Green Water Management for Water and Food Security in the Abbay Basin, Ethiopia

A Review

Working Paper No. 1

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Cover picture: Green water management terracing activities in the Abbay basin

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Acronyms and Abbreviations

BFI	Base Flow Index
CALM	Climate Action through Landscape Management
CBPWD	Community Based Participatory Watershed Development
CRGE	Climate Resilient Green Economy
CWP	Crop Water Productivity
E	Evaporation
ESIF-SLM	Ethiopia’s Strategic Investment Framework for Sustainable Land Management
ET	Evapotranspiration
FDRE	Federal Democratic Republic of Ethiopia
FFW	Food-for-work
GHG	Green House Gas
GoE	Government of Ethiopia
GTP	Growth and Transformation Plan
GWFI	Ground Water Flow Index
GWM	Green Water Management
ITPS	International Technical Panel on Soil
IWMI	International Water Management Institute
LAI	Leaf Area Index
MERET	Managing Environmental Resources to Enable Transition
MERET-PLUS	Managing Environmental Resources to Enable Transition through Partnerships and Land Users Solidarity
MoFED	Ministry of Finance and Economic Development
NAP	National Adaptation Plan
NGO	Non-Governmental Organization
PADEP	Peasant Agriculture Development Program
PSNP	Productive Safety Net Program
RLLP	Resilient Landscape and Livelihoods Project
RWH	Rainwater Harvesting
SCRP	Soil Conservation Research Project
SLM	Sustainable Land Management
SLMP	Sustainable Land Management Project

SNNPR	Southern Nations, Nationality and Peoples Region
SPCRP	Sirinka Pilot Catchment Rehabilitation Project
SSA	Sub Saharan Africa
SWC	Soil and Water Conservation
T	Transpiration
TAW	Total Available Water
UN	United Nations
UNEP	United Nations Environment Program
UNICEF	United Nations Children's Fund
USA	United States of America
VAM	Vulnerability Analysis &Mapping
WF	Water Footprint
WFP	World Food Production
WHO	World Health Organization
WLRC	Water and Land Resource Centre
WP	Water Productivity
WWAP	World Water Assessment Program

1. Introduction

It is widely recognised that the world is facing an unprecedented water crisis. Among the key factors influencing this situation are agricultural water management problems. Global water demand for all uses, currently about 4,600 km^3 per year, will increase by 20% to 30% by 2050, up to 5,500 to 6,000 km^3 per year as a function of population growth, economic development and changing consumption patterns, among other factors (Burek *et al.*, 2016; WWAP, 2018). Globally, water use for agriculture currently accounts for 70% of the total. Due to the increasing water demand for food, the projected competition for water, and the projected impacts from climate change, there is an urgent need for identifying new ways of water management (WWAP, 2016). Since agriculture is the largest water user, improving agricultural water productivity is considered as one of the most important responses to current and future water stresses (Rockstrom *et al.*, 2009; Molden *et al.*, 2010).

Agriculture is the main driver of Ethiopia's growth and food security. Ethiopia's agriculture system constitutes 46% of gross national production, employs 80% of its population, and generates 75% of export commodity value (MoFED, 2010). Production systems are dominated by smallholder farming under rain-fed conditions with little mechanization. Despite the recent progress, productivity of cereals is still very low, with average cereal yields ranging from 1.7 to 3.7 t/ha (CSA, 2018). There is a yield gap between on-station yield and actual farm yield (Mann and Warner, 2017; Taffesse *et al.,* 2012). For example, in Ethiopia the national average yield gaps for maize, wheat, and sorghum were 10.25, 6.06, and 4.85 t/ha, respectively (http://www.yieldgap.org/ethiopia). Such large yield gaps suggest untapped potential for yield increases. As reported by Rockström (2003), at low-yield range, there is a great potential to improve water productivity (up to five-fold). Water productivity increases dramatically, from ~ 2 kg grain/mm at ~ 0.5 t/ha yield to ~ 10 kg grain/mm of evapotranspiration flow at ~ 3 t/ha. Despite the great potential for upgrading rain fed agriculture, investments to reduce yield gaps and increase water productivity have been lacking. Such an improvement in water productivity by increasing crop yield offers 'windows of opportunity' for countries like Ethiopia as more frequent dry spells and droughts are occurring associated with the changing climate.

Literature shows that various factors contribute to yield gaps. For example, Van Dijk *et al.* (2017) and Van Dijk *et al.* (2020) outlined four components of total yield gap: (1) the technical efficiency yield gap; (2) the allocative yield gap; (3) the economic yield gap; and (4) the technology yield gap. The technology yield gap comprised the largest share of the total yield gap, partly due to limited use of fertilizer and improved seeds. Although the technology factors (e.g., increased input use and adoption of new technologies) comprised the largest share of the total yield gap (Van Dijk *et al.*, 2020; Assefa *et al.*, 2020), socioeconomic factors (e.g., profitability) are also important in reducing yield gaps. Reducing the technology yield gap also requires consideration of biophysical characteristics, such as soil erosion, rainfall variability, low soil infiltration, low soil water holding capacity, and poor water and nutrient uptake by crops (Rockstrom and Falkenmark, 2000). Most importantly, soil erosion and increasing rainfall variability caused by climate change pose considerable threat to national food security. The projected increases in temperature and temporal variability of rainfall due to climate change, causing recurrent drought and dry spells (IPCC, 2007), have been reported as a cause for crop failure or yield reduction in semi-arid and dry sub-humid tropics in general (Barron *et al.*, 2003). In the equatorial tropics, every 1°C increase in mean temperature is associated with a 10 percent decrease in crop yields (Sova *et al.*, 2019). Also, soil erosion, resulting in soil loss of 1.5 to 2 billion tonnes annually (35 t/ha), directly impacts food production in the Ethiopian highlands, estimated at a monetary value of US$1 to 2 billion per year (Sonneveld, 2002). The traditional agricultural practices on cropland are considered as major factors to the high level of soil erosion (Sonneveld and Keyzer, 2003; Hurni *et al.*, 2015). For example, conventional tillage practices in the Ethiopian highlands have been frequently reported as a major contributor to soil erosion, low infiltration and low agricultural productivity (Hurni *et al.*, 2005; Temesgen *et al.*, 2012).

Reversing the effects of soil erosion and improving water productivity will make a significant contribution to improve smallholders' livelihoods in the country. In view of this, different Green Water Management (GWM) interventions[1] have been implemented by the Government of Ethiopia (GoE) with support from multiple development partners. The major GWM related efforts in Ethiopia include the Food-for-Work (FFW) program (1973–2002), Managing Environmental Resources to

1 We define GWM interventions here as any intervention that attempts to increase rainwater stored in the soil. According to Rockstrom *et al*. (2010) these interventions may include implementation of (1) evaporation management, (2) in-situ water harvesting, (3) ex-situ water harvesting for dry spell mitigation, and (4) practices for improved crop water uptake.

Enable Transitions to Sustainable Land use project (MERET, 2003–2011), the Productive Safety Net Program (PSNP, 2005–present), Community Mobilization through free-labour days (1998–present), the Sustainable Land Management Project (SLMP, 2008–2018), Resilient Landscape and Livelihood Project (RLLP, 2019–2024), and the Climate Action through Landscape Management project (CALM, 2019–2024).

Although these efforts have resulted in many ecological benefits, the initiatives had some serious shortcomings. The focus of almost all projects has been on reducing soil erosion and reversing land degradation. While rainwater is a major contributor, by enabling agricultural production, to the livelihoods of smallholder farmers, particularly in the Abbay basin where there is little irrigation practice, rainwater management has not received adequate attention in water policy and strategy and in land rehabilitation programs. Interventions usually leave out rainwater management, which otherwise has a great influence on the sustainability of both surface water and groundwater (Hagos *et al.*, 2011). FDRE (2013) notes that inadequate agricultural water management is already affecting smallholder farmers in Ethiopia.

The concept of green water management is not new to Ethiopia. What is new is the need to increase awareness among all stakeholders about its potential large-scale impacts on agricultural productivity. There is no state-of-the-art synthesis that presents research results, gaps and future directions on green water management in the country in general and the Abbay basin in particular. In contrast, there are many studies and a few review reports on blue water resource situation of the Abbay basin and Ethiopia (e.g., Dile *et al.*, 2018; Taye *et al.*, 2015). Dile *et al.* (2018) reviewed research works conducted in the Abbay basin with emphasis on advances in blue water resources research. They highlighted the different types of hydrological models applied in the basin and data availability of runoff, groundwater recharge, sediment transport, and tracers. Taye *et al.* (2015) also did a review of works on the implications of climate change on hydrological extremes in the Blue Nile basin. Asmamaw (2017) reviewed the impacts of conservation tillage on water balance and crop yield in Ethiopia. The review, however, did not cover all aspects of green water management; it instead focused on one part of green water management, specially conservation tillage. None of the above-mentioned studies focused on green water management. The present study was, therefore, aimed at reviewing available evidence, and identifying knowledge gaps, on green water management in the Abbay basin.

2. Method

To obtain a comprehensive overview of studies on green water, a systematic review procedure was followed. Systematic reviews are useful for synthesizing trends and abstracting findings from large bodies of information (Petticrew and Roberts, 2008). The review focuses on peer reviewed publications in journals and other relevant technical and programmatic publications ("grey" literature) on green water management. During the initial screening process, three inclusion criteria were applied:

1. Search criteria indicated in search string in Table 1;
2. The publication is written in English; and
3. The publication focuses on hydrology or water resources.

During the data gathering stage, these criteria were translated into a search string that was designed to capture publications that deal with green water and its indicators (Table 1). Both academic literature and relevant technical and programmatic publications (grey literature) were targeted. The search string summarized in Table 1 was used to search peer-reviewed literature (i.e., scientific journals) from the Scopus database. The search returned 763, 16, 71, 25, 48, and 4 publications on green water, conservation agriculture, drought, water productivity, in situ water harvesting, and ex-situ water harvesting, respectively, that met the four inclusion criteria indicated in Table 1. The search was limited to the period from January 2000 to 2019. Scopus (https://www.elsevier.com/solutions/scopus) was selected because of its large archival of hydrology and water resources journals. After removing duplicates, bibliographic data from 359 publications were compiled using Mendeley Desktop reference manager software for analysis. The abstract, title, and keywords of each publication were used as retrieval/search units. Where these three areas provided insufficient information to make a decision on inclusion, the full text of the publication was examined. To capture ("grey" literature), we searched, among others, the International Water Management Institute Library Catalogue (https://www.iwmi.cgiar.org/publications/library-catalog/), the FDRE Ministry of Agriculture website, World Bank e-library (https://elibrary.worldbank.org/) and United Nations (http://www.un-ilibrary.org) repositories. A total of 45 grey literature were obtained from Google Scholar, which is widely known as a good source of grey literature (Giustini and Boulos, 2013). After screening 970 publications, 314 publications from Scopus and 45 grey literature from Google Scholar were retained for the review based on relevance from green water management perspective.

Table 1. Search string used in Scopus and the number of publications and grey literature included for the review

Theme	Sub theme	Search string	Number of publications screened	Number of publications retained for analysis
Scopus database				
General issues on green water	Green water	"green and blue water" OR "blue and green water"	763	260
Green water indicators in the Abbay basin	Conservation Agriculture	"conservation" AND "agriculture" OR "tillage" AND "blue" AND "Nile" OR Abbay	16	5
	Agricultural/ Meteor-ological drought	"drought" AND "blue" AND "Nile" OR Abbay	71	25
	Green water productivity	"aridity" AND "blue" AND "Nile" OR "Abbay"	23	11
	In situ water harvesting	"soil and water conservation" OR "terrace" OR "bund" AND "blue" AND "Nile" OR "Abbay"	48	10
	Ex situ water harvesting	"Rainwater" OR "water" AND "harvesting" AND "blue" AND "Nile" OR "Abbay"	4	3
Google scholar database				
General issues on green water			45	45
		Total	**970**	**359**

3. The different colours of water: Definition of concepts

The hydrologic cycle represents many colours of water, i.e., blue, green, ultraviolet, white and grey that differ in physical form, accessibility and human use, and exhibit various local and global challenges. Savenije (2000) introduced the concept of "rainbow of water" to refer to the different colours of water. All these water resources expressed by different colours have to be protected and optimized if agriculture has to meet the challenge of feeding over 9 billion people by 2050 while leaving enough water for other uses. Addressing water security by classifying fresh water resources into blue, green, ultraviolet, white and grey water is an appropriate method for water resources management (Schneider, 2013). For instance, the various components of water use can be quantified in the concept of "Water Footprint" by distinguishing the different colours of water (Hoekstra *et al*., 2011).

In the hydrologic cycle, there are two rainfall partitioning points. The first partitioning point occurs at the surface and the second partitioning point is located in the upper soil layer, the unsaturated zone (Fig. 1). The partitioning points determine how rainfall is partitioned into interception, infiltration, transpiration, percolation and surface runoff. These two partitioning points, thus influence how much of the rainfall goes to the different colours of water. The partitioning of rainfall at the first partitioning point (soil surface) depends on: (1) rainfall intensity, (2) soil wetness, (3) infiltration capacity of the topsoil, determined by soil surface conditions (including crusting and vegetation cover), and (4) slope length and steepness. The partitioning of water at the lower partitioning point depends on (1) water use by vegetation; (2) hydraulic conductivity of the deeper soil layers (Rockström, 1997), and (3) climatic factors (Rockström and Gordon, 2001). In the case of farmland, water use by vegetation involves crop, crop management and soil nutrient management.

