HYDROLOGICAL RESPONSE TO CHANGES IN LAND USE LAND COVER AND WATER HARVESTING TECHNOLOGIES IN ABREHA WEATSBEHA WATERSHED, NORTHERN ETHIOPIA.

INTRODUCTION
Rain-fed agriculture contributes more than 95% of food production in dryland of sub-Saharan Africa (Rockstrom 2000 and Wani et al 2009). Livelihood security of smallholder farmers is strongly dependent on rainfall distribution and land management practices (FAO 2010). Secured livelihood is achieved when there is uniform and sufficient rainfall distribution and sustainable land management (Branca et al 2013). However, this is not the case in the northern highlands of Ethiopia where the study area, Abreha WeAtsbeha is located. The rainfall is highly erratic, and mostly falls as intensive, often convective storms, with very high intensity and extreme spatial and temporal variability (Rockstrom 2000). Water in arid and semi-arid regions such as the study area is not only meager in absolute terms, but also scarce for natural and human uses (Siebert et al 2010). Rainfall is scarce and unreliable and concentrated during a short rainy season (July- August), with the remaining 8-10 months dry period (IFAD 2000). The usual high intensity of storms and low vegetation cover ensures a greater proportion of the rainfall runoff causing flash floods and erosion. As a result, between 70 – 85% of the rainfall in the water balance is “lost” from the cropping system as non-productive water flow (Rockström et al 2003, Haregewayn et al 2006, Vannaercker et al 2010). These factors consequently lead to a very high risk of annual droughts and intra-seasonal dry spells in such areas (Seleshi et al 2009, Taye et al 2013). Very poor and unsustainable agricultural practices coupled to the aforementioned conditions have a profound detrimental ecological impact like land degradation (Nyssen et al 2009). In reverse, land degradation also has its own influence on the hydrological response and land use land cover.
changes (Hargewyn et al, 2012, Gebresamuel et al, 2013, Nyssen et al, 2015, Fenta et al, 2016). Such complex interaction among the climate, the land use, and land cover in a watershed are common in the drylands (Ndloue et al, 2015). Sustainable water supply in the drylands requires an understanding of how the groundwater recharges and the effect of land use land cover change to properly plan and manage water uses.

Ethiopia, one of the Sub-Saharan Africa countries with about 70% of its total area categorized as dryland, is facing water scarcity (FAO 2010). The agriculture sector in Ethiopia is particularly vulnerable to rainfall variability and land degradation (NMA 2007). The densely populated and food-insecure highlands and the pastoral areas in the lowlands are highly vulnerable to droughts (Ngigi, 2003). Moreover, land degradation and associated environmental problems such as soil erosion, deforestation, loss of soil fertility and water stress threatens the sustainability of the country’s ecosystems (Nyssen et al, 2004, Chiemela et al, 2017). Improving the availability of water resources and the productivity of agricultural lands is a major challenge for the rural communities representing more than 85% of the population in Ethiopia (FAO 2010).

To this end, during the last couple of decades, a strategy that reduces land degradation and improves agricultural productivity by promoting better use of land and water resources has been implemented in Ethiopia (MoARD, 2005). To enhance soil moisture and recharge groundwater, various water harvesting practices with main focus on trapping rainwater and runoff were implemented in Tigray, northern Ethiopia since 1991. Extensive water harvesting technologies have been implemented with greater community involvement and the provision of free labor (Haregewyn et al, 2012). The introduction of the water harvesting technologies may have a profound influence on the hydrological processes such as the surface runoff and groundwater recharge. The objectives of this study were (i) to quantify the land use land cover changes in the last 23 years and (ii) to investigate the hydrological response of the watershed for the different water harvesting technologies implemented iii) to quantify the interaction between LULCC and water harvesting structures on hydrological response in the study watershed.

MATERIALS AND METHODS
Study Area Description
The study was conducted in Abreha WeAtsbaha watershed with two decades of impressive water harvesting practices. The study area is located between 13°48’–13°53’N & 39°28’–39°34’E in eastern Tigray, northern Ethiopia (Figure 1). It has a rugged topography with an area of 45.5% of hillside, 21.5% of intermediate and 34% of gentle slopes (WKA, 2014). The landscape is mountainous with an altitude ranging between 1901-2491 m.a.s.l. (Tadesse et al, 2016). It has a total area of 67.7 km² and drains to Suluh River. The watershed lies in a long valley running from north to south between a sandstone ridge on the west and a basalt ridge on the north east (Hailu et al, 2012). The geology is mostly sandstone and the soil is dominantly Haplic Luvisol with a textural class of 67% sand, 25% silt and 8% clay (Gebrehaweria, 2012, WKA, 2014 ). The soil has normally good infiltration but poor water holding capacity (Hailu et al, 2012). The soil depth varies from shallow (less than 50 cm) at the escarpments to more than 12 m at the gentle valley floor slopes where the hand dug wells are found. The climate is semi-arid with an annual total rainfall ranging from 350 mm to 700 mm. The rainfall is erratic and characterized by a strong seasonal variation with particularly wet months of July and August having an average monthly rainfall of 204 mm and 210 mm, respectively (Tadesse et al, 2016). The annual mean daily temperature is about 21°C.
Major Water Harvesting Technologies

