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Review Article

Revitalizing Key Conditions and Integrated Watershed Management to Mitigate Land Degradation and Sustain Water Availability for Agriculture in Semi-Arid Regions: A Case Study of Ethiopia

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Solomon Habtu[1]

1. Department of Land Resource Management and Environmental Protection, College of Dry Land Agriculture and Natural Resources, Mekelle University, Ethiopia

Land, the source of 97% of global food, remains threatened by progressive soil erosion-induced land degradation, such as in the semi-arid regions. To address this problem, soil and water conservation interventions have been implemented in watersheds across Ethiopia. Despite witnessing successful and positive impacts in some watersheds, the broader promotion of watershed-based interventions faces obstacles. Soil and water deteriorations persist in many of the watersheds in Ethiopia, leading to water shortages and related challenges in sustaining agriculture. The objectives of this research are thus to i) identify the main challenges and constraints hindering the promotion of watershed-based interventions in Ethiopia, and ii) identify key conditions for revitalizing the Integrated Watershed Management (IWSM) approach to mitigate soil erosion-induced land degradation, rehabilitate, and sustainably manage watershed resources. A systematic review of over 60 published articles, extracted from the internet database using various search engines such as Google Scholar, ScienceDirect, Academia.edu, and ResearchGate, was conducted. Additionally, valuable comments from 65 peer reviewers worldwide were collected through the Qeios platform during a posting period of more than two months, and these comments were utilized to update the first preprint version of this article. Based on the review, identified challenges and limitations include poor institutional support, lack of participation, inadequate planning of soil and water conservation (SWC) technologies, absence of research and development linkages, and insufficient capacity building. To address these challenges and limitations, recommendations for revitalizing the integrated watershed management (IWSM) approach and key conditions are discussed. The identified key conditions for revitalizing watershed-based interventions in Ethiopia include: i) ensuring institutional support and community participation, ii) strengthening the watershed-based intervention, and iii) establishing a watershed-based platform for scientific tools, research-based innovation, and capacity building to sustain water availability for agriculture in Ethiopia, serving as an experience for other semi-arid regions.

Corresponding author: Solomon Habtu, solomon.habtu@mu.edu.et

1. Introduction

Land is the source of more than 97% of the global food demand, with the remainder obtained from aquatic systems [1]. However, global lands have been undergoing degradation, prompting attention to soil and water conservation (SWC) since the 1930s in both developed and developing countries [2].

Global land degradation, a significant environmental problem, results from social, economic, and biophysical factors affecting various ecosystem services and degrading natural resources such as land, water, vegetation, and biodiversity [3][4]. In other words, land degradation can be defined as "the reduction in the capacity of the land to produce benefits from a particular land use under a specified form of land management," requiring evaluation in terms of both biophysical and socioeconomic aspects [5].

Land degradation and continuous desertification, caused by climate variability, global warming, human activities, and poor land management practices, are exacerbated by high population pressure, soil erosion by wind and water, low and highly variable rainfall, low rainwater use efficiency, poverty, low investments in water use efficiency measures, and inappropriate policies. Failure to address these factors timely may lead to a total collapse of global lands in the future [6][3][7][8][9][10][5].

Soil erosion, a form of land degradation, is a major factor leading to poor soil productivity and contributing to hunger and poverty in sub-Saharan Africa (SSA) [11][12][13][14]. It is considered a threat to soil resources and the sustainability of agriculture in general [10].

Ethiopia, one of the SSA countries, is characterized by a rugged and mountainous landscape and is highly affected by land degradation [15][16][17][18][19][12][20]. The problem has persisted since the early Axumite period in 400 B.C. With about 88% of its population concentrated in the highlands and over 85% relying on small-scale and subsistence agriculture, mainly (about 97%) rainfed [21], Ethiopia has been degraded by agricultural activities for at least three millennia [22]. Land degradation in the country is accelerating rapidly [5], contributing, among other things, to the loss of soil nutrients and consequently low agricultural productivity [23][19].

The soil erosion rate in the highlands of Ethiopia is quite high, exceeding tolerable levels and affecting the productive capacity of the soil system. The rate reaches over 130 t ha^{-1} $year^{-1}$ [24] and even up to 300 t ha^{-1} $year^{-1}$ on steep slopes and in areas with little vegetation cover [23], in contrast to the global maximum erosion rate of 30-40 t ha^{-1} $year^{-1}$ and soil formation rate of 1 t ha^{-1} $year^{-1}$ [25]. Consequently, 50% of the Ethiopian highlands have significant soil erosion, of which 25% is highly eroded and 4% is beyond reclamation [26][27][28], as the ongoing soil loss is estimated to be 20 to 40 times higher than the rate of soil formation [5].

Land degradation in Ethiopia is more of a human-induced phenomenon caused by continuous deforestation, agricultural over-utilization, and overgrazing by increasing human settlements than the impact of climate change. A typical example of this is the remaining indigenous forest patches within the compounds of many protected Orthodox churches and monasteries in northern Ethiopia [5].

Land degradation, low agricultural productivity, and poverty are interconnected critical problems in the Ethiopian Highlands [29]. To mitigate land degradation due to soil erosion, different SWC practices have been implemented in many regions of Ethiopia [23][12][20].

The main focus of SWC practices has been on minimizing soil erosion rather than increasing agricultural output, and those early initiatives were neither successful nor sustainable, with no clear synergies between watershed and farm-level interventions [23][14].

The drawbacks noted from SWC interventions have contributed to the development of a "participatory integrated watershed management strategy" since the end of the 1990s, where its main goals were to increase the productivity of water and land resources while maintaining the institutional and ecological viability of watershed management [23].

However, with the exception of a few exemplary watersheds, it has been confirmed that this participatory integrated watershed management strategy has not been widely implemented. So far, most [30][31][4][32][11][27][33][17][1][12][34][20][29] of the watershed-related research carried out in Ethiopia focused on impact evaluation at a specific watershed level, while some others[13,19,14,35,36,26,24,37,15,38,23; and 39] focused on comparative impact evaluation by considering more than one watershed.

Unlike these researches and annual soil and water conservation campaigns in Ethiopia, wider promotion and effective watershed-based interventions could not be realized to make a significant impact on the ongoing soil erosion-induced land degradation in many watersheds, such as in the Tigray region.

Moreover, the untreated watersheds (exposed to progressive soil erosion-induced land degradation) in Ethiopia pose a problem to many towns and cities, where uncontrolled and aggressive floods flow from the upper part of the watersheds. These towns and cities are being dissected and threatened by the temporal and spatial expansion of nearby gullies and river banks. These areas also face a shortage of water for agriculture and other purposes. Yet, no integrated watershed-based measures have been taken to address both land detachment and water scarcity in these areas.

The current research is initiated to further extend the review at the national level to i) identify the main challenges and constraints that hinder the promotion of integrated and sustainable watershed-based interventions in Ethiopia, and ii) identify the corresponding key conditions for revitalizing the Integrated Watershed Management (IWSM) approach to mitigate soil erosion-induced land degradation by rehabilitating and managing watersheds for sustainable water availability for agricultural development and livelihood changes in Ethiopia, serving as a lesson to other semi-arid regions facing similar issues.

To meet these objectives, a systematic review and analysis were carried out by collecting secondary data published in original and review research articles selected through an internet database search, mainly using Google Scholar, ScienceDirect, Academia.edu, and ResearchGate engines.

Accordingly, more than 60 reference materials relevant to the title and focusing on the extent and consequences of soil erosion-induced land degradation, semi-aridity and water shortage, history of soil and water conservation practices, success stories and impacts of watershed-based interventions, main challenges impeding further promotion of watershed-based interventions, and revitalizing watershed-based interventions for sustaining water resources and agriculture in Ethiopia and semi-arid regions were reviewed and synthesized.

The first preprint version of this article was posted on the Qeios platform for more than two months to collect valuable comments and feedback. Based on the collected and reorganized feedback from 65 peer reviewers worldwide, the article has been updated.

This article is organized in the following sections: *1st*, global and national level extent of land degradation; *2nd*, agricultural water availability in drylands as a background to the subsequent sections; *3rd*, mitigating soil erosion-induced land degradation in the case of Ethiopia with emphasis on experiences, impacts, and challenges of the interventions carried out so far; and *4th*, key conditions for revitalizing watershed-based interventions in Ethiopia as a lesson to semi-arid regions.

2. Extent of land degradation and drylands

Globally, soil erosion-induced land degradation affects about 1,100 million hectares of land annually, resulting in the transportation of 2.0 to $2.5*10^{10}$ Mg of soil to the oceans [27]. Approximately 10 million hectares of cropland are lost annually due to soil erosion [11]. Soil erosion by water accounts for 56% of the total degraded land surface of the world [1].

Global desertification has affected significant parts (70%) of the world, rendering lands devoid of vegetation cover with severe soil erosion, sediment detachment, and transportation during torrential floods, siltation of dams, etc. Dryland regions already occupy almost 40% of the world's land area and are known for their recurrent droughts, water scarcity, limited water supply, fragile ecosystems, and vulnerable environment [7].

