IWMI Research Report

152

Agricultural Water Storage in an Era of Climate Change: Assessing Need and Effectiveness in Africa

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Front cover photograph shows a small agricultural reservoir near Nekemte, Ethiopia *(photo credit:* Matthew McCartney, IWMI).

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Contents

Acronyms and Abbreviations

CC	Climate change
CCLM	COSMO-CLM, COnsortium for Small-scale MOdelling - CLimate Model
CIESIN	Center for International Earth Science Information Network
CRU	Climatic Research Unit
CV	Coefficient of variation
CVA	Coefficient of variation for annual rainfall
CVM	Coefficient of variation for monthly rainfall
DAG	Dependence on rainfed agriculture
DL	Dependence on livestock
IAM	Integrated Assessment Model
IIASA	International Institute for Applied Systems Analysis
ILRI	International Livestock Research Institute
SR	System Reliability
SRES	Special Report on Emissions Scenarios
SS	System Resilience
SSA	Sub-Saharan Africa
SV	System Vulnerability
SWAT	Soil and Water Assessment Tool
TRP	Total Rainfall per Person
UNH	University of New Hampshire, USA
WEAP	Water Evaluation and Planning (model)

Summary

By mitigating the vagaries of climatic variability, agricultural water storage is widely anticipated to make a key contribution to climate change (CC) adaptation, particularly in Africa. However, if the planning of water storage is not improved, it is likely that many investments will fail to deliver intended benefits. This report describes different agricultural water storage options and some of the possible implications of CC. It also describes the development of a simple diagnostic tool, based on a set of biophysical and demographic indicators, which can be used to provide a rapid (first-cut) evaluation of the *need* and *effectiveness* of different water storage options, under existing and possible future climate conditions. The tool was applied to sub-Saharan Africa and, in more detail, to the Volta Basin and the Ethiopian portion of the Blue Nile Basin. Throughout sub-Saharan Africa, the greatest need for storage was found to be in the Sahelian zone, the Horn of Africa and southern Africa, with more localized hot spots in southern Angola, Rwanda, Burundi and Uganda, as well as Malawi and Mozambique. In Ethiopia and Ghana, the greatest need was found not to be in areas with the least rainfall (as might have been anticipated), but rather in the areas with the highest population density. Based on changes anticipated by the realization of one downscaled 'middle impact' climate change scenario, the effectiveness of storage will decrease in both the Volta and Blue Nile basins in the future. The approach needs to be refined through further research and testing in real planning situations, but nevertheless provides the basis for a more rigorous approach to the planning of future agricultural water storage.

Agricultural Water Storage in an Era of Climate Change: Assessing Need and Effectiveness in Africa

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Introduction

Many of the world's poorest people, with their limited choices, inadequate access to resources and climate-sensitive livelihoods, are at risk from climate variability. In Africa, existing climate variability, and insufficient capacity to manage that variability, lies behind much of the prevailing poverty and food insecurity. Many of the nearly one billion people who are food insecure, are so, at least in part, because of their dependence on rainfed agriculture (FAO 2011). For many, their vulnerability is expected to increase with CC.

Similarly, national economies, highly dependent on rainfed agricultural production, are exceedingly vulnerable to both intra-annual and inter-annual fluctuations in rainfall and hydrology. For example, the occurrence of droughts and floods reduces economic growth in Ethiopia by more than one-third and similar climate-related losses have been reported in Kenya (World Bank 2006; Grey and Sadoff 2006). In India, good (i.e., high rainfall) monsoons are associated with high agricultural productivity and correlate with a strong economy, but weak or failed monsoons (droughts) result in widespread agricultural losses and substantially hinder overall economic growth (World Bank 2005). Hence, the vagaries of rainfall influence not only livelihoods and food security but also broader economic development (Brown and Lall 2006).

Under these circumstances, even relatively small volumes of water storage can, by safeguarding domestic supplies and supporting crops and/or livestock during dry periods, significantly increase agricultural and economic productivity and enhance people's well-being. For millions of smallholder farmers, reliable access to water is the difference between self-sufficiency in food and hunger. Yet, despite greater rainfall variability, per capita water storage in reservoirs is lower in Africa than elsewhere in the world (White 2005). Lack of water storage limits water availability for irrigation and is one of the main reasons why agricultural productivity remains low, particularly in sub-Saharan Africa (SSA) where it is typically less than 1 tonne per hectare (t ha^{-1}) (Peacock and Ward 2007).

There is a great deal of ambiguity about the magnitude of the threat CC poses to agriculture. There remains significant uncertainty about possible future rainfall trends throughout Africa (Christensen et al. 2007; Shongwe et al. 2009, 2011; Williams and Funk 2010). A recent study concluded that, "… the likely impacts of climate change on key staples and natural resources in developing countries in the coming decades are not understood in any great depth" (Thornton and Cramer 2012). What is more generally, though not universally, agreed is that CC will exacerbate 'natural' climate variability. Rainfall everywhere (even where the total increases) will likely become more variable, both in intensity and duration, resulting in increased frequency of droughts and floods (Bates et al. 2008). Consequently, water resource managers will be increasingly forced to plan and manage water resources (including water storage) under conditions of increasing uncertainty. Smallholder farmers will also have to cope with more difficult climate regimes. Already, although there is little congruence with scientific studies, there is growing anecdotal evidence of changing rainfall patterns in Africa that may reflect increases in both seasonal and inter-annual variability (Conway 2011).

Against this background, there is a re-emerging interest from donors to invest in water storage and irrigation infrastructure development; interventions that are seen as effective CC adaptation measures, because they increase water availability for agriculture. The current position of the World Bank is that water resource projects provide the basis for broad regional development, with "significant direct and indirect benefits for poor people" (World Bank 2004). As a result, the Bank is re-engaging in the development of water infrastructure and, in its current water sector strategy, has targeted a 50% increase in lending for water resource projects. In Africa, other institutions including the African Development Bank and the New Partnership for Africa's Development (NEPAD), have called for increased investment in the water sector (NEPAD 2003). The leaders of the G8 summit in Gleneagles in 2005, through the launch of the Infrastructure Consortium for Africa, committed a significant amount of aid to water infrastructure development. In addition, the European Union pledged to increase the volume of aid to developing countries, with a significant part going towards water infrastructure development projects, and with a special emphasis on Africa.

In 2005, the Commission for Africa called for the amount of arable land under irrigation to be doubled by 2015 (Commission for Africa 2005). However, between 2004 and 2007, the irrigated area increased by just 0.9%. In 2010, the Commission for Africa reiterated its call and noted the need for a sharp increase in investment in order to achieve the doubling of arable land under irrigation by 2015 (Commission for Africa 2010). China is also investing significantly in large-scale water storage throughout Africa (IRN 2006). More recently, Nelson et al. (2009) proposed annual investments of USD 3.1 billion globally (of which 30% was proposed for SSA) for irrigation expansion and improvements in irrigation efficiency to offset the negative effects of CC on agriculture. Much of this irrigation will require water storage.

Despite the recognized need for increased water storage, there is a continued debate about the most appropriate types of technology and, in particular, whether investment for poverty alleviation is best targeted at large- or small-scale interventions (McCully and Pottinger 2009). The idea of optimizing [artificial] water storage development through diversifying its options probably goes back to Keller et al. (2000). Van der Zaag and Gupta (2008) further examined options of developing dispersed storage through the basin in addition to large point storage. More recent studies suggest that, globally, soil storage enhancement and small-scale runoff harvesting can make a useful contribution to agricultural productivity under current and future climate conditions (Rost et al. 2009; Wisser et al. 2009).

In many developing countries, development planning is severely constrained by lack of financial and human resources, and, to date, there has been little systematic analysis of how CC may affect existing water storage or how to account for CC in the planning and management of new water storage schemes.

This report outlines a framework for assessing the *need* and *effectiveness* of a range of different water storage options. The approach relies on several broad criteria with underlying water storage-specific metrics. The method links biophysical and demographic elements of storage and, because it is linked to climate parameters, it provides a basis for assessment within the context of CC. The approach was applied to SSA and specifically to the whole of the Volta Basin and the upstream, Ethiopian, portion of the Blue Nile Basin.

Water Storage and Climate Change

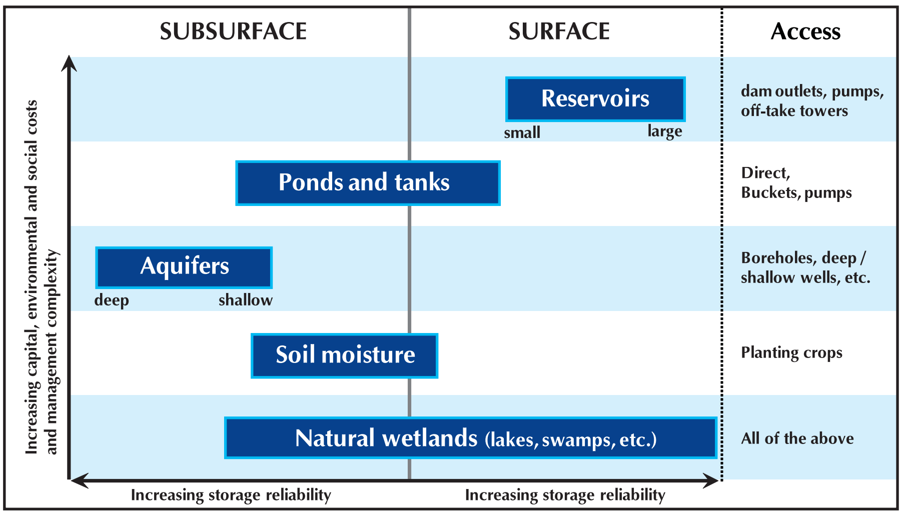
When it comes to storage, past water resource planning has focused mostly on large dams. While dams have made an important and significant contribution to human development, their construction is often controversial. In the past, there was often insufficient participation of local people in the planning process, consideration of alternative options was often not comprehensive, evaluation of environmental impacts was inadequate, and the impact on poor people living both upstream (in the area inundated by the reservoir) and downstream (where flows were modified) has rarely been addressed properly. Consequently, the legacy of large dams is mixed (WCD 2000).

For agriculture, dams are just one of a range of possible water storage options. Other options include: natural wetlands, enhanced soil moisture, groundwater aquifers and ponds/small tanks. In fact, agricultural water storage can be considered as an extensive continuum of surface and subsurface options (Figure 1). Their effectiveness varies, but, broadly, the deeper and/or larger the storage, a more reliable water supply can be ensured; the more 'natural' it is, the less complex and less costly it is to develop and access. Modes of management also vary considerably. In some cases, decision making and responsibility lies directly with an individual whilst relatively complex institutional arrangements are required in other instances. Hence, in any specific situation, each option needs to be considered in terms of technical feasibility, socioeconomic sustainability and institutional requirements, as well as impact on public health and the environment.

In any given location, the impact of different types of storage on poverty can vary significantly, with some options being much more effective in reducing poverty than others (Hagos et al. 2012). In other words, boreholes may have a greater impact than small reservoirs in some circumstances and vice versa in others. It is not always clear why a particular option is successful in some instances and seemingly ineffective in others. For example, in Ghana and Ethiopia, some small reservoirs have led to diversification, and more stable and reliable income for farmers whilst others, constructed nearby under seemingly almost identical conditions, have apparently failed to bring about significant change (Venot et al. 2012).

