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## Impacts of catchment restoration on water availability and drought resilience in Ethiopia: a meta-analysis

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### Abstract

The coupled land degradation-drought impacts have been central challenges to ecosystem functions and livelihood of farmers in Ethiopia. As a response, catchment restoration initiatives have been implemented since 1970s. The objective of this paper is to analyze the outcomes of the catchment restoration initiatives on water resources and drought resilience, using metadata from 106 peer reviewed journal articles comprising 361 paired-catchment case studies. The study shows exclosure, fanya juu and soil/stone bunds are major soil and water conservation (SWC) practices introduced to restore the degraded catchments in regions prone to land degradation (with a high value for degradation coefficient). Runoff was less in treated catchments ( $97\pm 29$  mm/year) than in control catchments ( $168\pm 77$  mm/year) ( $n=217$ ,  $p<0.0001$ ). A paired t-test also shows a lower runoff coefficient exists in the treated ( $13\pm 10\%$ ) catchments than control catchments ( $25\pm 15\%$ ) ( $n=57$ ,  $p<0.0001$ ). The conjunctive uses of SWC measures enhanced water infiltration into vadose and aquifer zones. These measures are effective in reducing unproductive water losses. Moreover, the water level in shallow wells raised from a depth of  $18\pm 11$  to  $2\pm 1$  m after catchment management. In the dry season, well-functioning catchments promoted upstream-downstream hydrological linkages. Such consistent water flow reduced hydrological, agricultural and socioeconomic drought effects in treated catchment. To conclude, catchment restoration practices at the degraded landscape have twin goals: enhancing freshwater availability and building drought resilience. We suggest scientists, donors and managers to work on spreading of restoration efforts to other degraded landscapes to improve water yield in the face of climate variability.

**Keywords:** moisture deficit, catchment restoration, runoff, resilience, Ethiopia

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## 1. Introduction

In the Anthropocene, drylands are sensitive areas to climate change (IPCC, 2014). Climate change increase recurrent drought in the drylands. Drought occurs when water availability drops below a threshold in arid and semi-arid regions. Drought can be disentangled into meteorological, agricultural, hydrological and socioeconomic droughts (Van Loon et al., 2016). These drought types affect ecosystem services and functions (Mekonnen & Hoekstra, 2016). Increasing temperature and low rainfall caused scarcity of groundwater and surface water. It is expected that drought will reduce 10 to 13% of the global freshwater resources in the future, and without action, it will result in a water crisis in 2030s (Wilby, 2019).

Ethiopia has been a hotspot of drought risk. Frequent drought events have been observed over time. The worst drought in 2015 with an economic loss of \$11.5 million (Gebremeskel et al., 2019) had the greatest hit on resource poor communities. The future hot and dry years will even worsen the water scarcity in the country (Coffel et al., 2019). Added to the impacts of drought, land degradation is a critical problem in tropical drylands of Ethiopia. Nyssen et al. (2014) showed slope gradient, population growth combined with low socio-economic conditions, and low vegetative cover are drivers of land degradation. Water erosion in highlands and decline of soil fertility reduced regulating, provisioning, and supporting ecosystem services (Abera et al., 2019). The processes of soil erosion have affected water availability in the catchment (Bond et al., 2008).

The synergistic impacts of drought and soil erosion pose a serious threat to rainfed agriculture. It was found land degradation and drought hinder the achievement of the United Nations Sustainable Development Goals (FAO, 2014). There is a widespread concern about how the poor survive under severe impacts of land degradation and drought (Falkenmark & Rockström, 2008). With this in mind, building resilience through adaptation and mitigation is crucial to reduce drought effects in the dryland agriculture (Cornelis et al., 2019). Notably, the marginal communities require building better resilience for environmental challenges (Falkenmark et al., 2019).

Intense land restoration and water harvesting, thus, could build resilience and preparedness against acute water shortage and soil erosion hazards mainly in the arid and semiarid zones. Here, land restoration refers to the recovery of ecosystem functions including hydrological balance, and ecosystem resilience (Stavi et al., 2020).

With the help of NGOs and governments, advances in the soil and water conservation (SWC) and sustainable land management (SLM) initiatives have embarked to restore degraded catchments in Ethiopia (Abera et al., 2020; Adimassu et al., 2018; Herweg & Ludi, 1999, WRI, 2015). Popular mass mobilization in the form of 20 free-labor days and with a motto of “be like bees” was used to restore barren slopes in Tigray since 1991 (Segers et al., 2008). Since 2011, Ethiopia has instituted a national physical SWC construction similar mass campaign every year in the high potential as well as low potential areas (drought-prone) (Mekuria et al., 2018).

In Ethiopia, managing environmental resources (1980s), SLM phase I (2008) and SLM phase II (2012) were implemented to meet societal needs and ecosystem functions (MoARD, 2014). Moreover, an integrated watershed management (IWM) program has been carried out since 2004 in the country (Haregeweyn et al., 2016). These land restoration practices became an integral part of the farming system (Nyssen et al., 2010). Mekuria et al. (2018) also reported implementation of SWC measures has been under taken as part of the agricultural extension package.

The land restoration initiatives for the last three decades improved degraded landscapes in Ethiopia. Runoff and sediment export have reduced in the central and northern highlands (SCRIP, 2000). In southwest Ethiopia, Kassa (2017) reported agroforestry practices have reduced hillside runoff production. Besides, Dagneu et al. (2015) and Tebebu et al. (2015) found catchment interventions reduced runoff volume downstream sites. Nyssen et al. (2014) also reported northern Ethiopia is greener than in the last 145 years. Asfaha et al. (2018) further added that steep catchments in the northern Ethiopian mountains are reforested since 1936. Furthermore, Munro et al. (2019) showed 85% of catchments in Tigray is restored over the last decades.

In general, the catchment restoration practices have transformed the degraded slopes into greener landscapes (Adimassu et al., 2017; Ayele et al., 2018; Gebremicael et al., 2020; Nyssen et al., 2008; Nyssen et al., 2010; Walraevens et al., 2015; Wolka et al., 2018a). These restored watersheds have improved ecosystem services and functions. At large, Tigray was awarded the “world's best land restoration policies” on combating desertification and land degradation evaluation (World Future Council, 2017).

The earlier scientific studies, however, were conducted over a limited variable, space, and time scales. With better spatial coverage, Abera et al. (2020) showed the impacts of land restoration on general ecosystem services in Ethiopia. We presume, however, the interlinkage between land restoration, water resources and drought were not addressed so far at country level. These previous

works were not strong to answer “where soil moisture is a limiting factor for biomass growth, how important are the catchment restoration in improving water resources and drought resilience in Ethiopia?”. Given this research question, this research connects, bridges, and recaps the previous studies related to the impacts of catchment restoration to provide a concrete knowledge for policymakers and stakeholders; it connects the dots of the findings.

Worldwide, the twinned or paired-catchment approach has been used since the 1920s to understand the hydrological response to headwater land use or cover (Brown et al., 2005; Van Loon et al., 2019). This approach requires similar biophysical characteristics of the catchments (Oudin et al., 2010). Besides, the same catchments need to be adjacent to each other. Likewise, the paired-catchment analysis of the scientific studies updates the outcomes of the catchment restoration in Ethiopia. In these twinned catchments, measured data on hydrological parameters from the control (non-conserved) and treated (conserved) sites with similar biophysical factors were used to build our metadata, that were further analyzed to understand the responses to catchment restoration.

The main objective of this paper is to collect, synthesize, and analyze the impacts of catchment restoration on hydrological behavior and drought resilience in Ethiopia. The specific objectives are (1) to explore the state-of-the-art evidence on SWC technologies applied in various climatic zones, (2) to elucidate if the catchment restoration harness on-site and off-site water yields, and (3) to examine if the treated catchments have reduced the drought categories in Ethiopia.

The research findings assist land managers to optimize the catchment restoration investments. This knowledge production may further contribute to the realization of Sustainable Development Goals (SDGs): protection and restoration of water (SDG6) and land degradation neutralization (SDG15) (Ringler et al., 2020) in the face of global water crisis.

## **2. Methods and materials**

### **2.1 Study area**

In this study, the major land mass of Ethiopia (Figure 1) is considered, the country is highly affected by drought and land degradation. Ethiopia is situated between 3° to 15°N and 33° to 48°E, with a total area of 1.13 million km<sup>2</sup>. The landforms of the study area comprise highlands, hills, lowland plains, and peaks, where mountains account for 45% of the overall topography (Figure 1). The elevation ranges from 125 m below sea level in the Dallol Depression to 4620 m a.s.l in the Simien

Mts. The highlands are surrounded by the lowland and semi-desert areas. Importantly, the elevation and topographic features strongly influence the rainfall patterns (Figure 3).

Based on the climate types of the world (Peel et al., 2007), arid desert, temperate dry winter and hot summer, and tropical savanna are the major climate types of Ethiopia. For better understanding, Figure 2 depicts the spatial distribution of mean annual rainfall regions in Ethiopia.

