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Watershed management, groundwater recharge and drought resilience: An integrated approach to adapt to rainfall variability in northern Ethiopia

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ABSTRACT

Rainfall variability coupled with poor land and water management is contributing to food insecurity in many sub-Saharan African countries such as Ethiopia. To address such challenges, various efforts have been implemented in Ethiopia. The objective of this study was to evaluate the long-term impacts of different soil and water conservation and water harvesting interventions on groundwater and drought resilience of the Gule watershed, northern Ethiopia. The study involved: (i) documentation of the approaches followed and the technologies implemented in Gule since the 1990s, (ii) monitoring the hydrological effects of the interventions for ten years, and (iii) evaluation of the effects of the interventions on groundwater (level and quality), spring discharge and suspended sediment concentration (SSC) in runoff. Results showed that interventions were implemented at different stages and scales. As a result of the interventions, the watershed was transformed into a landscape resilient to rainfall variability: (a) dry shallow groundwater wells have become productive and the level of water in wells has raised, (b) the groundwater quality has improved, (c) SSC in high floods has reduced by up to 65%, (d) discharge of existing springs has increased by up to 73% and new springs have started to emerge. Due to improved water availability, irrigated land has increased from less than 3.5 ha before 2002 to 166 ha in 2019. Communities have remained water-secure during an extreme drought in 2015/2016. Implementation of watershed management practices has transformed the landscape to be resilient to rainfall variability in a semi-arid environment: a lesson for adaptation to climate variability and change in similar environments.

1. Introduction

Land degradation threatens food production around the world and impacts biodiversity, soil and water quality (IPCC, 2012, 2019; Lambin et al., 2000). This is especially the case for arid and semi-arid zones of sub-Saharan Africa (SSA), which are characterized

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by low, erratic rainfall and infertile depleted soils (Sanchez, 2002). Availability of water, driven by climate, varies considerably over time, with significant intra- and inter-annual variations concentrated in poorer regions (Grey & Sadoff, 2007). Climate models show that semi-arid areas are likely to experience increased variability in rainfall and more extended drought periods in the coming decades (IPCC, 2019). In agrarian economies, climatic changes threaten both food security and economic development (Burney & Naylor, 2012). Water constraints are not always related to absolute water shortage but rather to the variability of supply, and water management to bridge dry spells can greatly reduce risks (Rockstrom et al., 2010). Large scale adoption of water harvesting (WH) (definition of terminologies is presented in Box 1) systems requires a paradigm shift in integrated water resources management in which rainfall is regarded as the entry point for the governance of freshwater, thus incorporating green (sustaining rainfed agriculture and terrestrial ecosystems) and blue (local runoff) water resources (Rockstrom et al., 2010).

In addition to surface water resources, groundwater is getting attention as an adaptation option for climate change (e.g. Stigter et al., 2023; Taylor et al., 2013; Taylor et al., 2022; Wilby & Dessai, 2010). Groundwater responds much more slowly to meteorological conditions than surface water and, as such, provides a natural buffer against climate variability, including drought (Calow et al., 1997). As indicated by different researchers (e.g., Bouwer, 2002; Dillon et al., 2022), groundwater recharge offers an opportunity to store excess water underground. Examples of structures constructed as water storages in dry river beds and reported to increase adaptive capacity to climate change conditions are sand dams (Lasage et al. 2015; Quilis et al., 2009; Cate & Paul, 2016; Yifru et al., 2021).

Ethiopia is one of the sub-Saharan African countries which is highly affected by land degradation (Haregeweyn et al., 2012; Nyssen et al., 2004, 2009; Tamene et al., 2006, 2011) and prone to recurrent drought and food insecurity (Awulachew, 2006; FAO, 2012). In response, a rich heritage of soil and water conservation (SWC) as well as WH practices has evolved. Though the history of these practices dates back to the Aksumite Kingdom (400 BCE to 800 AD) (Ciampalini et al., 2012), the implemented interventions have changed over time (Stocking, 1992; Osman & Sauerborn, 2001). The majority of the restoration and WH efforts conducted before mid-1990's were less successful (e.g., Bishaw, 2001) though there were few and isolated evidences of success stories (e.g., Descheemaeker et al., 2006; Mekuria et al., 2011). According to various studies (e.g. Bishaw, 2001; Hunting, 1976; Stocking, 1992) the reasons for the limited success of the earlier interventions were due to: (a) technical failures such as incorrect spacing and alignment of terraces, poorly organized nurseries and wrong choices of species, and (b) the top-down approach followed which has contributed to the limited adoption of the technologies and largely to community failure to protect and manage the options. After the 1980's, a shift took place from projects dealing mainly with physical and chemical aspects of degradation towards integration of a broader range of disciplines (Stocking, 1992). Especially after 2000, there was a major shift towards integration of WH and small-scale irrigation development with SWC practices. The latter also meant a broader look at watersheds as organizational units for SWC and water resources planning. As a result, the Tigray region in northern Ethiopia has been labeled as one of the most successful in terms of landscape restoration and is recommended to be taken as exemplary for sub-Saharan Africa and beyond (Tuinhof et al., 2012).