All of the possible agricultural water storage options are widely used throughout SSA (Table 1). However, with the exception of large dams, past storage development has occurred in an ad hoc 'organic' manner, largely through private, community

FIGURE 1. Conceptualization of the physical water storage continuum.



Source: McCartney and Smakhtin 2010.

TABLE 1. Typology and use of different agricultural water storage options.

Reservoirs
Reservoirs are water impounded behind small and large[1] dams constructed across streams and rivers. Small dams (often built simply by mounding earth) store relatively small amounts of water (a few hundred to a few thousand cubic meters) and often empty every year. Many small dams do not have outlets and water is simply removed by livestock drinking, pumping, and as a consequence of spilling and evaporation. They tend to be shallow with relatively large surface areas so that, in common with many ponds/tanks, up to 90% of the water may be lost through evaporation (Mugabe 2006). Large dams (often rock-filled or concrete) store millions and sometimes billions of cubic meters of water. As well as supplying water for irrigation and domestic purposes, many large dams also supply water for industrial purposes and for the generation of hydropower. In many parts of SSA, small dams and reservoirs make an important contribution to livelihoods through the provision of water for irrigation, livestock and domestic water purposes. For example, thousands of such dams have been constructed in the Volta Basin in northern Ghana and Burkina Faso. In contrast, only a relatively small number of large dams have been built in SSA (< 2,000 of the 55,000 built globally). The high costs of large dams in SSA result from the need to relocate (normally the poorest) communities from the inundated area, disruption of ecosystem services downstream and transmission of vector-borne diseases (e.g., malaria and schistosomiasis) (McCartney and King 2011).
Ponds and tanks
Ponds and tanks are cisterns or cavities (covered or uncovered) built to store water by individuals or communities. They are often linked with rainwater harvesting and store relatively small, but often vitally important, volumes of water. Ponds and tanks fill through either surface runoff or groundwater and differ from reservoirs by the absence of a dam. A common limitation is that they are usually shallow, with a relatively large surface area, so that often a significant proportion of the water is evaporated. Used for livestock watering, domestic purposes and sometimes small-scale irrigation (e.g., household kitchen gardens/plots), open water tanks lined either with rocks and mortise or with polyethylene sheets or geomembranes (i.e., to reduce infiltration losses) are a common feature in some parts of SSA. One major advantage is that they represent a decentralized system that enables individuals and communities to manage their own water for their own purposes. The increased storage of water often enables women, in particular, to increase small-scale gardening, improving diets, possibly health and very often incomes (Barron 2009). However, there may also be adverse public health impacts from vector-borne diseases such as malaria and schistosomiasis (Waktola 2008).
Aquifers
Groundwater is water stored beneath the surface of the earth in aquifers: the pores and fractures of sand, gravel and rock formations. This includes superficial groundwater stored in the sediments of temporary and ephemeral riverbeds, which may be enhanced through the construction of sand dams (Quilis et al. 2008). The amount of water that can be abstracted from a well in an aquifer is a function of the characteristics (particularly the permeability) of the rock (Todd 1980). Methods for increasing groundwater recharge include pumping surface water directly into an aquifer and/or enhancing infiltration by spreading water in infiltration basins. The introduction of deep drilling and pumping machinery from the 1970s has enabled the area utilizing groundwater to be extended in response to increasing population. Today, groundwater is used for domestic purposes over very large areas of SSA, but not for irrigation simply because application to fields is too difficult for poor farmers. It is estimated that SSA has as much as three times the available per capita groundwater of countries such as China and India, where groundwater plays a significant role in agriculture (Giordano 2006). However, the tube well revolution that has swept through much of Asia has not yet happened in Africa and its use in irrigated agriculture is very low. The most traditional and widespread use of groundwater in agriculture is for garden-scale irrigation of vegetables and seedlings, often from hand-dug wells, sometimes using treadle pumps. There are also examples of groundwater being used to provide supplementary irrigation to small-scale plots (typically 1-2 ha) and, very rarely, for the commercial cultivation of high-value vegetable crops in the vicinity of some cities. A crude estimate for groundwater-irrigated land in SSA is 0.85 million hectares (Mha) (i.e., around 1% of all arable land or 10% of all irrigated land) (Giordano 2006).
Soil moisture
Soil moisture is the water stored in soil pores. Globally, the total volume of water stored within the soil is huge. One estimate is that, at any given time, there is 16,500 Bm^3 of water in soils (i.e., 0.05% of the planet's total freshwater resources) (c.f. 12,900 Bm^3 in the atmosphere and 2,120 Bm^3 in rivers) (Shiklomanov 1993). However, at any given locality, the water stored is limited and quickly depleted by evapotranspiration. Because of this, in recent decades, there has been an increased interest in various in situ (i.e., in-field) rainwater management techniques that enhance infiltration and water retention in the soil profile. The objective of these techniques is to stabilize and enhance crop yields by increasing the effectiveness of rainfall. Widely referred to as soil and water conservation (SWC) measures, examples vary from place to place but the most promising techniques include deep tillage, reduced tillage, zero tillage and various types of planting basin.

(Continued)

[1] Large dams are defined as those greater than 15 m in height or with a storage capacity exceeding 3 Mm^3 for heights between 5 and 15 m (ICOLD 2003).

TABLE 1. Typology and use of different agricultural water storage options (Continued).

Natural wetlands
Lakes, swamps and other wetland types have provided water for agriculture for millennia, both directly (as sources of surface water and shallow groundwater) and indirectly (through soil moisture). Consequently, wetlands span the surface/subsurface interface and provide water in many different ways (Figure 1). As a result of their important role in the provision of water, wetlands are increasingly perceived as 'natural infrastructure'. Farmers are often skilled in the management of water within wetlands. Throughout West Africa, complex systems have been devised to control not only the frequency and timing of flooding, but also the depth and duration of standing water in inland valley wetlands (Wopereis and Deffoer 2007).

and local initiatives, with minimal planning. In some cases (e.g., where reservoirs have silted, wells are dry and ponds have aggravated negative health impacts), the lack of planning has resulted in less than optimal investments. Even where there has been more central planning, despite good intentions, it has not always been successful. For example, it is estimated that of around 4,000 rainwater harvesting ponds constructed in the Amhara region of the Abay River (Blue Nile) Basin in Ethiopia between 2003 and 2008, the majority were non-functional in 2009 (Tadesse et al. 2009). It is also estimated that in many countries in SSA, about 40% of the boreholes are not functional mainly due to poor construction and lack of professionalism in the well development sector (RWSN 2009). Broadly, the lack of success can be attributed to a range of factors, including poor site selection, design and technical problems (e.g., failure of lining materials leading to seepage), and lack of commitment by communities to maintenance (Eguavoen 2009).

In many places there is a paucity of information on existing storage. For example, in both the Volta (Ghana and Burkina Faso) and Olifants (South Africa) basins there are many thousands of small reservoirs but the exact numbers, let alone the volumes of water stored, are unknown (Johnston and McCartney 2010). Even where such data are available they are often dispersed and difficult to access. Furthermore, the basic scientific knowledge required for planning is also often inadequate. For example, understanding of flow and sediment regimes (necessary for dam design), knowledge of aquifer extent and recharge (necessary for groundwater exploitation) and understanding of current climate variability (necessary for all storage types) are often insufficient for detailed planning. As a result design failures are common, benefits are frequently sub-optimal and, in the worst cases, investments worsen rather than improve people's well-being.

All storage options are potentially vulnerable to the impacts of CC. By modifying both water availability and water demand, CC will affect the performance, cost and adverse impacts of different types of water storage option. In some situations, certain storage options will be rendered completely impracticable whilst the viability of others may be increased. For example, CC may have significant impacts on soil moisture. In arid regions, the proportional change in soil moisture can be much greater than the proportional change in rainfall (Chiew et al. 1995; de Wit and Stankiewicz 2006). Hence, less rainfall and longer dry periods mean that SWC measures may fail to increase and maintain soil moisture sufficiently, leading to increased frequency of crop failure. Groundwater recharge may be reduced if rainfall decreases or its temporal distribution changes in such a way that infiltration declines. Many aquifers near the coast will be at risk from saltwater intrusion as a result of sea-level rise. Ponds and tanks may not fill to capacity or the frequency of filling may be reduced, so that they are unable to provide sufficient water for supplemental irrigation. Changes in river flows may mean that reservoir yields, and hence assurance of water supplies, decline. Storage in ponds, tanks and reservoirs may also be reduced more rapidly as a consequence of increased evaporation and/or greater sediment inflows. Furthermore, both large and small dams as well as ponds and tanks may be at increased risk of both eutrophication and flood damage. Natural wetlands also face a range of CC-related threats arising from changes in hydrological fluxes (i.e., surface water and groundwater flows, and evapotranspiration), as well as increased anthropogenic pressures resulting directly and indirectly from CC.

In all cases, the externalities[2] associated with different storage types are also likely to be affected by CC. For example, although meteorological variables are not the only factor affecting CC and hence it is difficult to extrapolate, malaria transmission in the vicinity of some ponds, tanks and reservoirs may increase as the result of modified rainfall patterns and higher temperatures (Boelee et al. 2012). Impacts of dams on downstream river flows and on the livelihoods of people dependent on those flows, may be exacerbated by the effects of CC. This could, in turn, result in the need to release a greater proportion of the water stored to maintain the riverine environment and ecosystem services on which people depend. These and similar factors will affect the suitability of different water storage options in any specific situation.

Table 2 summarizes some of the potential risks for different water storage options as a consequence of CC and indicates some possible socioeconomic implications. However, in some places, CC will bring positive benefits and may improve the performance of some water storage options. For example, in some places, CC will increase flows into large reservoirs and increase groundwater recharge, with resultant positive social and economic impacts. The exact impacts, and whether they are positive or negative, will be site-specific and to a large extent dependent on exactly how different water storage options are managed.

Furthermore, the introduction of trends into hydrological behavior, as a result of CC, invalidates the assumption of stationarity[3], which has always been the basis for hydrological engineering. This will greatly increase the difficulties of the already complex task of planning, designing and managing water storage (Milly et al. 2008). For example, changes in flow regimes during the long lifetime of major water infrastructure, such as dams, will be large enough to fall outside the historic envelope of variability. Peak flows may increase and low flows may decline, affecting both the yield and the safety of dams. In some countries (e.g., Australia and the USA), consideration is being given to redesigning the overflow spillways of large dams to cope with enhanced floods anticipated to arise as a result of CC.

Hence, CC necessitates a fundamental rethinking of the way water resources, and particularly water storage options, are planned and managed. In all situations, maximizing the benefits and minimizing the costs of water storage options will, as in the past, require consideration of a wide range of complex and interrelated hydrological, social, economic and environmental factors. However, in a departure from the past, planning needs to be much more integrated across a range of levels and scales, and with much greater consideration of the full range of possible options and the potential implications of CC. To date, although there have been many studies on the effects of CC on hydrological regimes (e.g., de Wit and Stankiewicz 2009), relatively little consideration has been given to planning water storage in a world of CC.