In northern and central Ethiopia, rainfall is confined to two rainy seasons: *belg* (March-May) and *meher* or *kremt* (June–September). The *belg* period has a brief rainfall, whereas the *meher* period has a longer rainfall duration and amount. The latter being the primary rainy season supporting 90–95% of the total cereal grains production (Abera et al., 2019). In southern Ethiopia, however, the dry season is between December and February, whereas a long rainy season occurs between March and November, with annual rainfall depths that commonly reach up to 2000 mm/year (Kassa, 2017). Moreover, the average annual temperature varies from over 30°C in the lowlands to less than 10°C at high altitudes in Ethiopia.

Precambrian metamorphic rocks, Late-Paleozoic to Mesozoic marine and continental sediments, Cenozoic basic and felsic volcanic and volcano-sedimentary and volcanoclastic rocks are the major rocks in Ethiopia (Tadesse et al., 2003). Berhanu et al. (2013) also mapped that Lithic Leptosols (208,882), Humic Nitisols (134,722), Eutric Vertisols (115,208), Eutric Leptosols (71,269) and Chromic Luvisols (58,749) are the major soil types (all numbers are in km<sup>2</sup>). The remaining area of the country (515,171 km<sup>2</sup>) is covered by another 55 soil types in the country.

With an annual growth rate of 2.5%, the total population was approximately 105 million in 2017 (<https://data.worldbank.org/indicator>) in Ethiopia. Climatic conditions determine where people to settle in the country (Nyssen et al., 2014). It is reported that population densities are correlated to the land degradation coefficient; where less human settlements are found in the degraded areas and poor climatic condition.

## 2.2 Methods

### 2.2.1 Data sources and compilation

A systematic literature review is a valuable option to overcome lack of available data in similar case-studies (Padrón et al., 2017). We extracted peer-reviewed articles from global academic search engines and platforms, particularly Google Scholar, Web of Science, ScienceDirect, and ResearchGate. A step by step review procedure was used to explore the peer reviewed journal

articles. Using keywords, we built a conceptual mind map of the variables on the outcomes of catchment restorations on water availability and drought resilience in Ethiopia.

We searched the relevant articles up to 2019 (Figure 6), as the SWC interventions started in the 1970s (Munro et al., 2019). Spatially, the literature search was delimited to Ethiopia. Moreover, hydrological variables were delimited to the impacts of land restoration measures on hydrological parameters and drought resilience. Therefore, the inclusion criteria for article selection are time, space, and variables. Also, references cited in searched studies were considered for this study.

Each article used for this study passed via checking, exploring, intensive reading, and checking up. Next, the available were organized by lead author, publication year, location, elevation, rainfall, intervention type, ecosystem service, and impacts related to the hydrological components (such as runoff, runoff coefficient, evapotranspiration, infiltration rate, soil water content, pond water level and groundwater level).

### 2.2.2 Data analysis

The variables were standardized as mean  $\pm$  standard deviation ( $M \pm StDev$ ) of runoff depth (mm), runoff volume ( $m^3$ ), runoff coefficient (%) in the control (untreated) catchment, and treated (restored) catchments. Besides, the average values of evapotranspiration (mm), water levels in hand-dug wells and boreholes (m b.s.l), infiltration rate (mm/hour), soil hydraulic conductivity (mm/hour) and irrigated area (ha) were computed.

Elevation, rainfall, and slope gradient were mapped to understand the spatial distribution of the case studies. In an attempt to link the SWC outcomes with climatic variability, the aridity index and Fournier's degradation coefficient were also calculated and mapped. According to Peel et al. (2007), the aridity index ( $A$ , unitless) is computed as:

$$A = 0.05 \left( \frac{RF_y + 28}{T_y} \right) \dots \dots \dots (1)$$

Where  $RF_y$  (mm) is the mean annual rainfall,  $T_y$  ( $^{\circ}C$ ) is the mean annual air temperature. A lower value indicates high aridity of the area.

The degradation coefficient ( $C_f$ , mm) is calculated (Fournier, 1962) as follows:

$$C_f = \frac{RF^2}{RF_y} \dots \dots \dots (2)$$

Where RF is monthly rainfall in the wettest month of the year, and  $RF_y$  is the mean annual rainfall. The degradation coefficient expresses soil erosion in a specific area is dependent on annual and seasonal rainfall (Nyssen et al., 2014). Large values indicate a high potential for degradation. Boxplot, scatter plot, and bar graph were also used to explore the runoff and runoff coefficient between the treated and control catchments. After checking the normality of the data, a paired t-test was forced to compare the average runoff depths, runoff coefficients, and water levels between the treated and control catchments. Two-sample t-test was also employed to compare the average runoff response and runoff coefficient for various SWC practices at plot and catchment level. In addition, we run a pairwise correlation between the runoff depth reduction of major SWC practices (Fanja juu, grass strip, soil bund, and stone bund) and annual rainfall depth. We considered a 5% level of significance. Minitab (Version 20) software package was used to analyze the data.

### 3. Results and discussion

#### 3.1 Spatiotemporal distribution and characteristics of the reviewed case-studies

Most of the land restoration initiatives were confined to highlands (Figure 1) with steep slopes. The duration of these restoration projects is between 5 and 29 years. The elevation of the studies ranges between 1054 m and 3294 m, whereas the annual rainfall of these areas is  $1121 \pm 500$  mm/year (Figure 2). The intervention areas have a higher aridity index value (Figure 3), with at least semiarid, subhumid and humid climates. The average aridity index is  $3.3 \pm 0.93$  (unitless) ( $n=192$ ). Moreover, the average degradation coefficient of the study areas is  $50 \pm 22.2$  mm ( $n=192$ ). In this view, a higher degradation coefficient values (up to 99 mm) were found in areas with strong rainfall seasonality (Figure 1).

The land restoration densities were sparse in fragile and drought-severe regions mainly in the Afar and Somali peripheral areas. These areas have a lower value of aridity index (Figure 3) and a lower degradation coefficient (Figure 4). In agreement with Abera et al. (2020), most of the restoration projects were implemented in the highlands with a high degradation coefficient. Thus, land investment research projects were implemented in the highlands likely as these rainfed agricultural areas are more vulnerable to soil erosion (Hurni et al., 2015). And, the low degradation areas were not treated with SWC practices. In fact, these lowlands are not attractive for human settlement due to the harsh temperature condition and prevalence of diseases. Therefore, the catchment restoration in these marginal lands were not invested in the low potential areas.

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Introductions of SWC practices vary over time in Ethiopia. The traditional SWC practices dated back to 400 BCE (Ciampalini et al., 2012). Latter, the dryland farming research has started in 1960s. However, well planned SWC works (e.g., modern terracing) have started in Mekelle and Adigrat in 1970 as a response to the Sahel drought phases (Munro et al., 2019). After the 1972–73, modern terraces, check dams and re-vegetation were on a place for the recovery of agriculture. Since 1994, importantly, intensive SWC practices have been made in Ethiopia (Munro et al., 2019). The SWC related scientific research efforts began in 1988 and took off in 1997 (Figure 5). Indeed, there are other studies related to the effect of rainfall on soil detachment (Rose, 1960) and soil and erosion features (Virgo & Munro, 1978).

A total of 106 scientific articles were considered for this study. With an increasing trend between 1998 and 2019, we found 361 case-studies related to catchment rehabilitation impacts on hydrological variables; this indicates one article can report about more than one impact variable. The case studies (n=361) were undertaken at plots (65%), catchments (20%), landscapes (1%) and others (14%) levels. Our analysis reveals that most of the studies were undertaken at plot level. The case-studies comprised structural (n=210, 58%), biological (n=79, 22%), combined (n=45, 12%) and in-situ conservation (n= 28, 8%) measures (Figure 7). The result implies that most of the reported land restoration projects were focused on physical SWC practices. Historically, such SWC practices have been practiced in the central and northern highlands as these areas were most degraded areas in the country (Hurni et al., 2015; Munro et al., 2019; Nyssen et al., 2014).

### **3.2 Physical SWC structures enhance catchment water retention**

Fanya juu is the most reported conservation technology implemented in cultivated fields (Figure 6). It refers to the practice of digging a ditch on the contour and throwing the soil uphill to form an embankment (Thomas & Biamah, 1991). The structure reduced annual runoff from  $142\pm 17$  to  $84\pm 13$  mm/year (n=76,  $p<0.007$ ) (Table 1), and it also reduced the runoff coefficient by 11% (Table 2).

Soil bunds that practiced usually in farmlands reduced runoff from  $212\pm 17$  to  $119\pm 12$  mm/year (n=34,  $p<0.0001$ ) (Table 1). It reduced runoff coefficient by up to 40% (n=11,  $p<0.006$ ) (Table 2). As a result, it improved soil moisture by 20-60%. It is noted that level soil bunds are preferred if mean annual rainfall is less than 1400 mm (Wolka et al., 2018b), whereas graded soil bunds are constructed in areas with high rainfall ( $>1400$  mm/year) to discharge excess surface runoff (Hurni

et al., 2016). Importantly, stabilizing soil bunds with grass can reduce runoff by up to 330 mm/year, and decrease the runoff coefficient from 56% to 81%. In agreement with this metadata result, Amare et al. (2014) reported soil bund combined with elephant grass and denser rooting structure had the lowest runoff downstream.