Of the total global drylands, 12% is arid, 18% is semi-arid, and 10% is dry sub-humid [9], indicating that semi-arid regions have dominant coverage with a significant position in the globe (Figure 1). Similarly, 70% of the land mass of Ethiopia is dominated by drylands [35].

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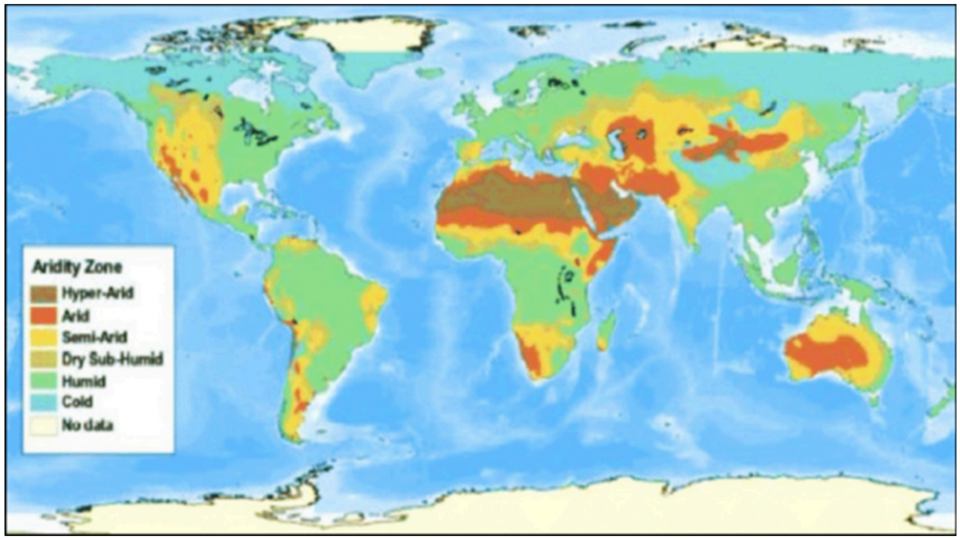

Figure 1. Map of global drylands [36]

Moreover, the global drylands are inhabited by a significant percentage (nearly 40%) of the global population, mainly those who are the poorest [9], 45% of the world's hungry, and 70% of the world's malnourished [25]. More than 20% of the world's rapidly growing population also lives in areas with a physical scarcity of water, though access to water resources remains critical for people's health and well-being [8].

To improve food security and reduce poverty in the global drylands, success in semi-arid regions is crucial, as further global climate change may convert parts of the semi-arid tropics to complete arid regions [25].

The land resources in Ethiopia are similarly prone to land degradation, with 31% experiencing severe land degradation and 63% desertification [2]. This is manifested in terms of soil and water degradation and loss of biodiversity, as the highlands are characterized by high-intensity rainstorms and extensive steep slopes exposed to high rates of soil erosion, nutrient loss, and a decline in productivity [4][26][27][37][33][1][38][29].

3. Agricultural water availability in drylands

3.1. Hydrologic characteristics of drylands

Drylands are generally characterized by a combination of low precipitation, high temperatures, and drying winds. According to UNESCO (United Nations Educational, Scientific and Cultural Organization), drylands are classified based on the aridity index (AI) as hyper-arid ($AI < 0.05$); arid ($0.05 < AI < 0.20$); semi-arid ($0.20 < AI < 0.50$); and dry sub-humid ($0.50 < AI < 0.65$) [39][9].

As an example, Figure 2 presents the long-term average precipitation for a typical semi-arid area in the northern part of Ethiopia. It shows that there is a significant monthly variation in precipitation, ranging from a minimum value of 1 mm $month^{-1}$ in January to a maximum value of 185 mm $month^{-1}$ in July.

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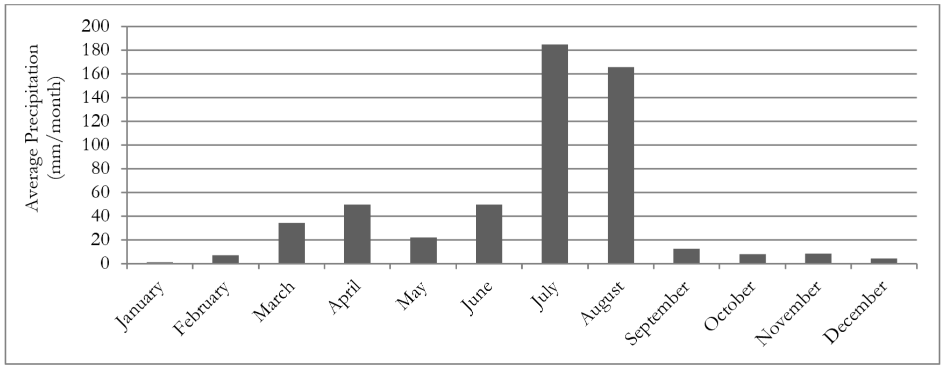

Figure 2. Average precipitation in Abraha we Atsbeha watershed, semi-arid Ethiopia

The rainfall season and peak rainfalls in the Abraha we Atsebea watershed, as well as in most semi-arid parts of Ethiopia, are concentrated within a few months (June-August) of the year, implying the need for proper harnessing of peak flows for utilization during the rest of the dry months of the year. However, the hydrological balance in semi-arid regions reveals that about 90% of water is often lost in the form of runoff during stormy rain, with only 10% left for productive transpiration and in the form of evaporation during times of low intensity. As shown in Figure 3, a lesser amount of about 15 to 30% of the precipitation is used for transpiration, while a similar amount is lost as runoff, and a significant amount of 30 to 50% is lost as evaporation [9][25].

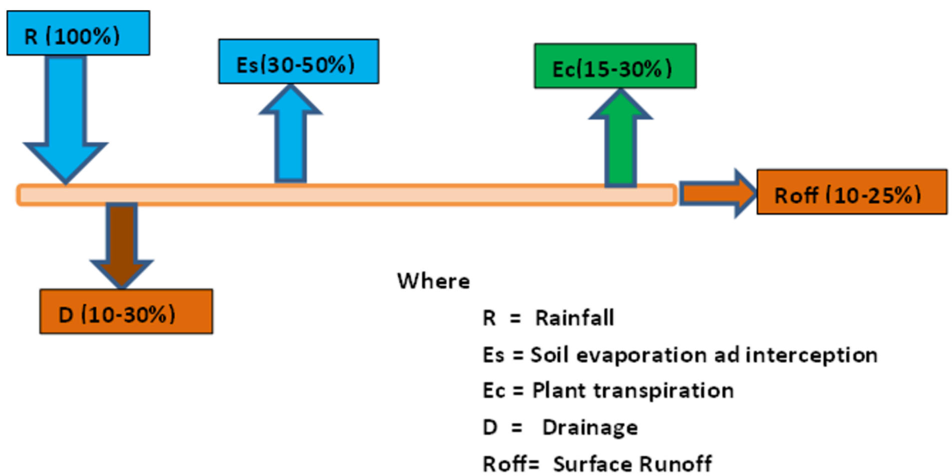

Figure 3. Rainfall partitioning in semi-arid regions [9]

The water balance in semi-arid regions (Figure 3) clearly indicates that a large proportion of rainfall (as much as 70% of the non-productive components of precipitation) may not be used directly in dryland crop production. Yet, this implies that there is great scope and opportunity to exploit benefits from such typical semi-arid water balances through suitable watershed-based interventions and improvements in water productivity by shifting the non-productive components (evaporation and runoff) to the productive component (transpiration). It is only 19.7% of the rainfall in SSA, for instance, that becomes available water for crops, indicating that the poor crop yields and crop failures in these regions are not due necessarily to low rainfall but due to the wastage of valuable rainwater [25].

The cause of this shortcoming could also be due to soil fertility depletion or soil physical deterioration (which in turn reduces infiltration and water-holding capacity) through the oxidation of organic matter [9]. In this case, desertification can thus be seen as a direct cause of soil nutrient losses, decreased infiltration and soil water-holding capacity, and impaired primary productivity [3].

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Considering the fact that most of the rainfall in drylands is lost by runoff and surface evaporation, groundwater recharge in the form of seepage through the soil profile is limited since groundwater recharge is largely dependent on the amount, intensity, and duration of the rainfall as well as soil properties (infiltration and water-holding capacity) [9].

The intensity of rainfall in dryland regions (e.g., in SSA) is usually greater than the soil infiltration rate and soil water holding capacity, which triggers runoff generation from the surface. The rainfall in this region is characterized by high losses of water due to excessive surface runoff following intensive rains and high evaporation during pre-planting and early crop growth stages. Moreover, uncontrolled runoff from untreated watersheds usually turns into aggressive and damaging flash floods, causing severe erosion, increased turbidity, and substantial water losses. Following these losses of valuable water resources, the chances for increased food insecurity, poverty, and subsequent threats to sustainable development in SSA are imminent. The erratic nature of the rainfall in this region, aggravated by climate change, is also expected to increase its variability [40].