There are 14 Water Harvesting Technologies (WHTs) that exist in the study area (Tadesse et al 2016). The WHTs in the watershed are constructed in three locations: the recharge zone (slopes greater than 15%), intermediate zone (slopes 5-15%) and discharge zone (slopes less than 5%). In the recharge zone, hillsides terraces, bench terraces and stone bunds are dominant soil and water conservation practices. The main purpose of these technologies is to reduce the slope length, minimize runoff and soil erosion, and enhance soil moisture and thereby increase crop and forage production on the pieces of plots (Figure 2). In most cases, they significantly improve watershed restoration, biomass production and recharging of water tables. In the intermediate zone, semi-circular bunds, percolation ponds, soil bund with trench and stone bund with trench are dominant. These technologies are constructed for minimizing run-off, reducing soil erosion, and enhancing soil moisture and serving as points of groundwater recharge. They are also used for rangeland and shrub land restoration. In the discharge zone, hand dug wells, check dams and diversion heads are the most common WHTs. These WHTs are used to extract the existing water resources in the catchment. Grass strips are other WHTs which are implemented in most of the cultivated areas with slopes ranging from 0 to 5%. The site suitability analysis for all WHTs in the study area by Tadesse et al (2016) revealed that the structures are constructed in an appropriate location. This indicates that the WHTs in the study area are in a good form with visible impact on watershed developments.

Figure 1: Location Map of Abreha WeAtsbaha Watershed in Tigray, Northern Ethiopia

Figure 2: Implemented Water Harvesting Technologies and its Hydrological Impact (in part) in Abreha WeAtsbaha.
Land Use- Land Cover Change

A transect map with three transect lines, 5-10 km distance in between, based on the slope gradient was prepared from top map and DEM using ArcGIS software. The aim of the transect was to locate points for soil sampling, existing water harvesting technologies and for land use/cover identification. One hundred thirty five GPS points were collected systematically following the transect lines for ground control. ERDAS 9.2 software was used to investigate the land use land cover change and change matrix. Present and past information on land cover change for the watershed was generated from remotely sensed data. The Ortho-rectified satellite imagery provides an excellent source of data for performing structural studies of a landscape (Zhang et al 2016). Landsat TM (1991) and ETM+ (2014) downloaded from Global Land Cover Files (GLCF) and Spot image of 2007 were used (Table 1). These sources of information were used to analyze the land cover changes of the study area over 23 years (i.e. before (1991), at the beginning (2007) and after the intervention (2014)). The 2007 spot image which has 5*5 m resolution was reduced to 30*30 m for the analysis purpose using Bilinear Resampling methods. This method is more spatially accurate and smooth images without stair-stepped effect than others (Anuj 2003).

Table 1: The Sensor, Scale, Date of Acquisition and Source of Images Used in the LULC Classification

<table>
<thead>
<tr>
<th>S/N</th>
<th>Image</th>
<th>Sensor</th>
<th>Resolution or Scale</th>
<th>Date of acquisition</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Landsat5</td>
<td>TM</td>
<td>30x30m</td>
<td>11/12/1991</td>
<td>GLCF</td>
</tr>
<tr>
<td>2</td>
<td>Landsat7</td>
<td>ETM</td>
<td>30 x30m</td>
<td>05/01/2014</td>
<td>GLCF</td>
</tr>
<tr>
<td>3</td>
<td>Spot image</td>
<td></td>
<td>5mx5m</td>
<td>12/12/2007</td>
<td>EMA*</td>
</tr>
<tr>
<td>4</td>
<td>SRTM Data</td>
<td></td>
<td>15m</td>
<td>2010</td>
<td>EMA</td>
</tr>
</tbody>
</table>

*EMA=Ethiopian Mapping Agency

Histogram equalizer in ERDAS was employed to aid visual interpretability in determining major land cover types of the images under investigation. Gaussian probability was used to assign each unknown pixel. Gaussian probability produces better results than minimum distance and Parallelepiped (Ehasan 2009). Tasseled cap transformation was applied as spectral enhancement techniques. Supervised image classification was done using maximum likelihood algorithm after all image enhancement combinations (Lillesand and Kiefer 2000, Leica Geosystems 2005). For the image analysis, a total of 170 ground control points (GCP) were used. The selection of the training sites was made based on actual field data (135 GCPs) and ancillary maps (35 GCPs from Google earth). The image classifications were performed using 45 training samples for each year. For accuracy assessment 5 GCPs for each land use types were used and total accuracy level was 90%. Classification accuracy was evaluated using confusion matrix to indicate the nature of classification error and correctness of the classification result. Kappa statistics was used to provide information matrices for individual land use as well as to statistically compare matrices (Lu and Weng 2007). Kappa coefficient is statistical measure of accuracy that represents the agreement between classified and observed land cover. Kappa coefficient ranges between 0 and 1 and as it tends to 1, the classification will become more accurate (Foody 2003).