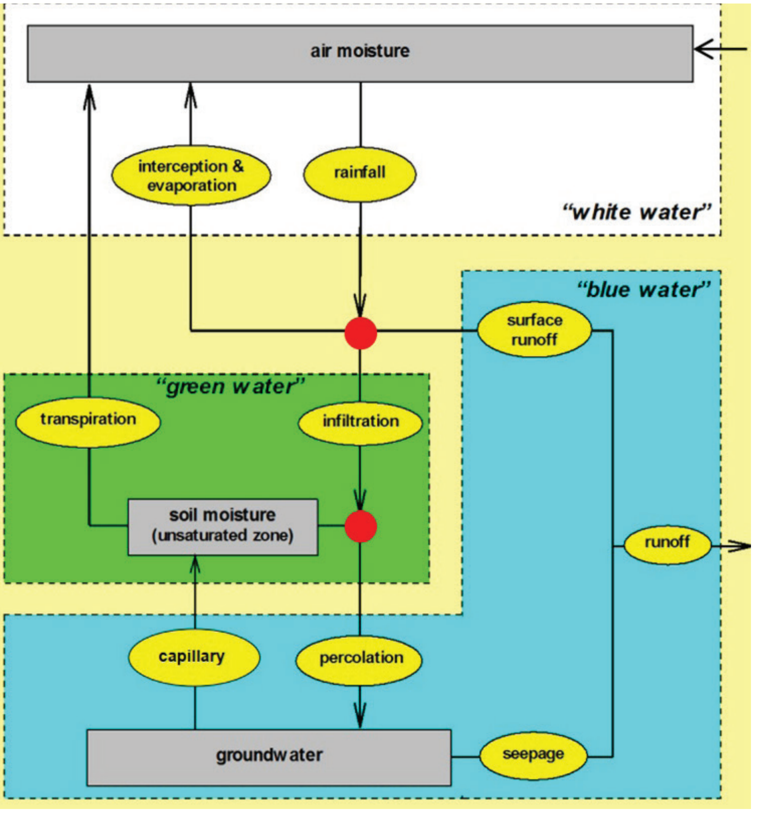

Figure 1.The Hydrological cycle, with 'white', 'green' and 'blue' water, and the two partitioning points (red dots)

Source: Van der Zaag and Savenije (2014)

3.1 Green water

Green water refers to the portion of rainfall that infiltrates into the soil and is accessible by plants to generate vapour flow that supports biomass growth. The concept of green water was first introduced by Falkenmark (1995) to distinguish it from blue water and to highlight the importance of soil water. Since then, it has been used by other researchers (e.g. Savenije, 2000; Falkenmark and Rockström, 2006; Rockström *et al.*, 2009; Hoekstra, 2019). Originally, Falkenmark (1995) defined green water as the fraction of rainwater that infiltrates into the unsaturated one and is used for biomass production. It was considered as a new term for evapotranspiration.

With its introduction into the literature, there was confusion about the division between green and blue waters (Ringersma *et al.*, 2003). For example, Rockstrom (1999) defined green water as "… the return flow of water to the atmosphere as evapotranspiration (ET) which includes a productive part as transpiration (T) and a non-productive part as direct evaporation (Es) from the soil, lakes, ponded areas, and from water intercepted by canopy surfaces". In this definition, there are two issues which are unclear: (1) one cannot see which part of ET originates from rainwater and which part from irrigation water, (2) open water evaporation and evaporation of intercepted water were included as non-productive fraction of green water. However, Savenije (1999) made the first confusion clear by defining the green water concept as transpiration of water derived directly from rainfall stored in the soil by plants. Savenije (1999) also removes the second point of confusion by introducing the concept of 'white water', which refers to that part of rainfall that returns directly to the atmosphere through evaporation of water intercepted by the ground cover and from bare soil. Thus, concept of white water excludes Rockstrom's "non-productive" green water. Hoekstra (2019) acknowledged the terms 'green' and 'blue' are labels that tell something about the origin of water. 'Green' thus means 'originating from rainwater' and 'blue' means 'originating from groundwater or surface water'.

For the purpose of this review, the term green water is used solely in the context of rain-fed land use (i.e. arable, grazing or forest). Thus, as conceptualized also in the World Water Vision document prepared for the World Water Council (Cosgrove and Rijsberman, 2000), green water resource is water held in the soil that is available to plants. Green water is the largest fresh water resource in the hydrologic cycle (Fig. 2). At the ground level, 65% of the continental precipitation forms total green water flow from forests, woodlands, wetlands, grasslands, and croplands and the remaining 35% forms blue water (Rockstrom *et al.*, 1999). Green water is an indispensable resource not only for food production in rain-fed agriculture, but also for the entire meat production in the livestock sector and the production of wood from forestry sector. Rain-fed agriculture, which uses green water, represents 80% of land under cultivation, and contributes 58% of global crop production (Bruinsma, 2009). This indicates the global role of green water in food and livelihood security of rural populations.

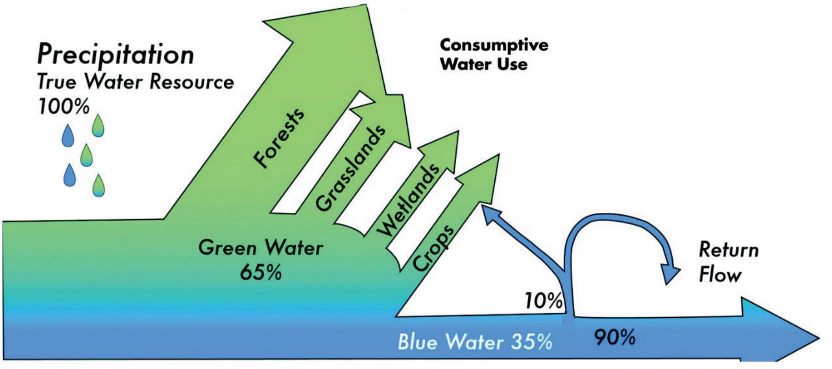

Figure 2. Continental precipitation partitioned into green water and blue water
Source: Falkenmark and Rockström (2010)

3.2. Blue water

Blue water refers to liquid water in rivers, lakes, wetlands, and aquifers (Rockström, 1997; Rockström and Falkenmark, 2000). Blue water originates both from the rainfall that reaches the soil surface, as runoff, and from the water that recharges the groundwater. Irrigated agriculture receives blue water from irrigation as well as green water from rainfall, while rain-fed agriculture only receives green water. Past strategies for food production have focused on blue water management works which require costly engineering works. The term "effective rainfall" was coined to be able to discard all steps between rainfall and blue water flows and to be able to use all blue water flows for a direct economic purpose. Conventional water resource assessments focus only on availability of blue water and its allocation for use in domestic, industrial, livestock, and irrigation sectors

3.4. Other water colours

White water: Precipitation intercepted by vegetation and other forms of land cover is temporarily stored on the leaves and other surfaces until it evaporates back to the atmosphere. White water thus refers to the portion of rainfall which is intercepted by vegetation and which immediately evaporates back to the atmosphere, as well as to non-productive open water and soil evaporation (Savenije, 2000).

Grey water: Grey water is the return flow, such as sewage water from cities and industries that flow back into rivers or percolate into aquifers. With appropriate treatment, this water can be used for various purposes, such as for flushing toilets, watering gardens and washing cars. Apart from the obvious benefits of saving water, reusing greywater keeps it out of the sewer or septic system, thereby reducing the chance that it will pollute the environment, including local water bodies.

Ultraviolet/ Virtual water: Virtual water refers to the water embodied in food imports (Allan, 1992). The term 'Ultraviolet water' was first introduced by Savenije (2000) to refer to the virtual water. This is the most interesting colour of the rainbow. In water scarce regions, the exchange of water in its virtual form is one of the most promising approaches for sharing international waters and to meet domestic food demands. Importing food is virtually also about importing water that would otherwise be needed for producing the food locally. Thus, virtual water is the amount of water that is used in the production of water consuming products for trade.

4. Significance of Green Water to Water and Food Security

4.1. Green water in the academic literature

Inventory of the number of publications on green water over the past twenty years (2000 –2019) indicated that the number showed a gradual increase since 2010 (Fig. 3). Because the publications were selected through a systematic process, this is an indication that scholarly attention to green water has been growing. Overall, about 53% of all publications reviewed were published in the past four years, i.e. between 2015 and 2019. Most of the studies (45%) were conducted at local level, followed by global scale (36%), and national level studies (19%).

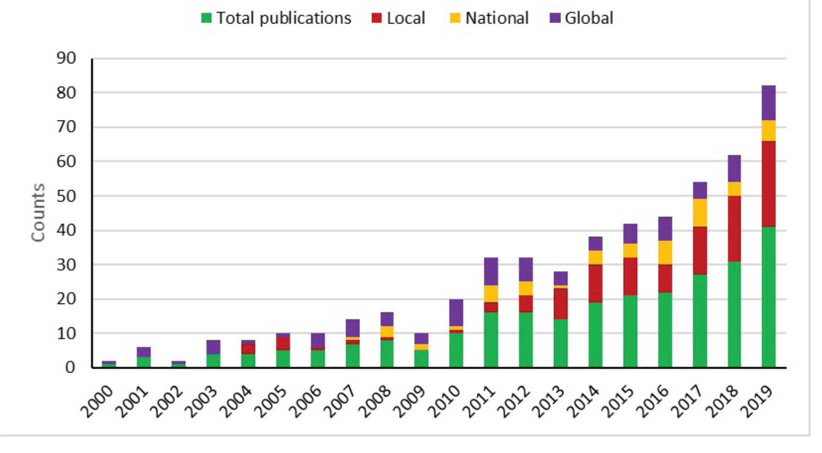

Figure 3. Number and spatial scale of peer reviewed articles about green water considered in this review

Further analysis of most widely cited green water publications in Scopus (Table 2) shows that most of these publications were published in hydrology/water resource- or ecological economics-oriented journals in the period between 2006 and 2011. The first publication that stands out in terms of the number of citations (Mekonnen and Hoekstra, 2011) is a study on water footprint of crops.

Table 2. Overview of the most cited peer reviewed articles about green water, receiving > 300 citations in Scopus until June 2020

Reference	**Title**	**Journal**	**# of Citations**
Mekonnen and Hoekstra, 2011	The green, blue and grey water footprint of crops and derived crop products	Hydrology and Earth System Sciences	716
Rost *et al*., 2008	Agricultural green and blue water consumption and its influence on the global water system	Water Resources Research	413
Chapagain *et al*., 2006	The water footprint of cotton consumption: An assessment of the impact of worldwide consumption of cotton products on the water resources in the cotton producing countries	Ecological economics	382
Falkenmark and Rockström, 2006	The new blue and green water paradigm: Breaking new ground for water resources planning and management	Journal of Water Resources Planning and Management	350
Siebert and Döll, 2010	Quantifying blue and green virtual water contents in global crop production as well as potential production losses without irrigation	Journal of Hydrology	324
Rockström *et al*., 2009	Future water availability for global food production: The potential of green water for increasing resilience to global change	Water Resources Research	317

4.2 The relevance of green water in water resource assessment

4.2.1 Green-blue analysis of water resource availability

Most water resource assessments and projections (Alcamo *et al*., 2007; Falkenmark, 1989; Islam *et al*., 2007; Shiklomanov, 2000) were focused on only blue water availability. Based on a blue water-biased estimate, large proportion of the world's population is estimated to face an absolute water scarcity over the next generation (Gerten *et al*., 2011), as it assumes that blue water is the only freshwater resource contributing to food production. However, green water makes up most of the water consumption in agriculture (Falkenmark and Rockström, 2004; Hoff *et al*., 2010; Rockström *et al*., 2009). According to Alcamo *et al*. (2007), a 60% increase in green water use and a 14% increase in consumptive blue water use in agriculture is expected by 2050 in sub-Saharan Africa. Several researchers have made green-blue analysis of water availability (e.g. Gerten *et al*., 2011; Mekonnen and Hoekstra, 2011; Rockström *et al*., 2009) and they indicated that many countries previously assessed as severely water stressed can produce enough food for their populations if green water is considered and managed well. Figure 4 shows that while more than 3 billion people experienced chronic blue water shortage in 2000; but, after taking the green water resource into account, the number pf people that suffer water shortage dropped to only less than 300 million or 4.5% of those who suffered chronic blue water shortage in 2000.