Stone bunds have been built along the contour of the hillslope (Figure 9A, topside). They are effective in moderate rainfall areas with available rock fragments. The metadata analysis shows these structures lead to an annual reduction of runoff from  $165 \pm 17$  to  $61 \pm 6$  mm/year ( $n=30$ ,  $p<0.0001$ ). Besides, they minimized a runoff coefficient up to 36% (Table 2). Analogously, Nyssen et al. (2000 & 2007) reported that better moisture storage was found in deep soil horizons on both sides of the stone bunds in northern Ethiopia.

Trenches are dug behind the stone bunds to collect runoff. These structures reduced runoff from 614 to 362 mm/year. Besides, they reduced the runoff coefficient from  $28 \pm 12$  to  $10 \pm 6\%$  ( $n=6$ ) (Table 2). With careful design, the trenches increased soil moisture up to 100%, recharging the groundwater. In line with this finding, the direct runoff retained within the trenches increased soil moisture and groundwater (Yaekob et al., 2020).

In gullies, gabion check dams are widely applied structures in the highlands. The installation of these dams reduced an annual runoff from about 152 to 97 mm/year. The structures enhanced the annual recharge from 8 to 108 mm/year. Consequently, the water table raised from 8.5 to 2.5 m b.s.l in the plain areas.

However, there has been frequent destruction of gabion dams in the mountain areas. To counteract the destruction of gabion dams, Nyssen et al. (2016) introduced boulder-faced log dams (1m deep). In this first study of its kind, the log-dam diffuses the peak flows over the channel width.

Similar to *Jessour* in Tunisia (Castelli et al., 2019a), overall, the check dams during the torrent beds increased soil water status (Nyssen et al., 2004). Elsewhere, Dile et al. (2016) found check dams caused a decrease of annual streamflow volume (14 to 33%).

In rainfed agriculture, conservation agriculture (CA) captures rainwater for crops. For example, a zero-tillage reduced seasonal runoff from  $25 \pm 4$  to  $10 \pm 7$  mm (Table 2). Moreover, a tied-ridge conserved water and reduced the amount of moisture that would lose due to excessive plowing. This technology reduced runoff depth  $85 \pm 20$  to  $37 \pm 19$  mm/year ( $n=4$ ) in croplands (Table 1). *Derdaro* also reduced seasonal runoff from 160 to 50 mm/year. Here *derdaro* and *terwah* are

traditional in situ conservation tillage practices. Furthermore, *terwah* reduced runoff from 134±31 to 58±4 mm/year (Table 1).

As opposed to the other conservation practices, land fallow increased runoff from 259 to 281 mm/year due to the absence of tillage. It should be noted that fallow increases soil quality over time during the same season. When tall and dense grasses colonize the fallow land, the volume of runoff decrease.

The application of CA as part of SWC reduced unproductive evaporation, and it, in turn, enhances soil moisture. Moreover, mulching reduces non-beneficial evaporation. Analogously, the application of CA improves soil water storage (Bossio et al., 2010; Critchley & Radstake, 2017; Knoop et al., 2012; Lanckriet et al., 2012). Conversely, the application of *terwah* and *derdaro* increased evapotranspiration from 46 to 131 mm/year (Table 3). Such on-site water loss was increased due to moisture exposure to the surface temperature.

The combined physical SWC measures were more effective in reducing overland flow than single measures (Figure 7). For example, combining an infiltration pond with a trench could contribute between 30% and 50% of total aquifer recharge. However, Taye et al. (2015) and Yaekob et al. (2020) reported the effectiveness of physical SWC measures declines with the age of the structure installation due to the lack of maintenance.

### **3.3 Biological SWC measures facilitate water infiltration**

The establishment of exclosures reduced annual runoff up to 323 mm/year (Table 2). A reduction of runoff increased up to 350 mm/year when the exclosure is combined with physical structures (Figure 7). The catchments with exclosures reduced the annual runoff up to 91%. Moreover, the areas closed for grazing and agriculture had lower runoff coefficients (4±5%) than the control sites (19±12%) (n=8). As a result, the baseflow from catchments with exclosures was 1.5 to 4 times greater than the baseflow from cropland. In the central and northern highlands of Ethiopia, Mekuria et al. (2018) stated exclosures are successful interventions, wherein the lowest runoff is associated with the living vegetation. If the farmers' economic needs are well considered, the exclosure remains a successful barrier to runoff and to increase water flows in the drylands.

Human-induced vegetation greening modifies the runoff generation downstream (Table 1). Tree planting on degraded catchments reduced an annual runoff depth from 242±23 to 148±34 mm/year (n=5). This result indicates tree planting brought an annual runoff reduction of 252 mm/year (Table

1). Simultaneously, tree planting reduced the runoff coefficient from 30 to 17%. Hence, tree planting on steep hillsides increased soil moisture from 17 to 35%. In agreement with this work, Stavi et al. (2020) stated vegetation breaks up the kinetic energy of rainfall, and thereby captures excess runoff. Overall, the presence of vegetation and forests regulates water fluxes in soil-vegetation-atmosphere continuum (Figure 9C), playing a crucial role in the water cycle.

Restoration of tree cover influences water availability (Descheemaeker et al., 2009). The myth makers states that “more trees means less water” in catchment (Sheil and Bargués, 2020). The deep-rooted trees have an eco-hydrological impact (Chanie et al., 2013); it reduces moisture. As opposed to this myth, myth breakers stated that trees can have a major positive influence on groundwater recharge mainly via infiltration and preferential flow. Although deep-rooted trees could transpire more water (Zhang et al., 2001), our metadata analysis reveals the overall water storage was higher in the vegetated hillsides. Thus, we support the idea that more trees are needed for more water yields in the drylands.

Contour grass strips (0.5-1 m width) are proved runoff barriers in degraded areas. The grass strips reduced annual runoff from  $118\pm 18$  to  $73\pm 10$  mm/year ( $n=47$ ,  $p<0.0001$ ) (Table 1). These barriers reduced the runoff coefficient from 22 to 4% ( $n=3$ ). The result shows grasses catch a lot of runoff and increased rate of infiltration into vadose and saturated zones. In line with this finding, Welle et al. (2006) found grass strips absorb runoff in Jijiga area of Somali region. Therefore, adapted vegetative and grasses have been best barriers to increase soil moisture (Critchley & Radstake, 2017).

Generally, the biological SWC measures facilitate infiltration to soils and groundwater. However, most of the catchment restoration projects have focused on physical structures with less attention to the multipurpose biological measures (Figure 5; Table 1). Equally to the physical structures, we need to strengthen the application of biological measures to improve the blue water (groundwater and surface water) and green water (soil water) storage. Herweg and Ludi (1999) also suggested that fanya juu, stone bunds and ditches must be supplemented with biological measures to improve storages of blue and green water resources.

### **3.4 Conjunctive uses of catchment restoration measures enhance water resources**

The uses of IWM (integration of various biological and physical structures) reduced runoff from  $234\pm 54$  to  $157\pm 62$  ( $n=5$ ) mm/year, with a difference of  $82\pm 71$  mm/year (Table 1). Comparative

analysis indicates that catchments with IWM ( $14\pm 12\%$ ) had lower runoff coefficients than the control areas ( $26\pm 19\%$ ) ( $n=10$ ). The restoration technology reduced a volume of runoff from 27 to 17% of the annual rainfall.

The IWM has improved groundwater recharge from 8 to 108 mm/year. It enhanced soil moisture storage from 30 to 63%. A quotient of groundwater flow to the total stream discharge (baseflow index) increased due to SWC practices from 15% to 53%. As a result, moisture storage increased baseflow from 108 to 125 mm/year ( $n=3$ ) at the river mouths; the low flows extended in the dry season. In the same vein of finding, Akale et al. (2019) showed the delayed flow due to IWM increased at the foot of the treated catchments.

The landscape restoration continuum has been introduced in Ethiopia. This restoration approach starts from the upper slope (trenches, moisture retention, and afforestation) and middle slope (check dams, percolation ponds, grass trips, and exclosures) to lower slope (check dams, plantation and spate system). Following this practice, groundwater raised from  $18\pm 11$  m b.s.l to  $2\pm 1$  m b.s.l ( $n=8$ ,  $p<0.008$ ) in 5 years. In this context, a catchment-wide ( $37\text{ km}^2$ ) interventions in a Mendae plain ( $5\text{ km}^2$ ) raised the groundwater level (Figure 9D). After the restoration of upstream areas, the delayed river flows increased in the central valley in the Abaha Weatsbeha. As a result, the groundwater level became within the farmers' reach. Over 200 large diameter wells were then dug for irrigation (Walraevens et al., 2015). Interestingly, the landscape restoration continuum could be a lasting solution to acute water scarcity in the low-lying areas. To conclude, multiple uses of catchment restoration tools improved water storage in arid and semi-arid areas.