The land use and land cover types were categorized based on cover density and purpose (Table 2). The entire watershed was classified into seven land uses specifically: bare land, grazing/grass land, cultivated land, shrub land, open forest and homestead or settlement.


<table>
<thead>
<tr>
<th>Land use</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bare land</td>
<td>Land devoid of vascular plants, composed of exposed rock and soil surface</td>
</tr>
<tr>
<td>Settlement</td>
<td>Area covered by villages including homestead farmland.</td>
</tr>
<tr>
<td>Cultivated land</td>
<td>Areas of land ploughed/prepared for growing rain-fed crops; this category includes areas currently under crop and fallow as well as land under preparation</td>
</tr>
<tr>
<td>Grazing/grass land</td>
<td>Open grassland/herb found in flat areas, areas having seasonal and permanent grass cover that is used for grazing; usually occurs on valley bottoms and sloping terrain.</td>
</tr>
<tr>
<td>Bush land</td>
<td>Dominant vegetation lower than 3m but higher than 1m with a canopy cover above 15%, or dominant vegetation below 1m with a canopy cover above 50%</td>
</tr>
<tr>
<td>Shrub land</td>
<td>Dominant vegetation lower than 1m, with a canopy cover below 10% but higher than 5%</td>
</tr>
<tr>
<td>Open forest land</td>
<td>Patches with a canopy cover over 10%. These can be remnant of high natural forest, found in small patches around churches, on steep slopes and less populated areas or recent eucalypt Plantations.</td>
</tr>
</tbody>
</table>
The magnitude and rate of cover change was then computed using the equation 1.

\[
R = \frac{(A_2 - A_1)}{[I_2 - I_1]} \quad \text{(Eq. 1)}
\]

Where,
- \( R \) = rate of land use land cover change in ha
- \( I_1 \) and \( I_2 \) = Initial and final study periods considered
- \( A_1 \) and \( A_2 \) = Area of cover in time \( T_1 \) and \( T_2 \), respectively in ha

**Hydrological Responses**

The Soil Conservation Service (SCS) - Curve Number (CN) method is employed to examine the impacts of land use land cover change and water harvesting techniques on runoff response. Details with regard to SCS-CN are found in NRCS (2004) and Luxon and Pius (2013). The method is used because of its simplicity to apply in data scarce areas (Gebresamuel et al 2010, Teka 2014, Taye 2015). It also takes into account the physical and hydrological conditions of the catchment (NRCS 2004)

\[
Q = \frac{(P-I_a)^2}{P-I_a+S} \quad \text{(Eq. 2)}
\]

Where, \( Q \) is cumulative runoff (mm), \( P \) is storm rainfall (mm), \( I_a \) is initial abstraction loss (mm) and \( S \) is dimensionless potential maximum retention which is estimated from runoff curve number, CN using Equation 3.

\[
S = \frac{25400}{CN} - 254 \quad \text{(Eq. 3)}
\]

in which \( CN \) represents the runoff potential of the land uses and covers.

To develop a relationship between \( I_a \) and \( S \) for a specific watershed, long-term data on rainfall and runoff is required. However, \( I_a \) can be assumed to be a function of the maximum potential retention \( S \) as is indicated in NRCS (2004). Nonetheless, in Ethiopian condition with more open areas and intensive WHTs, the proportional value might not be as high as 20% (Descheemaeker et al 2008, Taye 2015). Descheemaeker et al (2008) developed a relationship between the initial abstraction \( I_a \) and the maximum potential retention \( S \) for northern Ethiopian highlands. The authors found the initial abstraction \( I_a \) to be 5% of the maximum potential retention \( S \) for semi-arid Ethiopian conditions. Their finding was also validated by Teka (2014) and Taye (2015). These studies clearly indicated that the runoff estimate for northern Ethiopian highlands using \( I_a = 0.25S \) is exaggerated at least by 15%. Thus, for this study, the empirical relationship developed for the northern Ethiopian highlands \( (I_a = 0.055S) \) was adopted and runoff response was estimated (Equation 4) as:

\[
Q = \frac{(P-0.055S)^2}{P+0.055S} \quad \text{for } P > 0 \quad \text{(Eq. 4)}
\]

As is depicted in NRCS (2004), a new set of curve numbers must be developed when a relationship different from \( I_a = 0.2S \) is used. Hence, to compute a new set of CN values from \( I_a = 0.05S \), the relationship between \( S_{0.2} \) and \( S_{0.05} \) established in Taye (2015) and Shi et al (2009) is used as is indicated in equation 5.

\[
S_{0.05} = 1.33S_{0.2}^{1.15} \quad \text{...(Eq. 5)}
\]

Area weighted average runoff for the entire watershed was then estimated as:

\[
Q_A = \frac{\sum_{i=1}^{n} \left( \frac{(P-0.055S_i)^2}{P+0.055S_i} \right) A_i}{A} \quad \text{(Eq. 6)}
\]

Where, \( Q_A \) is area weighted runoff (mm), \( A \) = total area of the catchment (ha) and \( Ai \) = the area of each land use type (ha).