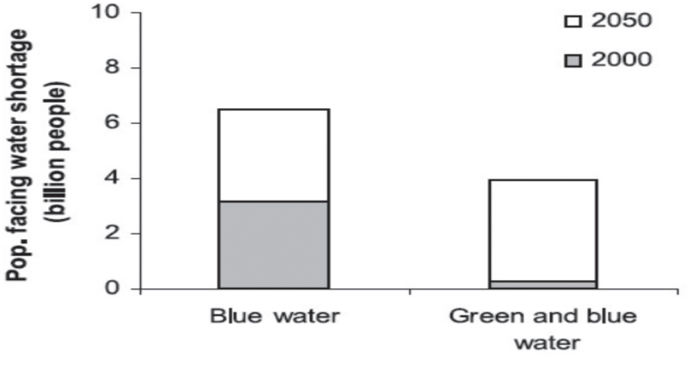

Figure 4. Number of people (in billions) that are facing water shortage in 2000 and 2050 when accounting only for blue water compared with accounting for blue and green water resources

Source: Rockstrom *et al*. (2009)

4.2.2. Green water in water footprint analysis

The concept of "water footprint" introduced by Hoekstra and Hung (2002) and subsequently elaborated by Hoekstra and Chapagain (2008). Water footprint (WF) is defined as the total volume of freshwater that is used to produce the goods and services consumed by people of a nation (Hoekstra *et al*., 2011). Water footprint analysis provides a useful framework to assess the amount of water required to produce a product and find water saving options and thereby contributing to a better management of water resources (e.g. Ercin and Hoekstra, 2014; Vanham *et al*., 2013). WF has three components: green, blue, and grey (Hoekstra *et al*., 2011). The green water footprint is the volume of rainwater consumed, which is particularly relevant in crop production. The blue water footprint refers to consumption of blue water resources (surface and ground water). The grey water footprint is an indicator of the degree of freshwater pollution and it is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards.

4.3. Green water-use versus blue water-use

The relative importance of green water-use in relation to food security and water security has been noted by many researchers (Falkenmark and Rockstrom, 2004; Molden, 2007; Keys and Falkenmark, 2018). Despite its importance, green water is probably the most under-valued resource of all water resources and often not featured on the water agenda. Among the compelling reasons that make investing in green water-use more important as summarized in Table 3 are: (1) green water is dominant in food production globally as well as in Sub-Saharan Africa, (2) blue water-based food production (i.e. irrigation) is expensive due to its high cost of capital and labour investment, (3) environmental impact of green water-use is minimum as compared to irrigation, (4) irrigation alone will not be able to provide the food needed to feed the growing global population by 2050, (5) green water-use generally has a lower opportunity cost than blue water, and (6) green water has strategic importance in international commodity trade (i.e. virtual water trading).

Table3.Comparisonofgreenwater-use(rain-fedagriculture)andbluewater-use(irrigatedagriculture)

Green water-use	Blue water-use
• Covers 80% of land under cultivation, and contributes 60-70% of global crop production	• Covers 20% of land under cultivation, and contributes 30-40% of global crop production
• Low investment cost of capital and labour	• High investment cost of capital and labour
• Low negative environmental externalities	• High negative environmental externalities
• Adequacy of green-blue water for food production	• Inadequacy of blue water alone for food production
• Lower opportunity cost in green water use	• High opportunity cost in blue water-use
• Significant contribution in virtual water trade	• Less contribution in virtual water trade

4.3.1. Dominance of green water in food production

Green water is the main source of food production at the global level. Rain-fed agriculture (i.e green water-based agriculture) represents 80% of land under cultivation, and contributes 60-70% of global crop production (Bruinsma, 2009; Falkenmark and Rockström, 2004). It is widely known that the major grain exporters –USA, Canada, France, Australia and Argentina – produce grain in highly productive rain-fed conditions (green water-based agriculture). In sub-Saharan Africa, food production almost entirely depends on green water (i.e. 95% of the cropland). In many parts of the world, food production depends largely on green water and only desert areas depend entirely on blue water. Irrigated areas account for 34% of crop production, yet only cover 24% of all cropland (Siebert and Doll, 2010). Figure 4 shows strong green water dependency for food production around the world. The food insecurity reality in Ethiopia therefore demands an urgent shift in thinking towards giving adequate attention to green water management for food production.

4.3.2. Low investment cost of capital and labour

Green water-based food production is less costly compared to irrigation. Irrigated agriculture has played a vital role in increasing agricultural production globally, but the high investment costs and failures of many past irrigation projects have made governments and donors cautious to invest more in irrigation projects (Inocencio *et al.*, 2006). Inocencio *et al.* (2006) analysed 314 irrigation projects implemented from 1967 to 2003 in 50 countries and found that irrigation projects in SSA are more expensive than those in other developing regions. With rising concerns over the high cost of expanding irrigation, improving rain-fed agriculture has received increased attention.

4.3.3 Low negative environmental externalities

The environmental impact of irrigation systems depends on the nature of the water source, quality of the water, and how water is delivered to the irrigated land. The major environmental impacts of irrigation include water logging, salinization, and soil degradation (Wang, 2004). Salinization is a worldwide problem, particularly acute in semi-arid areas that use large amounts of irrigation water and are poorly drained. Where salinization occurs, additional water may be needed to 'flush out' the salts beyond the root zone of crops. With increasing concerns over irrigation-induced environmental impacts, upgrading rain-fed agriculture is gaining increased attention.

4.3.4. Inadequacy of blue water for food production

It is increasingly becoming clear that irrigation will not be able to provide the food needed to feed the increasing world population. When comparing 2050 food needs with projected increased demand of water for producing such food, given feasible development of irrigated agriculture and improved efficiency of rain-fed agriculture, there still remains the challenge of additional need for water (Rockstrom *et al.*, 2009; Mekonnen and Hoekstra, 2011; Gerten *et al.*, 2011). This could only come from green water resources from horizontal expansion or intensive systems (which increase inputs on a planted area in order to increase yields). In order to meet immediate food demands, farmers in many rain-fed areas have expanded production into marginal lands (e.g. Teferi *et al.*, 2013). These fragile areas are susceptible to environmental degradation, particularly deforestation and soil erosion. Because of these environmental consequences of area expansion, crop yield growth is preferred to increasing area planted in rain-fed systems. Therefore, intensive cropping systems that involve increased inputs, such as labour, fertilizers, pesticides, or improved varieties to increase yields are essential for rain-fed crop production. Sustainable intensification of green-water-based agriculture development can increase production while limiting environmental impacts. According to Rosegrant *et al.* (2002), the three primary ways to improve rain-fed agricultural production system are: 1) to increase effective use of rainfall through improved rainwater management; 2) to increase crop yields in rain-fed areas through agricultural research; and 3) to reform policies and increase investment in rain-fed areas.

4.3.5 Low opportunity cost in green water use

Green water generally has a lower opportunity cost than blue water (Hoekstra *et al.*, 2001; Albersen *et al.*, 2003). The use of green water for agriculture has no major competition with other uses. Unlike blue water, green water cannot be automatically reallocated to other uses besides natural vegetation or alternative rain-fed crops (De Fraiture *et al.*, 2004). Since blue water resources are generally scarcer, when exporting countries use green water resources, they incur a lower opportunity cost in water use, holding other factors constant (Hoekstra et al., 2001; Albersen *et al*., 2003; Chapagain *et al.*, 2006).

4.3.6 Green water in crop trade

The strategic importance of green water in international commodity trade has been noted by many authors (e.g. De Fraiture *et al*., 2004; Allan, 2006; Chapagain *et al.*, 2006). It is also well known that major grain exporters (i.e USA, Canada, France, Australia and Argentina) produce grain in highly productive rain-fed conditions (Aldaya *et al*., 2010). The virtual water content (m^3/ton) of primary crops can be calculated as the crop water use at field level (m^3/ha) divided by the crop yield (ton/ha) (Allan, 1997, 1999). Virtual water flow represents the amount of water embedded in products traded internationally (Hoekstra and Chapagain, 2011).

The direct impact of exporting water in virtual form is to generate foreign exchange for the exporting country. The indirect positive effect of this kind of virtual water flows is that it generates water savings in the countries that import those commodities (Hoekstra and Chapagain, 2008). Through importing virtual water embodied in agricultural commodities, a water-scarce country saves the amount of water it would have required to produce those commodities domestically. But, according to De Fraiture *et al*. (2004) and Chapagain *et al.*, 2006), virtual water flow can save water globally in two conditions: (1) if a water-intensive commodity is traded from an area where it is produced with high water productivity (ton/m^3) to an area with lower water productivity, and (2) if the virtual water flow saves irrigation water when the exporting country cultivates under rain-fed conditions, while the importing country would have relied on irrigated agriculture.

5. Pathways to Improving Green Water Productivity

5.1. Need for water productivity improvement

Water productivity (WP) is as a measure of the ability to convert water into food (Kijne *et al*., 2003). It is described as the total agricultural return per unit water used or depleted, or simply as 'crop-per-drop' (Cook *et al*., 2006; Molden *et al*., 2010). WP, is also referred to as green WP or crop WP or water use efficiency. A growing body of literature (CA, 2007; FAO, 2004; McGlade *et al*., 2012; Rockström *et al*., 2010, 2007) concurs on the great potential of water productivity (WP) improvement to help feed the growing world population. FAO (2004) stated that improving agricultural water productivity is an important solution to addressing global water challenges. McGlade *et al.* (2012) identified WP as important indicator of water use in a green economy. Rockstrom *et al.* (2007) assessed that WP gains may reduce additional water needs in agriculture by 45% by 2050. Thus, improvement of water productivity is an important response to the growing water scarcity.

Improvement of WP comes from either the same production from less water resource, or a higher production from the same water resource. By reducing the amount of water required for crop production, increasing WP is a key strategy for achieving food security and water sustainability in a world with growing demands for both. According to Rockstrom *et al.* (2010) and Rockstrom (2003) there are two primary strategies to improve green water productivity: (1) maximizing soil water availability, and (2) maximising crop water uptake. Table 4 lists the different green water management strategies that can increase grain yield and improve WP for smallholder farmers.

Table 4. Green water management strategies to improve green water productivity

Green water management strategy	Purpose	Management options/types
In-situ water harvesting	Maximize rainfall infiltration and optimize available water capacity	Measures that improve soil cover (e.g. green cover, mulch); measures that enhance organic matter / soil fertility (e.g. manuring); and conservation tillage.
	Slowdown runoff and reduce soil erosion	Terraces, soil/stone bunds, tied ridges, furrow systems, e.t.c.
	Harvest rainwater where it falls	Micro-catchments (triangular and semi-circular bunds, negarims, eyebrow, micro-basins); Macro-catchments (stone bunds, large trapezoidal and semi-circular bund):
Ex-situ water harvesting	Harvest and divert rainwater for dry spell mitigation	Farm ponds, micro-dams
Evaporation management (vapour shift)	Reduce early season evaporation	Dry planting, Mulching, Intercropping
	Reduce evaporation flux with increased canopy by reducing energy inflow through advection	Agroforestry, Intercropping, Vegetative bunds, Mulching
Crop management	Maximise productive green water flow	Soil fertility management, crop rotation, improved crop varieties, conservation tillage, terrace and bunds

Source: Adapted from Rockstrom (2003), Rockstrom *et al.* (2010), Cornelis *et al.* (2019)

5.2. Vapour shift

In semiarid areas, up to half of the rainwater falling on agricultural land is lost as non-productive evaporation. This is a key opportunity for improving green water productivity through shifting non-productive evaporation (*E*) (i.e. soil evaporation and interception) to productive transpiration (*T*) (i.e. vapour shift), with no downstream blue water trade-off, through management of soil physical conditions, soil fertility, crop varieties, and agronomy (Rockström, 2003). This vapour transfer of the evaporative loss into useful transpiration by plants is a particular opportunity in arid, semiarid, and dry sub humid regions to increase green water productivity.

Rockström (2003) reviewed cereal yield datasets from both tropical and temperate regions, and found that when yields double from 1 to 2 t/ha in semiarid tropical agroecosystems, green water productivity improves from approximately 3,500 m^3/t to less than 2,000 m^3/t (Fig.5(a)). This means improvement in crop yield will result in increase in WP for low-yielding farming systems in rain-fed agriculture. This is a result of the shift in the two components of evapotranspiration (i.e. Evaporation and Transpiration). A vapour shift is easily achieved when yields start exceeding 2 t/ha (Rockstrom and Falkenmark, 2000). At the low yield level, much of the evapotranspiration is soil evaporation and transpiration increase as yields increase. Soil evaporation decreases dramatically as the crop canopy covers more of the soil surface. At low yields, evaporative losses of water from the soil are high because of the sparse canopy coverage of the soil. When yield levels increase, soil shading improves; and when yields reach 4–5 t/ha and greater, the canopy density is so high that the opportunity to reduce evaporation in favour of increased transpiration declines, lowering the relative improvement of water productivity. Rockstrom (2003) discusses two ways of achieving such a vapour shift (Fig. 5(b)). The first is by reducing early season evaporation through early planting, intercropping (to rapidly develop a canopy cover), and mulching (i.e. direct conversion of evaporation to transpiration). The second is by reducing evaporation flow by increasing the canopy via agroforestry.