On the other hand, the dryland regions are characterized by a commonly dropping trend of water sources (water table, spring, and river flow), leading to water scarcity and competition for water between agriculture and other multiple uses in the face of more frequent extreme weather changes and greater aridity resulting from climate change. The droughts in drylands can be manifested in terms of *meteorological drought* ("when there is departure of precipitation from normal"), *agricultural drought* ("situations where the amount of soil water is no longer sufficient to meet the needs of a particular crop"), *hydrological drought* ("when surface and subsurface water supplies are below normal"), and *socioeconomic drought* ("when physical water shortages begin to affect people") [9]. In addition to these calamities, pollution of water resources from industries exacerbates water degradation [25].

3.2. Challenges of dryland agriculture

The rapid population growth in drylands, mostly in many developing countries, has placed tremendous pressure on the natural resource base. It also leads to increasing water requirements for various uses, such as industry and domestic use, at the expense of irrigation needs [9]. This pressure is exacerbated by deforestation, land use change, and unwise management of water resources, resulting in the alteration of watershed water flows and hydrological processes [41]. Additionally, croplands are often badly eroded due to the unfavorable trends of rapid population growth, causing landlessness, adding more pressure on grazing and forests, and leading to encroachment onto marginal (steep) land [25].

In semi-arid regions, insufficient precipitation seriously limits organic matter production, and warm conditions generally accelerate the decomposition of in-situ soil organic matter during periods of favorable soil-water conditions, while crop residues are often removed for livestock feed or household fuel in many developing countries [9].

In semi-arid regions of Asia and Africa, it has been revealed that there are large yield gaps, with farmers' yields being two to four times lower than achievable yields for major rainfed crops [25]. Crop water productivity in the SSA drylands is thus generally low due to combined factors of poor water management, soil management, and crop management [39].

Dryland farming is practiced in regions where water management continues to play a decisive role, and the lack of soil moisture limits crop or pasture production. It is thus dependent solely on the water available from precipitation and on stored soil water during the growing season. It is also affected by other problems such as insects, intense torrential rains, and high winds [9].

Working on soil and crop management practices can reduce the impact of droughts on dryland agriculture, considering the fact that dryland farming is a risky enterprise in the absence of preventive measures for soil erosion-induced land degradation.

4. Mitigating soil erosion-induced land degradation in semi-arid regions

4.1. Experiences of SWC Practices in Ethiopia

Ethiopia has traditional experiences in natural conservation practices such as the stone-bund terrace systems (locally called the "Daget") in the Tigray region, which have been practiced for more than 2500 years since around 400 B.C. [42][15][43], and pond and roof rainwater harvesting that date back to

560 BC in the Axumite period [44]. The SWC measures in Konso and North Omo, the Gedio traditional agroforestry practice, and the Borana traditional natural resources conservation practices are recognized indigenous experiences in the country [45][44].

Land degradation induced by soil erosion in Ethiopia started to be addressed through Government-initiated SWC activities (through the construction of terraces and tree plantations) following the droughts and famines of the 1970s and 1980s [31][45][4][32][26][33][16][17][43][24][23][38][13][20][14] to enhance agricultural development and rural livelihoods [4][19].

The SWC approach in Ethiopia has evolved from 1970 to date, which could be grouped into two: i) (1970-1999) and ii) from 2000 onwards. In the first period, the approach was more top-down, incentive-driven, focused on SWC structures, characterized by low survival of plants and low livelihood benefits, while the second period was relatively characterized by an improved approach of community-based integrated watershed management (that integrates physical structures such as terraces, bunds, trenches) and biological measures (such as the plantation of forest seedlings, fruit trees, and grass), improved conservation of natural resources, and improved income of communities. Moreover, the second approach is expected to effectively consider multiple linkages between livelihood and natural resource management [13][14][33].

Hence, the incentive-based (food for work) program in the 1970s has been changed to an integrated watershed management approach, creating multidimensional opportunities with benefits realized at some household and community levels depending on a specific watershed (as impacts on outcomes usually depend on specific biophysical, institutional, and socioeconomic factors) [14].

Figure 4 shows a typical scene of constructed physical and biological measures along with water augmentation in the Azera watershed, Tigray, Ethiopia.

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Figure 4. Typical scene of constructed physical and biological measures along with water augmentation in the Azera watershed, Tigray, Ethiopia (Source: GIZ and Google Satellite Hybrid, 2019)

4.2. Impacts of watershed-based SWC interventions in Ethiopia

The implementation of watershed-based SWC measures can be regarded as a win-win solution to create opportunities for increased water availability for different uses while reducing the negative consequences caused by surface runoff [25]. Retaining freshwater sources through SWC is also quite critical to support rural human populations in dry regions [8].

SWC measures can contribute to increased watershed-level recharge of rainwater in the soil by retarding or minimizing the movement of surface runoff and prolonging the opportunity time for infiltration and/or directly concentrating it where the water is most needed to be stored [40][25].

If properly practiced, watershed-based SWC can enhance crop production, food security, and household income [29] and can contribute to long-term agricultural sustainability [28] particularly in such a water-scarce semi-arid region.

Globally, there are exemplary areas where SWC interventions have been successfully carried out, and good lessons can be learned. These include: the Loess Plateau and the Three Gorges Area in China, Mayurakshi, Salaiyur, and Adarsha Watersheds in India, Sepetiba Bay watershed in Brazil,

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Anyangcheon watershed in Korea, Lam Sonthi watershed in Thailand, Kiroka village in Tanzania, Merguellil catchment in Tunisia, and Machakos district in Kenya [43].

There are also exemplary and successful watersheds in Ethiopia where the watershed-based SWC practices have contributed to restored landscapes and improved lives of rural communities in areas where land degradation used to be predominant [33][43][1].

Table 1 presents the success stories of two typical watersheds in Tigray, northern Ethiopia. The changes in the watersheds from degraded to rehabilitated areas, as well as overall positive changes, are noted as good lessons for other watersheds in semi-arid regions.

The peculiarities of these watersheds that contributed to their successes include a suitable biophysical setup, particularly the presence of permeable geology for water percolation at the upper watershed and relatively impermeable geology for storing water at a shallow depth by constructing water harvesting structures. Additionally, community involvement played a crucial role, with the community investing all available resources such as labor, time, and local materials in an organized way and with a sense of ownership. This involvement extended to watershed interventions and sharing benefits, leading to a meaningful change from a drought-prone area with a high level of land degradation and high dependence on the Productive Safety Net Programme (PSNP) to a drought- and rainfall variability-resilient area (Table 1).

The success of the Abraha we Atsbeha watershed in Tigray, northern Ethiopia, is also presented pictorially in Figure 5, which shows an integrated view of a rehabilitated upper part of the watershed, water retention ponds storing water at the mid-watershed, and a groundwater well for irrigated vegetable fields at the lower watershed.

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Abraha we Atsbeha watershed	Sero watershed
Initial situation: • used to be the most drought-prone area with a high level of land degradation, • over 90% of the community in this watershed were dependent on the Productive Safety Net Programme (PSNP) prior to 2005 and used to live under dire conditions, **Biophysical setup:** • presence of suitable and permeable geological formations (sandstone and colluvial deposits) and soil texture at the upstream for recharge through percolation to replenish groundwater at a relatively impermeable downstream bedrock **Community participation:** • well-organized community with a sense of ownership participated throughout the watershed interventions **Changes:** • transformed from a degraded hillside and hunger-strike village into a well-treated watershed and productive farmlands and improved in biodiversity, • showed a remarkable change of 80 to 100% reduction in soil erosion, • showed quite significant changes in water availability from no sign of water up to 30 m depth in 1990 to a 1.5 m ground level rise and improvement in groundwater quality (TDS) in 2014/15, • over 300 hand-dug shallow groundwater wells were developed in 2014/2015 and have been utilized afterwards for small-scale irrigation, water supply, and livestock watering **Benefits and recognition:** • increased irrigated area from 2.5 ha in 1995 to over 110 ha in 2014 at Mindae sub-watershed alone, • farmers became able to harvest up to three times a year and increase crop yield from less than 0.24 ton ha^{-1} to over 1.45 ton ha^{-1} (due to both water and fertilizer availability), • a watershed that became internationally recognized and was awarded the 2012 Equator Prize at Rio+20 hosted by the UN Development Programme (UNDP).	**Initial situation:** • known for being the most drought-prone area with a high level of land degradation, • known for being the most degraded landscape having a critical shortage of water availability, • most (over 70%) of the local community around this watershed were dependent under the Productive Safety Net Programme (PSNP) before 2002 **Biophysical setup:** • permeable geology and soil texture at the upstream suitable for recharge through percolation to replenish groundwater at a relatively impermeable downstream bedrock **Community participation:** • The community is well-organized with a sense of ownership of the watershed interventions **Changes:** • Regeneration of indigenous trees and improvements in biodiversity in the watersheds, • the area became resilient to droughts and high rainfall variability, **Benefits:** • irrigated area has increased from 2.3 ha in 1995 to 720 ha in 2013, • average crop productivity increased from 0.38 ton ha^{-1} before 2005 to 1.93 ton ha^{-1} in 2013, • job opportunities for the youth have been created in irrigated agriculture, and migration has reduced.