The upslope catchment treatment has increased freshwater resources downstream (Figure 9D). The upstream-downstream discharge linkage has improved availability, leading to less water use connectivity between the communities along the river courses (Figure 9D). With limited trade-offs, a decreased in the peak flows, but increased in low flows, have positive implications for upstream and downstream social-ecological systems (Dile et al., 2016). However, Negash et al. (2020) argue headwater hydrological water retention via SWC could reduce the downstream flood-based farming system during the rainy seasons.

The average runoff response of catchment level was higher ( $118.7\pm 12.9$  mm) than the runoff reduction at plot level ( $63\pm 7.9$ mm) ( $p<0.01$ ). However, the runoff coefficient response at plot level ( $14\pm 11\%$ ) was higher than at catchment level ( $12.37\pm 10.93\%$ ) ( $p>0.05$ ).

Based on the pooled metadata, a paired t-test result shows the runoff depth of the treated catchments ( $97\pm 29$  mm/year) was lower than the corresponding benchmark catchments ( $168\pm 77$  mm/year) ( $n=217$ ,  $p<0.0001$ ) (Figure 8). The runoff coefficients of treated  $13\pm 10\%$  and control ( $25\pm 15\%$ ) catchments also showed a marked difference ( $n=57$ ,  $p<0.0001$ ). Moreover, the study reports that there were a contrasting runoff and runoff coefficient between the control and treated catchments. In the central highlands of Ethiopia, a 44% reduction in discharge was observed due to the integrated SWC measures (Yaekob et al., 2020). Gebremicael et al. (2020) further confirmed that the drastic reduction in runoff has improved baseflow by 55% due to the intensive SWC works in northern Ethiopia.

In agreement with Guyassa et al. (2018), we conclude that the integrated uses of catchment rehabilitation measures transformed from the “runoff contributors/leaky” to the “runoff absorbers/water conservers”, but this is an insufficient panacea.

### **3.5 Performance of catchment restoration measures varies over space**

It is stressed that one type of SWC measure could not fit all climates types/elevations in Ethiopia. To begin with areas with annual rainfall is less than 500 mm (drought prone area), an intercept (cut-off point) could indicate that there is minimal effect of catchment treatment on reducing runoff in the arid climates (Figure 10). In such in highly eroded areas, the catchment treatment effects should be concentrated on gullies.

With a semi-arid climate, moisture conservation practices are given top priority. In this climate zone, the aridity index is lower than humid and subhumid climates or elevated areas (Figure 3). Similarly, the degradation coefficient of the area is low (Figure 4). On a relative basis, this implies there is a lower potential for land degradation in the area. However, moisture deficit is a critical challenge for rainfed agriculture. Thus, water harvesting structures could be successful interventions in responding to the summer runoff and conserving moisture (Figure 10).

The subhumid areas have rainfall between 500 and 1300 mm per year. Based on monthly rainfall, mean annual rainfall and mean annual air temperature, the degradation coefficient (Figure 4) and aridity index (Figure 3) fall between semiarid and humid climate types. At a time of intense rainfall, conservation ditches are needed at the top-slope to flash out the excess water. In the mid-slope of the production area, however, adding tied-ridges to the ditches is required to increase infiltration during the low rainfall seasons. Among the basket of options, fanya juu, soil bund, and grass strip

are perhaps suitable SWC measures to this climate zone (Figure 10). As noted by Tebebu et al. (2015), a top priority could be given to re-vegetate degraded areas in order to reduce moisture deficits during dry years.

In humid areas with secure high rainfall (>1300 mm), we need to prioritize the soil conservation and the draining of excess water. In such conditions, cross-slope barriers allow safe drainage of the extra runoff downstream. In this landscape, the aridity index is higher, and there is no problem with moisture stress. Moreover, larger volume of monthly rainfall in the wettest month gives a larger degradation coefficient in the hydrological year (Figure 4). As a result, the degradation coefficient value could be severe. Hence, properly managed waterways are needed along the mountain slopes to protect the river incision and gully development (Dagneu et al., 2015).

Figure 11 presents the runoff depth reduction with the aridity index and degradation coefficient. Importantly, the runoff reduction between 0.5 and 150 mm corresponds with an aridity index of 1.5 and 4.3 (Figure 11A). Moreover, most of the degradation coefficient of the case-studies align between 16% and 85% (Figure 11B). The findings of this study imply that the runoff reduction has a direct relationship with the aridity index and degradation coefficient.

The runoff depth reduction of fanja juu ( $r=0.36$ ,  $p<0.007$ ), grass strip ( $r=0.51$ ,  $p<0.001$ ), soil bund ( $r=0.31$ ,  $p<0.05$ ), and stone bund ( $r=0.57$ ,  $p<0.002$ ) and annual rainfall depth showed a positive correlation (Figure 10), indicating that there there is a high runoff depth reduction with increasing rainfall depth.

We learn that the SWC measures have shown mixed results in terms of their effectiveness in Ethiopia. Qualitative data highlight that many SWC measures have been in celebrated progress. For example, installation of exclosures and stone bunds at degraded landscapes are successful interventions in the semiarid hilly regions of Tigray due to the popular support and capitalization of available resources. Gebremeskel et al. (2018) also added that exclosures and enriching plantations were found to be the most important tools for the observed environmental recovery in northern Ethiopia.

In contrast, water harvesting schemes showed limited success in these areas (Balehegn et al., 2019) due to the top-down approach, overambitious development projects, insufficient institutional support, lack of project follow up, and lack of rainfall were frequently reported constraints of success of SWC structures. In addition, lack of inputs such as stones and labor affected the performance of the SWC practices.

In high potential area, farmers in areas of secure high rainfall had serious complaints about adaptation of the SWC structures as they occupy precious cropping area (Herweg and Ludi, 1999). Development of waterlogging, rodents and weeds also hindered the success of the SWC structures. As a result, poor success of catchment restorations was shown in the area (Mekuria et al., 2018). We infer that the failures of sustainable SWC implementations were similar across the central highlands, eastern highlands, southern highlands, northwestern highlands, and northern highlands (Tefera & Sterk, 2010).

### **3.6 Catchment restoration builds drought resilience**

In Ethiopia, now more than ever, drought resilience is required to address drought impacts on poor communities. The land restoration and water management strategies could buffer drought shocks. The contribution of restoration intervention measures on reducing the major drought types (meteorological, hydrological, agricultural and socioeconomic) is discussed hereunder.

The atmosphere is a starting point of drought development, known as meteorological drought (Figure 12). The presence of minimum rainfall in a rainy season due to weather systems and climate feedbacks causes a meteorological drought. . Once this drought occurs, the best resilience strategy is through farmers' adaptive capacity. Individual livelihood strategies distribute the risks of meteorological drought. For example, the protection of forests, conservation of water, and afforestation typically enhance carbon sinks and reduces releasing carbon to the atmosphere (Figure 9; IPCC, 2014). Also, appropriate uses of technologies minimize the imbalance of weather and climate systems (that caused minimum rainfall). Otherwise, this drought type grows into another drought type, hydrological drought (Barker et al., 2016; Van Loon et al., 2016).

Hydrological drought occurs when available water declines due to rainfall deficient. It is related to dry periods of surface and subsurface hydrology. Catchment characteristics influence the extent of hydrological drought; where degraded areas store less water. Also, poor water consumption intensifies the hydrological drought (Wada et al., 2013). This result implies inappropriate climate-catchment-human interactions aggravate drought severity. Against this background, a practical solution could come from rehabilitating watershed and effective water management. Exclosures, tree planting, bunds, and terrace reduce water losses, and these measures improve the quantity and quality of water in the soil, rivers, and aquifers (Table 3). Otherwise, hydrological drought transfers into an agricultural drought in the regions (Van Loon & Laaha, 2015).

Agricultural drought refers to water deficit in soils (Van Loon et al., 2016). Crop growth suffers from a lack of soil moisture due to both rainfall variability and inappropriate anthropogenic activities. Where agriculture is core for societies, adaptive catchment management is required to overcome the water shortage for crops. To this effect, hydraulic roughness such as soil bund, stone bund, and CA are required to store moisture. In addition, water planning, water flow regulation, and supplementary irrigation build a substantial resilience to agricultural drought. In this context, Kosmowski (2018) further reported physical structures buffered crop growth against the 2015 severe drought in Ethiopia. At a time of drought, the diversion of river baseflow into croplands also reduced the effect of agricultural drought up to 30% (Gebregziabher et al., 2016).

Socioeconomic drought is a mismatch between human demand and supply of water (Figure 12). Similar to the influence on hydrological drought, human activities disrupt water system. As a response, conjunctive uses of enclosures, terraces, and bunds are viable strategies to increase the baseflow and new spring development to fulfill societal and environmental needs (Table 3). Lasage et al. (2015) also reported that water harvesting structures help to adapt to climate change and mitigate household water shortages under the ongoing climate change.