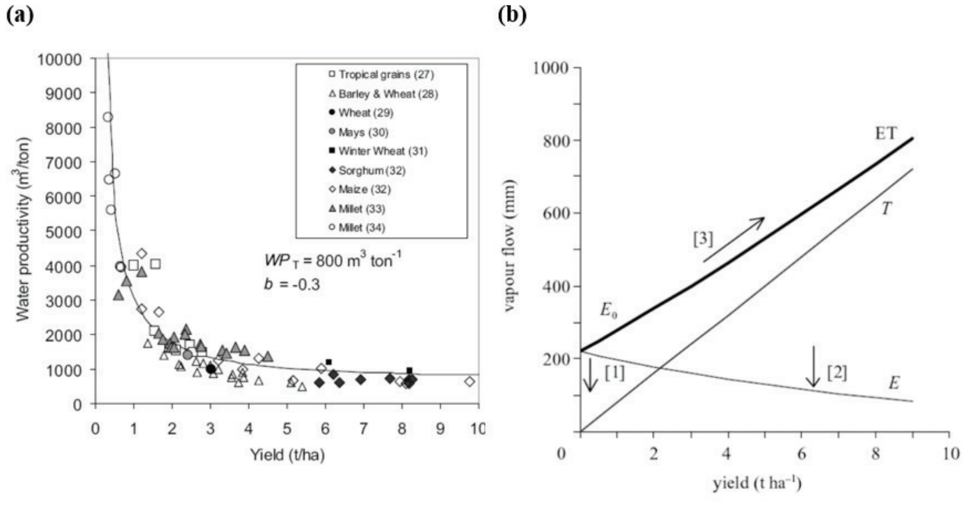

Figure 5. (a)The dynamics of green water productivity and yield for cereal crops in tropical and temperate farming systems, (b) the relationship between yield and the different components of vapour flow: E, Evaporation; T, Transpiration

Source: Adapted from Rockstrom *et al.* (2003)

5.3. In-situ water harvesting

Rainwater harvesting (RWH) is the process of collecting and improving the productive use of rainwater, and reducing unproductive runoff (Liniger *et al.*, 2011). In-situ RWH basically prevents net runoff from a given area by retaining rainwater and prolonging the infiltration period. According to Liniger *et al.* (2011) the purposes of measures involved in in-situ RWH are: to retain runoff, to impede runoff, and trap runoff.

Retain runoff (avoid runoff): the main purpose of technologies categorized under this is to retain water on the land in order to encourage rainfall infiltration (Liniger *et al.*, 2011). Thus, water storage is improved within the rooting depth of plants, and groundwater tables are recharged. The technologies involved are measures that improve soil cover (e.g. green cover, mulch); measures that enhance organic matter, or soil fertility (e.g. manuring); and conservation tillage. These measures are basically agronomic measures that do not lead to change in the landscape or slope profile.

Impede runoff and reduce soil erosion: the purpose here is to slow runoff and reduce soil erosion (Liniger *et al.*, 2011). Reducing soil erosion contributes to maintaining rooting depth and thereby increasing total available water (Stroosnijder, 2009). This can be accomplished through the use of terraces, earth and stone bunds, and tied ridges among other techniques. Measures for reducing soil erosion can increase total available water (TAW). The maximum amount of stored water in the root zone available for plant growth (i.e. TAW) is a very important soil characteristic because it determines the survivability of plants in a dry spell. The value of TAW is determined by the rooting depth, the layer from which plant roots can extract water during transpiration, and the factors which determine the value of field capacity and wilting point. Stroosnijder (2009) notes that soil erosion reduces the total green water available (i.e. TAW) significantly in two ways: 1) the removal of top soil and the subsequent reduction of soil rooting depth, 2) the selective removal of the finer particles resulting from soil erosion changes to a coarser soil texture (i.e. coarse textured soil has lower value of TAW compared with fine textured soil for a given depth). Thus, soil erosion reduces green water availability.

Trap runoff (harvest runoff): in-situ RWH measures in this category are meant to capture and store rainfall where it falls (Liniger *et al.*, 2011). This can be accomplished through the use of micro-catchment technologies, such as triangular and semi-circular bunds, half moon, and eyebrow. Runoff water is collected within the basin from the area above and impounded behind the structure. Excess water is discharged around the tips and is intercepted by the next row of micro basins. Micro-catchment systems are characterized by relatively small catchment 'C' (<1,000 m^2) and cultivated area 'CA' (< 100 m^2) with C:CA = 1:1 to 10:1 (Liniger *et al.*, 2011).

5.4. Ex-situ water harvesting for dry spell mitigation

The ex-situ RWH systems are defined as systems which harvest rainwater from catchments located outside crop land (Falkenmark *et al.*, 2001; Linger *et al.*, 2011). The rainwater capture area varies from being a natural soil surface with a limited infiltration capacity, to an artificial surface with low or no infiltration capacity. They can either be macro (large) or small external systems. Mitigating dry spells through use of ex-situ RWH for supplemental irrigation will ensure that there is enough water during critical crop growth stages and can significantly increase yields (Barron and Okwach, 2005; Linger *et al.*, 2011; Oweis and Hachum, 2009). An extra 10 – 25% of ex-situ rainwater harvested and made available during critical periods of plant growth can double or triple yields (Critchley and Scheierling, 2013; Linger *et al.*, 2011). Evidence (e.g. Agarwal, 2000; Hatibu *et al.*, 2003) shows that the key factor limiting improving yields is not amount of rainwater, but its variability, characterized by few rainfall events, and high frequency of dry spells and droughts that affect crop yields in rain-fed agriculture in semiarid and dry sub-humid regions (Falkenmark *et al.*, 2001). Ex-situ RWH technology is one of the technologies that helps to supply water for supplementary irrigation to bridge dry spells. In drier areas, ex-situ RWH coupled with in-situ RWH as well as improved soil fertility management and crop management are proved to have great potential to increase crop yields, perhaps because poor management of soil fertility contributes to low rainwater use efficiency (Rockström, 2000; Rockstrom *et al.*, 2007).

5.5. Conservation tillage

There is a growing body of literature indicating that the conventional tillage in the tropics, based on soil inversion using plough, contributes to soil degradation (e.g. Giller *et al.*, 2009; Mango *et al.*, 2017). Plough pans impede infiltration of rainwater and root penetration, and frequent soil inversion results in oxidation of organic matter and soil erosion by wind and rain (Benites *et al.*, 1998; Temesgen *et al.*, 2012; 2009). Conservation tillage plays a significant role to reduce soil degradation resulting from intensive tillage, thereby reducing runoff and increasing infiltration (Rockström *et al.*, 2009).

In Ethiopia, oxen-ploughing using *maresha* (traditional tillage implement) is a significant contributor to soil degradation because of repeated cross-ploughing (Temesgen *et al.*, 2009). Cross-ploughing is the practice of orienting the directions of two consecutive tillage operations perpendicular to each other. Due to the geometry of *maresha* plough, V-shaped furrows are created, while leaving strips of unploughed land between consecutive furrows. During the next tillage, farmers cannot easily access the unploughed strips without resorting to cross-ploughing. To alleviate this problem, researches have been going on in the Abbay basin to develop a locally adaptive improved implements that can achieve reduced tillage, as well as conservation of soil and water (Temesgen *et al.*, 2009; Temesgen *et al.*, 2012). *Berken* plough is a recently developed tillage implement that can disrupt the plough pan, eliminate cross ploughing, reduce number of tillage and improve infiltration with reduced traction power requirement (Muche *et al.*, 2017). The new plough penetrates deeper at the centre while cutting shallow on both sides of the ripped line (Muche *et al.*, 2017).

Despite the high advantages of conservation farming, its adoption among farmers in SSA has been limited (Rockstrom *et al.*, 2009). One of the reasons for the low adoption of conservation tillage is the traditional focus of conservation tillage on minimum/no-tillage systems from the whole range of conservation tillage types (Dumanksi *et al.*, 2006). It has been suggested that conservation tillage systems geared towards improved water management are better adapted to resource limited smallholder farmers in rain-fed areas (Rockstrom *et al.*, 2001).

5.6. Crop management

The amount of green water available in the root zone is determined not only by soil water availability in the root zone, but also by plant water uptake capacity. Plant water uptake capacity can be increased (the ratio T/ET is increased) when deficiencies related to crops are rectified. Plant deficiencies are manifested as poor water and nutrient uptake capacity and are due to weak root systems and poorly developed canopies rendering optimal uptake of soil water and nutrients impossible even where available. Any activity related to increasing crop yield will also improve green water productivity (Rego *et al.*, 2006; Rockström, 2000; Rockstrom *et al.*, 2007). Measures related to crop management involve soil fertility management, improved variety selection, and improved pest and disease management. Water productivity was increased by 70–100% for maize, groundnut, mung bean, castor and sorghum by adding micronutrients such as boron, zinc and sulphur by adding micronutrients in India (Rego *et al.*, 2006). Thus, improved crop and soil management practices increase both crop yield and water productivity.

5.7. Integrating incentive mechanisms in GWM

Green Water Credits (GWC) is a mechanism for incentives offered to upstream farmers in exchange for specified GWM activities that determine the supply of fresh water to downstream users (Geertsma *et al.*, 2010). GWC is a particular case of Payments for Ecosystem Services (PES). The GWC scheme has been adopted in Kenya in the Upper Tana basin and provided the financial opportunities for farmers to enhance their GWM practices (Hunink *et al.*, 2012). Incentive schemes of this kind will also serve as a tool for farmers to enhance their GWM practices in the Abbay basin. Absence of short-term benefit in implementing GWM practices by poor farmers has been noted as the major limitation of the past efforts, however (Adimassu *et al.*, 2017). Thus, GWC can be implemented to increase smallholders' interest in adopting and maintaining GWM practices.

6. Green Water Management in Ethiopia

6.1 Green Water Footprint of Ethiopia

The water footprint of production measures the amount of pressure that is being put on local water resources and forms the basis for determining whether they are being used in a sustainable way. Ethiopia's water footprint related to agricultural production, industrial production and domestic water supply for the period 1996-2005 was 77.8 Gm^3/yr (97% green, 2% blue, 1% grey) (Hoekstra and Mekonnen, 2012**).** About 97% of the total water resource use of Ethiopia is green water footprint, i.e., the amount of water consumed by plants from rainfall stored as soil moisture (Fig. 6 and Table 5). Approximately, 75% of the annual green water footprint of agricultural production is consumed in crop production, while 25% is used for grazing. Crop production in Ethiopia has a green water footprint of 56.5 billion m^3/yr. Only 2% of the water footprint is blue water footprint. The total annual blue water footprint is 1.85 billion m^3, of which 34.5% is used for animal water supply, 63.6% is used for watering crop plants, 1.8% is used for domestic water supply, and 0.1% is used for industrial water use (Table 5).

Table 5. The water footprint of Ethiopia's national production systems (Mm^3/yr)

Type of water footprint	Agricultural production			Industrial production	Domestic water supply	Total	%
	Water footprint of crop production	Water footprint of grazing	Water footprint of animal water supply				
Green	56485	18858	-	-	-	75343	97
Blue	1173	-	638	1.1	33.3	1846	2
Grey	327	-	-	20.0	299.7	647	1
Total	57985	18858	638	21	333	77835	100

Source: Hoekstra and Mekonnen (2012) and the Water Footprint Network (https://waterfootprint.org/en/)

Increasing water productivity in agriculture (i.e. reducing the water footprint per unit of production) will contribute to reducing the pressure on the freshwater resources (Rockström, 2003). Mekonnen and Hoekstra (2014) developed water footprint benchmark values for crop productions worldwide. The benchmark values indicate how efficiently water is being used in producing a crop. It also shows the potential for increasing water productivity through green water management techniques.

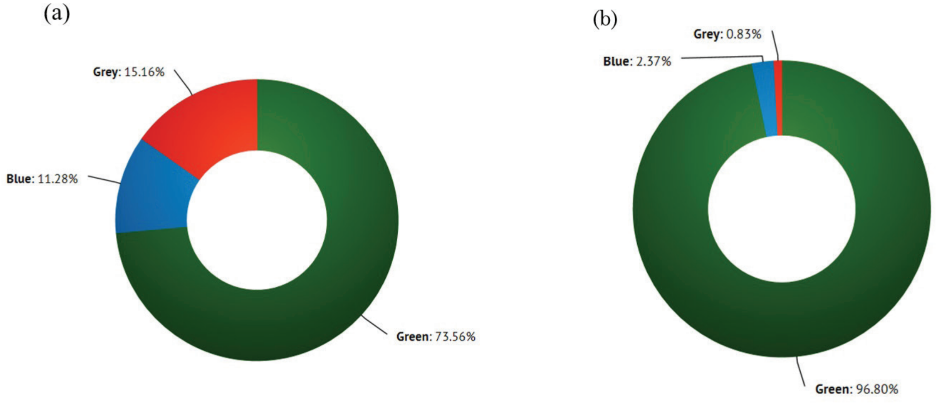

Figure 6. The water footprint of global (a) and Ethiopia (b) production (Mm^3/yr)

Source: Analysis by authors based on data from Hoekstra and Mekonnen (2012)

Higher water footprint compared to the global benchmark indicates low water productivity. Benchmark comparisons for three major crops selected for their dominant share of the total crop production and green water footprint for Ethiopia show that maize has a green + blue water footprint of 4211 m^3/t of production and its 25^{th} percentile benchmark green+ blue water footprint is 562 m^3/t of production (Table 6). This indicates there is a huge opportunity for improving water use efficiency of maize through improving yields per unit of water consumed. Similarly, sorghum is the crop consuming the second largest share of green water in Ethiopia and it has a water footprint of 4968m^3/ton of production. Since the 25^{th} percentile benchmark water footprint of sorghum (1122 m^3/t) is much less than the current national water footprint of Sorghum (Table 6), there is a significant opportunity for improving water use efficiency. In all cases, water productivity of the crops is low when compared with the global water footprint benchmarks. Increasing land and water productivity for maize, sorghum and wheat will increase the country's food security.

Implementing green water management practices that improve yield per hectare without increasing the water footprint will increase productivity of land and water resources. How various green water management interventions affect water footprint, and what practices are required to reduce water footprint to at least 25th percentile benchmark of water footprint values of different crops constitute an important research area.