Table 1. Success stories in two watersheds in Tigray, Ethiopia [15]

The specific indicators for success in watersheds in Ethiopia include: regeneration and afforestation of the degraded land, reduction in runoff and soil loss, emergence of new springs and re-emergence of dried-up springs, groundwater recharge and rise, improvement in soil fertility, increase in irrigation area, rise in crop productivity, enhancement of animal feed, and changes in the community's livelihood [45].

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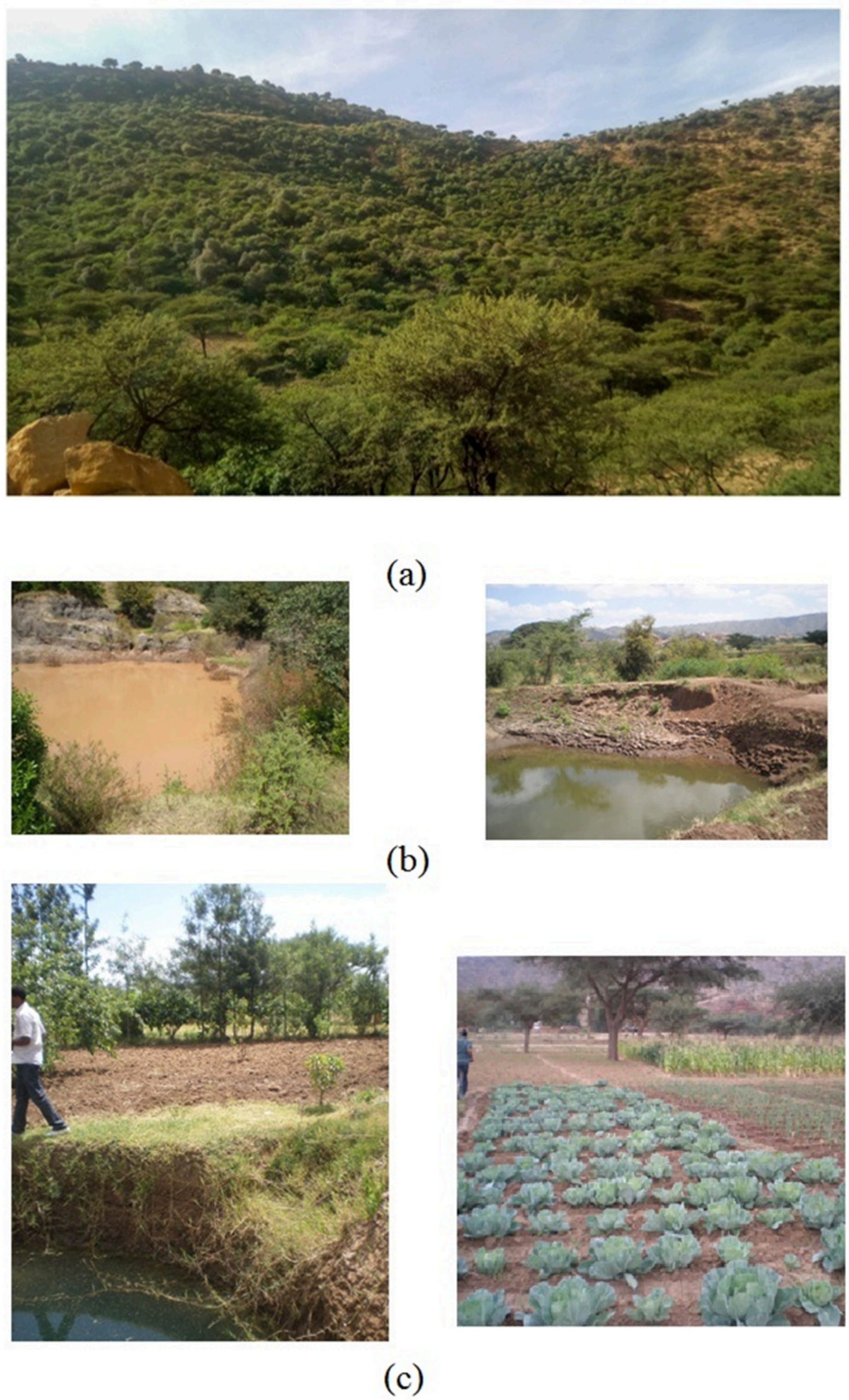

Figure 5. Abraha we Atsbeha watershed (a) rehabilitated part of the upper watershed, (b) water retention ponds at mid-watershed, and (c) groundwater well and irrigated vegetable fields at lower watershed

The implementation of various watershed-based SWC activities has enhanced infiltration and groundwater conditions, while concurrently reducing flooding and soil erosion. In-situ soil

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conservation, water harvesting, and the construction of small reservoirs have significantly decreased sediment yield and runoff coefficients at the catchment scale, leading to increased water table levels and subsequent improvements in livelihood [22]. Furthermore, field research has confirmed positive quantitative changes in terms of seedling survival rate, vegetation composition and density, soil loss reduction, runoff reduction, groundwater table rise, water availability, and crop productivity increase, as well as improved fodder availability in different parts of Ethiopia, as presented in Table 2.

Indicator	Extent of impact
Seedling survival rate, composition and density of vegetation	• Survival rate of seedlings, vegetation composition, and coverage density improved by more than 30% between 1993-1999 and 2005 in Medego watershed, Tigray region, Northern Ethiopia [19].
Soil loss reduction	• Sediment yield decreased by 61% at the catchment outlet of Gule watershed of Tigray [46], • Soil erosion in Gule watershed of Tigray reduced by 50% (from 29 t ha^{-1} yr^{-1} in 2002 to 14 t ha^{-1} yr^{-1} in 2015 on average) [15], • Soil erosion reduced by more than 80% and 50% in Abraha we Atsbeha and Gerebshelela, respectively[14], • Average sheet and rill soil loss from all land use classes decreased by 89% from 117 t $ha^{-1}y^{-1}$ in 2004 to 12.48 t $ha^{-1}y^{-1}$ in 2009 in Enabered watershed, northern Ethiopia [19], • Soil loss was reduced by an average of 37% at the plot level, and sediment yield at the watershed level was reduced by about 74% in Gudo Beret watershed in the central highlands of Ethiopia [37].
Runoff reduction	• Runoff reduced in Abraha we Atsbeha by 18.2% between 1991 and 2007 and by 48.2% between 2007 and 2014; in Inderta by 27%; in Mayzegezeg by 81%; in Mayleba by 20-30%[30][47][48][49], • Runoff decreased by 27% from 7.92 M m^3 in 2004 to 5.75 M m^3 in 2009 in Enabered watershed, northern Ethiopia [19], • Runoff reduced by an average of 27% at the plot level in the Gudo Beret watershed of the central highlands of Ethiopia [37].
Increase of spring discharge and emergence	• Spring discharge increased in Gule watershed of Tigray by up to 73%, • New springs emerged [15].
Groundwater table rise and water availability	• Groundwater table level increased in Abraha we Atsbeha from 15 m in 1998 to 2-3 m in 2014, and water supply coverage reached 96%; water availability for irrigation and domestic uses in Gule watershed increased by 33%[24][30][46], • Groundwater level rose from a depth of 28.5 m in 2001 to about 1 m in 2014 in Mariam Shewito watershed in Tigray [15].

Table 2. Impact of watershed-based SWC practices on selected indicators

Moreover, field research carried out in two watersheds in southern and south-central Ethiopia confirmed that watershed-based SWC interventions had positive impacts on the improvement of soil physical properties, specifically bulk density and soil organic carbon (SOC), as shown in Table 3. Under such positive changes, soil moisture, water holding capacity, and crop production are improved [32].

Name of watershed	Impact of SWC on soil physical properties
Ezha watershed in southern Ethiopia	• The highest average bulk density of 1.50 g cm^{-3} was recorded in the un-conserved land, while the lowest average bulk density of 1.35 g cm^{-3} was obtained in treated (conserved) land, • A higher mean value of soil moisture content (14%) was achieved in the conserved land, while a lower moisture content of 12% was observed in un-conserved land [11].
Sibiya Arera watershed in south-central Ethiopia	• The lowest mean soil bulk density (1.17 g cm^{-3}) was obtained in treated fields with physical and biological measures, while fields without treatment had the highest mean bulk density of 1.36 g cm^{-3}, and • The highest value of 2.37% soil organic carbon (SOC) was recorded in treated fields as compared to the lowest value of 1.4% in the untreated fields [32].

Table 3. Impact of watershed-based SWC practices on soil physical properties in Ethiopia

Cumulatively, based on positive experiences, it has been confirmed through various field researches that SWC interventions have had positive impacts on crop productivity, the expansion of irrigation areas, the availability of animal fodder, and an increase in income, leading to subsequent livelihood improvement in various watersheds in Ethiopia, as shown in Tables 4 and 5.