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[2] Externalities are the effects (positive or negative) of an action (on other parties) which are not taken into account by the perpetrator.

[3] This presumes that hydrological processes fluctuate within an unchanging envelope of variability (i.e., there is no systematic change in either the mean or the variance of time series). System dynamics remain constant, so that, at any given location, the statistical properties of all aspects of the hydrological cycle (e.g., rainfall amounts, seasonal soil moisture fluctuations, streamflows and flood frequencies) can be estimated from observations. Furthermore, the longer historic records are available, the more confidence can be placed in these estimates.

TABLE 2. Climate change risks for different storage types in SSA and the possible social and economic implications.

Storage type	Risks associated with CC*	Social and economic implications
Reservoirs	• Reduced inflow, resulting in longer periods between filling. • Higher evaporation, increasing the rate of reservoir depletion. • Infrastructure damage due to higher flood peaks. • Improved habitat for disease vectors (e.g., mosquitoes). • Increased risk of eutrophication and salinization. • Increased siltation.	• Increased failure to meet design specifications (irrigation and hydropower generation, etc.). • Increased costs due to the need to redesign infrastructure (e.g., spillways). • Increased risk of waterborne diseases (e.g., malaria).
Ponds/tanks	• Reduced inflow, resulting in longer periods between filling. • Higher evaporation, increasing rates of pond/ tank depletion. • Infrastructure damage due to higher flood peaks. • Improved habitat for disease vectors (e.g., mosquitoes). • Increased risk of eutrophication and salinization. • Increased siltation.	• Increased failure to provide water requirements of the community and households. • Increased labor requirements and costs to repair structures. • Increased risk of waterborne diseases (e.g., malaria).
Aquifers	• Reduced recharge, resulting from modified rainfall intensities. • Reduced recharge, resulting from land-cover modification and increased soil moisture deficits. • Saline intrusion in aquifers near the coast.	• Falling water levels make it increasingly costly to access groundwater. • Poor water quality makes groundwater unsuitable for use.
Soil moisture	• Reduced infiltration, resulting from modified rainfall intensities. • Waterlogging, resulting from modified rainfall intensities and duration. • Longer dry periods, resulting from altered temporal distribution of rainfall. • Depleted soil moisture, arising from higher evaporative demand. • Soil erosion, resulting from modified rainfall intensities and duration. • Reduced soil quality (including water-holding capacity and nutrient status), resulting from modified rainfall and temperature.	• Decreased productivity – more frequent crop failures and reduction in yields.
Natural wetlands	• Reduced rainfall and runoff inputs, resulting in wetland desiccation. • Higher flood peaks, resulting in wetland expansion and flooding of fields and homes. • Improved habitat for disease vectors (e.g., mosquitoes).	• Increased failure to provide water requirements of the community and households. • Loss of water-dependent ecosystem services (including flow regulation and groundwater recharge). • Increased risk of waterborne diseases (e.g., malaria).

Note: * It is important to note that these risks will not be universal. In some places, CC will cause the reverse impact and may have positive rather than negative social and economic implications.

Evaluating Water Storage Options

Synopsis

When water storage is being considered as a possible adaptation measure for CC, key considerations for water resource planners and managers are how to determine current and future water storage needs (i.e., needs assessment) and how to compare and select from different water storage options (i.e., options assessment). In the past, there has generally been little explicit consideration of these issues, even for large dam construction. For smaller infrastructure, where planning is often less formalized, needs are usually regarded as self-evident and alternative options are rarely considered.

Decisions about future water storage need to be based on consideration of a wide range of factors. The diagnostic framework proposed here provides an approach for an initial appraisal of two key elements of water storage:

- the **need** for storage; and
- the **effectiveness** (i.e., technical performance) of storage options, both in isolation and in combination.

The framework encompasses a set of indicators which can be used to evaluate different water storage types under current and possible future climate conditions. The indicators selected do not provide a comprehensive coverage of all aspects that need to be considered when making decisions about water storage. However, they do highlight key elements which can be used to quickly determine if particular options are, or are not, likely to be appropriate. This can be followed by a much more detailed evaluation of those storage options which are considered to be most successful in the places where they are most needed.

All the indicators are based on assumptions about the factors which are important, informed by literature reviews and, to a large extent, intuitive understanding. However, as far as possible the indicators are:

- objective/quantitative;
- the same for all storage types;
- applicable across a range of scales (i.e., from local to national);
- applicable under current conditions as well as under CC scenarios;
- as simple as realistically possible (i.e., determined in the simplest way possible); and
- easily communicated to interested parties (i.e., can be displayed graphically).

While changes in climate, population and land use are fundamental to the estimation of future agricultural water storage, the magnitude and direction of change for all of these parameters is unknown and varies under different scenarios. For the analyses presented in this report, the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) A1B scenario (Nakicenovic and Swart 2000), downscaled using the COSMO-CLM (CCLM) dynamic regional climate model (Hatterman 2011), was used for all indicators, where it is currently possible to estimate future values based on scenarios. The SRES A1B scenario describes a future world of very rapid economic growth, global population that peaks at 8.7 billion in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. It is distinguished from other scenarios by the technological emphasis on a balance between fossil-intensive and non-fossil energy sources (Nakicenovic and Swart 2000). As such, it is a relatively conservative, but not overly cautious, representation of possible future conditions with changes that, at the global level, lie between extremes produced by other emission scenarios (i.e., A2 – extensive fossil fuel use, and B2 - moderate increase in greenhouse gas concentrations).

The Need for Water Storage

Decisions relating to water resources and water storage must be based on clearly identified needs. Assessing the demand for water, in relation to both local and national development goals, is a prerequisite for evaluating different storage options. At any location the need for agricultural water storage is a function of a wide range of factors. However, in broad terms, the need for water storage can be anticipated to be the greatest in situations where: i) water is needed for agriculture (crop or fodder); ii) rural population density is high and thus likely to be vulnerable to climate impacts; iii) the amount of rainfall per person on agricultural land is low (i.e., high population density and/or low rainfall); and iv) there is high unpredictability in annual rainfall totals and rainfall is highly seasonal. Each of these factors can be expressed as an index derived from a number of indicators.

In this study, the need for agricultural water storage was assumed to be a function of five, dimensionless, indicators (Table 3). Analyses were conducted for three periods: 2000, 2050 and 2100 under the SRES A1B scenario. The need for storage was mapped by combining available spatial datasets (Table 3) in a simple overlay model. As the population data for 2050 and 2100 are only available at the national scale and do not show within-country variations in population density, the results should only be used for inter-country comparison. However, for 2000, higher resolution biophysical data and sub-national population data are available (Table 3), and these were used to give insights into within-country variations for the year 2000. Hence, one dataset (low resolution) was used for the regional analyses to enable comparison between the 2000 situation and future scenarios (Table 4), and another dataset (high resolution) was used to enable within-country comparison of the current (2000) situation (Table 5).

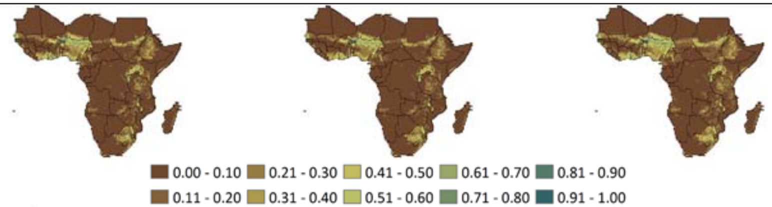
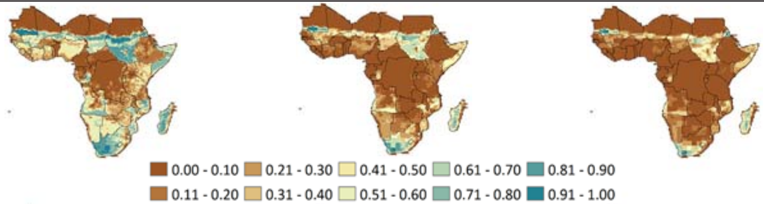
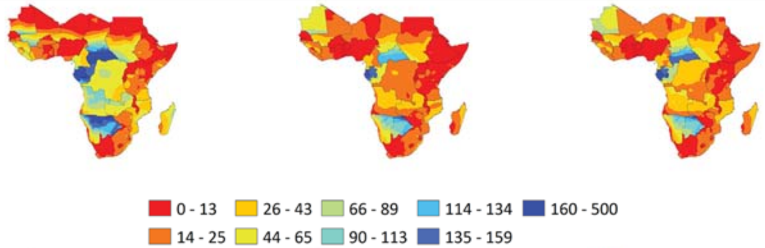
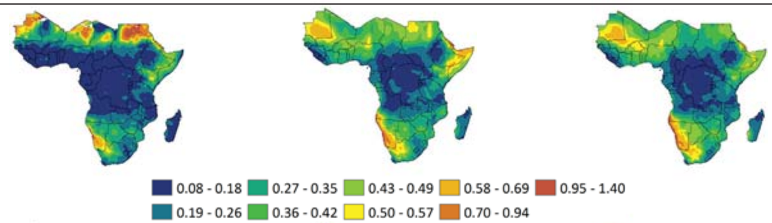
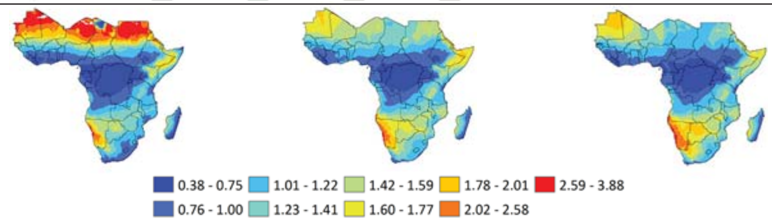
TABLE 3. Indicators used to establish the need for water storage.

	Indicators		Explanation
	Subregional: Current (i.e., 2000) situation - Ethiopia and Ghana	Regional: Current (i.e., 2000) and future (i.e., 2050 and 2100) situations - SSA	
DAG (1-9)	Fraction of agriculture that is rainfed (Fischer et al. 2002).	Projection of fraction of cropland (Hurtt et al. 2009).	The greater the fraction of rainfed cultivation or livestock (subregional), or cropland or pasture (regional), the greater the likelihood that water storage can usefully contribute to increased productivity and bring livelihood and economic benefits.
DL (1-9)	Livestock density (total livestock units)*.	Projection of fraction of pasture (Hurtt et al. 2009).	
TRP (1-9)	Mean annual rainfall divided by population density on 0.5° x 0.5° grid.	Projection of mean annual rainfall divided by country-level projections of population.+	The lower the total rainfall per person, the greater the need for water storage.
CVA (1-9)	CV of annual rainfall derived from mean annual rainfall (1971-2000) (0.5° x 0.5° grid).	Projection of CV of annual rainfall derived from simulated mean annual rainfall (0.5° x 0.5° grid).+	Unpredictability of rainfall across years is an indicator of hydrological extremes. The higher the CV, the greater the likelihood of devastating floods and extended drought.
CVM (1-9)	CV of monthly rainfall derived from the Climatic Research Unit (CRU) dataset (1971-2000) (0.5° x 0.5° grid).	Projection of CV of monthly rainfall derived from simulated mean monthly rainfall (0.5° x 0.5° grid).+	The greater the seasonal variation in rainfall. the greater the need to regulate it.