Table 6. Green water footprint for selected crops at different production percentiles

Crop	Green–blue water footprint (m^3/ton) at different production percentiles				National water footprint (m^3/ton)	Green water footprint (%)	Blue water footprint (%)
	10th	*20th*	*25th*	*50th*			
Maize	503	542	562	754	4211	99.00	1.00
Sorghum	1001	1082	1122	1835	4968	99.82	0.18
Wheat	592	992	1069	1391	3583	98.91	1.09

* ***Note:*** According to Demeke *et al.* (2012), maize is the most important cereal, accounting for 17 percent of the per capita calorie intake, followed by sorghum (14%), and wheat (13%). The water footprint of a crop is compared to the 25th percentile water footprint for production globally for that crop. This is used as the global benchmark.

Source: Authors' analysis based on Data from Mekonnen and Hoekstra (2011, 2014)

6.2 Green water management programs and practices in Ethiopia

6.2.1 Overview of selected GWM projects

In Ethiopia, large-scale programs of restoration of degraded lands were started from the mid-1970s and have continued to date with varying scales and foci (see Table 7 and Annex 1). The important components have been rehabilitation of degraded lands and management of rainwater, and involved: a) construction of ex-situ water harvesting structures such as farm ponds for supplementary irrigation, b) construction of in-situ water harvesting structures such as terraces, bunds, check dams, and cut-off drains, c) implementation of agronomic measures such as conservation tillage and mulching, and d) afforestation and revegetation of fragile and hillside areas.

Following the severe drought that persisted for three consecutive years between 1972 and 1974/75, a Food-For-Work (FFW) project was initiated with support from the United Nations World Food Program (WFP) in 1974 in the northern part of Ethiopia (mainly Tigray and Wollo areas). The program, which was started in the form of relief assistance, gradually shifted to supporting development activities with the objective of addressing land degradation, which was identified as an underlying cause to the problem of food shortages and vulnerability to the recurrent droughts (World Bank, 1985; WFP, 1989).

In a similar effort, the Government of Ethiopia, with assistance from the World Bank, formulated another project named "Drought Areas Rehabilitation Project" (World Bank, 1974). The project had nine components ranging from infrastructure development to establishment of the *Sirinka* Pilot Catchment Rehabilitation Project (SPCRP), which was intended to establish a long-term strategy for rehabilitation of drought-prone areas. By 1984, the project had managed to construct soil bunds and grass strips equivalent to180 km that protected over 600 ha of land from soil erosion, and it also designed new conservation tillage implements, and distributed over 600,000 tree seedlings (World Bank, 1986). The project served as a turning point in establishing the linkage between degradation of land resources and local drought impacts.

In 1980, a WFP supported project, called 'Project 2488 (Rehabilitation of Forest, Grazing and Agricultural Lands)' was launched as the culmination of its food-for-work project that had been running earlier, during the late 1970s (WFP, 1989). According to WFP, the main objectives were rehabilitation of forest, grazing and agricultural lands which involved land terracing, tree planting and other improvements to farmer-owned lands. Activities were designed to increase crop yields by reducing land degradation, and thereby improve food security. Over its 20-year life span, Project 2488 laid the foundations for a following project, the Managing Environmental Resources to Enable Transitions to Sustainable Land Use (MERET) project (Nedessa and Wickrema, 2010). This also involved changes in focus and approaches: i) food-for-work for large infrastructure development and forestry (1981–1993); ii) introduction of participatory approaches for activities identification (1994–2000); and iii) focus on livelihoods (from 2000/2001).

After its formal launch in 2003, the MERET project supported more than 50 activities in three broad areas: i) physical and biological measures of soil and water conservation, ii) livelihoods, and iii) capacity building. A significant achievement of this program was the production and dissemination of the 'Community-Based Participatory Watershed Development' (CBPWD) guideline (MoARD, 2005a; 2005b). The guideline is now the standard handbook and training manual for watershed management practices in Ethiopia. As a project, MERET has made substantial achievement in improving livelihood and food security opportunities for drought-stricken areas and it also created capacity for other land management projects. However, MERET was able to reach only about 4% of the areas requiring soil and water conservation in the country (Nedessa and Wickrema, 2010).

MERET Plus ('MERET through Partnerships and Land Users Solidarity') was the last version of MERET (2007–2011) that was implemented in highly degraded and food-insecure areas: 65 *woredas* in the regions of Tigray, Amhara, Oromia, SNNPR, Dire Dawa and Somali (WFP, 2009). The project sites were identified using vulnerability analysis and mapping (VAM), agro-ecological and farming system evaluations and evidence from the field, in consultation with relevant governmental agencies at all levels. The aim of MERET Plus was to address land degradation and introduce practices and skills to improve land husbandry in highly degraded and food-insecure areas while diversifying income-generating opportunities and ensuring sustainability of the natural resource base (WFP, 2009; Nedessa and Wickrema, 2010). This aim is similar to the previous MERET project, but MERET–Plus emphasizes effective partnerships for sustainable land management (SLM) and community-driven assets-creation targeted towards the resource-poor (WFP, 2009). Its package also includes soil and water conservation measures, soil fertility management, agroforestry and forestry, income generation, homestead gardens development and crop diversification, rainwater harvesting and small-scale irrigation.

Table 7. Land rehabilitation and rainwater management programs and projects since the mid-1970s in Ethiopia

No	Project name and years of operation	Source of information
1	Food-for-work project (FFW) (1974–1980)	WFP, 1989
2	Drought Areas Rehabilitation Project (1974–1984)	World Bank, 1974; 1985
3	Project 2488 -Rehabilitation of Forest, Grazing and Agricultural Lands (1980–2002)	Nedessa and Wickrema, 2010
4	Peasant Agriculture Development Program (PADEP): Bure-Silala Soil Conservation and Watershed Management (1988–1997)	World Bank, 1988
5	Managing Environmental Resources to Enable Transition (MERET (2003–2006)	MoARD, 2005a; 2005b; Nedessa and Wickrema, 2010
6	Managing Environmental Resources to Enable Transitions to More Sustainable Livelihoods (MERET-PLUS (2007–2011)	WFP, 2009
7	Community-based Integrated Natural Resources Management in Lake Tana Watershed (2009–2018)	FDRE, 2019
8	Productive Safety Net Program (PSNP) (2004-todate)	MoARD, 2014
9	SLMP-I (2008–2013)	World Bank, 2008
10	SLMP-II (2013–2018)	World Bank, 2013
11	Resilient Landscapes and Livelihoods Project (RLLP) (2019–2024)	World Bank, 2018
12	Climate Action through Landscape Management (CALM) Program (2019–2024)	World Bank, 2019

6.2.2 Ethiopia's Strategic Investment Framework for Sustainable Land Management (ESIF-SLM)

The Government of Ethiopia developed a multi-year (2009–2024) Strategic Investment Framework for Sustainable Land Management (ESIF-SLM) to guide the prioritization, planning and implementation, by both public and private sectors, of current and future investments in SLM (ESIF-SLM, 2010). Since 2010, ESIF-SLM has guided efforts to address land degradation, reduce vulnerability to climate chocks, provide land tenure security, and address knowledge and institutional capacity constraints at local, regional and national levels. The first SLM Project (SLMP-I, 2008 - 2013) designed for implementation of the ESIF-SLM framework and its second phase, SLM Project-II (2013–2018), have been already completed. ESIF-SLM is currently in phase 3, which is running from 2019 to 2024. The continued relevance of SLM projects is also reflected in the two recently approved follow-on World Bank-supported projects, the Resilient Landscapes and Livelihoods Project (RLLP) and the Climate Action through Landscape Management (CALM) Program.

The SLM program is directly related to green water management and thus it is evidently important in improving green water management. And the ESIF-SLM clearly puts activities which can increase soil moisture (green water) as one of the principles that underlie SLM. It states that "all practices including agronomic, vegetative and structural measures, which increase soil moisture content, shall be implemented in combination and in integrated manner" (MoARD, 2010).

6.2.3 Resilient Landscapes and Livelihoods Project

The Resilient Landscapes and Livelihoods Project (RLLP) aims to enhance resilience and productivity of treated landscapes and livelihoods through the provision of capital investments, technical assistance and capacity building at national, regional, woreda, kebele and community levels (World Bank, 2018). The RLLP was meant to build on the results of SLMP I & II and also introduce measures to address climate change/variability-related risks and minimize Greenhouse Gas (GHG) emissions so as to meet the Growth and Transformation Plan (GTP) and the Climate Resilient Green Economy (CRGE) goals of the country. The RLLP implements core investments in biophysical watershed restoration with a set of associated activities supporting sustainable livelihoods in restored landscapes of 152 major watersheds located in the Ethiopian highlands. These investments will also bring water productivity improvements in smallholder rain-fed farming systems.

6.2.4 Climate Action through Landscape Management Program

The Climate Action through Landscape Management (CALM) Program was approved on 13th June 2019. The CALM Program aims to increase adoption of sustainable land management practices and to expand access to secure land tenure in non-rangeland rural areas (World Bank, 2019). It is also aimed at providing results-based financing for selected elements of the third phase of Ethiopia's Strategic Investment Framework (ESIF-3) for SLM (i.e. RLLP). Thus, the CALM Program supports the ESIF to address land degradation and enhance rural livelihoods.

6.2.5. Mass mobilization for watershed management

Besides the programs and projects discussed above and other small-scale efforts, the government has been regularly mobilizing rural people for watershed management works since 2010/11 in the four regional states of Amhara, Tigray, Oromia, and SNNP, where land degradation is a serious problem.

Through this campaign-based mass mobilization program, people are expected to contribute at least 20 days per year of voluntary labour towards building public infrastructure or managing watersheds. The work is not paid. Communities in the rural areas implement both physical and biological soil and water conservation measures on private farms and communal lands. This is a largescale activity; for instance, the Amhara region alone mobilized 4.5 million people per day for the conservation activities. The total free community labour mobilized for watershed management activities in the period 2013–2015 is estimated to be ETB 27.82 billion (US$1.35 billion) (Langan *et al.*, 2015).

6.2.6 The National Adaptation Plan (NAP)

Ethiopia's National Adaptation Plan (NAP-ETH) acknowledges the role of improving agricultural productivity in enhancing food security and adapting to climate change. The NAP-ETH has identified 18 adaptation options (FDRE, 2019). Three of those adaptation options are related to green water management. These are: (i) Enhancing food security by improving agricultural productivity in a climate-smart manner; (ii) Strengthening sustainable natural resource management through safeguarding landscapes and watersheds; and (iii) Improving soil and water harvesting and water retention mechanisms.

7. Green Water Management in the Abbay Basin

7.1 SWC activities in the Abbay basin

According to WLRC (2018), the coverage of existing terraced landscape in the Abbay basin is about 2.8mha, and this is out of more than 10.3mha of land that is said to require terracing (Table 8 and Fig.7). Nationwide, the GoE's target to achieve landscape restoration is 22 million ha by 2030. Although the scale of SWC activities in the Abbay basin has increased significantly since the 1973/74 drought, only a fraction of the land in need of terracing has been treated so far. The current coverage of terraces is the cumulative result of many initiatives over the years under development-partner-financed projects and mainstream government programs, which are discussed in Section 6.2. The existing physical conservation structures are found mainly in Gojjam, Wello and Debre Birhan areas (Fig. 7).

Table 8. Extent of terraced landscape and area that needs terracing in the Abbay basin

Area	Area (ha)	Percentage
Terraced landscape	2,777,988	27
Area that needs terracing	7,529,289	73
Total area that requires terracing	10,307,277	100

Source: Authors' analysis based on data from WLRC (2018)

In addition to those programs and projects described in Section 6.2, there are several important projects in the Abbay basin with explicit watershed management components. These include the Koga Irrigation and Watershed Management Project (AfDB 2001); the Tana Beles Integrated Water Resources Development Project (World Bank, 2008); the Community-Based Integrated Natural Resource Management Project; and the Eastern Nile Watershed Management Project. The principal technical document guiding the design and implementation of the interventions is the Community-Based Participatory Watershed Development Guidelines prepared under the auspices of the Ministry of Agriculture (MoARD, 2005a; 2005b).