Name of Watershed	Impact of SWC on crop productivity
Debre Yacob micro-watershed in northwest Ethiopia	• Teff yields on control fields averaged 2946 kg ha^{-1}, while yields on bunds stabilized with Sesbania sesban and pigeon pea fields were 4344 and 4484 kg ha^{-1}, respectively [23].
	• Finger millet on untreated fields was 1200 kg ha^{-1}, and 1716 kg ha–1 for bunds stabilized with Sesbania sesban, and 1856 kg ha^{-1} for bunds stabilized with pigeon pea [23]
	• Maize on control fields was 2946 kg ha^{-1} and 4344 kg ha^{-1} on bunds stabilized with Sesbania sesban and 4484 kg ha^{-1} for bunds stabilized with pigeon pea [23].
Anjeni watershed in northwest Ethiopia	• Teff productivity on control was 0.49 t ha^{-1} and 0.95 t ha^{-1} on SWC-treated fields, • Barley productivity on control was 0.61 t ha^{-1} and 1.86 t ha^{-1} on SWC-treated fields, • Maize productivity on control was 0.77 t ha^{-1} and 1.73 t ha^{-1} on SWC-treated fields [23].
Gule watershed in the Tigray region of northern Ethiopia	• Wheat productivity increased from 2.1 to 2.4 t ha^{-1} after treatment with SWC practices, • Teff productivity increased from 1.4 to 1.5 t ha^{-1} after treatment with SWC practices, • Maize productivity increased from 3.1 to 4.8 t ha^{-1} after treatment with SWC practices, • Barley productivity increased from 1.7 to 2 t ha^{-1} after treatment with SWC practices, • Sorghum productivity increased from 2.1 to 2.2 t ha^{-1} after treatment with SWC practices, and • Finger millet increased from 1.7 to 2.2 t ha^{-1} after treatment with SWC practices [46].

Table 4. Impact of watershed-based SWC practices on crop productivity in Ethiopia

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Indicator	Impact description at specific watershed
Irrigation area, crop and fodder production	• irrigated area increased by 20-30% and by 5% in Abraha we Atsbeha and Gerebshelela watersheds in Tigray, respectively [14], • irrigated area increased from less than 3.5 ha in 2002 to 166 ha in 2019 in Gule watershed in Tigray and became resilient to droughts and high rainfall variability [15], • irrigated area in the dry season increased from about 1.5 ha in 1998 to 250 ha in 2014 in Mariam Shewito watershed in Tigray(Kifle et al., 2023), • irrigated area increased from less than 3 ha in 2004 to over 360 ha in 2014 in Dibdibo watershed in Tigray following the construction of 35 check-dams, which served as surface water storage and groundwater recharge [15].
Fodder availability	• fodder availability increased in Gule watershed in Tigray by 10% [46], • animal feed shortage reduced by about 100% and 80% in Abraha we Atsbeha and Gerebshelela, respectively [14].
Contributions of irrigation to increase in household income and livelihood change	• watershed management in six watersheds in Ethiopia has improved farm incomes by 50% on average [14], • income in Gule watershed increased by 56% following the SWC interventions [46], • income of women-headed farmers increased by 24.3% from livestock and by 68.8% from crop production following small-scale irrigation interventions in Kilte Awlelalo in Tigray [50].

Table 5. Contributions of watershed-based SWC practices to the expansion of irrigation area, animal fodder availability, and income increase and livelihood improvement

Moreover, Negash et al. [44] confirmed that rainwater harvesting (RWH) practices (in-situ and micro-catchment methods) can enhance the soil water content of the rooting zone by up to 30% and reduce the negative effects of dry spells. It improved grain yields by up to 56%. When combined with extra fertilizer, it can even increase grain yields by 200-600% compared to practices without it.

Successful watersheds have indeed minimized the risk of crop failures by 10 to more than 50%, while access to health and education improvements ranged from 20 to 50% after watershed interventions [14].

4.3. Challenges and limitations of watershed interventions in Ethiopia

Generally, the intention of watershed-based interventions in Ethiopia is to contribute to the prevention and rehabilitation of watersheds and the preservation, conservation, and sustainability of all land resources to improve the living conditions of the community throughout a watershed. In that aspect, the limited achievements in converting degraded sites to productive areas (good experiences for lessons to others) are already discussed in the previous sections.

However, there have also been prevalent failures noticed in different watersheds in Ethiopia [51][52][45]. Based on a critical review of these watershed interventions so far, it is possible to detect that the national-level approach has practically tended to be a mere implementation of SWC activities, while the expectations are to realize the integration of social, economic, and environmental issues [53][14].

Based on the intensive literature review and own field observations, the various technical and institutional-related bottlenecks that retard the expansion of proper watershed-based SWC interventions in Ethiopia are discussed as follows:

i) Poor institutional support

At the national level, there is no practical institutional support focusing on specific watershed levels. This problem can be described in terms of a lack of awareness among policymakers of the current trends and impacts of degradation, the absence of legal assurance, and practical policy modalities to consider the entitlement of watershed-based cooperatives or organizations.

Based on own field observations, a typical example of this problem is presented. It is the case at Tanqua watershed in Tigray, northern Ethiopia. In this watershed (representing other untreated watersheds in the country), there is a clear failure of watershed-based interventions. As shown in Figure 6, the uppermost part of this watershed is dominated by poor watershed cover and more cultivable areas that are vulnerable to soil erosion-induced land degradation by surface water flow (runoff). The erosion features at upstream and downstream are as shown in Figure 6.

Consequently, in-situ soil detachment and transportation are quite evident, as shown in the downstream part of the watershed where transported materials are deposited, and the riverbanks (waterways) are excessively widened from time to time (Figure 6). This problem is evidenced by local inhabitants and own repeated field observations.

The lack of upstream-downstream connectivity prevailing in such a specific watershed and other similar watersheds demands realistic institutional and policy support to mitigate further land degradation as early as possible before it becomes too late.

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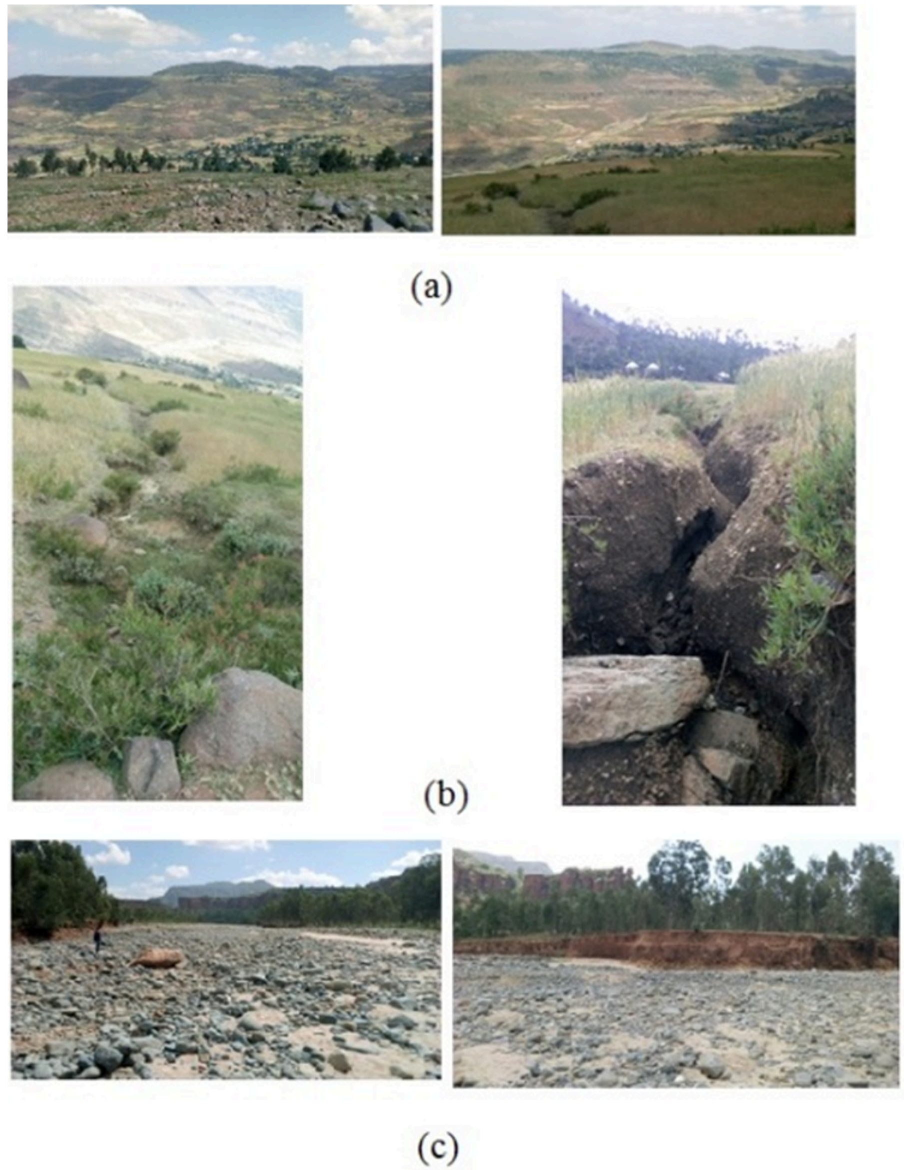

Figure 6. Lack of upstream-downstream connectivity at Tanqua watershed in Tigray, northern Ethiopia (a) poorly covered scene of upper watershed, (b) erosion features at upper watershed, (c) excessive material deposition and highly eroded scene of river banks at the lower part of the watershed

The lack of watershed-based institutions affects the successful management of watersheds in various ways: poor linkage between concerned stakeholders, lack of commitment to address problems, poor sharing of information between different departments responsible for watershed-based interventions, lack of upstream-downstream synergy to resolve conflicts of interest, and failure to ensure equitable and fair sharing of benefits among upstream-downstream communities. Additionally, there is no continued monitoring and maintenance, as well as a lack of funding required to cover costs for physical and biological measures and to run overall watershed-based management on a sustainable basis.

ii) Lack of participation

In most cases of SWC interventions in Ethiopia, the approaches have been top-down and coercive, not involving farmers in planning and considering their indigenous knowledge [2][45][4][11][24][15][43][38][14][19].