Source: * Data obtained from the livestock density database of the International Livestock Research Institute (ILRI) (available at http://www.ilri.org/GIS, accessed on May 09, 2011).

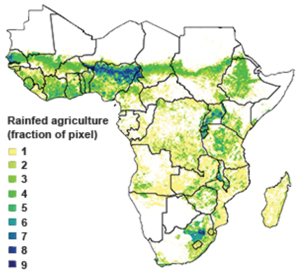
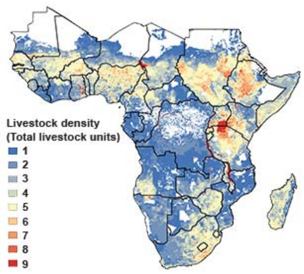
Note: + all projections are derived from SRES A1B scenario of possible future conditions.

TABLE 4. Data inputs to the index for the regional analyses of the need for water storage.

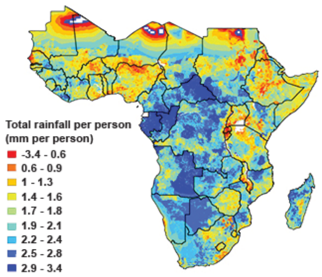
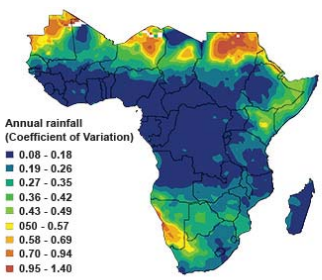
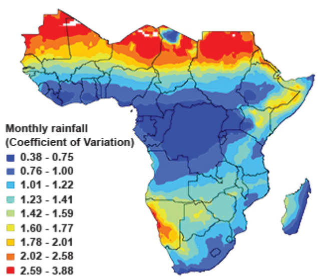
Indicator	Input datasets	Source	2000	2050	2100
DAG	Fraction of cropland: SRES A1B scenario and the IAM model.	UNH land-use harmonization dataset (Hurtt et al. 2009)			
DL	Fraction of pasture: SRES A1B scenario and the IAM model.	UNH land-use harmonization dataset (Hurtt et al. 2009)			
TRP	Total rainfall: Current (1971-2000) Future (2021-2050) - SRES A1B scenario. Future (2071-2100) - SRES A1B scenario. Population density: SRES A1B scenario (IIASA downscaled to national level).	CRU dataset* CIESIN 2002			
CVA	Coefficient of variation (annual): Current (1971-2000) Future (2021-2050) - SRES A1B scenario. Future (2071-2100) - SRES A1B scenario.	CRU dataset*			
CVM	Coefficient of variation (monthly): Current (1971-2000) Future (2021-2050) - SRES A1B scenario. Future (2071-2100) - SRES A1B scenario.	CRU dataset*			

Source: * Data obtained from the database of the Climatic Research Unit (CRU), University of East Anglia, UK (available at http://www.cru.uea.ac.uk/data, accessed on January 12, 2011).

TABLE 5. Data inputs to the index for subregional analyses of the need for water storage.

<table>
<tr><th>Indicator</th><th>Input datasets</th><th>Source</th><th>2000</th></tr>
<tr><td>DAG</td><td>Fraction of agriculture that is rainfed</td><td>Fischer et al. 2002</td><td>
</td></tr>
<tr><td>DL</td><td>Total livestock units</td><td>ILRI[+]</td><td>
</td></tr>
<tr><td>TRP</td><td>Total rainfall (mm)

Population density (0.5° x 0.5°) grid</td><td>CRU dataset[*]

CIESIN 2002</td><td>
</td></tr>
<tr><td>CVA</td><td>Coefficient of variation (annual):
Current (1971-2000).</td><td>CRU dataset[*]</td><td>
</td></tr>
<tr><td>CVM</td><td>Coefficient of variation (monthly):
Current (1971-2000).</td><td>CRU dataset[*]</td><td>
</td></tr>
</table>

Source: [+]Data obtained from the livestock density database of the International Livestock Research Institute (ILRI) (available at http://www.ilri.org/GIS, accessed on May 09, 2011).

[*] Data obtained from the database of the Climatic Research Unit (CRU), University of East Anglia, UK (available at http://www.cru.uea.ac.uk/data, accessed on January 12, 2011).

The need for storage was computed using the following equation:

$$NEED = (DAG + DL + (1 - TRP) + 0.5(CVA + CVM))/36 \quad (1)$$

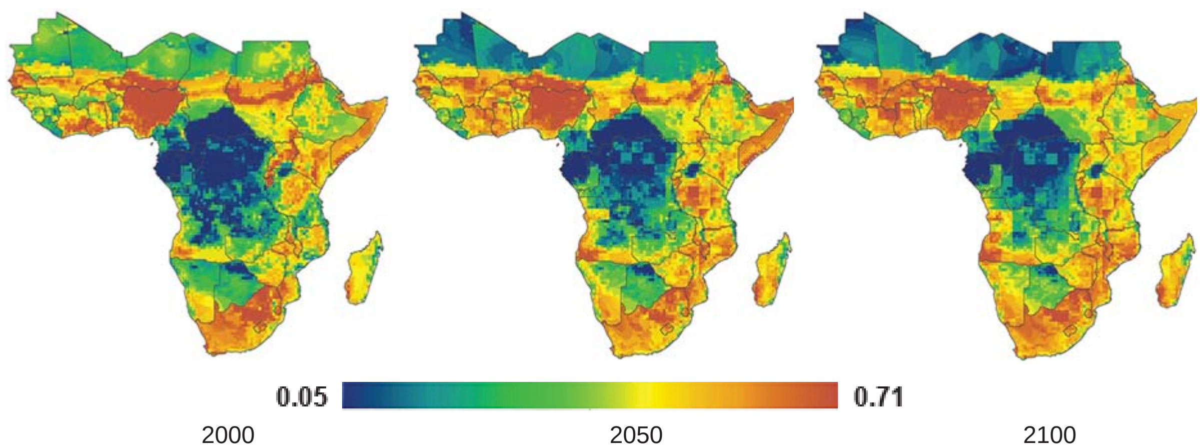
where: DAG = dependence on agriculture[4] (i.e., proportion of this agriculture in a single grid cell)
DL = dependence on livestock (i.e., proportion of pasture in a single grid cell)
TRP = Total rainfall (mm) per person (mean annual rainfall divided by population density)
CVA = CV of annual rainfall
CVM = CV of monthly rainfall
36 = maximum total across all indicators

In order to identify the storage need for the poor (i.e., those most likely to be dependent on agriculture for their livelihoods and well-being), it would be necessary to include poverty data. However, because no projections of poverty are available for the SRES A1B scenario in the future, this was not included in the analyses. Rather, it was assumed that areas of extensive agriculture, high population and high climatic variability broadly match the areas with the highest poverty rates.

In order to combine the different spatial data in the analysis, it was necessary that all layers were normalized (i.e., followed the same scale of values) and that all revealed the pertinent variation held within the dataset. To do this, all indicator data were divided into nine classes prior to combining. For most indicators, higher values correspond to greater need. The exception is the total rainfall per person indicator, which is the reverse and so was inverted in Equation 1. To obtain nine classes, data values were re-classified using the Jenks natural breaks classification method (Jenks 1977). This aims to present a series of break values that best represent the actual breaks in data as opposed to some arbitrary classification scheme. For the regional analyses, in order to ensure direct visual comparison between each indicator for all scenarios (i.e., 2000, 2050 and 2100), the natural breaks for the period with the greatest range were selected and the same classification scheme was applied to the other two scenarios.

The results are displayed as a continuous range of values between 0 and 1 (see Equation 1) from 'low' to 'high' need for storage. The main purpose of the indicators is to enable a spatial comparison across SSA. Figure 2 shows the results of the SSA regional analysis for 2000, 2050 and 2100. Figure 3 presents the results of

FIGURE 2. Maps of water storage need in SSA.



[4] N.B. for the current situation at the national level, this is the proportion of rainfed cultivation at each pixel location; for the regional analysis at 2000, 2050 and 2100, this is the proportion of all agriculture at each pixel location.

the 2000 country-level analyses, using Ethiopia and Ghana as examples. The need indices are also presented in radar diagrams (Figure 4). These summarize changes over time and enable comparison of the higher resolution data for Ethiopia and Ghana.

Table 6 provides a summary of storage need and how this changes over time in each of the countries in SSA. Table 6 also shows existing storage in large reservoirs (expressed in terms of cubic meters per capita), where these data are available. The data highlight that there is no correlation between current need (as determined using Equation 1) and existing large reservoir storage (Figure 5). This is because: i) existing storage was not factored into the analysis, since the data are not generally available in spatially disaggregated form; and ii) large reservoir storage may be used for many purposes including hydropower generation, so is not automatically a good indicator of the need (or not) for agricultural water storage. Some of the largest reservoirs in Africa (e.g., Akosombo and Kariba) are primarily used for hydropower generation and explain the high per capita storage in some countries (i.e., Ghana, Zambia and Zimbabwe). Figure 5 highlights the importance of the right 'kind' of water storage for agriculture; high per capita storage may be necessary but is not, in itself, sufficient if it is not the right type of storage.

FIGURE 3. Maps of water storage need for Ghana and Ethiopia based on current (2000) conditions.

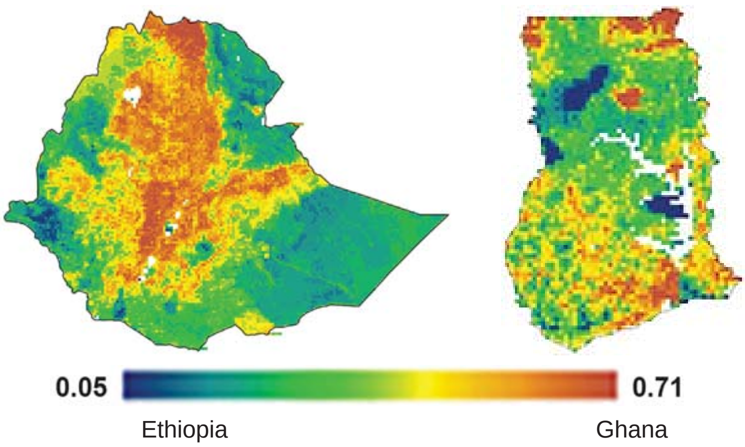
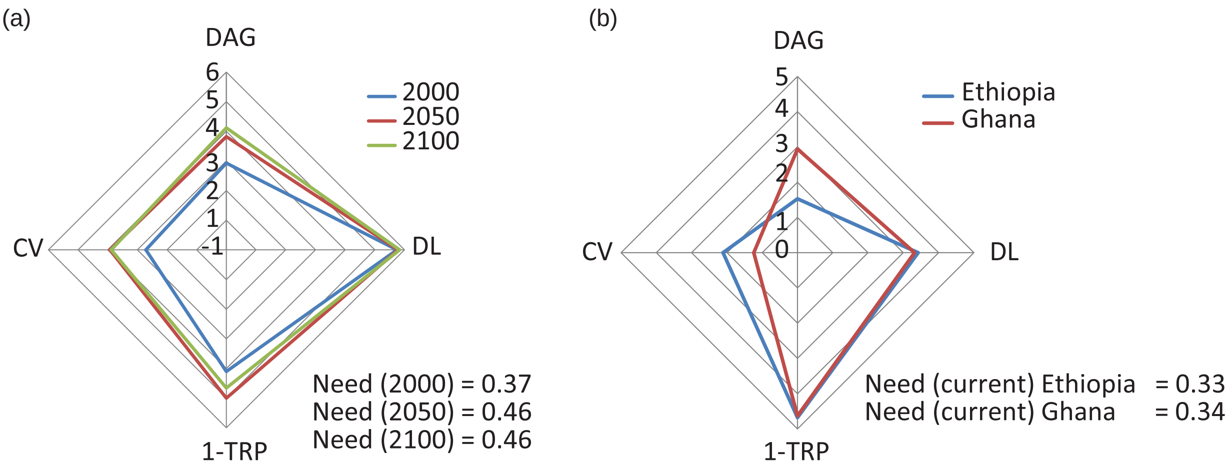


FIGURE 4. a) the average 'need' for water storage across SSA in 2000, 2050 and 2100; and b) current need for water storage in Ethiopia and Ghana.[5]



[5] 'Need' is calculated as defined in Equation 1.