The volume of runoff generated from the watershed was also calculated as:

\[
Q_V = 10 \times Q_A \times A \quad \text{(Eq. 7)}
\]

Where, \( Q_v \) is runoff volume (m³), \( Q_A \)-runoff depth (mm) and \( A \)-catchment Area (ha).

**Model Parameters**

To estimate the runoff response of a watershed using the CN method, the study requires information on daily rainfall, land use/land cover, watershed treatments, soil texture for hydrological soil group classification, and catchment area (NRCS 2004 and Taye 2015).

**Precipitation**

To compute the hydrological response for different years and interventions, this paper assumes the precipitations as constant factor. Since the same magnitude of rain for 1991(before intervention), 2007(at the start of interventions) and 2014 (after intensive interventions) is required, the maximum likelihood method of frequency analysis was used. The daily rainfall data for 24 years (1992-2015) was collected from Wukro meteorological station and Annual Daily Maximum Rainfall (AMP) data was generated. The rainfall frequency for the return periods of 2, 5, 10, 25, 50 and 100 years (Figure 3) was computed using Weibull probability plotting.
position (Weibull 1939). Probability plotting of hydrological data required individual observations which represents the same population but independent of each other (Haan 2002). A sample will not contain the smallest or largest value of the unknown population (Hosking and Wallis 1997). Thus, plotting positions of '0 and 1' should be avoided from the sample series unless one has additional information on the population limits. For a given AMR size n, ranked in descending order, if the distribution is assumed to be uniform, the probability \( p_r \) related to the \( r \)-th ordered AMP is given as:

\[
pr = \frac{r}{n+1}
\]  
(Eq. 8)

The corresponding return period is therefore estimated using:

\[
Tr = \frac{1}{pr}
\]  
(Eq. 9)

A regression model that shows the annual maximum rainfall \( v \), return period was developed (Figure 3) and used to determine the runoff response due to the interventions. The goodness-of-fit of the regression model was judged with \( R^2 \) value of 97.9%. The graph shows that for the AMP can be good to use for further modeling as an input.

**Figure 3:** The Regression Model for Rainfall Event for the Return Period 2, 5, 10, 25, 50 and 100 years

### Hydrological Soil Groups

Soil texture and depth data have been collected to assign soils of the watershed into different hydrologic soil groups (HSG). During the field survey, using auger 80 composite soil samples were collected for soil texture analysis. The soil samples were taken after clustering the area into sampling unites. The sampling unites were based on geopedological approach in which lithology, slope gradient, land use type and practices were among the factors. For each sample unites, five composites were collected from 0-30 cm depth using Auger. The soil texture was analyzed using pipette method. The soil textural class in the study area is dominantly sandy loam (43.5%) and loamy sand (39.5%). The remaining textural classes are sandy clay loam (7.7%), loam (4.8%) and silt clay loam (3.7%) (Figure 4).

**Figure 4:** Soil Textural Class Map of Abreha WeAtsbeha

The assignment of the soils of each land use into hydrologic soil groups was done based on NRCS (2004) criteria. In addition, the soil textural class for each land use was prepared by overlaying the land use/land cover maps on the textural class map. Thus, the HSG of each land use was determined and is presented in Table 5. Majority of the soils in the study area can be categorized as
HSG-A. The watershed had HSG-D rock outcrop class which covers below 1% of the total area of the watershed where the infiltration rate is minimum and runoff potential is high. The bare lands and settlement areas are found nearby the rock outcrop with shallow soils with soil depth less than 50 cm but coarse texture soils were categorized under HSG-B. The study assumes there is negligible variation in soil texture in the watershed due to the short time intervals that exist between the years considered for the analysis.

**Watershed Treatments**
Watershed conditions such as the type of land use, the WHTs and the hydrological conditions were investigated following the transect survey. The hydrologic condition of the land uses found in the study area could be termed as “good (NRCS 2004)” except for the cultivated and grass/grazing lands (Table 3). The major crops grown in the cultivated lands were wheat, beans, tef, barley and flax. The crops were planted in a contour close enough to each other in such a way that can minimize evaporation from the soil surface. The cultivated land was treated dominantly by grass strips and was classified as ‘fair’ (NRCS 2004)” condition. The same is true with grass/grazing lands.