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Moreover, the applied interventions are of a blanket type, practicing the same SWC technology throughout the country without taking local social and biophysical differences in watersheds into account. This is characterized by the misuse of incentives, creating misconceptions in watershed projects, and undermining their contribution to sustainable development [4][11]. At the national level, practices have been characterized by inadequate community participation, disregard for indigenous knowledge, and ignorance of the interests of rural communities.

Consequently, the success of SWC activities in Ethiopia has been minimal due to a lack of involvement of local people in planning and implementation, poor implementation and maintenance of SWC structures (characterized by mostly mass campaigns without full community participation, intended simply to achieve the planned quantity of construction per season with minimal focus on farmers' interests and involvement) [31][26][33][29].

The seriousness of the government's focus on watershed-based interventions and avoiding ignorance of watershed deteriorations makes a difference; for example, excessive erosion rates on the Chinese Loess Plateau were strongly reduced through massive government interventions in implementing mitigating measures [10].

iii) Inadequate planning of watershed-based SWC interventions

There is improper application of SWC technologies, measurement methods, monitoring, and maintenance practices in most watersheds in Ethiopia. In other words, there is a mismatch between landscape characteristics and recommended options [24][43][19] since technology recommendations are based on a blanket approach throughout all watersheds. Yet, there are significant ecological, economic, and social variations in each watershed that affect the impacts of SWC technologies [20].

Scientific knowledge and soil erosion-related data, as well as methods of estimation, are often poor and misleading in selecting, designing, and constructing appropriate SWC measures in a particular watershed. Erroneous predictions of basic data such as the quantity of soil loss, discharge of floods, and land use-land cover result in the wrong selection of erosion hotspots (requiring urgent treatment), erroneous cost-benefit analysis, misinformation of stakeholders, and ultimately affect the adoption rate [10].

There has also been a lack of or poor appropriate monitoring and maintenance of watersheds after implementing SWC options [24][43][19]. The effectiveness of SWC practices declined over the years due to the lack of maintenance [37], and physical SWC structures deteriorated by 47-67% after watershed projects phased out in six watersheds in Kilte Awlelalo, Tigray, due to the lack of regular maintenance and limited support of biological measures [54].

Generally, SWC measures have been practiced in the absence of site-specific conservation plans, land suitability studies, and scientific design. They are dominated by the inappropriate application of SWC technologies specific to a watershed. There is less integration among social, technical, and institutional disciplines in a watershed [24][43][19].

iv) Absence of research and development linkages

In addition to inappropriate SWC technological practices in Ethiopia, there are limitations in utilizing scientific inputs (such as a scientific approach, technical knowledge, technological preferences and transferring, and application of scientific research results to site-specific problems) and limited efforts to link watershed development activities with scientific research.

Mostly, the effectiveness of the impacts of watershed-level SWC interventions in Ethiopia (improvement of ecosystem services, minimizing flooding hazards, improving soil erosion, soil properties, and water holding capacity, recharge capacity, spring abundance, rise of the groundwater table, crop productivity, and livelihood change) is less studied and researched [17].

In line with this gap, Negash et al. [44] emphasized that, with ample support from local research and development, coupled with comprehensive government backing, Ethiopia could replicate the remarkable results achieved in China through the enhancement of dryland agriculture.

v) Insufficient capacity building

Generally, there are capacity-related limitations in most watersheds in Ethiopia that discourage research-based SWC interventions. The capacity-related limitations consist of a shortage of skilled manpower in research-based interventions and a lack of awareness among policymakers.

Mostly, SWC interventions are restricted to the blanket approach of the Ethiopian Ministry of Agriculture. The recommendations are disseminated to the grassroots level through its structure at

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various levels. The affiliation of its human resources is more on extension with a critical limitation on research-based development [51][52][53][45].

In addition to the overall capacity constraints on research-based interventions, there is also a critical lack of awareness among policymakers. They aren't quite aware of the extent and impacts of land degradation to date, the demand for appropriate policy and strategy, socio-economic and bio-physical constraints, resource and incentive constraints, as well as a lack of community awareness [45][12].

Considering all of the aforementioned constraints of watershed-based SWC interventions, various key conditions are discussed in the next sections to revitalize water availability and agriculture in the case of semi-arid areas of Ethiopia in particular and in other semi-arid regions in general by taking the watershed as an entry point to implement IWSM and realize sustainable livelihood improvements [25].

5. Key conditions for revitalizing watershed-based interventions in Ethiopia: Lessons for other semi-arid regions

The key conditions identified for revitalizing and strengthening watershed-based interventions in Ethiopia are derived from the challenges and limitations observed in such interventions in the country. These challenges include poor institutional support, lack of participation, inadequate planning of watershed-based SWC interventions, absence of research and development linkages, and insufficient capacity building.

5.1. Revitalizing the Integrated Watershed Management (IWSM) approach and its Focus

Integrated Watershed Management (IWSM) is described as "an adaptive, integrated, and multidisciplinary systems approach that aims to preserve productivity and ecosystem integrity regarding water, soil, plants, and animals within a watershed, thereby protecting and restoring ecosystem services for environmental, social, and economic benefit" [53][52].

In the IWSM approach, a watershed is considered a "planning and development entity" where water, ecosystem, and human needs are addressed simultaneously. This approach identifies and builds upon mutually supportive approaches across sectors to explore synergies [3].

The sustainable management of watersheds in drylands is essential for achieving food security and conserving biomass and biodiversity [9]. Integrating and focusing on both biophysical factors and socio-economic issues in a watershed is crucial for ensuring the success and sustainability of watershed-based interventions and management [20].

Under the IWSM umbrella, it is possible to integrate key conditions for sustaining water availability and agriculture to improve livelihoods. Land and water resources in a watershed can be managed in an integrated manner to realize sustainable livelihoods while protecting the environment.

For the successful implementation of the IWSM approach, it is recommended to incorporate the following key conditions into watershed-based interventions in Ethiopia and semi-arid regions to sustain water availability and agriculture.

5.2. First key condition: Assuring institutional support and community participation

5.2.1. Assuring institutional support

In nations like Ethiopia, experiencing progressive land degradation, it is crucial to enact an institutional and legal framework identifying each watershed as an entity with its specific organization responsible for the sustainable development and management of watershed-based land and water resources.

The organization responsible for a watershed needs to be legally registered and entitled as a watershed organization or cooperative with clear rights, duties, and responsibilities for the efficient and effective implementation, monitoring, and evaluation of the IWSM at a specific watershed. The watershed-based organization needs to have a clear administration modality and organogram involving stakeholders within the watershed, including upstream and downstream communities, local administrators, experts from various sectors, researchers from universities and research centers, NGOs, policy makers, and legal organizations.

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To address benefit sharing and secure financial resources in a watershed, the IWSM organization should be responsible for generating new funding sources for the conservation, restoration, and valuation of natural resources, making each watershed self-financed and capable of resolving its cost-benefit-sharing conflicts through its organization. However, legal support through the IWSM institutional setup is required to make the financial system functional on a sustainable basis [14].

Payment for Environmental Services (PES), based on the successful experiences of Latin American countries, can be practiced as a compensation mechanism, where service providers are paid by service users. In Costa Rica, the PES system has been applied and even has a legal framework and institutional support from the state. In Colombia, the electricity sector finances watershed management projects. This system can be applied not only to generate compensation from payments made by downstream water users but also to stipulate more watershed-based claims for biodiversity conservation, scenic beauty, and carbon sequestration [55].

To successfully implement a PES system, the establishment of a cause-effect relationship between land use (upstream) and the service users (downstream) at the watershed level is required. To this effect, considering the local conditions of the institutional framework and the biophysical characteristics of the area is necessary. Moreover, it has been learned that PES systems are more easily managed and more effective in small-scale watersheds, such as at micro-watershed levels (ibid).

5.2.2. Assuring community participation

The participation of all stakeholders (from the local to the national level), and most importantly, the community within a watershed, is crucial for creating a sense of ownership and the success of IWSM [56]. Community participation in sorting out demand-driven activities and overall watershed management can contribute to the success of watershed-based interventions [14].

According to various authors [4][23][38], participatory technology development, making good use of indigenous knowledge, and improving farmers' participation in conservation activities are considered enabling conditions for sustainable watershed interventions.