TABLE 6. Estimated national average water storage need in 2000, 2050 and 2100 for countries of SSA.

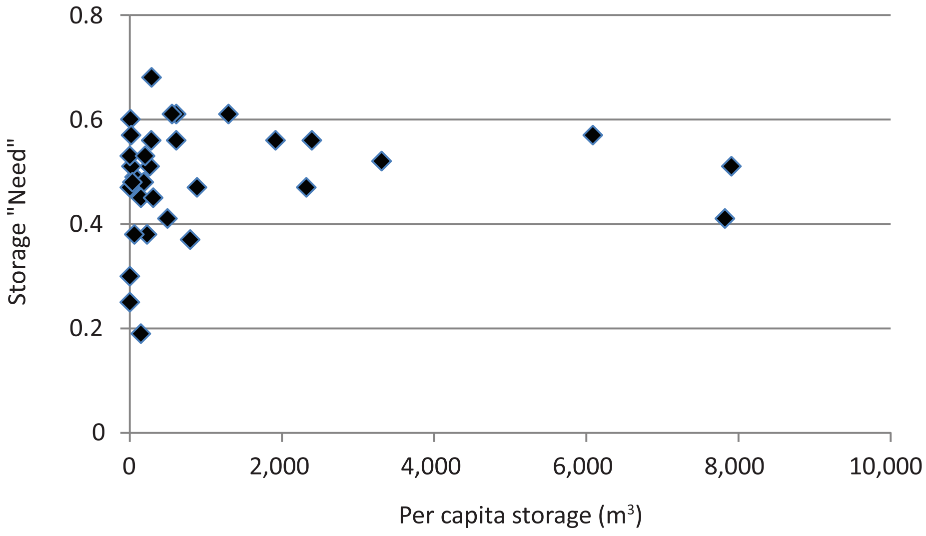
Country[#]	Current large reservoir storage (m^3/capita)[+]	2000	2050	2100
Angola	495	0.41	0.54	0.57
Benin	3	0.47	0.60	0.63
Botswana	226	0.38	0.48	0.51
Burkina Faso	261	0.51	0.65	0.70
Burundi	-	0.65	0.66	0.64
Cameroon	797	0.37	0.48	0.48
Central African Republic	-	0.16	0.29	0.27
Chad	-	0.45	0.52	0.49
Côte d'Ivoire	1,915	0.56	0.66	0.67
Democratic Republic of the Congo	1	0.30	0.40	0.40
Djibouti	-	0.57	0.66	0.61
Equatorial Guinea	-	0.29	0.38	0.36
Eritrea	8	0.60	0.63	0.63
Ethiopia	67	0.49	0.58	0.58
Gabon	146	0.19	0.25	0.24
Gambia	-	0.59	0.68	0.71
Ghana	6,088	0.57	0.66	0.68
Guinea	184	0.48	0.58	0.60
Guinea-Bissau	-	0.52	0.65	0.68
Kenya	611	0.56	0.61	0.61
Lesotho	1,299	0.61	0.67	0.68
Liberia	60	0.38	0.50	0.51
Madagascar	24	0.51	0.61	0.63
Malawi	3	0.53	0.64	0.66
Mali	886	0.47	0.53	0.54
Mauritania	145	0.45	0.44	0.44
Mozambique	3,312	0.52	0.65	0.67
Namibia	310	0.45	0.58	0.61
Niger	-	0.51	0.53	0.51
Nigeria	288	0.68	0.74	0.74
Republic of the Congo	2	0.25	0.38	0.38
Rwanda	-	0.60	0.61	0.60
Senegal	20	0.57	0.64	0.66
Sierra Leone	38	0.48	0.54	0.53
Somalia	-	0.59	0.69	0.64
South Africa	612	0.61	0.67	0.69
Sudan*	201	0.53	0.55	0.52
Swaziland	554	0.61	0.68	0.68
Tanzania	2,324	0.47	0.62	0.63
Togo	285	0.56	0.62	0.63
Uganda	2,394	0.56	0.59	0.59
Zambia	7,824	0.41	0.52	0.54
Zimbabwe	7,911	0.51	0.62	0.65

Source: [+] Data obtained from the geo-referenced dams database of the Food and Agriculture Organization of the United Nations (FAO) (available at http://www.fao.org/nr/water/aquastat/dams/index.stm) and World Bank population data (Africa Development Indicators - http://data.worldbank.org/data-catalog) (both websites accessed on March 08, 2013).

Notes: [#] Small islands (i.e., Seychelles, Cape Verde, Comoros, Mauritius, and São Tomé and Príncipe) are not included in the analyses.

[*] Sudan and South Sudan combined.

FIGURE 5. Comparison of existing large reservoir storage, expressed in terms of per capita storage and storage need, estimated using Equation 1.



Effectiveness of Water Storage

A number of risk-based indicators have been used to evaluate the *effectiveness* (i.e., technical performance) of water storage in terms of *reliability, resilience* and *vulnerability* (Hashimoto et al. 1982). Over any given period of time:

- reliability is a measure of frequency of failure of the storage to deliver water to satisfy all demands;
- resilience is a measure of speed of recovery from failure of the storage to deliver water to satisfy all demands; and
- vulnerability is a measure of the extent of failure of the storage to deliver water to satisfy all demands.

In the past, these indices have been used almost exclusively for large reservoirs and have been determined in relation to whether or not a reservoir is in a satisfactory state (S) (i.e., able to meet all the specified demands on the water) or an unsatisfactory (failed) state (F) (i.e., unable to meet all the specified demands on the water) (Moy et al. 1986; Vogel et al. 1999). However, the indices have not been applied to other water storage types. In the current study, these standard terms were modified so that they could be applied to a range of storage options, not just reservoirs. Enhanced climatic variability will have impacts on the technical performance of water storage systems. Since all the indices are influenced by climate, they can be used to evaluate performance under possible future climates (Vogel et al. 1999; Fowler et al. 2003).

The approach was applied using data obtained from computer modeling studies that investigated the impact of CC in the Volta and Blue Nile basins. In both cases, three models were used in combination to assess the implications of the SRES A1B scenario on water resources. The dynamic regional climate model, CCLM, was used to determine climate projections. The outputs generated from CCLM (i.e., rainfall, temperature and potential evapotranspiration) were used as input to a hydrological model (SWAT), which was parameterized, calibrated and validated with observed climate and hydrological data. Results of the SWAT modeling (i.e., projections in river flow and groundwater recharge), in conjunction with projected water demands, were used as input to the Water Evaluation and Planning (WEAP) model to determine the water resource implications. Details of the modeling are presented in McCartney et al. (2012) and McCartney and Girma (2012).

Table 7 provides a summary of the climate changes anticipated by this realization of the SRES A1B scenario in both basins. As with all CC modelling, there were limitations in the modelling procedure. The results relate to a single representation of the possible consequences of one particular CC scenario derived from one set of models. Each of the models has associated error and uncertainty. The lack of hydrological data in both basins made it difficult to calibrate and validate aspects of the modelling. For example, there were no groundwater data with which to calibrate the groundwater recharge estimates. Hence, an assumption had to be made that, if the SWAT model was simulating river flows reasonably, this meant that it was also providing plausible estimates of groundwater recharge. In reality, this may not have been the case and SWAT may have been simulating river flows adequately while misrepresenting the processes that generate runoff (van Griensven et al. 2012). Furthermore, it is likely that some errors have been compounded by the different models and others have cancelled each other out. However, because of the complexity of using multiple models and lack of data for calibration/validation, it was not possible to quantify the overall error in the simulation results. The limitations in the modelling mean that the results of the study should be treated as indicative, rather than absolute.

The indicators of effectiveness were determined for the following four water storage options in each of 18 sub-basins delineated in both the basins:

- Large reservoirs.
- Ponds/tanks.
- Aquifers.
- Soil moisture.

To evaluate the impacts of CC, this was done for each of three 30-year time ‘windows’ (periods in Table 7). Both existing and planned large reservoirs and future demands (e.g., for irrigation) were included (i.e., a so-called “full development scenario”) (McCartney et al. 2012; McCartney and Girma 2012). It is important to note that, in both basins, the large reservoirs provide water not only for agriculture, but also for hydropower generation, and industrial and domestic uses.

For the large reservoirs and the ponds/tanks, the analyses were conducted using simulated monthly values of the volume stored (m^3) at the end of each month. Each large reservoir was treated separately with the buffer condition (i.e., the level of storage at which restrictions are imposed on water releases to meet demands) defined as the satisfactory/unsatisfactory threshold. If there was more than one large reservoir in a sub-basin, each

TABLE 7. Basin-averaged climatic and hydrological variables for three periods (1983-2012, 2021-2050 and 2071-2100) for the Volta Basin and the Ethiopian portion of the Blue Nile Basin.

Period	Average annual temperature (°C)[#]	Rainfall (mm)[#]	Potential evapotranspiration (mm)	Actual evapotranspiration (mm)	Averaged annual flow (m^3s^{-1})[+]
			Volta		
1983-2012	30.3 (0.008)	835 (0.12)	2,729	717	1,610
2021-2050	31.3 (0.011)	757 (0.11)	2,813	668	1,217
2071-2100	33.9 (0.012)	666 (0.15)	3,323	606	885
			Blue Nile		
1983-2012	20.9 (0.027)	1,310 (0.12)	1,363	539	1,661
2021-2050	21.9 (0.044)	1,290 (0.13)	1,405	522	1,720
2071-2100	24.9 (0.031)	1,110 (0.15)	1,535	525	1,336

Source: Adapted from McCartney et al. 2012; and McCartney and Girma 2012.

Notes: [#] Numbers in brackets are the Coefficient of Variation.