The Ethiopian topography allows to convert the floods into socioeconomic benefits (Figure 1). The low-lying areas such as grabens receive huge floods during the rainy seasons. In this view, western escarpments of the Rift Valley release flash floods to the grabens. Golina River ( $\approx 297 \text{ km}^2$ ) could eject up to  $732 \text{ m}^3/\text{s}$  (Meaza et al., 2019). As a result, about 1.2 million ha of flat areas receive a flood in the Afar lowlands.

We ask a question “why we face critical drought impacts if there is a huge volume of unused floods flowing downstream?”. In such environment, thus, an introduction of modernization of spate irrigation could improve the community’s drought resilience (Gumma et al., 2020; Meaza et al., 2017; Meaza et al., 2018). In low-lying areas, improving flood management is important in water catchment management (Demissie et al., 2021).

Appropriate uses of runoff along roadsides and footpaths could build drought resilience to water shortage (Knoop et al., 2012; Woldearegay et al., 2019). In this decade, water harvesting near roads has been effective. In more than 10 countries, and integrating road and water development contribute to flood protection and sand harvesting (<http://roadsforwater.org/>). Closer to road bodies, infiltration bunds, culvert flood water spreaders, half moons, infiltration trenches, water ponds, and recharge ponds are effective for water harvesting along the roadsides. According to the

metadata analysis, hillside road-driven soil moisture benefited on average 100 ha per km on both sides of the road. Therefore, water harvesting from the roads, new railways, and footpaths could store water in soil and groundwater that can be used in time of water shortage.

There is a strong link between the drought types (Figure 12; Medeiros & Sivapalan, 2020). Notably, the meteorological drought is a driver for the other main drought types. Hence, catchment restorations could disconnect the chains of drought types. For instance, a healthy soils and vegetation cover have a linking role between the surface and atmosphere. Hence, keeping the healthy soils and vegetation could regulate the various drought categories we experience in arid and semiarid regions.

Lessons from this study show catchment restoration buffers droughts. In line with this, Castelli et al. (2019b) demonstrated that improving soil water storage by SWC practices mitigated the hot temperatures. This finding implies that degraded landscape restoration regulates meso-climate in agroecosystems. Insights from the Nile basin further showed SWC technologies buffer against crop production risk in the face of climate change and variability (Kato et al., 2011).

#### **4. Conclusions**

Land restoration efforts have been implemented in Ethiopia. The objective of this work is to grasp the impact of these restoration measures on the hydrological variables and drought resilience. A paired catchment approach was used to address the research question. The study shows exclosure, fanya juu and soil and stone bunds are among the catalogue of catchment management options. These SWC practices and management water along the degraded slopes were effective in reducing excess runoff. As a result, the water infiltrated into the soil contributed to streamflow during the extended dry seasons.

The appropriate restoration interventions increased groundwater recharges, leading to better baseflow. Additionally, water interdependence between headwater and downstream communities was reduced over time. As a result, water availability increased development of on-site small-scale irrigation and large-scale irrigation downstream sites. Thus, the trend of irrigated agriculture has been growing in many areas due to the catchment treatment.

Farmers increased their resilience against the impact of recurrent droughts. The integrated catchment restorations become water insurance to meet both the societal needs and ecosystem functions. These findings provide an important reference basis for the planning of soil and water

conservation investments. The catchment restoration efforts were effective to improve water storage on catchments. However, these restored catchments may not be enough to drive dryland secure agricultural sustainability in Ethiopia. Most of the landscapes have remained untreated hitherto, while the impacts of soil erosion and drought are gratifying over space and time. High potential for soil erosion exists in the highlands with high aridity index and degradation coefficient values, whereas critical water shortage is situated in the lowlands with low aridity index and degradation coefficient.

The success stories reported here provide an impetus to replicate the best restoration practices to another drought and erosion hotspots. Along with upscaling the best catchment restorations in the highlands, construction of flood harvesting strategies are crucial to buffer drought shocks mainly in the lowlands. Therefore, suitable catchment restoration and water harvesting efforts are required to break the “dry gets drier and wet gets wetter” paradigm. As the “future is much closer than it used to be”, researchers, governments and stakeholders need to join their efforts to tackle the coupled soil erosion - drought impacts through restoring the degraded landscapes in arid and semiarid regions.

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### **Data Availability Statement**

The metadata used for this study are compiled into a table, accounting about 13 pages. In this view, absolute location, the specific interventions related to the catchment restoration, the hydrological behaviour as impacted by the interventions, annual runoff depth after and before the rehabilitation intervention are key variables available. We will provide the metadata based on readers' request.

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Table 1: Runoff response (mm/year) to major catchment restoration measures. Restoration measures reported in <4 studies are not included in this table.

Restoration type	Catchment interventions	Mean± StDev	Min.	Max.	
Structural	<i>Fanya juu</i> * (n= 76)	Treated	84±13	14	652
		Control	142±17	21	688
		Difference	66±6	7	264
		Treated	37±4	10	86

Structural	Infiltration pond (n=4)	Control	72±65	32	147
		Difference	35±22	22	61
Structural	Soil bund* (n=34)	Treated	119±12	11	503
		Control	212±17	12	688
		Difference	94±8	1	315
Structural	Stone bund* (n=30)	Treated	61±6	8	289
		Control	165±17	31	96
		Difference	77±14	67	708
Biological	Grass strip* (n=47)	Treated	75±10	0	607
		Control	118±14	1	688
		Difference	54±55	13	239
Biological	Tree planting (n=5)	Treated	148±34	18	362
		Control	242±23	40	614
		Difference	94±10	1	252
Combined	IWM (n= 5)	Treated	157±62	84	222
		Control	234±54	152	284
		Difference	82±71	11	200
On-site	Straw mulch (n= 5)	Treated	24±15	3	36
		Control	48±16	40	76
		Difference	25±21	3	48
On-site	Tied-ridge (n=4)	Treated	37±19	13	76
		Control	85±20	47	118
		Difference	47±13	32	63
On-site	Zero grazing (n=6)*	Treated	51±3	11	95
		Control	95±5	9	150
		Difference	44±2	-2	58
On-site	<i>Terwah</i> (n=4)	Treated	58±4	98	160
		Control	134±31	22	93
		Difference	38±3	13	76

\* Means of treatments are significant at  $p < 0.0001$ . The other interventions are not tested as they have insufficient number of counts.

Table 2: The response of runoff coefficients (%) to catchment restoration measures.

Restoration type	Catchment interventions	Mean± StDev	Mini	Maxi	
Structural	Fanya juu (n=6)	Treated	18±18	0	54
		Control	24±22	1	65
		Difference	6±5	0	11
Structural	Soil bund (n=11)*	Treated	14±3	11	19
		Control	28±14	18	56

Structural	Stone bund (n=7)*	Difference	14±13	5	40
		Treated	13±11	2	32
		Control	23±14	8	43
Structural	Trench (n=6)	Difference	11±8	4	36
		Treated	10±6	5	21
		Control	28±12	10	43
Biological	Exclosure (n=6)	Difference	17±10	4	29
		Treated	4±5	0	13
		Control	19±12	11	35
Combined	IWM* (n=10)	Difference	16±10	7	33
		Treated	14±12	1	39
		Control	26±19	5	55
On-site	Zero grazing (n=4)	Difference	14±13	4	40
		Treated	10±7	6	19
		Control	25±4	23	30
		Difference	15±3	12	17

\* are significant at  $p < 0.001$ . Catchment restoration measures with 4-6 counts were not tested, and those with  $< 4$  counts are not included in the table.

Table 3: Comparison of hydrological components before and after catchment restoration.

Hydrological component (process)	After intervention			Before intervention		
	M±SD	Min	Max	M±SD	Min	Max
Runoff (mm/year) (n=217)	105±13.5	0	688	165±16	0.8	708
Runoff coefficient (%) (n=57)	11±10	0	34	20±14	0.01	65

Evapotranspiration (mm/year) (n=4)	120 ±13	108	131	46±0	46	46
Infiltration rate (mm/hour) (n=4)	23.48±8	18.8	36	16.4±5.8	6	19
Soil water content (%) (n=12)	27±14	8	60	15±6	3	24
Pond water level (depth in m) (n=6)	3.2±1.2	1.7	5	10.5 ±3.3	7	15
Groundwater level (depth in m) (n=9)	3±2	1	5	17±12	3	33

**Figure captions**

Figure 1: The location of Ethiopia, elevation and spatial distribution of the case studies included in this study. .

Figure 2: Annual rainfall regions (A-E) in Ethiopia. Mean rainfall data were obtained from Enhancing National Climate Services data for development in Africa (Dinku et al., 2018). The boundaries for rainfall regions (approximates) are adapted from Krauer (1988). Accordingly, A stands for short summer rains, B long rains (spring and summer merged), C Not sure, D minor spring rains and major summer rains and E short spring rains.

Figure 3: Spatial distribution of aridity index and project interventions.

Figure 4: Spatial distribution of Fournier's degradation coefficient and studied catchment management activities.

Figure 5: Temporal distribution of articles on hydrological response to catchment interventions.

Figure 6: The major categories of SWC practices and number of cases studied in Ethiopia. Others refers to in-situ conservation.