Moreover, in the Ethiopian context, there needs to be a shift from "PSNP and free labor approaches in SWC" community engagement and mobilizations to "Community ownership of long-term natural resource management" [24], which can also favor suitable conditions for meaningful and reliable community livelihood change through practicing various socio-economic activities (such as irrigation, apiculture, animal feed development and fattening, aquaculture, agribusiness) throughout a watershed.

5.3. Second key condition: Strengthening watershed-based intervention

5.3.1. Strengthening upstream-downstream connectivity of a watershed

A watershed needs to have a distinct map in which watershed-based interventions would be proposed to replace blanket-based interventions. Each watershed needs to have its own specific and required maps of land use-land cover, topography, vegetation, climate, soil types and properties, soil management, water sources, hydrology, geomorphology, hydrogeology, settlements, socio-economy, and institutional conditions [24][23][19]. Identifying and considering specific biophysical and geological situations of a watershed can ensure the success of watershed-based interventions.

The availability of water resources across the watershed, particularly in the downstream part of the watershed, is dependent on the land management practices in the upstream areas. And, the degradation in the upstream areas does have an impact on the downstream areas in various ways. Watersheds with permeable geology and soil texture are suitable for replenishing groundwater recharge through percolation at the upstream part of a watershed [14]. The upstream parts of the Gule and Abraha we Atsebeha watersheds in Tigray, northern Ethiopia, for instance, are characterized by high permeability rock, while the downstream part of the watersheds is characterized by low permeability rocks (Tillites) underlying the unconsolidated sediments, and create a suitable situation for having water storage in the soil deposits and groundwater availability [15].

Strengthening upstream-downstream connectivity of a watershed is thus required by considering watershed processes as cause-effect relationships. Most of the erosion and material detachment usually occur at the upper part of a watershed due to deforestation and improper land husbandry. Negative effects of flooding, erosion, sedimentation, and reduction of water flows occur at the downstream part of a watershed as a consequence of improper interventions upstream. However,

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proper interventions can also have positive effects in terms of recharge or an increase in water sources, reduction of flooding, and sedimentation. There must be a causal link between upstream land and water use and downstream impacts [19].

Considering such a cause-effect relationship, site-specific (watershed-based) efforts can be promoted to bring degraded lands back to productive lands, while restoring surface vegetation and soil functions, particularly the water retention capacity of soils [3].

The interconnection of upstream resources (such as water and land) with downstream impacts and externalities (coexistence of land and water resources) is one of the core features of proper watershed-based management [45].

5.3.2. Implementation of appropriate SWC measures suitable to a specific watershed

To properly manage land and water resources in drylands, conditions need to be revitalized to improve water availability for multiple uses. In a world where the majority (80.6%, 94.5%, 96.7% of total arable lands globally, in Africa, and in SSA, respectively) is rain-fed agriculture, irrigation practices need to be practiced as a reliable supplement to fill the soil moisture insufficiency and satisfy the water needs of the crops[25].

The successful implementation of SWC measures in a watershed is believed to be an entry point and one of the decisive conditions to improve soil organic matter and soil water holding capacity and ultimately water recharge and availability for irrigated agriculture on a sustainable basis [9]. Effective management of soils, rainfall, runoff, and groundwater in rainfed agriculture can thus be realized through the implementation of various SWC measures (that include water harvesting structures and groundwater recharging measures) [25]. Hence, the implementation of SWC and the rehabilitation of degraded lands can be regarded as the first step to improve soil moisture in drylands by retaining moisture, reducing runoff, reducing evaporation, and improving infiltration.

Appropriate SWC measures need to be selected based on watershed-based suitability studies that integrate biophysical and socioeconomic characteristics of the watershed (such as land use, geomorphology, hydrology, hydrogeology, slope, community preference, and livelihood). Moreover, characterizing the local agro-ecological system, agricultural systems, and local knowledge and skills existing in a watershed [10][23][38] are required to ensure better adoption and expansion of SWC. The selection of technologies in each watershed should thus shift from "trial and error" to "well-designed and planned" practice and link with the specific landscape while following the "start from the head principle" approach in implementation [24].

Considering the fact that water is the prime resource in dryland-watershed management [25] with unpredictable and declining rainfall, various types of in-situ and ex-situ water harvesting schemes are required as part of the overall SWC intervention at the watershed level. These schemes improve water availability for multiple purposes, requiring the capturing, storing, and diverting of seasonal excess runoff with effective water use (water productivity) [40]. Moreover, these SWC practices, by boosting water availability in drylands, create favorable conditions for irrigation and other socio-economic activities, providing opportunities for economic benefits for society beyond increasing drought resilience capacities [9][41].

At the watershed level, land and water can be managed in an integrated manner, that is, by shifting from rainfed to supplemental irrigation using harvested runoff water or recharged groundwater. It would thus be possible to bring additional water and irrigate rainfed fields through SWC interventions, enabling the growth of crops even in places where this was not possible previously [39]. In a watershed treated with SWC measures, the dryland water management strategy of controlling runoff through in-situ and ex-situ water harvesting practices is a key task in any dryland cropping system [9].

Positive changes in water availability in treated watersheds are essential for the success of these practices. Experiences indicate that it is possible to increase the crop productivity from 1.5 t ha^{-1} in rainfed to about double (3.1 t ha^{-1}) in irrigated practice. The unlocking of the potential of vast rainfed production needs to be facilitated through watershed-based interventions accompanied by subsequent irrigation practices [25].

The implementation of SWC favors the establishment of vegetation cover in degraded areas to improve crop growth and address poverty through increased productivity (by increasing yields and reducing the risk of crop failure), and diversified agriculture (horticultural cash crops, rearing dairy animals) [40].

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To this effect, baseline data are required to evaluate changes due to IWSM interventions [25] since watershed-based interventions need to be evaluated in terms of environmental soundness, economic viability, and social acceptability [52]. According to Dilnesa and Kelemu [23], the success of SWC practices in a watershed is, in fact, influenced by a variety of factors that include: the age of structures, integration of physical and biological activities, the type of physical practices, soil fertility status of the land at the time when SWC measures were applied, and consideration of data on soil, crops, and management for SWC interventions at fields, farms, and watershed levels on a sustainable basis.

Continued maintenance of the implemented SWC structures is also required to renovate the functionality of the structures over time due to the infilling of the structures with sediments [15][23].

5.4. Third key condition: Establishment of a watershed-based platform for scientific tools, research-based innovation, and capacity building

5.4.1. Access to scientific tools

The lack of sufficient scientific inputs [56] and the prevalence of various constraints (such as poor infrastructure, inherently low soil fertility in drylands, frequent occurrence of drought, severe degradation of the natural resource base, and poor social and institutional networks) retard the success of IWSM [8].

It is of paramount importance to create access to scientific tools such as simulation modeling and decision support systems (DST) [5] for integrating and simulating the effects of soil, crops, weather, and management options, remote sensing (RS), geographical information systems (GIS), global positioning systems (GPS), and information and communication technology (ICT), automatic weather stations (AWS), water balance models, mobile devices, and server technologies for data storage and dissemination. Establishing an intelligent watershed information system (IWIS) would also help to integrate all these scientific tools (technologies) for efficient management of watersheds through IWSM [25].

Among others, the application of scientific tools such as high-resolution remotely sensed data in conjunction with conventional data can provide valuable and reliable inputs for quantifying and mapping watershed area, size, shape, topography, drainage pattern, and landforms for watershed characterization and analysis. These details can be used for the quick prioritization of watersheds for the implementation of IWSM based on natural resource constraints and potentials in a watershed, such as natural resource status, socio-economy, biophysical setup, soil erosion proneness, sediment yield, flooding, and poverty (ibid).

Thus, in implementing the IWSM approach to sustainably manage land and water resources in the dryland regions, new evaluation methods and the fusion of development and research are required to carry out field measurements, modeling, and remote sensing, and to evaluate water resources and resolve regional and local issues [9].

5.4.2. Research-based innovation

To ensure the sustainability of the IWSM interventions, the development interventions need to be supported by research-based suitable innovations at each watershed level.

The watershed-based research can prioritize major issues related to improving field water productivity, reconditioning soil resources for water management, identifying drought-resistant and adaptive plants in a watershed, and evaluating the effectiveness and feasibility of soil and water technologies practiced in the watershed to develop best-performing and efficient innovations for the specific watershed.

i) Improving water productivity

In most drylands, such as in SSA, water is a critically scarce resource, and the amount of water available for supplemental irrigation is generally limited. Under such conditions, identifying an efficient application of water through watershed-based and on-field research is crucial to increase water use efficiency and reduce water losses [56].

In the face of a critical shortage of land and water resources, research must be carried out to succeed in producing more food with less water (increased water productivity) to cope with the increasing pressures on water resources and the increasing demands for food and fiber. Improved water use efficiency and productivity can contribute to food security through the conservation of water via

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various types of structures and agronomic management, which can improve water productivity by 50–100% [25].