[+] Flow at the Ethiopia-Sudan border for the Blue Nile and inflow to the Akosombo Reservoir for the Volta. Changes in flow reflect changes arising from CC alone.

index was computed as the average for all the reservoirs in that sub-basin. The storage of the small ponds/tanks were aggregated in each sub-basin and simulated in the WEAP model as a single reservoir. This is not ideal because it was necessary to estimate an elevation-storage relationship for the aggregated storage, which in reality is likely to be very different to that of the individual small ponds. However, it was necessary because it was not possible to simulate the many hundreds of small ponds separately. The analyses in this study were conducted for the aggregated total using 'empty' as the satisfactory/unsatisfactory threshold.

Although ponds/tanks are being promoted by federal and regional governments in Ethiopia, in contrast to the Volta, there is currently no information on locations or volumes of water stored in these structures. Consequently, the analyses for ponds/tanks were only completed for the Volta.

For soil moisture, the analyses were conducted using the simulated wet-season soil moisture stored in the soil profile (mm), derived from SWAT. Ideally, this would have been linked to the soil moisture content at the permanent wilting point (i.e., the minimal point of soil moisture a plant requires not to wilt). At any given location, the permanent wilting point is an integrated effect of plant, soil and atmospheric conditions. However, soil texture is the most important control and thus permanent wilting point may be estimated from the particle size distribution of a soil (i.e., percentages of clay, silt and sand, where the percentage of fine clay is particularly important), as well as from the percentage of organic matter, bulk density, instability of the soil in regard to swell/shrink properties (found in vertic topsoils) and the change of clay content with depth. A map of the water content at permanent wilting point has been derived for South Africa based on soil properties (Schulze and Horan 2008), but similar maps are not currently available for elsewhere in SSA. In the absence of such maps, a threshold for satisfactory/unsatisfactory was set as the mean of the current (i.e., 1983-2012) SWAT-simulated average wet-season moisture storage across the whole basin (i.e., 366 mm for the Blue Nile and 141 mm for the Volta). Although arbitrary, this enabled sub-basins with generally drier soils to be distinguished from those with generally wetter soils and hence enabled spatial as well as temporal variability to be determined. The wet season was defined as June to October for both the Blue Nile and the Volta.

For groundwater, the analyses were conducted using the simulated annual groundwater recharge estimates (mm) derived from SWAT. The satisfactory/unsatisfactory threshold was set separately for each sub-basin as the mean of the current (i.e., 1983-2012) recharge in each.

Both reliability and resilience are expressed as values between 0 and 1. However, to enable direct comparison, vulnerability had to be normalized. This was achieved in each case by expressing vulnerability as a proportion of the maximum possible failure to deliver over each period of interest (Table 8). To compute indices for the storage systems (comprising different storage types) in each basin, the indices derived for individual storage types were combined by simple addition to compute overall system reliability, resilience and vulnerability (Table 9). The overall effectiveness of the storage system in each basin was computed using the following equation:

$$\text{EFFECTIVENESS} = 0.33 * (SR + SS + (1 - SV)) \tag{2}$$

where: SR = system reliability (defined in Table 9)
SS = system resilience (defined in Table 9)
SV = system vulnerability (defined in Table 9)

The greater the overall effectiveness of the storage system, the higher the value of EFFECTIVENESS (0-1).

TABLE 8. Definitions of reliability, resilience and vulnerability for different water storage types.

Term	Reservoirs	Ponds/tanks	Aquifer	Soil moisture
Reliability (R) - the probability that the water stored is in a 'satisfactory' state (i.e.,can meet demands).	For large reservoirs, it is common for restrictions on water supply to be imposed when a buffer condition is reached. Thus: $\boldsymbol{R_R = 1 - \frac{n_r}{n}}$ R_R = reservoir reliability; n_r = length of time with restrictions (i.e., volume is less than the buffer volume); n = total length of time.	For small tanks/ponds, it is rare to have a buffer volume and reliability can be based on the frequency with which the tank/pond empties: $\boldsymbol{R_T = 1 - \frac{n_e}{n}}$ R_T = tank reliability; n_e = length of time the tank is empty; n = total length of time.	For groundwater, reliability is defined in relation to recharge and whether, in any given year, this falls below a critical value: $\boldsymbol{R_G = 1 - \frac{n_g}{n}}$ R_G = groundwater reliability; n_g = number of years that recharge is less than mean annual recharge; n = number of years.	For soil moisture, reliability is defined in relation to wet-season soil moisture content and whether this falls below a value that will limit crop yield: $\boldsymbol{R_S = 1 - \frac{n_s}{n}}$ R_S = soil moisture reliability; n_s = number of years in which crop yields are limited by water stress in the wet season; n = total number of years.
Resilience (Rs) - the capability of the water stored to return to a 'satisfactory' state from an unsatisfactory state (i.e., a conditional probability).	The average probability that a reservoir will (in any given time step) return from a situation, in which constraints to demand are applied, to a situation when there are no constraints to supply: y = Prob{RSt + 1 Є S│RSt Є F} RS = reservoir storage partitioned into S, the set of satisfactory conditions (i.e.,no constraints), and F, the set of unsatisfactory conditions (i.e., constraints).	The average probability that the empty pond/tank will (in any given time step) contain some water: y = Prob {TSt + 1 Є S │TSt Є F} TS = storage partitioned into S, the set of satisfactory conditions (i.e., with some water in storage), and F, the set of unsatisfactory conditions (i.e., empty)	The average probability that the aquifer will, in any given year, return from a situation, in which recharge is below a critical value, to a situation where it is greater than that critical value: y = Prob {GWt + 1 Є S│GWt Є F} GW = groundwater level partitioned into S, the set of satisfactory conditions (i.e., recharge exceeds critical value), and F, the set of unsatisfactory conditions (i.e., recharge less than the critical value).	The average probability that, if soil moisture constrains crop yields during one wet season then it will not constrain crop yields in the next year: y = Prob {SMt + 1 ЄS│SMt Є F} SM = soil moisture yield partitioned into S, the set of satisfactory conditions (i.e., crop yields are unconstrained by water), and F, the set of unsatisfactory conditions (i.e., crop yields are constrained by water).
Vulnerability (V) - the likely magnitude of a failure, if one occurs.	The magnitude of the largest deficit (Dmax) over the period of interest. Derived as a combination of both the deficit and the time that the deficit is experienced: Dmax = max{∑C-Xi, i=1…..N} C = the buffer storage; Xi = the observed storage (i.e., between the buffer and storage); i = time steps when the reservoir storage is below the buffer. Normalized by expressing as a proportion of the maximum possible deficit over the period of interest.	The magnitude of the largest deficit (Dmax) over the period of interest. Derived as a combination of both the deficit and the time that the deficit is experienced: Dmax = max{∑Xi, i=1…..N} Xi = pond/tank volume; i = time steps when the pond/tank storage is zero. Normalized by expressing as a proportion of the maximum possible deficit over the period of interest.	The magnitude of the largest deficit (Dmax) over the period of interest. Derived as a combination of both the deficit and the time that the deficit is experienced: Dmax = max{∑C-Xi, i=1…..N} C = critical groundwater recharge (mm); Xi = the observed groundwater recharge; i = time steps when the groundwater recharge is less than the critical level. Normalized by expressing as a proportion of the maximum possible deficit over the period of interest.	The magnitude of the largest deficit (Dmax) over the period of interest. Derived as a combination of both the deficit and the time that the deficit is experienced: Dmax = max{∑C-Xi, i=1…..N} C = wet-season soil moisture storage (mm) at which crop yields are affected by water stress; Xi = the observed soil moisture; i = time steps when the soil moisture is less than the level at which crop yields are affected. Normalized by expressing as a proportion of the maximum possible deficit over the period of interest.

Note: The *a* Є *S* means *a* is an element of the set S. *a* Є *F* means *a* is an element of the set F

TABLE 9. Indicators used to determine the effectiveness of storage options or a storage system.

	Indicators	Explanation
System Reliability (SR) (0-1)	The probability that the system is in a satisfactory state (i.e., the storage can meet demands). Defined as the sum of reliabilities for all storage types in a system: $SR = 0.25 * (R_R + R_T + R_S + R_G)$ *where:* R_R is the average reliability of all the reservoirs. R_T is the average reliability of all the ponds/tanks. R_S is the average reliability of the soil moisture. R_G is the average reliability of the groundwater. (all defined in Table 8)	The greater the value of SR, the more reliable the system. The individual reliability values will indicate where reliability within the system is strongest/weakest.
System Resilience (SS) (0-1)	The capability of the system to return to a satisfactory state from a state of failure. Defined as the sum of resilience for all storage types in a system: $SS = 0.25 * (S_R + S_T + S_S + S_G)$ *where:* S_R is the average resilience of all the reservoirs. S_T is the average resilience of all the ponds/tanks. S_S is the average resilience of the soil moisture. S_G is the average resilience of the groundwater. (all defined in Table 8)	The greater the value of SS, the more resilient the system. The individual resilience values will indicate where resilience within the system is strongest/weakest.
System Vulnerability (SV) (0-1)	The maximum duration of system failure and the cumulative maximum extent of system failure. Defined as the sum of vulnerability for all storage types in a system: $SV = 0.25 * (V_R + V_T + V_S + V_G)$ *where:* V_R is the average vulnerability of all the reservoirs. V_T is the average vulnerability of all the ponds/tanks. V_S is the average vulnerability of the soil moisture. V_G is the average vulnerability of the groundwater. (all defined in Table 8)	The greater the value of SV, the more vulnerable the system. The individual vulnerability values will indicate which storage types are potentially most vulnerable.

Figures 6 and 7 present the results of the analyses for each storage type in each sub-basin of the Volta and Blue Nile basins, respectively, for the three time windows. In the Volta, the results for large reservoirs have been aggregated to show the results in relation to the four major sub-basins (i.e., the White Volta, the Black Volta, the Oti and the Lower Volta). In the Blue Nile Basin, and for all other indicators, the results are presented for each sub-basin.

For all the indicators, the value for the whole of each of the Volta and Blue Nile basins was computed as the average of the value in each of the 18 sub-basins for each time window (Table 10). The overall effectiveness of the storage systems in each basin, in each time window, are presented in Table 11 and summarized as radar diagrams in Figure 8.

FIGURE 6. Reliability, resilience and vulnerability of different water storage types in the Volta Basin for the three time windows (1983-2012, 2021-2050 and 2071-2100).