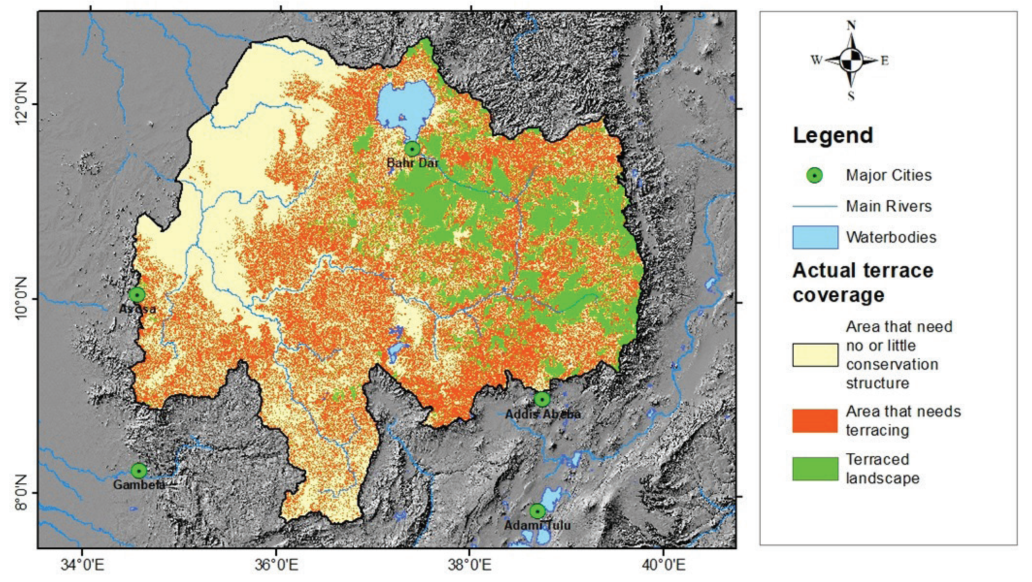

Figure 7. The coverage of terraced landscape in the Abbay basin

Source: Authors analysis based on data from WLRC (2018)

7.2 Yield and water productivity gaps in the Abbay basin

Table 9 shows the yield gap and green WP gaps for the three major crops in the Abbay basin in the period 1998–2012. The yield gap (Yg) is the difference between water-limited yield potential (Yw) and actual yield (Ya). For rain-fed crops, although Yw represents the ceiling yield (Van Ittersum and Rabbinge, 1997), achieving yields of 80% of Yw is realistic and profitable (Lobell et al., 2009). The exploitable yield gap represents the difference between Ya and 80% of Yw (Fig. 8). There is a large yield gap between potential farm/on-station yield and actual farm yield. For example, the average yield gaps for maize, wheat, and sorghum in the Abbay basin are 2.34, 1.96, and 2.11 t ha^{-1}, respectively, in the period 1998–2012 (Table 9). Rain-fed maize has the highest yield potential and largest yield gap, whereas sorghum has the smallest potential and yield gap. High yield gaps indicate that there is scope for improvement before reaching the practical limit of observed yield gaps (i.e. 80% of Yw) in the near future in rain-fed agriculture, if appropriate land and water management measures are taken. Significant reductions in crop yield gaps in the basin are highly required by improving crop yields in order to meet the growing food demand and to reduce poverty as well.

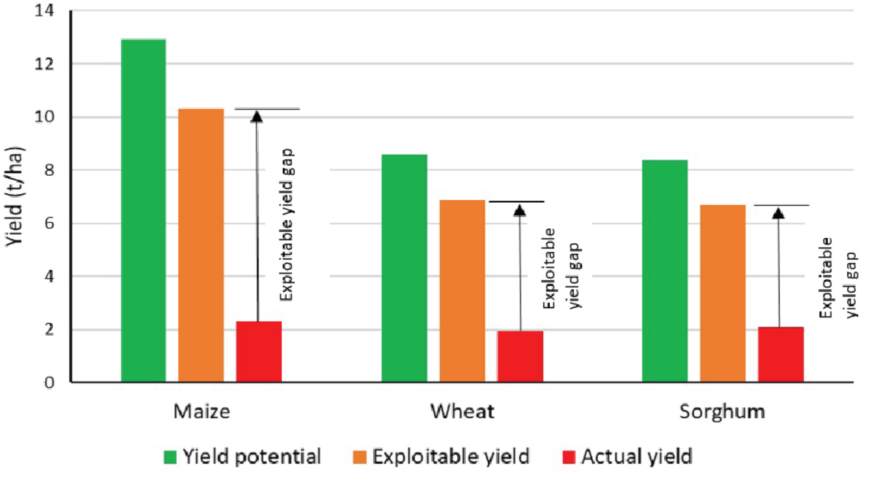

Figure 8. The exploitable yield gap[2] of the three major crops in the Abbay basin in the period 1998–2012

Source: Authors' analysis based on data from http://www.yieldgap.org/)

As shown in Table 9, the prevailing water productivity of the three major crops (i.e. maize, sorghum, and wheat) is very low in the Abbay basin, much less than the world average water productivity. Average water productivity was 3.51 kg/ha per mm (2.64 - 4.88 kg/ha per mm) for maize, 5.02 kg/ha per mm (3.9 - 6.26 kg/ha per mm) for wheat, and 4.27 kg/ha per mm (3.26 - 4.96 kg/ha per mm) for sorghum. Sadras *et al*. (2011) compared water productivity values for major crops and found ranges amounting to 6–23 kg/ha per mm for maize, 5-10 kg/ha per mm for wheat, and 5-21kg/ha per mm for sorghum. Those wide ranges indicate considerable potentials for improvement of the water productivity of the major crops in the Abbay basin.

The wide range of values of CWP for the same crop shows the effects of climatic factors (such as evaporative demand of the atmosphere and rainfall pattern) influencing water productivity. The highest and lowest values of CWP for maize were observed in the period 1998–2012 in Shambu research station (4.88 kg/ha per mm) and Jimma research station (2.64 kg/ha per mm), respectively. So, Shambu's agro-climate is highly suitable for production of maize in terms of both

2 Exploitable yield gap is the difference between actual yield and 80% of water-limited yield (Yw)

grain yield and water productivity. For sorghum, the highest CWP was recorded in Gondar (4.96 kg/ha per mm), while the lowest CWP was observed in Pawe (3.26 kg/ha per mm). For wheat, the lowest and highest values of CWP were observed in Ayira (3.9 kg/ha per mm) and Sheno (6.26 kg/ha per mm), respectively. The highest yields are not necessarily associated with the highest CWP (e.g. wheat and sorghum). However, for maize Shambu area has the highest average yield of 2.91 t/ha with the highest water productivity of 4.88 (kg/ha per mm).

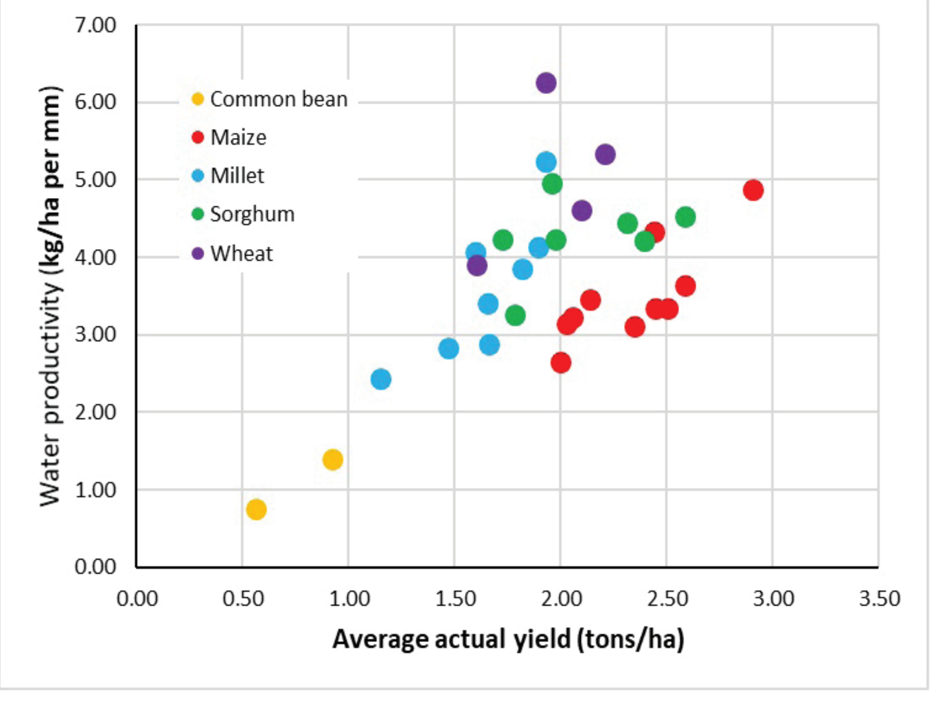

Figure 9. Relationship between actual yield and water productivity in the period 1998–2012
Source: Authors' analysis based on data from http://www.yieldgap.org/

As shown in Figure 9, the CWP ranges from ~2 kg/ha per mm at ~ 0.5 t/ha yield to ~5 kg/ha per mm of consumptive green water flow at ~3 t/ha using data collected from 12 Agricultural Research Centres in the Abbay basin. This suggests the possibility to increase CWP by increasing crop yields through mechanisms such as soil fertility management, crop selection, and use of improved tillage. This concept is also widely acknowledged also by other researchers (e.g. Rockström *et al.*, 2007; Wani *et al.* 2009). Rockström (2003) revealed the non-linear relationship between CWP and crop yield by considering yield range of 0.5–10 t/ha from both tropical and temperate regions, where the curve flattens out and the water use efficiency does not increase any further beyond 3 t/ha.

Table 9. Crop Water Productivity (CWP) gap and yield gap for major crops in the Abbay basin in the period 1998–2012

Crop	Location	Statistics	Ya	Yw	Yg	80%Yw	WPa	WPp	WPg
Maize	Assosa		2.03	17.13	15.10	13.70	3.15	26.55	23.41
	Pawe		2.44	12.13	9.69	9.70	4.32	21.50	17.18
	Ambo		2.45	9.55	7.10	7.64	3.34	13.04	9.70
	Bahir Dar		2.05	10.87	8.82	8.70	3.22	17.06	13.83
	Adet		2.51	13.11	10.60	10.48	3.34	17.47	14.13
	Ayira		2.35	18.07	15.72	14.46	3.11	23.94	20.83
	Jimma		2.00	15.75	13.75	12.60	2.64	20.80	18.16
	Nekemte		2.58	12.71	10.13	10.17	3.64	17.89	14.26
	Debre Markos		2.14	9.68	7.55	7.75	3.46	15.69	12.23
	Shambu		2.91	9.97	7.07	7.98	4.88	16.73	11.86
		Mean	2.34	12.90	10.55	10.32	3.51	19.07	15.56
		SD	0.29	3.12	3.24	2.50	0.64	4.08	4.27
Wheat	Ambo		2.21	8.65	6.44	6.92	5.33	20.87	15.53
	Adet		2.10	9.54	7.44	7.63	4.60	20.91	16.31
	Ayira		1.61	8.02	6.41	6.42	3.90	19.48	15.58
	Sheno		1.93	8.15	6.22	6.52	6.26	26.48	20.22
		Mean	1.96	8.59	6.63	6.87	5.02	21.93	16.91
		SD	0.26	0.69	0.55	0.55	1.01	3.10	2.23
Sorghum	Assosa		1.98	8.26	6.28	6.61	4.23	17.69	13.46
	Pawe		1.78	5.83	4.05	4.67	3.26	10.67	7.41
	Bahir Dar		1.73	6.34	4.62	5.08	4.22	15.52	11.30
	Gondar		1.96	7.62	5.66	6.10	4.96	19.29	14.33
	Ayira		2.40	9.74	7.35	7.79	4.21	17.12	12.91
	Nekemte		2.31	9.77	7.45	7.81	4.45	18.78	14.33
	Shambu		2.58	11.08	8.49	8.86	4.53	19.41	14.88
		Mean	2.11	8.38	6.27	6.70	4.27	16.93	12.66
		SD	0.33	1.93	1.61	1.54	0.52	3.08	2.60

Note: Ya, actual on-farm yield (t ha^{-1}), Yw, water-limited yield potential (t ha^{-1}),Yg yield gap (t ha^{-1}), 80% of Yw, WPa, actual on-farm water productivity (kg ha^{-1} mm^{-1}),WPp, water-limited potential water productivity for rain-fed crops (kg ha^{-1} mm^{-1}) WPg, water productivity gap (kg ha^{-1} mm^{-1})

Source: Based on data from http://www.yieldgap.org/

7.3 Hydrological and agronomic impacts of GWM at experimental scales

7.3.1 Impacts of conservation tillage on soil moisture

***Spatial variability of soil moisture*:** Asmamaw *et al.* (2012) reported significant difference in soil moisture content at the lower side (0.323±0.003m^3 m^{-3}) as compared to the upper side (0.305 ±0.003m^3m^{-3}) of *fanya juu* bunds under conventional tillage. Whereas, no significant difference in soil moisture content between upper side (0.275±0.003m^3m^{-3}) and lower side (0.278±0.002m^3 m^{-3}) of the bund was observed under conservation tillage (Table 10). This indicates that conservation farming could cause the soil water to be stored uniformly in the upper and lower sides of the bunds. Implementation of terraces alone may not affect the desired outcome of improved green water management. For example, crops gown behind *fanya juu* terraces usually appear yellow with stunted growth under conventional tillage. Besides, water-logging is a common problem behind *fanya juu* (Temesgen *et al.*, 2012). However, if plough pans are disrupted through conservation farming, better soil aeration could be achieved through improved drainage.

Soil moisture as a function of soil depth**:** According to Temesgen *et al.* (2012), the impact of conservation tillage is visible in the lower layer of the soil profile. Soil moisture in traditional tillage was significantly higher than that of conservation tillage in the upper layer of the soil profile (0–15cm). Whereas, in conservation tillage, significantly higher soil moisture was observed at the lower layer (at 15–30 cm) as compared to the traditional tillage. This is mainly explained by increase in soil penetration resistance as depth increases (viz. by 1 megapascals (MPa) at the soil surface versus 3 MPa at 15cm depth). A soil penetration resistance experiment carried out in Enerata watershed in Gozamn district (in the Abbay basin) shows that a rise in penetration resistance starts at 10 cm (i.e. the average depth of operation of the Maresha plough) and the resistance peaks at 20 cm depth (Temesgen *et al.*, 2012). Another experiment conducted by Tibebu *et al.* (2017) revealed that soil penetration resistance value increased with depth in Anjeni and Debre Mewi watersheds for cultivated land. A difference of 1 MPa was observed between the top soil layer (0–15 cm) and bottom soil layer (15–30 cm). A soil penetration resistance value of 2 MPa indicates the presence of hardpan, where roots cannot penetrate, and soil water movement is restricted.