Figure 7: Decrease in runoff response as a result of catchment restoration (difference between control and treated sites). Numbers in the brackets indicates number of case-studies.

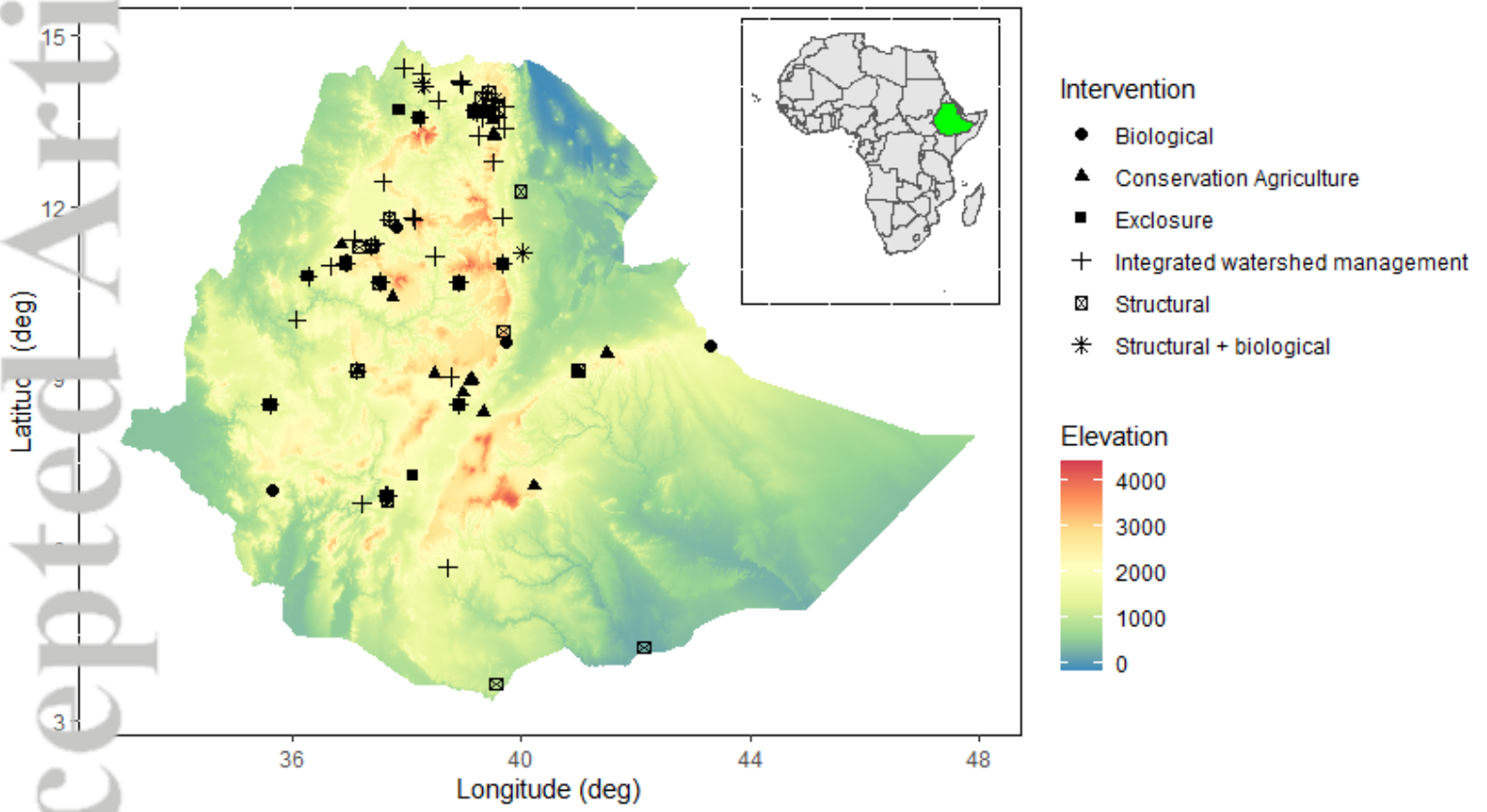
Figure 8: Boxplot comparing A) the runoff (n=217), and B) runoff coefficient (n=57) between treated and control catchments.

Figure 9: Typical catchment management activities securing water for humans and nature: A) terracing and half-moon rainfall interception at May Shugala headwaters (Jun/2015), B) constrained flash flood at Aba'ala graben bottom (Jul/2016), C) contrasting view of reforested land at Gira Kahsu escarpment (Feb/2014) and D) improved baseflow in the re-greened catchment of Abraha Weatsbeha.

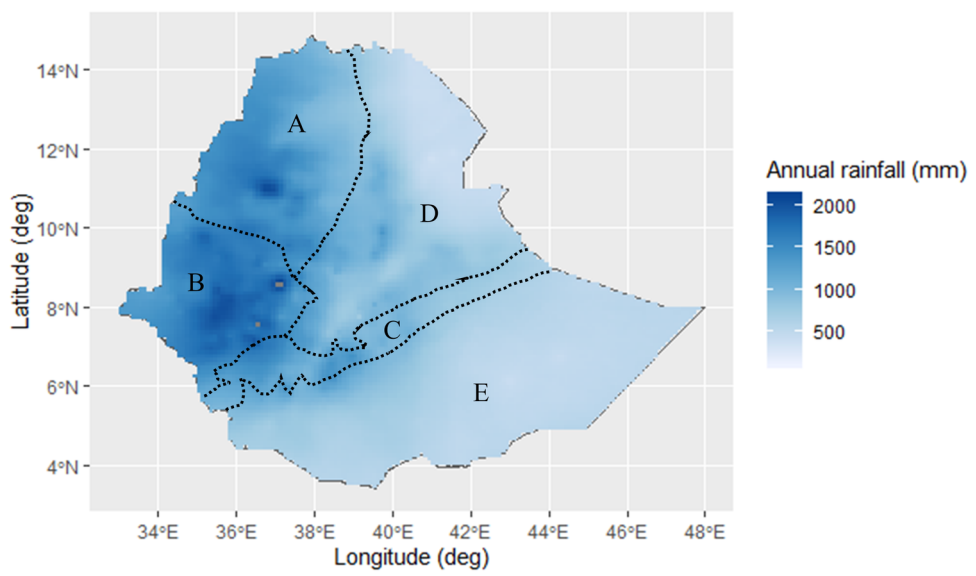
Figure 10: Performance of restoration measures in reducing runoff in regions with different rainfall.

Figure 11: The scatter plot of runoff depth reduction (due to SWC practices) with aridity index and degradation coefficient.

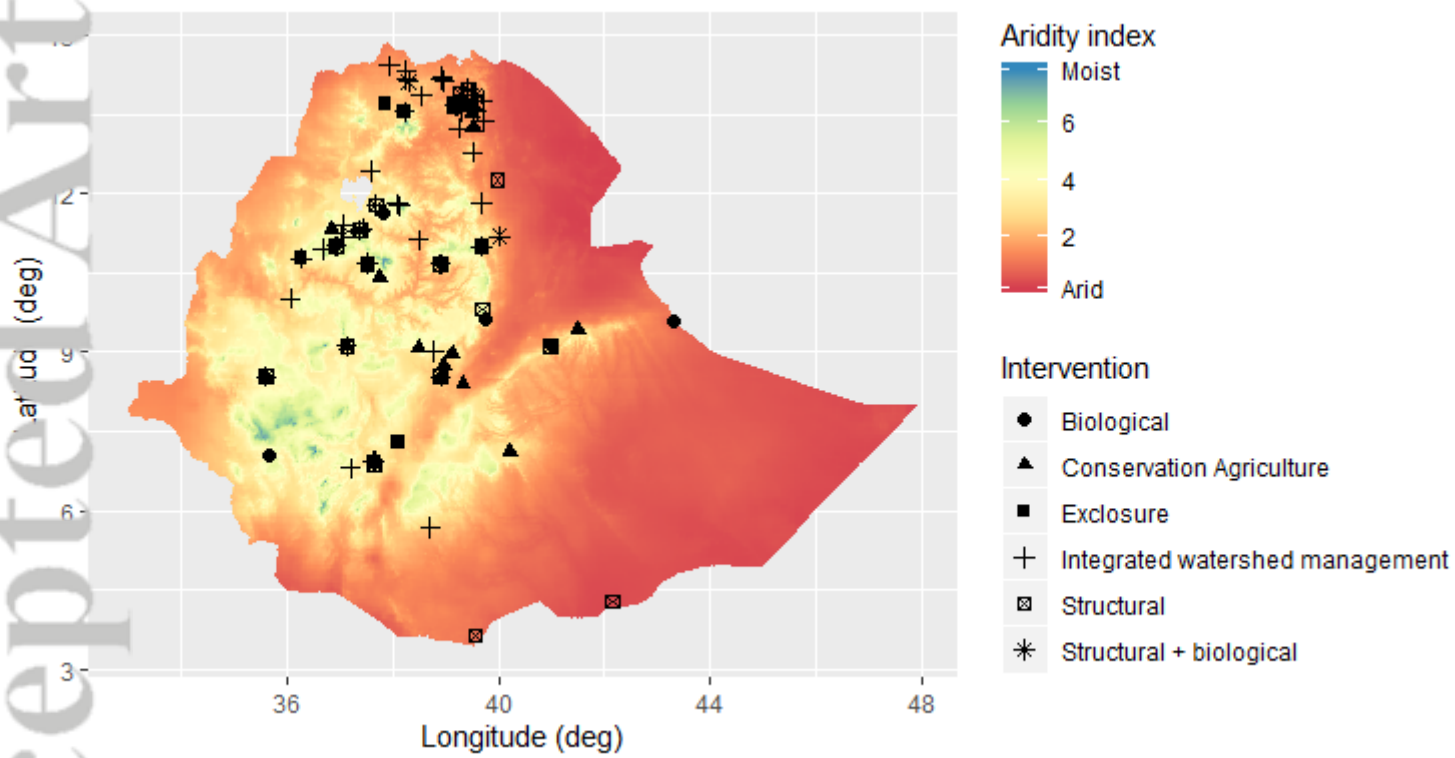
Figure 12: Catchment restoration responses to the various drought categories in Ethiopia. The readers are suggested to start with atmosphere, drought types, human activities, negative impacts, catchment restoration measures and positive impacts to the atmosphere.