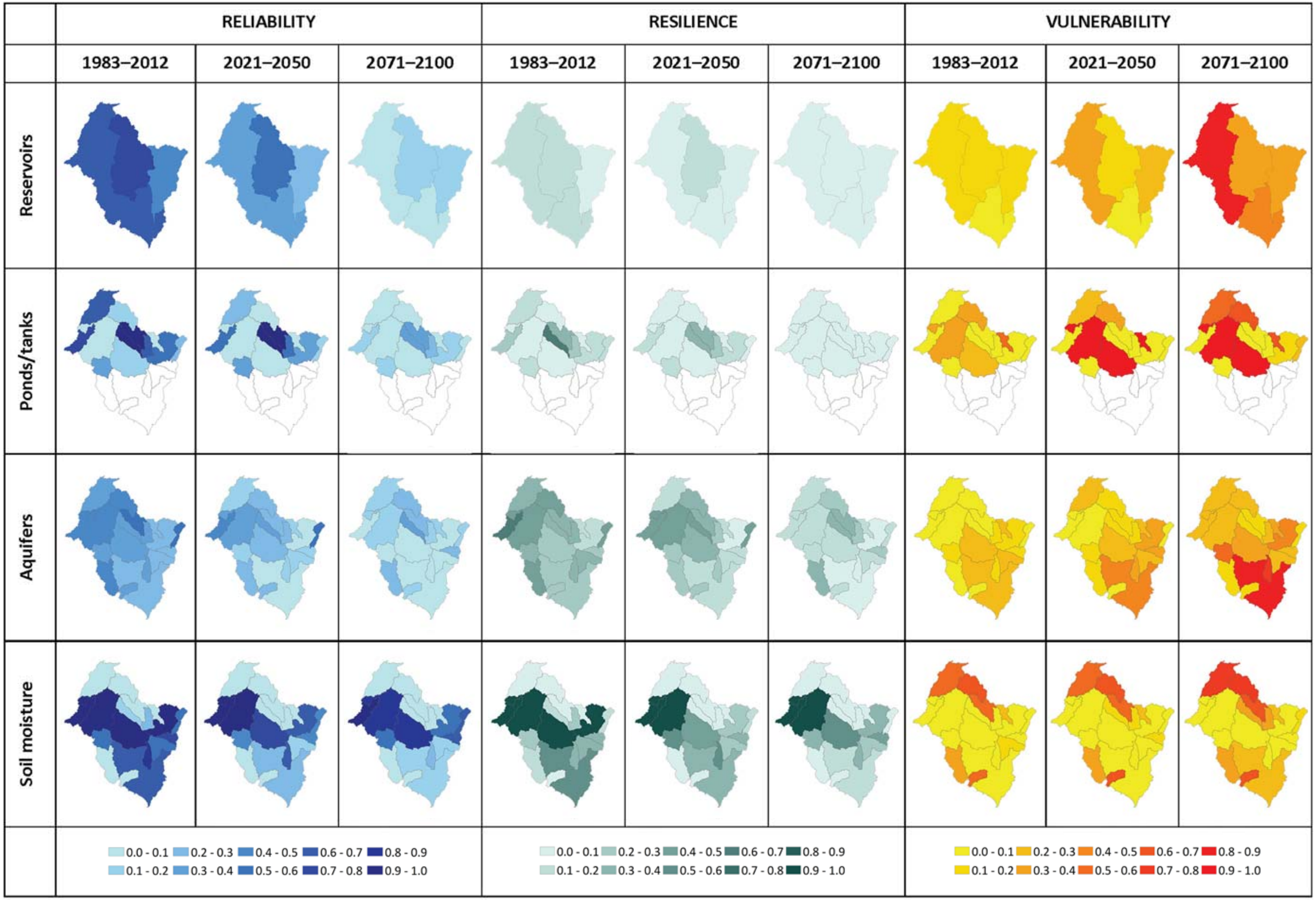


FIGURE 7. Reliability, resilience and vulnerability of different water storage types in the Ethiopian portion of the Blue Nile Basin for the three time windows (1983-2012, 2021-2050 and 2071-2100).

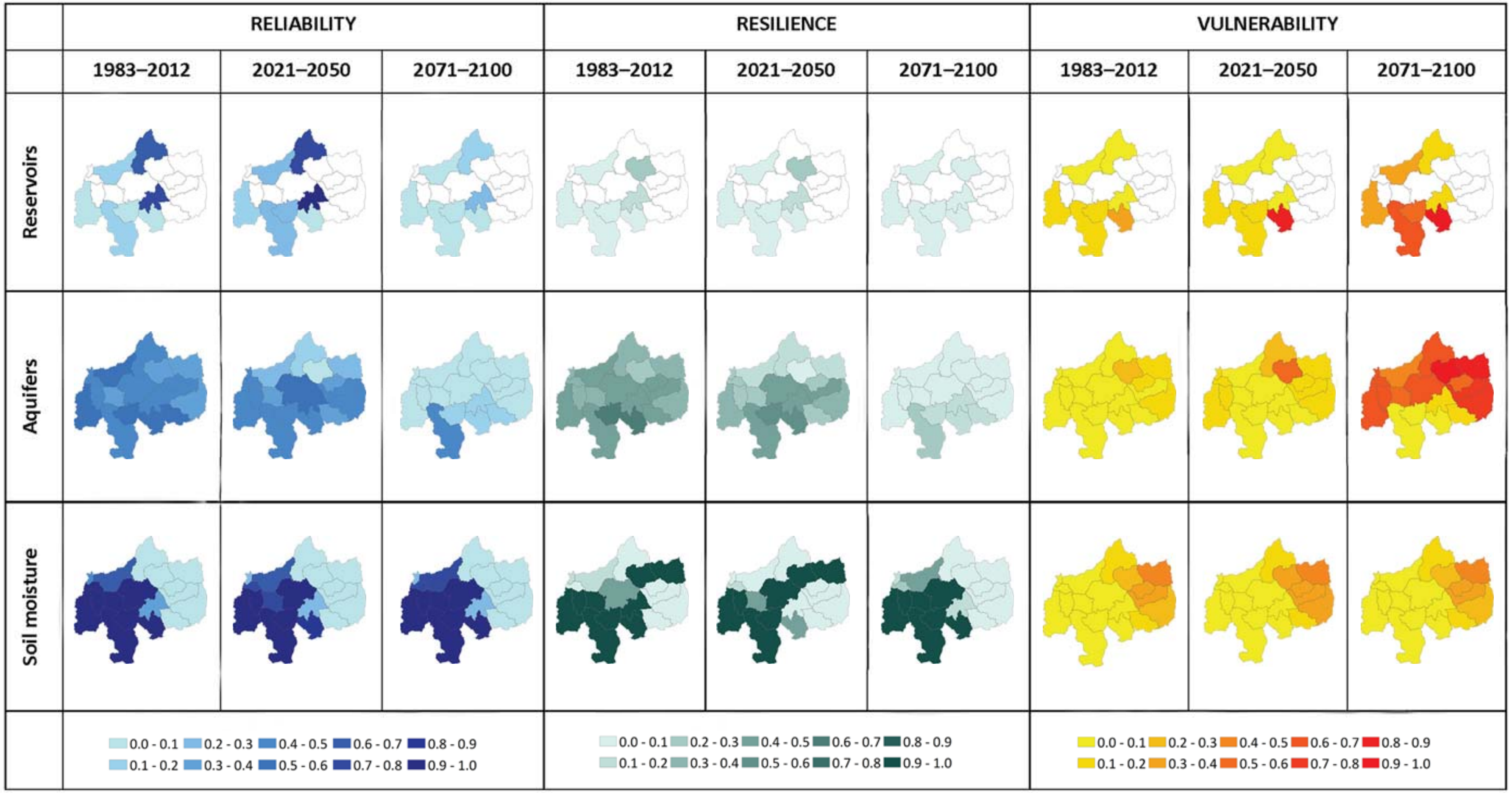


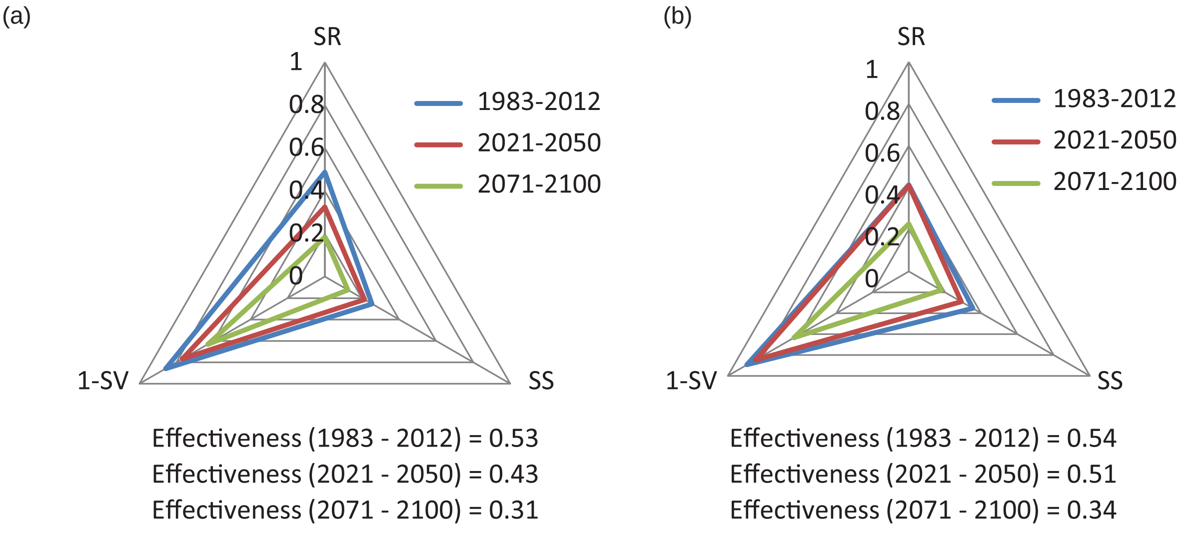
TABLE 10. Basin average reliability, resilience and vulnerability for different storage types in the Ethiopian Blue Nile and Volta basins for three time windows (1983-2012, 2021-2050 and 2071-2100) under the SRES A1B scenario.

	Reliability			Resilience			Vulnerability		
	1983-2012	2021-2050	2071-2100	1983-2012	2021-2050	2071-2100	1983-2012	2021-2050	2071-2100
	Volta								
Large reservoirs	0.62	0.36	0.11	0.11	0.09	0.03	0.12	0.20	0.51
Ponds/tanks	0.47	0.34	0.14	0.19	0.12	0.05	0.15	0.31	0.38
Groundwater	0.39	0.25	0.16	0.35	0.27	0.16	0.12	0.20	0.32
Soil moisture	0.47	0.35	0.33	0.37	0.28	0.26	0.18	0.22	0.27
Average	0.49	0.33	0.19	0.26	0.22	0.13	0.14	0.23	0.37
	Ethiopian Blue Nile								
Large reservoirs	0.25	0.36	0.08	0.08	0.08	0.02	0.13	0.20	0.46
Ponds/tanks	-	-	-	-	-	-	-	-	-
Groundwater	0.48	0.39	0.10	0.44	0.33	0.08	0.07	0.13	0.52
Soil moisture	0.51	0.48	0.50	0.54	0.46	0.44	0.12	0.13	0.12
Average	0.41	0.41	0.23	0.35	0.29	0.18	0.11	0.15	0.37

TABLE 11. Overall effectiveness of storage systems in the Ethiopian Blue Nile and Volta basins for the three time windows under the SRES A1B scenario.

	Volta			Ethiopian Blue Nile		
	1983-2012	2021-2050	2071-2100	1983-2012	2021-2050	2071-2100
Effectiveness	0.53	0.43	0.31	0.54	0.51	0.34

FIGURE 8. Effectiveness of water storage for three time windows (1983-2021, 2021-2050 and 2071-2100) in a) the Volta Basin; and b) the Ethiopian portion of the Blue Nile Basin.