Table 10. Impacts of conservation tillage on surface runoff, soil moisture, soil loss, infiltration, grain yield and biomass expressed as per cent deviations (%) from the conventional tillage

Type of conservation tillage	Crop type	Surface runoff (%)	Soil moisture	Infiltration	Soil loss (%)	Grain Yield (%)	Biomass (%)	Reference
Berken tillage	Maize	-53		102%	-53	5	48	Muche, 2020
Winged subsoiler tillage with *fanya juu*	Wheat	-48	-3% at 0-15cm depth 9% at 15-30cm depth	46%	-37	35	40	Asmamaw et al., 2012; Temesgen et al., 2012
	Tef	-15			-9	28	14	Temesgen et al., 2012
Deep tillage with hoe	Maize	-58		88%	-42	10		Hussein et al., 2019

7.3.2. Impacts of conservation tillage on surface runoff and soil loss

Compared with traditional tillage, plots treated with conservation tillage resulted in better moisture retention, low surface runoff and soil loss. The role of conservation tillage in reducing runoff and soil loss has been demonstrated by different authors (Table 10) Berken tillage and deep tillage reduce surface runoff by 53% and 58%, respectively, as compared to conventional tillage on maize plots by allowing more infiltration through disrupting plough pan (Hussien *et al.*, 2019). Surface runoff reductions were 15% on *tef* plots and 48% on wheat plots (Temesgen *et al.*, 2012). This may indicate that conservation tillage treatment could be effective more on wheat fields in terms of reducing surface runoff and soil loss. Higher negative deviation values are associated with higher effectiveness of treatments in reducing surface runoff and soil loss.

Conservation tillage showed apparent potential benefit to improve infiltration. For example, Berken tillage allowed 102% increase of infiltration on maize plots and winged subsoiler induced a 45% increase of infiltration on wheat plots (Table 10). Significant differences in cumulative infiltration in the soils were reported between winged subsoiler (16.92±0.17 cm) and traditional tillage (11.6±0.11 cm) treated plots in Enerata watershed (Asmamaw *et al.*, 2012).

7.3.3. Impacts of conservation tillage on biomass and grain yield

Table 10 shows the effects of conservation tillage on grain and biomass yields of wheat, *tef* and maize in the Abbay basin. In Robit watershed, Berken tillage significantly increased biomass yield by 48%, but slightly increased grain yield by 5% compared to conventional tillage (Habtamu *et al.*, 2020) and deep tillage with hoe yielded a 10% increase in grain yield compared to traditional tillage (Hussien *et al.*, 2019). An experiment conducted at Enerata watershed by Temesgen *et al.* (2012) showed that the mean values of both biomass and grain yields from plots treated with winged subsoiler were higher than those from traditional tillage although the differences were not statistically significant at $\alpha = 0.05$. This could be attributed to high variation in soil fertility as replications were made in different farmers' fields.

7.3.4. Impacts of terraces/bunds on surface runoff, soil loss and crop yield

Several studies in the Abbay basin showed statistically significant reductions in soil loss for a majority of SWC treatments when compared with sites without conservation measures (Table 11). The reduction in soil loss ranged from 25% at Enerata where *fanya juu* was practiced to 86% at Dibatie (soil bund with grass strip) (Temesgen *et al.*, 2012; Herweg and Ludi, 1999). Comparisons of *fanya juu* and soil bund in their effectiveness of reducing soil loss show mixed results. For example, at Andit Tid, reduction of soil loss by 41% and 63% were observed on soil bund and *fanya juu*, respectively. At Anjeni, a 68% reduction of soil loss on *fanya juu* and a 66% reduction of soil loss on soil bunds were observed. This indicates that there are no significant soil loss differences between *fanya juu* and soil bund. Also, Herweg and Ludi (1999) noted no significant soil loss differences between most SWC treatments, and hence there is no 'best' measure as such. Another important point could be absolute soil erosion rates on treated plots might still be above a given tolerance level and there is a need for further development of SWC technologies (Herweg and Ludi, 1999).

Runoff was considerably reduced at all sites reviewed here; thus, the goal of moisture conservation was met (Table 11).

Table 11. The average relative impact (%) of SWC (in-situ water harvesting) measures on soil loss, runoff, crop yield and biomass compared with local cultivation practices

Location	SWC structure	Runoff	Soil loss	Grain yield	Biomass	References
AnditTid on 24% Slope (1987–1991)	*Fanya juu*	-2	-63	-50	-45	Herweg and Ludi, 1999
	Soil bund	-5	-41	-12	-11	
	Grass strip	-33	-73	-39	-37	
Anjeni on 28% slope (1986–1990, 1992)	*Fanya juu*	-33	-68	+4	-5	
	Soil bund	-32	-66	-13	-13	
	Grass strip	-41	-72	0	+8	
Anjeni on 12% slope (1986–1990, 1992)	*Fanya juu*	-50	-81	+14	+5	
	Soil bund	-40	-63	-6	-12	
	Grass strip	-19	-57	+14	+11	
Anjeni at catchment level	*Fanya juu*	-11				Hurni *et al.*, 2005
Enerata on 9-11% slope 2011	*Fanya juu* with conservation tillage		-25	+32	+28	Temesgen *et al.*, 2012
Guder on 15% slope	*Fanya juu*	-32	-72			Ebabu *et al.*, 2019; Sultan *et al.*, 2018
	Soil bund	-27	-67			
	Soil bund with Grass strip	-29	-77			
Aba Gerima On 15% slope	*Fanya juu*	-29	-61			
	Soil bund	-20	-60			
	Soil bund with Grass strip	-22	-66			
Dibatie On 15% slope	*Fanya juu*	-35	-63			
	Soil bund	-29	-68			
	Soil bund with Grass strip	-43	-86			
Debre Mewi On 10% slope	Soil bund	-36	-57			Amare *et al.*, 2014
	Soil bund with local grass	-17	-26			

The reduction in surface runoff ranged from 2% at Andit Tid (*fanya juu*) to 50% at Anjeni (*fanya juu*). The reduction of runoff due to higher infiltration rates resulted from SWC measures on treated plots. However, at the catchment level, there were mixed results (Hurni *et al.*, 2005). In Anjeni, Minchit catchment, the rainfall–runoff coefficient did not substantially decrease during the period 1984–2000. The catchment was treated with intensive soil and water conservation measures since 1986, the runoff coefficient, however, showed an insignificant trend towards less runoff, from about 47% at the beginning of conservation in 1984 to about 42% in 2000 (Hurni *et al.*, 2005). Therefore, implementation of soil and water conservation may not necessarily lead to a significant decrease of total annual catchment runoff rates over time. This suggests that additional catchment scale experiments and scenario analyses are required to understand catchment scale dynamics over long years.

Significant variability is reported in the impact of soil and water conservation measures on crop yield. As opposed to the expected benefit of conservation measures on grain yield, an experiment at Andit Tid showed a reduction in grain yield (Herweg and Ludi, 1999). The highest increase in grain yield (28%) has been reported at Enerata on a plot treated with *fanya juu* (Temesgen *et al.*, 2012). Hereweg and Ludi (1999) noted that at Anjeni grain yields from on-farm experimental plots treated with conservation measures rarely increased during the first three to five years of SWC works.

7.4. Downstream impacts of GWM in the upstream

The hydrologic effect of GWM interventions is generally to delay surface runoff and increase infiltration. At the catchment scale, this is expected to result in reductions in flood peaks and surface runoff volumes and increase in dry season flows. In the Abbay basin, the effects of soil and water conservation on runoff were considerably reduced surface runoff rates on conserved cultivated plots compared to non-conserved plots. At the catchment level, however, there were mixed results because apparently many factors contribute to the increase or decrease in river discharge, which includes base flows. At an experimental plot (6 m × 30 m) level, Hurni *et al*. (2005) reported a long-term (1984–2000) average reduction of surface runoff by 39% at Anjeni (Minchet catchment) due to soil and water conservation measures on cultivated land compared with non-conserved cultivated land (Table 12). However, at catchment scale, the runoff coefficient showed an insignificant decreasing trend, from about 47% at the beginning of conservation in 1984 to about 42% in 2000. This suggests that the conservation work in Anjeni contributed to enhanced dry season flow in this catchment. In another sub-humid catchment in *May bar* (located on the ridge of Abbay basin and Awash basin), for an observation period of eight years (1982–1989), the runoff-reduction effect was more pronounced. The runoff coefficient changed from 32% in 1982 (1431 mm rainfall) to 15% in 1989 (1406 mm rainfall) after intensified soil and water conservation had been carried out in 1983 (SCRP, 2000a). In contrast, in a humid Hulet Wenz catchment at Andit Tid research station, the runoff coefficient increased from 30% in 1983 (1547 mm rainfall) to 43% in 1992 (1472 mm rainfall) after implementation of conservation structures.

Table 12. Impact of GWM intervention on runoff coefficient based on data from SCRP research stations in the Abbay basin

Research station	Impact of GWM intervention	Geology	References
AnditTid (Area: 477.3 ha Climate: Humid)	Runoff coefficient increased from 30% in 1983 to 43% in 1992	Volcanic rocks: hyolites, trachites, tuffs and basalts	SCRP, 2000b
Anjeni (Area: 113.4 ha Climate: sub-humid)	Runoff coefficient reduced from 47% at the beginning of conservation in 1984 to about 42% in 2000	Tertiary olivine basalt and tuff	Hurni *et al.,* 2005
Maybar (Area: 112.8 ha Climate: sub-humid)	Runoff coefficient reduced from 32% in 1982 to about 15% in 1989	Volcanic Trapp series with alkali-olivine basalts	SCRP, 2000a

No study has explored why mixed results are obtained at the catchment scale, such as in the SCRP research stations. The mixed findings are perhaps related to the geologic formation of the catchments. A catchment may respond fast or slowly after GWM interventions depending on its geologic formation and acquirer characteristics.

Catchment geology is known to be one of the most important variables for base flow index (BFI) estimation (Longobardi and Villani, 2008; Bloomfield *et al.*, 2009). Similarly, a study by Mwakalila *et al.* (2002) indicated that BFI has a strong relationship with climate and geology. Abebe and Foerch (2006) established a relationship between climatic, morphologic and geologic features of a catchment to its BFI in the Wabi Shebele river basin of Ethiopia and they showed a strong relationship between BFI and geology. Catchments with high climate index (high rainfall or low evapo-transpiration) underlain with granites or basalt tend to give high base flow. Nyssen *et al.* (2010) reported a rise in groundwater table after conservation measure (stone bunds and check dams) in May ZegZeg catchment (Tekeze river basin, northern Ethiopia) where the geology is Antalo limestone layers overlain by Amba Aradam sandstone. However, it is very difficult to come up with conclusive statement by taking only a three-month data after the catchment management. Akale *et al*. (2019) computed groundwater flow index (GWFI=annual subsurface flow/total flow) for the period 2010–2015 based on hydrological model results of Tikur-Wuha watershed (in the Abbay basin) during (2010–2011) and (2012–2015) GWM interventions. The average GWFI was less (average of 62%) before implementation than after (average 64%). The catchment appeared to respond fast because the GWFI showed slight increase in the early phase of the implementation (year 2012), and showed a decrease in the year 2015.

It is not clear whether the intercepted surface runoff by the in-situ RWH measures can be transferred into baseflow and increase the streamflow in dry seasons. Thus, upgrading rain-fed agriculture through investments in in-situ and ex-situ RWH systems may result in water trade-offs with downstream users and ecosystems (Calder, 1999). However, the downstream impacts on stream flow from small-scale water storage systems have been shown to be very limited (e.g. Schreider *et al.*, 2002; Sreedevi *et al.*, 2006). When in-situ RWH is implemented, water is being used close to the source (i.e. rainfall) and, as a result, less water is lost as runoff and soil loss is reduced. Hence, upstream capture and use of rainwater saves water which might otherwise be lost by evaporation along the way to downstream without any beneficial use. The effect of large-scale adoption of both in-situ and ex-situ RWH practices on blue water resources downstream is not known and it is still a subject of discussion.

A "win-win" GWM option for both downstream water users and upstream rain-fed farmers would be to focus more on practices related to evaporation management or vapour shift (i.e. turn E into T and a higher T/ET ratio), which can increase crop yields and improve WP without affecting downstream water users (section 5.2 for detail explanation). The interventions involved in vapour shift are dry planting, mulching, conservation tillage, agroforestry, intercropping and vegetative bunds. These activities are being practiced in the southern part of Ethiopia; but, upscaling towards the Abbay basin is needed. Such upscaling requires shifts in farmers' behaviour through investment in agricultural research and improving extension services to address the knowledge and information gaps.