**Table 3: Land Use, Water Harvesting Technologies and Hydrologic Conditions of Abreha WeAtsbaha in 2016.**

<table>
<thead>
<tr>
<th>Land use</th>
<th>Watershed innervations</th>
<th>Purpose</th>
<th>Status</th>
<th>Slope %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hillsides</strong></td>
<td>Bench Terraces</td>
<td>Fruit production, tree survival, land rehabilitation, runoff reduction and groundwater recharge</td>
<td>Good</td>
<td>15-30</td>
</tr>
<tr>
<td></td>
<td>Hillside Terraces</td>
<td>Slow down runoff and enhancing infiltration and regeneration</td>
<td>Good</td>
<td>30-65</td>
</tr>
<tr>
<td><strong>Exclosures</strong></td>
<td>Stone Bunds</td>
<td>Land rehabilitation, reducing slope and reducing runoff risks</td>
<td>Good</td>
<td>15-30</td>
</tr>
<tr>
<td></td>
<td>Semicircular Bunds</td>
<td>Groundwater recharge and runoff reduction</td>
<td>Good</td>
<td>0-5</td>
</tr>
<tr>
<td><strong>Bottom hill /Exclosures</strong></td>
<td>Percolation Ponds</td>
<td>Groundwater recharge</td>
<td>Good</td>
<td>5-15</td>
</tr>
<tr>
<td><strong>Spring point</strong></td>
<td>Spring Developments</td>
<td>Harvest spring water</td>
<td>Good</td>
<td>5-42</td>
</tr>
<tr>
<td><strong>Cultivated land</strong></td>
<td>Stone Bund with Trenches</td>
<td>Reducing runoff and increase soil moisture conservation</td>
<td>Fair</td>
<td>5-15</td>
</tr>
<tr>
<td></td>
<td>Soil Bund with Trenches</td>
<td>Soil moisture conservation, reducing runoff and soil erosion</td>
<td>Good</td>
<td>5-15</td>
</tr>
<tr>
<td></td>
<td>Grass strips</td>
<td>Soil and water conservation</td>
<td>Fair</td>
<td>0-5</td>
</tr>
<tr>
<td></td>
<td>Hand Dug Wells</td>
<td>Irrigation and domestic water supply</td>
<td>Good</td>
<td>0-5</td>
</tr>
<tr>
<td><strong>Upper Stream Bed</strong></td>
<td>Sediment Storage Dams</td>
<td>Sediment trapping</td>
<td>Good</td>
<td>0-10</td>
</tr>
<tr>
<td><strong>Beds, river streams, river beds and gullies and stream beds</strong></td>
<td>Permeable Rock Dams</td>
<td>Irrigation, gully rehabilitation and groundwater recharge</td>
<td>Good</td>
<td>0-15</td>
</tr>
<tr>
<td></td>
<td>Stone Check Dams</td>
<td>Gully rehabilitation and erosion control</td>
<td>Good</td>
<td>0-5</td>
</tr>
<tr>
<td><strong>Marginal lands</strong></td>
<td>Hand Pump Wells</td>
<td>Water supply</td>
<td>Good</td>
<td>0-5</td>
</tr>
<tr>
<td></td>
<td>Percolation Ponds</td>
<td>Groundwater recharge, and erosion control</td>
<td>Good</td>
<td>0-5</td>
</tr>
<tr>
<td><strong>River beds /Grazing land</strong></td>
<td>Diversion Heads</td>
<td>Rise water head for irrigation</td>
<td>Good</td>
<td>0-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>For free grazing and growing grass for animal feed</td>
<td>Fair</td>
<td>0-5</td>
</tr>
</tbody>
</table>

**RESULTS AND DISCUSSIONS**

**Land Use Land Cover Changes**
The land use/land cover map for the year 1991, 2007 and 2014 are presented in Figure 5. The accuracy of the classification was 80.0%, 87.5% and 85.7% with a Kappa coefficient of 0.80, 0.86 and 0.83 for the years 1991, 2007 and 2014, respectively. Foody (2003) recommended an accuracy of 0.80 and above as acceptable for change analysis. The dominant land cover types of Abreha WeAtsbaha watershed in the year 1991 were bare land (33%), cultivated land (30%) and shrub land (32%) of the total area (Figure 5). This indicates that the watershed was highly degraded, deforested and drought affected before the massive water harvesting practices have been introduced (Seleshi et al 2009, Tsegay et al 2010, WAC 2013, Kifle 2015). This goes in line with the findings of Abegaz (2004) and Nyssen et al (2008) who revealed that the northern Ethiopia highlands were...
highly degraded due to unsustainable agricultural land management, deforestation and civil wars among others.

**Figure 5: Land Use Land Covers Map of Abreha WeAtsbaha for 1991, 2007 and 2014**

In the last 23 years, dynamic cover change has taken place in most land use land cover types (Figure 6). There were newly emerged land use/cover types in the study area. Bush land and open forest appeared in the LULC images of 2007 and 2014 which were not existent in the LULC images of 1991 (Figure 5). The LULC images of 2007 and 2014 showed that the bare land coverage has declined to 26.2% and 8.6% while the bush land increased to 7.4% and 18.1% and open forest cover to 5% and 12% respectively (Figure 5). The bare lands have been converted to other LULC types mainly to open forest and bush lands through time. The land cover change matrix of 1991 to 2007 indicates that 7.2 ha and 119.2 ha of bare land was converted to open forest and bush lands (Table 4). In 2014, the change was magnificent and has raised to 296.7 ha and 694.2 ha, respectively. This is mainly the impact of the newly introduced approach of constructing different water harvesting technologies in conjunction with exclosures. For instance, in 2007 open forest emerged from shrub lands account around 93% and 2% was from degraded lands. The contribution of shrub lands decreased to 60% while those of bare lands increased to 37% in 2014 mainly due to the gully rehabilitation through the implementation of integrated water harvesting technologies. Over the two decades, about 45% of shrub land was converted to bush and open forest lands whereas above 70% of grass land was maintained.