Discussion

The objective of this study was to develop a pragmatic approach for determining the need for agricultural water storage, and the effectiveness of different storage options under both existing and possible future climate conditions in SSA. The framework developed is perceived as a tool for preliminary assessment that can be used to encourage and guide more detailed feasibility studies.

The results from the study indicate that the need for agricultural water storage is currently greatest in the Sahelian zone, the Horn of Africa and southern Africa, with more localized hot spots in southern Angola, southern Ghana, Rwanda, Burundi and Uganda, as well as Malawi and northern Mozambique (Figure 2). The results also indicate that, if CC occurs as anticipated by this realization of the SRES A1B scenario, in conjunction with predicted population change, the need for water storage will increase across most of SSA. However, there is little change in the areas with the most critical need, with the exception of the addition of Madagascar.

The more detailed analyses of the current situation in Ethiopia and Ghana (Figure 3) indicate that:

i) the greatest need in Ethiopia is in the Central Highlands; and

ii) the greatest need in Ghana is in the south and, in patches, in the more arid north of the country.

In both Ethiopia and Ghana, the greatest need is not, as might be expected, in the driest parts of the country but rather in those areas with the highest population density. In both cases, high variability in rainfall means that even though the mean annual rainfall is relatively high there is still a significant need for storage, in order to fulfill the requirements of large rural populations who depend on agriculture for their livelihoods.

The results from the analyses of effectiveness, in both the Volta and the Ethiopian portion of the Blue Nile basins, indicate that the overall effectiveness is currently approximately the same in both basins. Furthermore, it will decrease over time in both basins as a consequence of CC anticipated by the realization of the SRES A1B scenario (Table 11; Figure 8). The decline in overall effectiveness is initially more rapid in the Volta Basin, with a significant decrease prior to 2050. In contrast, the overall effectiveness of storage in the Blue Nile decreases only slightly prior to 2050, but declines rapidly thereafter. Thus, by the end of the century, overall effectiveness is again similar, although significantly reduced from the current condition, in both basins. The difference in the pattern of decline in overall effectiveness largely reflects anticipated differences in the CC-induced rate of decline in rainfall and hence runoff in the two basins. In this realization of the SRES A1B scenario, annual rainfall is anticipated to decrease steadily throughout the twenty-first century in the Volta Basin, but is only anticipated to decline significantly after about 2050 in the Blue Nile Basin (Table 7; McCartney et al. 2012; McCartney and Girma 2012).

A summary of the anticipated impact of the SRES A1B scenario on the effectiveness of different storage types in both basins is presented in Table 12. These results indicate that, overall, the reliability and resilience of all forms of storage decrease and vulnerability increases as a consequence of CC. However, there are differences as to how CC affects the different components of effectiveness of the different storage types, and how these impacts vary across the two basins (Figures 6 and 7).

The results derived are based on a range of simplifying assumptions. Foremost amongst these are that, something similar to the SRES A1B scenario will come to pass and the one realization generated from a single downscaled General Circulation Model (GCM) - selected because it produced the best simulation of current conditions - is a reasonable indication of the changes that arise as a consequence of CC. Ideally, the analyses should be repeated using a number of emissions scenarios and model simulations to determine the

TABLE 12. Summary of the anticipated impacts of CC on the effectiveness of different water storage types in the Volta Basin and the Ethiopian portion of the Blue Nile Basin.

	Volta Basin
Large reservoirs	Current reliability is reasonably high, as would be anticipated for large volumes of storage, but declines as a consequence of CC and reductions in flow. Resilience is low (i.e., large reservoirs are generally slow to recover from failure) and deteriorates as a consequence of CC. Vulnerability is currently relatively low and increases significantly as a consequence of CC.
Ponds/tanks	These only occur in significant numbers in the northern part of the basin. Current reliability is low because many ponds and tanks empty every year. Reliability declines as a consequence of CC, but the decrease is less than that for large reservoirs. Resilience is high (i.e., they recover from failure quickly), but decreases as a consequence of CC. Vulnerability is currently low, but slightly greater than large reservoirs. It increases significantly as a consequence of CC.
Groundwater	Current reliability is moderate and decreases as a consequence of CC; reduced rainfall results in reduced recharge. Resilience of groundwater is reasonable across most of the basin (i.e., recharge tends to recover following years of low recharge) and declines uniformly as a consequence of CC. Vulnerability is relatively low, but increases as a consequence of CC, particularly in the south of the basin.
Soil moisture	Current reliability and resilience are highest in the center and south of the basin, and vulnerability is highest in the north. As a consequence of the anticipated CC, reliability declines, particularly in the south, resilience declines throughout the basin and vulnerability increases most significantly in the south of the basin. These changes reflect changes in rainfall and hence infiltration.
	Ethiopian portion of the Blue Nile Basin
Large reservoirs	Current reliability of existing and planned large reservoirs is lower than those in the Volta, reflecting the lower total storage in the Blue Nile (i.e., 167,079 Mm^3 versus 203,437 Mm^3) and greater flow variability. Reliability increases by mid-century, reflecting the slightly higher and more reliable flow in this period, despite the slight reduction in rainfall. This highlights the importance not just of mean rainfall, but also its temporal distribution. Reliability decreases significantly by the end of the century. Resilience is low but stable till mid-century before declining significantly by the end of the century. Vulnerability is initially low but, as with the Volta, increases significantly as a consequence of CC.
Ponds/tanks	N/A
Groundwater	Current reliability and resilience are reasonably high, but both decrease as a consequence of CC with a similar pattern of change throughout the basin. Vulnerability is relatively low, but increases as a consequence of CC, particularly in the north of the basin.
Soil moisture	Current reliability and resilience are reasonable, particularly in the southwest and center of the basin. Reliability remains fairly constant until the end of the century, but resilience declines slightly as a consequence of CC. Current vulnerability is slightly high in the north and east of the basin and increases moderately in relation to CC.

Note: N/A = Not applicable.

likely range of impacts on different storage types. Other limitations are associated with the models used and the fact that it was not possible to validate the approach.

In this study, the effectiveness of the different storage types in each basin was analyzed separately. This is justified because, unlike domestic and industrial water, agricultural water is often only supplied by one storage option. However, this is not always the case and in future it is probable that in order to safeguard agricultural water, interconnected systems will become increasingly common. In such systems failure to supply water may occur only when concurrent shortfalls arise in more than one storage type. In such a situation, what is of interest is the overall effectiveness of the composite system (Fowler et al. 2003). More research is required to determine how the effectiveness of such systems can be deduced.

As the primary concern for agricultural water, is the ability to maintain a supply of crop and livestock production, it would seem rational that future work should develop indicators that reflect more closely actual crop (and livestock) water requirements rather than the proxies (particularly for soil moisture and groundwater) used in the current study. For example, for crops, although it requires more information than was available in this study, indicators derived from 'permanent wilting point' would be potentially a better indicator of sufficient/insufficient water within the soil. Furthermore, in the current study, equal significance was given to all terms. In future analyses, consideration should be given to weights, so that system indicators in some way reflect the relative proportion of different types of storage. For example, though the total volume of water stored maybe the same, a system comprising one very large dam and one small pond will be very different to a system comprising one large dam and a hundred small ponds. Ideally, the indicators would reflect such differences.

The results from the current study should not be considered definitive, but only an 'indication' of much broader and complex social concepts. The results are suitable for comparative assessments, priority setting, targeting of possible interventions in areas with the greatest storage need and to provide an indication of how the different aspects of effectiveness of different storage options may change as a consequence of future climate conditions. However, much more detailed, site-specific studies are essential prior to interventions being implemented. In order to derive actionable, context-specific interventions, it is necessary to 'zoom in' to identify options with the greatest potential for meaningful impact. These more detailed studies should not only include more detailed evaluations of both the need and effectiveness (based also on local knowledge and requirements), but, very importantly, must also include assessments of economic viability, the likely social and health impacts, and the possible environmental impacts of different storage options. It is, therefore, essential to conduct detailed economic analyses in conjunction with both environmental and social/health impact assessments to evaluate the most appropriate and suitable interventions given the specific context of a particular area.

Conclusions

As elsewhere, agriculture in SSA is likely to be transformed as a result of CC in combination with numerous other drivers of change. Water, already a key constraint to agricultural production in many places, will likely become even more critical. Agricultural water storage in its various different forms, if planned and managed correctly, can increase water security and make an important contribution to safeguarding livelihoods and reducing rural poverty.

To date, the planning of agricultural water storage in SSA has typically occurred with minimal planning and in a largely ad hoc manner. Consequently, the results have been mixed. In some places water storage has considerably improved the livelihoods and well-being of rural communities, but in others it has not. In some cases failure occurs as a consequence of poor technical design, but in others the socioeconomic context is such that increased water storage simply fails to bring intended, though often unspecified, benefits.

By modifying both water availability and water demand, CC will affect the performance, costs and externalities of all types of water storage. As a result, ill-conceived water storage structures constructed today will be a waste of scarce financial resources, and rather than mitigate may aggravate unpleasant CC impacts. The realities of CC are such that if the performance of agricultural water storage is to be enhanced in future, much closer attention must be paid to planning and management.

Key to planning and management of water storage are determining current and future needs, and making appropriate choices from the suite of options available. In any given situation this requires an understanding of a range of biophysical and socioeconomic issues that influence different water storage types, both in isolation and in combination within a basin.

This study developed a diagnostic tool for more rigorously assessing different water storage options. The approach, which integrates biophysical and demographic indicators, provides a way of evaluating both the need and the effectiveness of different water storage options. Because several of the indicators relate to climate, it is possible to use computer modeling results to evaluate need and effectiveness under both existing and possible future climatic conditions.

Application of this tool to SSA, in conjunction with a downscaled SRES A1B scenario and predicted population increase, indicates that the need for agricultural water storage is currently greatest in the Sahelian zone, the Horn of Africa and southern Africa, with more localized hot spots in southern Angola, southern Ghana, Rwanda, Burundi and Uganda, as well as Malawi and northern Mozambique. In future, the need for water storage will increase across most of SSA, but there will be little change in the areas of most critical need. More detailed evaluation of Ethiopia and Ghana indicated that the greatest need was not in areas with least rainfall, but rather in areas with the highest population density, such as the Central Highlands of Ethiopia, and in the south and, in patches, in the more arid north of Ghana. As a result of changes in climate, the effectiveness of existing and currently planned water storage will likely decrease in both the Volta and Blue Nile basins in the future.

These results emphasize the need to pay closer attention to the planning of future water storage. Careful consideration needs to be given to integrated approaches which maximize the complementarities of different storage options. Consequently, in contrast to the past, planning needs to be much more integrated across a range of levels and scales, with much greater consideration of the full range of possible options and the potential implications of CC.

The water storage management tool developed in this study needs to be refined through further research and application in real planning situations. However, it represents a 'first step' towards more systematic decision making, more targeted, and hopefully sustainable water storage interventions, which will result in tangible benefits for rural communities now and in the future despite the potential implications of CC.

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