Effective water conservation and saving systems need to be identified through research and implemented to mitigate droughts while improving in-situ soil moisture conservation for agricultural uses by reducing evaporation and implementing conservation agriculture. Practicing appropriate water management activities with the purpose of producing more crops using less water in both rain-fed and irrigation schemes can contribute to overcoming crop water shortages and improving water productivity [41].

Improving water productivity is thus a key research topic for unlocking the potential of optimizing watershed-based water management and rainfed agriculture. Improving water productivity at the watershed level may consider research targeting supplementary and deficit irrigation practices. In Kenya, the yield of onions increased about sevenfold (from 1.6 t ha^{-1} to 11.9 t ha^{-1}) [25] due to supplementary irrigation [57]. Binyam and Desale [40], similarly, evidenced that supplementary irrigation contributed to a crop yield increase of 20%. An increase in seasonal plant water use by 25 mm could also increase the average yields of wheat, maize, and sorghum by 30, 38, and 58 %, respectively, in China [9], of which 47% of the average wheat yield was influenced by the soil water storage at sowing [58]. To this effect, deficit irrigation is also considered "a promising and effective mitigating strategy" to improve crop yield and water productivity [57].

In SSA, most (96%) areas are irrigated using surface flood irrigation methods, which are not very efficient and result in high water losses through seepage and evaporation, while 10–35% losses occur in unlined canals [6]. Hence, water must be used efficiently in these regions, in particular by improving irrigation water deliveries through a range of technical and management practices. These include the promotion of drip and sprinkler irrigation, more precise application of practices, canal lining or delivery through pipes, and reduced allocations of water to farmers or pricing to influence demand [41][57].

An irrigation system needs to focus on maximizing the evapotranspiration component (productive loss) with added water (supplementary irrigation) while minimizing unproductive losses (runoff and deep percolation). Yet, to realize water productivity, understanding soil-crop systems and designing appropriate practices for water conservation and supplementary and complementary irrigation strategies are crucial [9].

In many regions of the world, there are opportunities to increase water productivity in rainfed, irrigated, livestock, and fishery systems by adopting breeding strategies and proven agronomic and water management practices. SSA and South Asia (with very low yields, extreme poverty, and many poor people highly dependent on agriculture) can be targeted for increasing water productivity. Addressing water productivity in such areas can both reduce the amount of additional water needed for agriculture globally and help to reduce poverty [57]. Wherever water appears to be a more limiting factor than land, maximizing water productivity is more important than ever [25]. Christopher et al. [39] confirmed that there are opportunities to improve crop water productivity in drylands by two to four times if technical, resource, and market hurdles can be overcome.

ii) Reconditioning soil resources for water management

Crop yield cannot be significantly improved without ensuring soil fertility and moisture in combination [25]. For this, reconditioning the soils is required to improve infiltration rate, water-holding capacity, and transpiration while reducing runoff and soil evaporation [9][25]. Improving soil organic matter to recondition the soils can be initiated by creating a permanent cover on the soil to reduce or eliminate runoff and erosion, and to reduce soil surface temperatures that can slow down the decomposition of organic matter. To reduce or reverse soil erosion, it is also imperative to reduce or avoid tillage practices, which drastically increase the rate of decomposition, and thereby maintain cover on the soil surface in cropping systems [9].

Mitigating soil loss through SWC measures can thus contribute to the maintenance and increase of soil organic matter. The availability of soil organic matter improves soil properties such as water-holding capacity, fertility, and productivity of soils [9]. Investments in soil fertility improvements can increase rainwater productivity and crop yields by 70 to 120% with the availability of both micronutrients and adequate nitrogen and phosphorus [25].

iii) Identifying drought-resistant and high-yielding varieties in a watershed

Apart from soil reconditioning, drought-resistant and adaptive plants and suitable perennial grasses can be identified and cultivated in a watershed. In dealing with agropastoralism and dryland problems, positive changes have been noticed following increased exchanges and closer collaboration through increased interaction between pastoralists and farmers. Providing incentives to livestock herders to improve herd management can support ecosystem services in a watershed. A total shift towards more integrated approaches to agro-ecosystem management of crops, trees, livestock, and the reuse of resources for feed or soil fertility, as well as policy supports to facilitate the adoption and dissemination of good practices, are required [3].

An increase in cereal production in developing countries may ultimately be realized through the watershed-based development of irrigated lands coupled with high-yielding varieties (HYVs). This requires improvement of soil- and water-management practices on existing rainfed lands (producing more cereal grains with the same or less amount of water through better water management), water harvesting, and water conservation, as well as through increased water-use efficiency of both irrigated and non-irrigated agriculture [9].

5.4.3. Capacity building

The institutional arrangement for a watershed needs to create capacity-building opportunities for watershed-based development through:

i) Training human resources

Access to various training disciplines ranging from tailored short-term courses to various high-level specialized degree programs (BSc, MSc, PhD) is required for the implementation of IWSM on a sustainable basis.

ii) Integration of agricultural inputs

Integrating agricultural inputs (such as improved and high-yielding varieties, fertilizers, and pesticides) with water availability (through water harvesting) is required to boost crop production.

The semi-arid tropics, in particular, have high potential for increasing crop yield due to abundant solar radiation. It is evidenced that 70% of grain production comes from intensification through yield increases per unit land area, while the expansion of agricultural areas alone can only contribute to the remaining 30% [25].

Successful farming in drylands demands integrated management of soil, water, crops, and plant nutrients. Integrated nutrient and water management options, as well as the use of improved cultivars in semi-arid regions, have significantly increased rainwater productivity and grain yields [9][25]. However, the success of agricultural development depends on whether its water harvesting and management are economically, environmentally, and socially feasible and sustainable [9].

Integrated physical and biological conservation practices, capacity building, researching technology, and adoption [23][38] in watersheds that have agro-ecological-based SWC measures have contributed to reduced vulnerability to soil erosion and food insecurity [20].

In summary, Figure 7 illustrates the schematic layout of key conditions recommended for the successful implementation of the IWSM approach, specifically focusing on watershed-based interventions in Ethiopia and semi-arid regions to sustain water availability and agriculture

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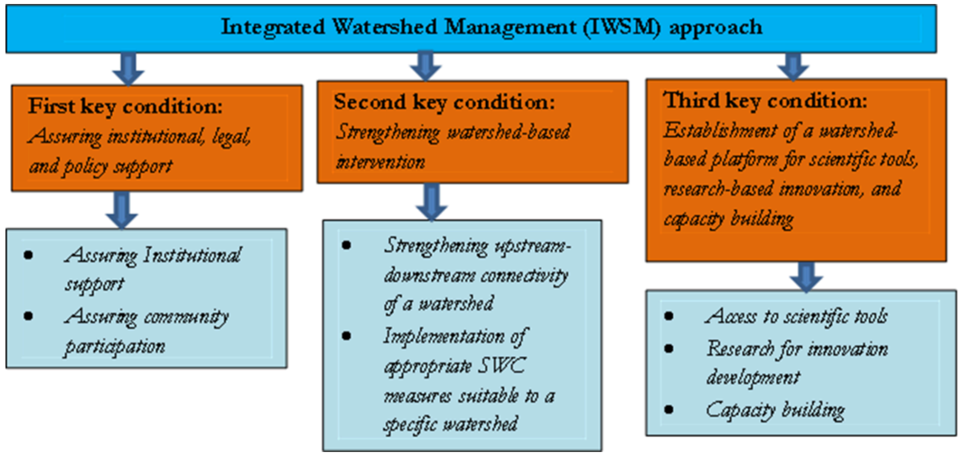

Figure 7. Integration of key conditions in the IWSM approach for sustainable water availability and agriculture in semi-arid regions

6. Conclusions

In the face of progressive soil erosion-induced land degradation and subsequent deterioration of land and water resources in watersheds of semi-arid regions, proper measures are demanded to sustain soil and water resources and dryland agriculture. In Ethiopia, soil and water conservation interventions have been practiced in watersheds since the 1970s as a response to the problem.

Following these interventions, some positive impacts have been observed in successful watersheds, while the broader promotion of watershed-based interventions is still impeded, and soil and water deterioration are widely manifested in many watersheds in Ethiopia due to various challenges and constraints, causing water shortages and related problems that hinder sustainable agriculture.

Based on this review, a list of challenges and limitations has been identified, including poor institutional support, lack of participation, inadequate planning of watershed-based SWC interventions, absence of research and development linkages, and insufficient capacity building.

To address the challenges and limitations that hinder the further promotion of successful watershed-based interventions in Ethiopia, a list of key conditions to revitalize such interventions is discussed and recommended. These key conditions include revitalizing the integrated watershed management (IWSM) approach and its focus, ensuring institutional support and community participation, strengthening the watershed-based intervention, and establishing a watershed-based platform for scientific tools, research-based innovation, and capacity building to sustain water availability for agriculture in Ethiopia—a lesson for semi-arid regions.

Statements and Declarations

Data Availability

Data sharing is not applicable to this article as no new data were created or analyzed in this literature review-based study. All information synthesized is available in the cited references.

Author Contributions

Conceptualization, methodology, investigation, writing—original draft preparation, writing—review and editing: S.H.

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