**Table 4: Land Use Land Cover Changes Matrix During Periods (1991-2014)**

<table>
<thead>
<tr>
<th></th>
<th>1991</th>
<th>2007</th>
<th>2014</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bare land</td>
<td>Grassland</td>
<td>Settlement</td>
<td>Cultivated land</td>
<td>Shrub land</td>
<td>Total</td>
<td>Bare land</td>
<td>Grassland</td>
<td>Settlement</td>
<td>Cultivated land</td>
<td>Shrub land</td>
<td>Total</td>
<td>Bare land</td>
<td>Grassland</td>
<td>Settlement</td>
<td>Cultivated land</td>
<td>Shrub land</td>
</tr>
<tr>
<td>2007</td>
<td>1658.9</td>
<td>23.0</td>
<td>16.8</td>
<td>39.7</td>
<td>34.3</td>
<td>1772.7</td>
<td>488.6</td>
<td>15.6</td>
<td>14.7</td>
<td>36.8</td>
<td>26</td>
<td>581.7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grass land</td>
<td>39.8</td>
<td>106.5</td>
<td>5.4</td>
<td>48.0</td>
<td>32.0</td>
<td>231.7</td>
<td>70.7</td>
<td>118.1</td>
<td>6.4</td>
<td>40.0</td>
<td>95.7</td>
<td>330.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Settlement</td>
<td>7.4</td>
<td>10.7</td>
<td>169.4</td>
<td>7.3</td>
<td>28.8</td>
<td>223.6</td>
<td>10.5</td>
<td>8.3</td>
<td>178.9</td>
<td>5.4</td>
<td>21.3</td>
<td>224.4</td>
<td></td>
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<tr>
<td>Cultivated land</td>
<td>35.4</td>
<td>7.0</td>
<td>16.0</td>
<td>1380.2</td>
<td>90.6</td>
<td>1529.2</td>
<td>42.9</td>
<td>5.7</td>
<td>21</td>
<td>1395.5</td>
<td>63.1</td>
<td>1528.2</td>
<td></td>
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<td></td>
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<tr>
<td>Shrub land</td>
<td>349.5</td>
<td>9.9</td>
<td>24.2</td>
<td>485.4</td>
<td>1312.8</td>
<td>2181.8</td>
<td>613.8</td>
<td>8.3</td>
<td>9.7</td>
<td>442.1</td>
<td>982.7</td>
<td>2056.6</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Bush land</td>
<td>119.2</td>
<td>10.5</td>
<td>5.5</td>
<td>19.0</td>
<td>347.3</td>
<td>501.5</td>
<td>694.2</td>
<td>9.6</td>
<td>6.6</td>
<td>48.8</td>
<td>472.9</td>
<td>1232.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Open Forest</td>
<td>7.2</td>
<td>4.1</td>
<td>5.2</td>
<td>6.2</td>
<td>301.6</td>
<td>324.3</td>
<td>296.7</td>
<td>6.1</td>
<td>5.2</td>
<td>17.2</td>
<td>485.7</td>
<td>810.9</td>
<td></td>
<td></td>
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<tr>
<td>Total</td>
<td>2217.4</td>
<td>171.7</td>
<td>242.5</td>
<td>1985.8</td>
<td>2147.4</td>
<td>6764.8</td>
<td>2217.4</td>
<td>171.7</td>
<td>242.5</td>
<td>1985.8</td>
<td>2147.4</td>
<td>6764.8</td>
<td></td>
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</table>
Generally, the increased vegetation cover is related to the massive integrated watershed management efforts of the regional state of Tigray. Many researchers also reported an increase in vegetation cover in the region as the result of massive investment in water harvesting structures in combination with area exclosures and reforestation programs on degraded lands (Nyssen et al 2008, Haregeweyn et al 2012, Teka et al 2014). A study by Nyssen et al (2009) and Haregeweyn et al (2012) indicated an overall vegetation cover increment by more than 100% in many areas of the region because of the massive integrated watershed management and exclosures. Descheemaeker et al (2006) reported that in the year 1991, as exclosures introduced on degraded steep areas, more than 73% of bare lands were converted to other land cover types. Such restoration of natural vegetation, planting of fodder trees, and protection of existing shrubs and trees has changed the watershed from a highly degraded land to an evergreen environment (Figure 6). Recently, most gullies in the study area have been rehabilitated with plantation, and some are being used as water harvesting structure. The streambeds are being used to plant different multipurpose plant species.

![Figure 6: Impact of Water Harvesting Treatments on Successful Gully Rehabilitation: From Left to Right Before Intervention (GIZ 2010), During Intervention (GIZ 2010) and After Intervention (observed in 2015).](image)

**Hydrological Responses**

The hydrological responses of the watershed in the years 1991 (before), 2007 (at the beginning) and 2014 (after most of the massive water harvesting interventions have been implemented) are shown in Table 5. Table 5 shows the land uses, land cover types of the entire watershed and their hydrological soil groups dominant by HSG ‘B’ and ‘A’ (NRCS, 2004); hydrological conditions changed from poor before the intervention to average good conditions after implementation of WHTs, the CN based on modified maximum retention potential equation.