8. Summary, Lessons Learned and Research Needs

8.1 Summary

The review has shown the significance of green water-based food production, and the fact that it is probably the most under-valued resource of all water resources and often not featured on the water agenda. Rain-fed agriculture represents 80% of land under cultivation, and contributes 60–70% of global crop production. In SSA, food production almost entirely depends on green water. For example, 97% of the total water resource use of Ethiopia is green water footprint and agriculture, the backbone of the country's economy, is green-water-based. Average crop yield of rain-fed cereals in Ethiopia is, however, very low compared to the global average of 3.9t/ha. Using data collected from 12 agricultural research centres in the Abbay basin, this review revealed significant yield gap and water productivity gaps for cereals, indicating considerable scope for improvement of the water productivity of the major cereal crops cultivated in the basin. At low-yield range, there is a great potential to improve water productivity (up to a five-fold increase). This suggests the high possibility to increase crop yields by increasing water productivity through mechanisms such as soil fertility management, crop selection, and use of improved tillage.

The review noted compelling reasons that make investing in rain-fed agriculture more important in relation with irrigation. These are: (1) blue water-based food production (i.e. irrigation) is expensive due to its high cost of capital and labour investment; (2) environmental impact of green water use is minimum as compared to irrigation; (3) irrigation alone will not be able to provide the food needed to feed the growing population by 2050; (4) green water generally has a lower opportunity cost than blue water; (5) green water plays a significant role in international commodity trade (through supporting the production, for example, of coffee and oilseed crops); and (6) rain-fed agriculture is a means of livelihood security for the majority of poor small-holder farmers.

In calling for improved green water use efficiency, four broad categories of methods have been reviewed: in-situ water harvesting, ex-situ water harvesting, vapour shift (evaporation management) and crop management. The GWM practices range from soil amendments, conservation tillage practices, soil and water conservation practices, use of mulches and crop residue, to runoff harvesting techniques. The most widely implemented GWM practice in the Abbay basin is found to be terracing. The coverage of existing terraced landscape is about 2.8 million ha (27%), and this is out of at least around 10.3 m ha of land that apparently requires terracing. Various nationwide GWM initiatives supported by multiple development partners since the mid-1970s have contributed to the current coverage of terraces. The major GWM-related efforts in Ethiopia include the food-for-work (FFW) program (1973–2002), the MERET project (2003–2011), the PSNP program (2005–present), community mobilization through free-labour days (1998–present), the SLM program and its SLM projects (2008–2018), the RLLP, (2019–2024), and the CALM program (2019-2024). These initiatives indicate that there are fertile grounds for improved implementation of GWM and it can be integrated within various existing projects/programs.

This review has shown the impact of these interventions, particularly terraces/bunds on surface runoff, soil loss and grain yield. Although terraces/bunds are more successful in reducing soil loss for the majority of SWC treatments when compared with sites that did not receive conservation measures, absolute soil erosion rates on treated plots remained above tolerable limits. This suggests the need for integration of terraces with other technologies or further development of the terracing practice in terms of design. Terraces/bunds are found to be effective in reducing runoff considerably at plot scale. However, at the catchment scale, mixed results have been reported probably because many factors contribute to the increase or decrease in river discharge, which includes baseflows. This suggests additional catchment scale experiments and scenario analysis are required to understand catchment scale dynamics over long years. The review revealed significant variability, and hence inconclusiveness, also in results regarding the impact of soil and water conservation measures on crop yield.

This review has also shown that conservation tillage practices are successful in causing uniform spatial soil moisture distribution in the upper and lower sides of bunds, thereby reducing water logging effect of *fanya juu*. Thus, integration of different GWM technologies such as conservation tillage and terrace will result in the desired outcome of uniform soil moisture distribution in farms. Depth-wise, conservation tillage reduces soil penetration resistance and increases infiltration by breaking down the hardpan. Conservation tillage integrated with terrace has been effective in reducing surface runoff and soil loss, and increasing infiltration and grain yield. It is also known to be a “win-win” GWM option for both downstream water users and upstream rain-fed farmers, which can increase crop yields and improve WP without affecting downstream water users. Other interventions similar to conservation tillage are dry planting, mulching, conservation tillage, agroforestry, intercropping and vegetative bunds.

In sum, despite the high dependence of agriculture on green water, the agriculture sector development programs, strategies and policies have given little attention to green water management and usage in ways that increase water productivity. Regardless of the great potential, as shown by the results of the few programs and projects, for upgrading rain-fed agriculture, investments in measures to reduce yield gaps and increase water productivity in the Abbay basin are scarce and require a lot to be done.

8.2 Lessons learned

Following the famines of the 1970s and 1980s, the Ethiopian government, supported by donors and NGOs, has been involved in ambitious land conservation efforts which included several GWM interventions. In the past three decades, Ethiopia has adopted far more participatory (farmer-led) approaches, a livelihood focus, and an integrated watershed paradigm than in the past. These changes demonstrate the readiness for learning from experience and the benefits of changing approaches based on lessons learned along the process. Some of the important achievements include:

- The production and dissemination of the 'Community-Based Participatory Watershed Development' (CBPWD) guideline. The guideline is now the standard handbook and training manual for watershed management practices in Ethiopia.

- Every succeeding project has taken lessons from pre-existing projects and thus created capacity for other land management projects. The current GWM projects are focused on livelihood improvement and asset creation apart from activities on soil erosion control.

- There has been a shift in approach from top-down to somewhat bottom-up planning approach in soil and water conservation activities. This is well described in Annex-1.

Although those conservation interventions have resulted in many ecological benefits, the large-scale efforts had some serious shortcomings. Those shortcomings include the following ones.

- The past interventions have not achieved a transition from reversing land degradation to a goal of increasing and sustaining land and water productivity.
- Despite the importance of the resource, GWM has not been given adequate policy attention.
- There have, of course been, few measures in the form of sustainable land management and those have yielded encouraging results in increasing crop yield and WP. There is thus, huge potential to increase both yield and WP.
- Investments on GWM are scarce in the Abbay basin though. Much more needs to be done to address the areas that have not been treated with any SWC measures.
- Farmers are reluctant to keep the implemented SWC measures sustainably because most technologies were not adaptive to the local situation and were donor driven. Farmers' participation in selection of sites and technologies for interventions is still inadequate.
- Implementing the SWC measures requires labour, and farmers are reluctant to implement such labour- intensive measures without getting immediate benefits.
- Past interventions and researches have focused on single-practice interventions as opposed to integrated multiple interventions. For example, integration of terracing with conservation tillage might bring a larger impact on crop yields.
- Finally, although past interventions were mostly watershed-based, they have not considered up-stream-downstream linkages.

8.3 Implications for further research

- Water has been left out in different watershed management programs of the country and this has led to weak water management investments in rain-fed agriculture areas.
- Increasing the productivity of the whole landscape requires a shift in paradigm from a narrow focus on erosion control to a broader blue-green

water management approach in a watershed. Changes in land use upstream will affect water flows downstream, which in turn may lead to undesirable trade-offs between water for food production in upper catchments (i.e. green water use) and blue water availability downstream. Upstream areas, often rain-fed areas, are seen primarily as blue water-generating zones. Research and development efforts on incentive mechanisms for upstream farmers in exchange for specified GWM activities that sustain the supply of freshwater to downstream users, are required.

- Despite the large number of studies on individual GWM measures, impact studies on integrated catchment management are rare, particularly in the Abbay basin. Thus, studies on the hydrological impacts of integrated GWM interventions and its implications for livelihoods are needed.
- The effects of soil and water conservation measures on runoff considerably reduced surface runoff rates on conserved plots compared to non-conserved plots. At the catchment level, however, mixed results are reported. One can therefore assume that a thorough implementation of soil and water conservation might lead to decrease of total annual catchment runoff rates over time (reduced green water storage). However, the interventions might have positive effect on agricultural production, carbon storage and soil biodiversity. Therefore, new way of looking into the impacts of interventions on green water, blue water, and crop yield (food security) by considering catchment similarity is critically important.
- No or little attention has been given to GWM interventions other than those practices which reduce soil loss. For example, it is widely known that conservation farming improves grain yield by enhancing root growth and infiltrating more rainfall deeper into the soil profile particularly in soils with compacted low permeability sub-layers. However, little is known about the level of impact on the hydrology and agronomic effects of conservation tillage considering homogenous hydrological zones.
- While rainwater is the major contributor to livelihoods in the Abbay basin, little attention has been given to its management in the programs, policies and strategies. A future SLM program in the Abbay basin should aim at applying an integrated approach to rain water management that acknowledges the vital role played by both green and blue water flows in sustaining direct and indirect ecological functions and services benefiting the rural communities.

Annex

Annex 1. Land rehabilitation and rainwater management programs and projects since the mid-1970s in Ethiopia

Project name and years of operation	Activities related to green water management	Project site	Approach	Source of information
WFP food for-work projects (1974-1980)	Reforestation, soil and water conservation	Drought-prone areas	Emergency operations that responded to food crises	WFP, 1989
Drought Areas Rehabilitation Project (1974-1984)	Construction of diversion canals, improved moldboard plough, establishment of soil bunds and grass strips, contour farming and tree planting on degraded hills	Parts of Tigre and Wollo Provinces which were affected by drought	• Principally responding • to the needs of drought affected people, developing long-term strategy for development of the highlands. • Top down approach	World Bank, 1974; World Bank, 1985
Project 2488 -Rehabilitation of Forest, Grazing and Agricultural Lands (1980-2002)	Afforestation, on-farm and hill-side terracing, area closure and gully control	Ethiopian highlands on 117 watersheds, 3.5 million ha	• 1980-1993: i) top-down • government managed watershed approach; ii) focus on large watershed areas; iii) very limited level of long-term planning with activities defined on the basis of available food aid; iv) total lack of ownership by the community of the assets created. • 1994-2000: i) a more community-friendly smaller scale of planning, ii) introduction of local-level participatory planning approach (LLPPA) with a focus on smaller watershed activities. • From 2000: participatory monitoring and evaluation practices, integrating agricultural packages with income generating activities.	Nedessa and Wickrema, 2010)

Project name and years of operation	Activities related to green water management	Project site	Approach	Source of information
Peasant Agriculture Development Program (PADEP): Bure-Silala Soil Conservation and Watershed Management (1988-1997)	Construction of physical works such as gully control structures, water ponds, soil bunds, area closure, afforestation in appropriate areas and improved farming practices	North-west Ethiopia (Bure-Silala)	• Top-down approach in planning and implementation • Watershed-based (10,000 ha Bure watershed in Gojam, a 2,500 ha sub-watershed -- Silala) • Conservation Based Development approach, recommended by the Ethiopian Highland Reclamation Study, which sees conservation measures as an important step in the attempt to increase agricultural productivity among small-scale farmers.	World Bank 1988
Managing Environmental Resources to Enable Transition (MERET) (2003-2006)	Soil and water conservation measures, livelihood improvement activities, and capacity development production and dissemination of the 'Community Based Participatory Watershed Development' (CBPWD) guidelines	Ethiopia's chronically food insecure 72 woredas: Tigray (17), Amhara (23), Oromia (16), SNNP (12), Somali (3), Dire Dawa (1)	• Community-driven and refined LLPPA • Focus on smaller watersheds (500-600 ha) • Systematic targeting using vulnerability analysis and mapping • Shift from technical focus to capacity building and income generation	Nedessa and Wickrema, 2010; MoARD, 2005a, 2005b

Project name and years of operation	Activities related to green water management	Project site	Approach	Source of information
Managing Environmental Resources to Enable Transitions through Partnerships and Land Users Solidarity (MERET-PLUS) (2007-2011)	more emphasis on community capacity building, homestead production and income generation Soil and water conservation measures, soil fertility management, agroforestry and forestry, income generation, homestead gardens and crop diversification, rainwater harvesting and small scale irrigation	Highly degraded and food-insecure areas: 65 woredas in the regions of Tigray, Amhara, Oromia, SNNPR, Dire Dawa and Somali	• Participatory and community-based watershed development	WFP, 2009
Community-based Integrated Natural Resources Management in Lake Tana Watershed (2009-2018)	• helping communities prepare and implement 650 watershed management plans • establishing a database of existing land-use patterns and natural resources • rehabilitating severely degraded lands, • supporting soil and water conservation measures	Amhara region, 21 Woredas, with a total area of 1.5 million hectares	Participatory and community-based watershed development	FDRE, 2019
Productive Safety Net Program (PSNP) (2004-todate)	• Public works focus on soil and water conservation measures, development of water infrastructure	Food insecure households in drought prone areas across the country	Integrated community-based watershed development	MOA, 2014

Project name and years of operation	Activities related to green water management	Project site	Approach	Source of information
SLMP-I (2008-2013)	• Farmland and Homestead Development • Communal Land and Gully Rehabilitation • Community infrastructure development such as water harvesting systems	High potential areas in 45 selected watersheds	Participatory and community-based watershed development	World Bank, 2008
SLMP-II (2013-2018)	• Sustainable natural resource management in • public and communal lands • Homestead and farmland development, • livelihoods improvements and Climate Smart Agriculture	135 watersheds in six regions, i.e., Oromia, Amhara, Tigray, SNNP, Gambella and Benishangul Gumuz	Participatory and community-based watershed development	World Bank, 2013
Resilient Landscapes and Livelihoods Project (RLLP) (2019-2024)	• biophysical watershed restoration with a set of associated activities supporting sustainable livelihoods in restored landscapes.	Ethiopian highlands in152 major watersheds	Participatory and community-based watershed development	World Bank, 2018
Climate Action through Landscape Management (CALM) Program (2019-2024)	• adoption of sustainable land management practices and to expand access to secure land tenure in non-rangeland rural areas	Ethiopian highlands in 500 major watersheds	Participatory watershed management and rural land administration	World Bank, 2019

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