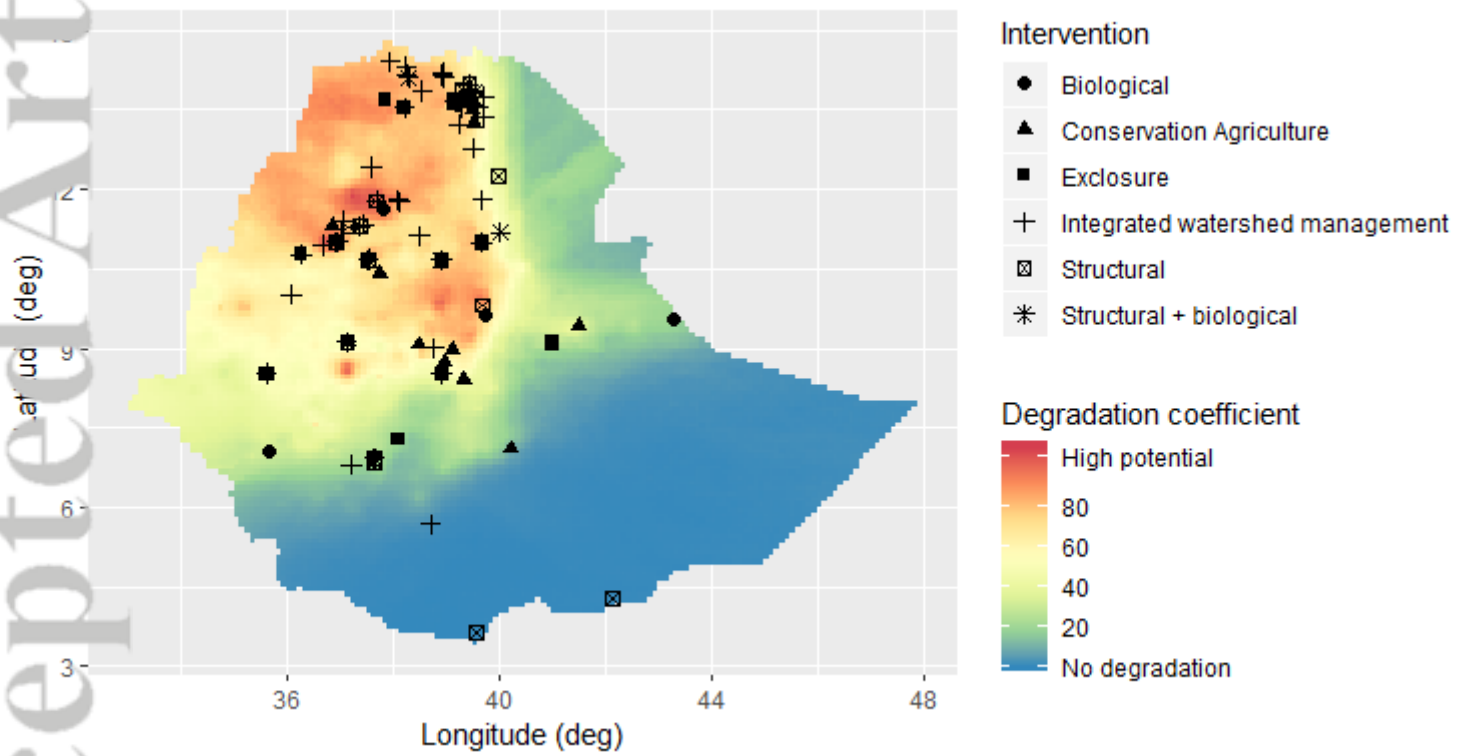
LDR\_4125\_study\_area\_revised.tif



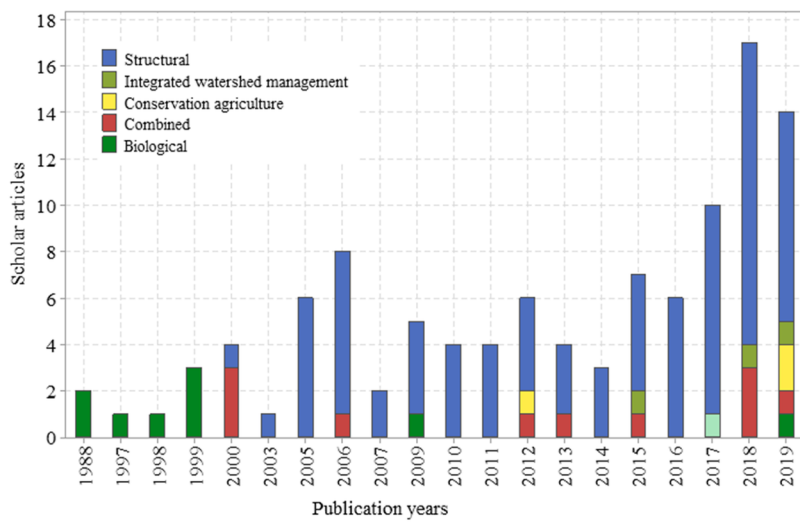
LDR\_4125\_Figure 2 Rainfall distribution.tif



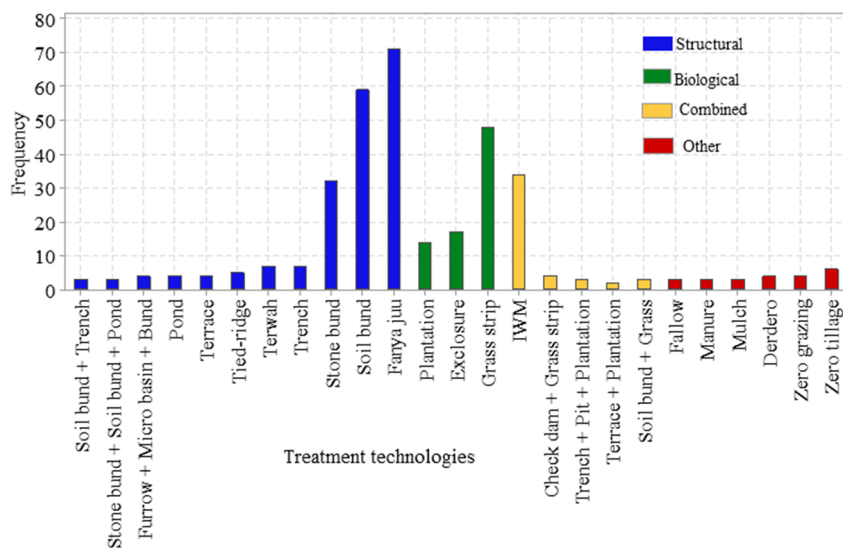
LDR\_4125\_Figure 3 Distribution of aridity index.tiff



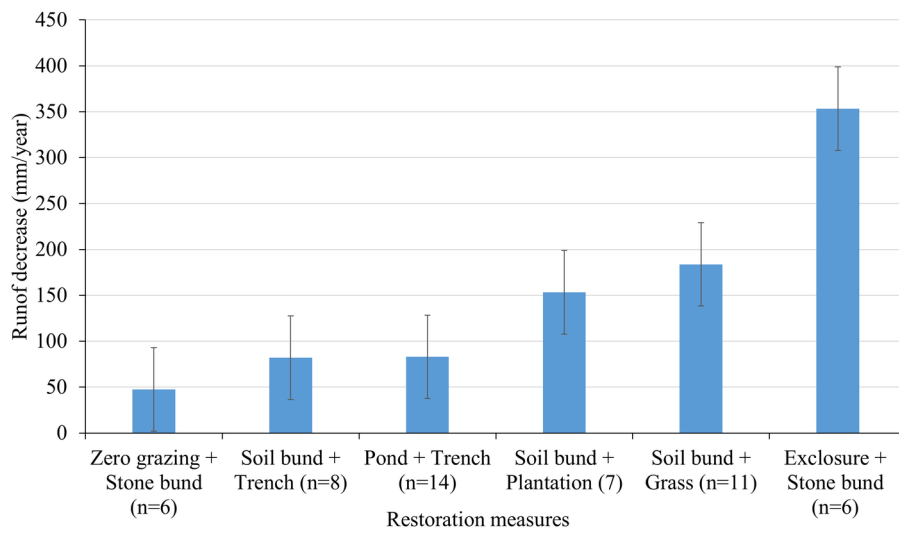
LDR\_4125\_Figure 4 Distribution of degradation coefficient.tiff