**Table 5: Runoff Response Changes after Water Harvesting Interventions (1991-2014) for Average Antecedent Moisture Condition**

<table>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Cultivated land</td>
<td>1985.8</td>
<td>1529.2</td>
<td>1518.4</td>
<td>A</td>
<td>Poor</td>
<td>poor</td>
<td>Fair</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>2</td>
<td>Grass land</td>
<td>171.7</td>
<td>231.7</td>
<td>328.3</td>
<td>A</td>
<td>Poor</td>
<td>Poor</td>
<td>Fair</td>
<td>68</td>
<td>68</td>
</tr>
<tr>
<td>3</td>
<td>Bare land</td>
<td>2154.6</td>
<td>1759</td>
<td>569.7</td>
<td>B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>86</td>
<td>86</td>
</tr>
<tr>
<td>4</td>
<td>Shrub land</td>
<td>2147.4</td>
<td>2181.8</td>
<td>2041.4</td>
<td>A</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
<td>77</td>
<td>72</td>
</tr>
<tr>
<td>5</td>
<td>Bush land</td>
<td>-</td>
<td>501.5</td>
<td>1203.4</td>
<td>B</td>
<td>-</td>
<td>poor</td>
<td>Good</td>
<td>-</td>
<td>67</td>
</tr>
<tr>
<td>6</td>
<td>Open forest</td>
<td>-</td>
<td>324.3</td>
<td>819.3</td>
<td>A</td>
<td>-</td>
<td>poor</td>
<td>Fair</td>
<td>-</td>
<td>45</td>
</tr>
<tr>
<td>7</td>
<td>Settlement</td>
<td>242.5</td>
<td>223.6</td>
<td>221.5</td>
<td>B</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>74</td>
<td>74</td>
</tr>
<tr>
<td>8</td>
<td>Rock outcrop</td>
<td>62.8</td>
<td>62.8</td>
<td>62.8</td>
<td>D</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>94</td>
<td>94</td>
</tr>
</tbody>
</table>

The runoff volume generated from an event rainfall in the years 1991, 2007 and 2014 showed a decreasing trend (Figure 7). This study finds an average runoff reduction by 18.2% between 1991 and 2007; and 47.8% between 2007 and 2014. In 2007, the impact of the water harvesting technologies in reducing the runoff was not as large as in 2014. For instance, for the rainfall event with 2 years return period (i.e., 50.7 mm), the runoff volume has decreased by 62.3% (i.e. from 8019.5 m³ in 1991 to 6362.3 m³ in 2007 and 3011.9 m³ in 2014). Over all, the direct runoff from the entire...
watershed has decreased by 57.2% in the last couple of decades.

**Figure 7:** The Direct Runoff (Q) Response for the year 1991 (Q1991), 2007 (Q2007) and 2014 (Q2014) for the Return Periods of 2, 5, 10, 25, 50 and 100 years

This change was attributed to a decrease in the runoff coefficient due to the implemented intensive water harvesting measures (Table 3). Except for the cultivated and grasslands, almost all of the watershed areas have been well treated with both physical and biological soil and water conservation measures (Table 3). These interventions created an opportunity of residence time for a proportion of the rainfall that could have left the area as overland flow to infiltrate, percolate and recharge the groundwater.

More than 50% of the runoff for the whole watershed is contributed from bare land areas (Figure 8). Due to the various water harvesting practices implemented in this area, runoff volume decreased by 73.5% between the years 1991 and 2014. For instance, for the 100 years rainfall event (i.e., 199.4 mm), a total of 64,323.85 m$^3$ surface runoff has been captured by the various water conserving structures implemented on bare land areas. Implementation of such water harvesting structures normally will not only reduce the runoff but also will affect the land use land cover dynamics (Gebresamuel et al 2010, Nyssan et al 2010, Hargeweyn et al 2012 and Teka et al 2014) and thus influence the hydrological regime. This has also been strengthened by Descheemaeker et al (2008) that compared with hydrological soil group and other CN parameters for the different land use/land cover types, the land use types explained the variability in surface runoff production for hillslope in Tigray.

**Figure 8:** Land Use Based Runoff Changes (1991-2014) in Abreha WeAtsbaha Watershed for 2 Years Rainfall Event

Land uses with less vegetation cover are subjected to high surface runoff and low retention capacity (Figure 8). However, shrub lands with relatively good vegetation cover were the other higher source of surface runoff in the watershed (Figure 8). Though trends of runoff generated from all land uses (Figure 8) decreased with an increase in water harvesting interventions, the relative change from shrub lands and cultivated lands is not as large as from the bare lands. For example, the simulation result from the 25 years return period of rainfall (143.5 mm) showed that the runoff volume from cultivated land decreased by 33.2% between 1991 and 2014.

