104]



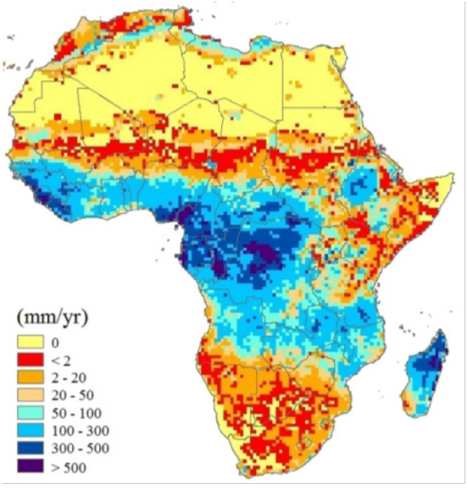
Recharge is a critical element of sustainable groundwater development.

Groundwater resources are augmented by recharge derived from precipitation that infiltrates through the soil to shallow and deep aquifers. In some cases, shallow groundwater is replenished by seepage from streams and rivers[75]. Figure A3.2 shows that groundwater recharge rates across the regions vary from <1 mm per year in arid settings through >500 mm per year in the tropics[28]. Although Sub-Saharan Africa's distribution of renewable groundwater is highly skewed towards the wetter equatorial regions, groundwater development has been most concentrated in the drier regions with precipitation rates of <1,000 mm per year (Figure A3.2) and limited surface water storage opportunities . Rainfall patterns and rainfall intensity are also known to have an important effect on groundwater recharge[97].

The region has scope for successfully developing groundwater supplies for small-scale uses if boreholes and wells are sited, designed and constructed using the best available scientific knowledge and information.

On the whole, information to support successful groundwater development remains limited, although recent efforts have helped to consolidate knowledge at national and continent levels[107]. In some countries where the dependence on groundwater is high, more focused efforts have improved the knowledge base on groundwater resources. Success rates for newly constructed wells and boreholes have improved with the provision of quantitative information on physical properties such as aquifer characteristics, groundwater recharge rates, flow regimes and water quality. In worst case scenarios, up to 90% of existing groundwater infrastructure can fail to meet expectations for a variety of reasons that include seasonal drying, low-yields, pump failure, and lack of safety for human consumption. In some cases, available groundwater is unattractive, and has problems with taste, and odour [108,109,110].

Figure A3.2. Average annual groundwater recharge from 1960 – 2000
Source: Altchenko and Villholth, (2015)[36]



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109. Mwathunga E., Fallas H.C., MacAllister D.J., Mkandawire T., Makuluni P., Shaba C., Jumbo S., Moses D., Whaley L., Banks E., Casey V. and MacDonald A.M. (2019) Physical factors contributing to rural water supply functionality performance in Malawi. Nottingham, UK, British Geological Survey, 24p. (OR/19/057) (Unpublished).

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A3.2 Water quality

Throughout Sub-Saharan Africa, groundwater is generally of adequate physical, chemical and microbial quality for most uses, yet specific issues do arise for specific parameters in particular settings.

Health risks are largely associated with elevated concentrations of arsenic and fluoride, or deficient concentrations of iodine. In some locations, levels of total dissolved solids (i.e. salinity) in groundwater are too high for drinking and irrigation. Elevated nitrate concentrations derived from sewage waste or fertilisers can also be problematic in some cases[111]. The specific water quality issues associated with different hydrogeologic environments are briefly summarised as follows[77]:

- **Weathered basement rocks underlying 40% of Sub-Saharan Africa's land area:** Groundwater is generally of good quality (occasional elevated sulphate, iron or manganese), but is vulnerable to contamination.
- **Consolidated sedimentary rocks underlying 32% of Sub-Saharan Africa's land area:** Groundwater quality is generally good, but can be high in salinity at depth, or have locally high levels of sulphate, iron or manganese. Occasionally water can be 'hard' (elevated bicarbonate) or have high iron and manganese where the groundwater is deep and devoid of oxygen (i.e., anoxic conditions).
- **Unconsolidated sediments underlying 22% of Sub-Saharan Africa's land area:** Groundwater quality is generally good, but problems can occur due to elevated levels of naturally present constituents such as iron, arsenic and nitrate. Groundwater with elevated iron is more widespread compared to arsenic, but pose minimal health concerns although fouling of water pumps and well screens may arise. Shallow wells are vulnerable to contamination from pit latrines and agro-chemical use.
- **Volcanic rocks underlying 6% of Sub-Saharan Africa's land area:** Groundwater quality can sometimes be problematic in volcanic rocks, as minerals present in the rock can dissolve into the groundwater. Fluoride concentrations in excess of the World Health Organization (WHO)'s drinking water guideline of 1.5 mg/L can lead to health problems such as dental or skeletal fluorosis. This is common among people who live in the Rift Valley (East Africa to Southern Africa) in Kenya, Ethiopia and Tanzania. In Ethiopia, high fluoride is a risk for a population of close to 8.5 million people, with nearly 40% of deep wells and boreholes and 20% of shallow wells in the Rift Valley having fluoride concentrations unsuitable for drinking. Maps showing the indicative fluoride concentrations across the African continent have been prepared[112].

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