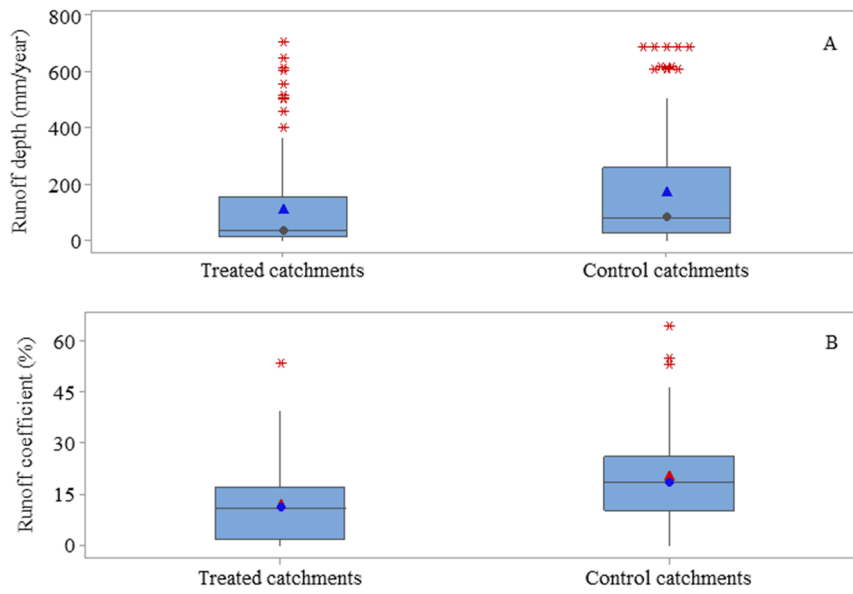
LDR\_4125\_Figure 5 Distribution of articles .tif



LDR\_4125\_Figure 6 Categories of SWC practices .tif



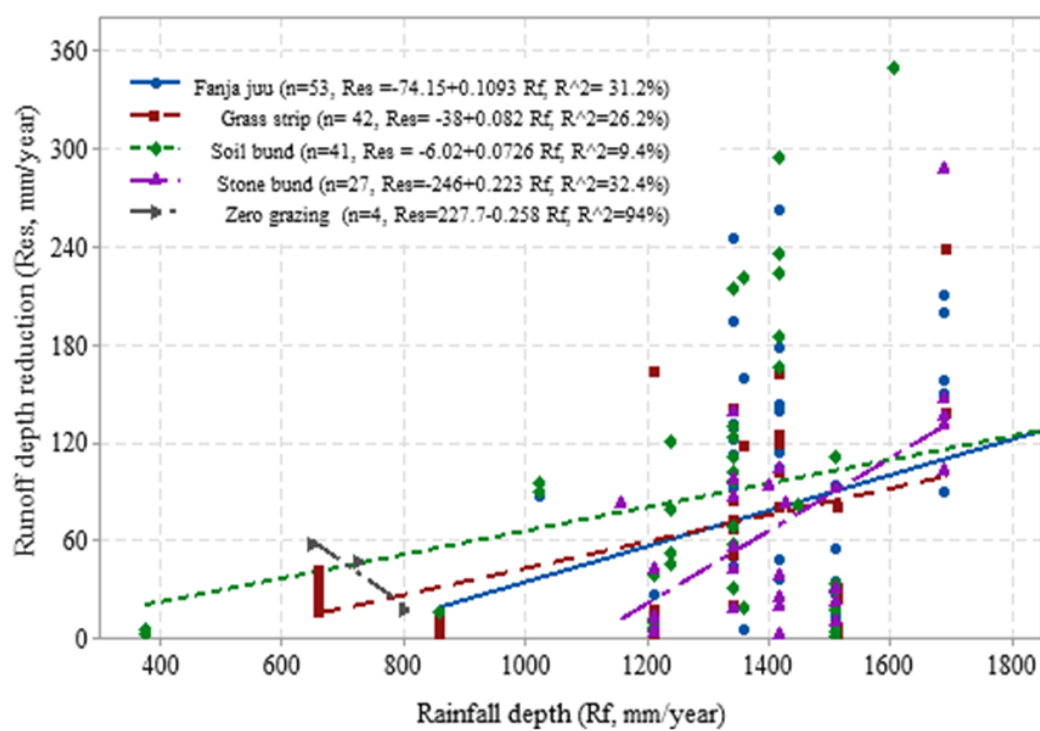
LDR\_4125\_Figure 7 Decrease in runoff response.tif



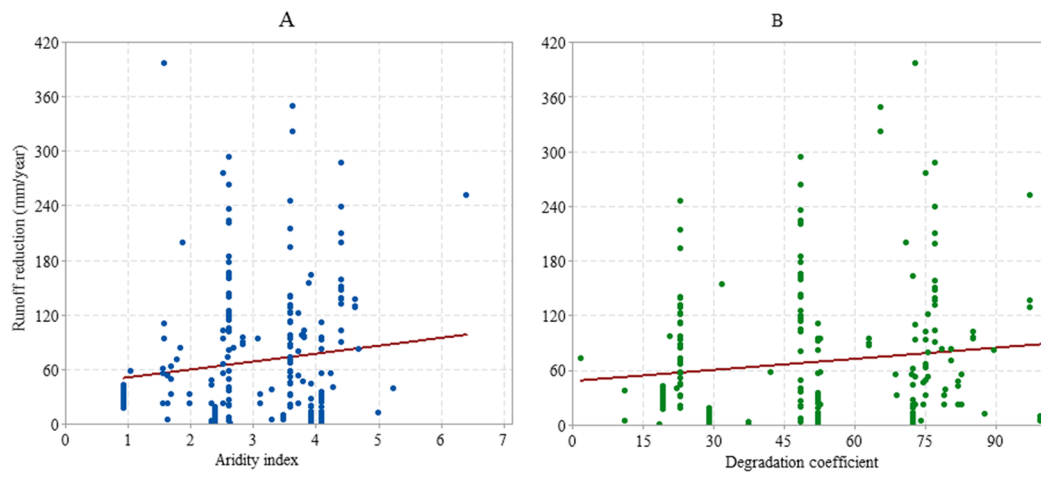
LDR\_4125\_Figure 8 Box plot of runoff.tif



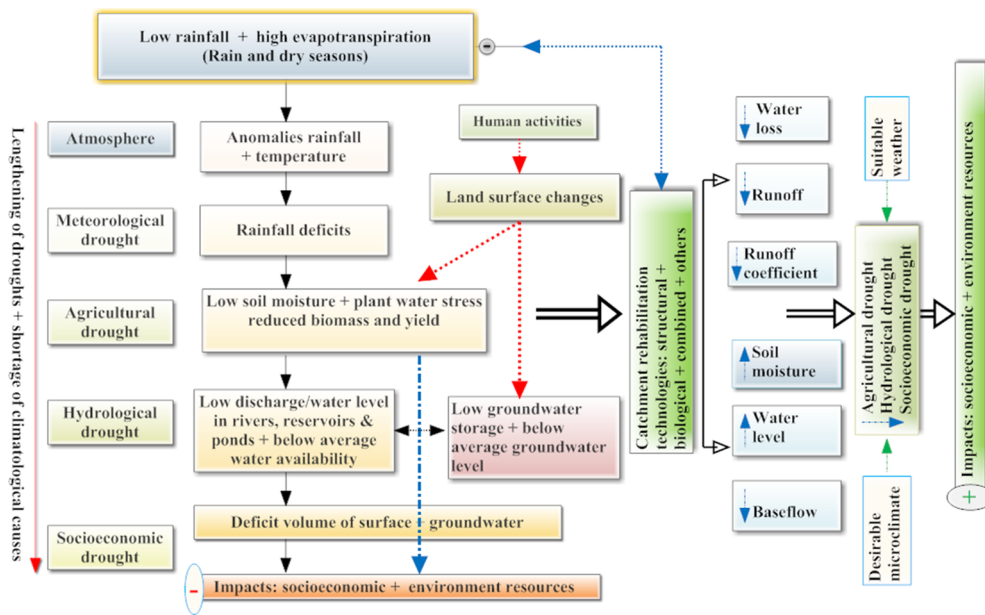
LDR\_4125\_Figure 9 Catchment management activities.tif



LDR\_4125\_Figure 10.tif



LDR\_4125\_Figure 11 Scatter plot of runoff depth reduction.tif



LDR\_4125\_Figure 12 Rehabilitation responses to drought.tif