The relative change in runoff generated decreased as the magnitude of rainfall event increased (Table 6). For instance, if two year and 100 year rainfall events for the years of 1991 and 2014 are compared, the runoff generated from this events decreased by 62.4% and 54.8% respectively. This is directly related with the water holding capacity of the soil (Gebresamuel et al 2010, Taye et al 2015). Such decrease in surface runoff promotes gully rehabilitation and increases soil depth and water-retention capacity (Hargeweyn et al 2012).
The findings of this study are in line with similar studies (eg. Haregeweyn et al 2012) in the region and elsewhere. As a result of water harvesting interventions, vegetation cover and surface roughness have been evolving through time (Figure 6). These changes have led to a massive decrease of runoff. Similar studies also supported this findings that runoff is significantly decreased due to the intervention of WHTs in the northern highlands of Ethiopia: in Enabered Watershed by 27 % (Haregeweyn et al 2012); in six different agro-ecological watersheds by10 – 60% (Herweg and Ludi 1999); in Mai Zeg-Zeg watershed by 81 %, (Nyyssen et al 2010); in May Leba watershed by 20 to 30% (Taye et al 2015). Descheemaeker et al (2009) also found WHTs in exclosures have the ability to infiltrate 30% of the total annual rainfall thereby reducing runoff to a larger extent. These authors indicated that WHTs are initially more effective in reducing runoff and their effectiveness declines over time. The reduction in effectiveness of the WHTs is attributed to the storage capacity loss due to sediment deposition. On the other hand, Gebresamuel et al (2010) indicated that an increasing surface runoff was observed in areas where poor watersheds management induced land degradations and deforestation are prevalent. A simulation study in West Africa (Li et al 2007) reported similar thoughts that under totally deforested areas, the surface runoff and annual stream flows increased by 35-50%. This is true for a degraded watershed. If proper watershed management is put in place, the runoff which could occur will decrease gradually. This can stimulate regeneration and rehabilitation of degraded ecosystem.

In Abreha WeAtsbaha, the various types of water harvesting structures implemented are meant to capture rainwater and runoff that could have been lost in the form of surface runoff. They provide the means for the rainwater to infiltrate and recharge groundwater table. Kifle (2015) and Tadesse et al (2016) indicated that the groundwater table level has increased from 15 m deep in 1998 to 2-3 m deep in 2014. The impact is clear in that the community is now able to tap groundwater at a depth of 3 to 4 meters for domestic and irrigation purposes. Since the implementations of the water harvesting technologies, the total water supply coverage of the watershed has reached about 96% (WKA 2014) with a travel time to water sources of 25-30 minutes. The average daily domestic water supply per household of the watershed is reported as 100 litter/day (equivalent to five Jerry cans). The source of domestic water supply is mainly from groundwater through shallow hand dug wells, shallow borehole springs and deep wells.

**CONCLUSIONS**

In Abreha WeAtsbaha watershed, various water harvesting technologies have been implemented, in the last 23 years, to improve the availability of surface and groundwater for different purposes. The technologies are now playing significant role in turning the heavy rains that could have eroded the watershed into an opportunity to recharge the groundwater and rehabilitate the ecosystem while providing water for irrigation. For this study area, the impact of more than 14 WHTs was evaluated. After the implementation of integrated watershed managements that have been practiced for the last 23 years (1991-2014), the land use/land cover has shown positive changes and new land use types such as bush lands and open forests have emerged to an area of 1232.1 and 810.9 hectares respectively. The change in the proportion of bare land reduced from 33% in 1991 to 8.6% in 2014. The area of the newly emerged land uses, the bush lands and open forests increased from nearly 0 in 1991 to 18.1% for bush lands and 12% for open forest in 2014. From the entire watershed, the

<table>
<thead>
<tr>
<th>Return period (years)</th>
<th>Runoff response (Q)</th>
<th>Relative runoff change</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>8019.5</td>
<td>6362.3</td>
</tr>
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<td>5</td>
<td>20885.5</td>
<td>16902.4</td>
</tr>
<tr>
<td>10</td>
<td>57954.4</td>
<td>47614.3</td>
</tr>
<tr>
<td>25</td>
<td>79593.6</td>
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</tr>
<tr>
<td>50</td>
<td>104750.3</td>
<td>86603.7</td>
</tr>
<tr>
<td>100</td>
<td>157965.1</td>
<td>131062.2</td>
</tr>
<tr>
<td>Average change</td>
<td>18.2</td>
<td>47.7</td>
</tr>
</tbody>
</table>
volume of runoff generated so far has been reduced by 57.2% between 1991 and 2014. There was an average runoff reduction by 18.2% between 1991 and 2007, and 47.8% between 2007 and 2014. The impact of the water harvesting technologies in reducing the runoff was not that significant in 2007 compared to their impact in 2014. The implementation of water harvesting technologies have, therefore, significant impact in reducing runoff and increasing groundwater level from 15 m deep in 1991 to 2-3 m deep in 2014. The enhanced soil moisture has great influence on the vegetation and rehabilitation of the watershed. Thus, the intensive and integrated water harvesting intervention, innovations and commitments as a package, should be scaled up and replicated to similar agro-ecological areas. Finally, this study suggests that the ecosystem services and environmental effects are still lacking.

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