Over the years, several watershed management practices, which include in-situ and ex-situ WHs, exclosures and other biological measures have been implemented in Ethiopia. These interventions are reported to have resulted in a number of benefits, namely reduction in soil erosion (Descheemaeker et al., 2006; Gebremichael et al., 2005; Herweg & Ludi, 1999; Nyssen et al., 2009; Tamene et al., 2011), improvements in soil moisture (Grum et al., 2017; Negusse et al., 2013; Nyssen et al., 2010; Yaekob et al., 2020) and enhancements in availability of surface water (Vohland & Barry, 2009). Though several studies have been carried out to assess the effects of watershed management, most of them have focused on erosion rate, soil moisture content, sediment and nutrient transport. In recent years, some studies (e.g., Woldearegay et al., 2006; Woldearegay et al., 2018; Woldearegay & van Steenbergen, 2015) have reported improvements in groundwater recharge and water quality as a result of landscape restoration with case studies from different parts of northern Ethiopia. However, the effects of watershed management on groundwater recharge and their significance on drought resilience remain poorly understood due to several reasons (Woldearegay, 2015): the previous interventions were implemented without detailed evaluation of the hydrogeological conditions of the landscapes; no long-term hydrological monitoring is available as most research projects are short-term (in most cases not more than 5 years) and monitoring or further observation cease before or at the end of the project time; government institutions do not have a long-term plan on hydrological monitoring - especially on groundwater recharge, spring discharge and sediment concentrations.

This study therefore used long-term monitoring in the Gule watershed, northern Ethiopia, with the objective to evaluate the effects of the different SWC and WH interventions on groundwater, sediment concentration in streams and drought resilience. The evaluation is based on up to ten years of groundwater (level and quality), spring discharge as well as sediment concentration and retention monitoring in different parts of the watershed.

Box 1

Definition of terminologies.

a) ***Water Harvesting (WH)*** is the collection and management of floodwater or rainwater runoff to increase water availability for domestic and agricultural use as well as ecosystem sustenance (Mekdaschi & Liniger, 2013).
b) ***Watershed management and development*** is the conservation, regeneration and the judicious use of the natural (land, water, plants, and animals) and human habitat within a shared ecosystem (geological, hydrological-aquatic and ecological) located within a common drainage system (UNEP, 2009).
c) ***Soil and Water Conservation (SWC)*** is defined as activities at the local level which maintain or enhance the productive capacity of the land in areas affected by, or prone to, degradation (WOCAT, 2007).
d) ***Groundwater recharge*** is defined in a general sense as the volume or process of downward flow of water reaching the water table, forming an addition to the groundwater reservoir (de Vries & Simmer, 2002).
e) ***Static groundwater level*** refers to level at which water stands in a well or unconfined aquifer when no water is being removed from the aquifer either by pumping or free flow (Driscoll, 1986).

2. Materials and Methods

2.1. Characteristics of the area

The study area, Gule watershed, is located in Tigray National Regional state, Northern Ethiopia; bounded by the coordinates 13°51′59″-13°54′40″N and 39°27′16″-39°29′49″E and has a catchment area of around 12 km^2 (Fig. 1).

With regard to hydro-meteorological data, Wukro station (located at 35 km from the study site) was considered to represent the study site for several reasons: (a) it is the closest station with continuous long-period records of rainfall, (b) it has similar altitude to the study site (elevation 1900–2600 m asl), and (c) except for small hills in between there are no major mountain ranges between Wukro station and the study site. Hydro-meteorological data of the area (ENMSA, 2020) for the years 1995–2019 (Wukro station) show that: (a) the main rainy season is June to September, with minor rain in February to May. The mean annual rainfall of the study area varies from 370 to 758 mm with nearly uniform trend (Fig. 2a) with most of the rainfall being in the months June and September (Fig. 2b). The average daily temperature of the area ranges between 15 and 25 °C.

The study area has variable terrain characteristics: steep to cliff forming topography at the upper part of the watershed (elevation up to 2600 m a.s.l.), moderately steep to gentle at intermediate areas, and nearly flat terrain at the lower part (elevation 1900 m) of the study area.

The major land uses in Gule watershed include: (a) cultivable land (48.4%), shrubland (44.2%), grassland (6%) and woodland (1.4%). No major change in land use was observed between the years 2006 and 2019 except for a small decrease in shrubland (0.35%) and a slight increase in woodland (0.38%) as evaluated by digitizing high spatial resolution of Google Earth images, a method considered to be suitable for classification of land uses for small catchments (Grum et al., 2016; Hu et al., 2013) such as Gule watershed.

2.2. Evaluations of soil and rock properties in the watershed

Detailed mapping and evaluation of the properties of rocks and soils in the watershed was done in the field and laboratory. Soils and rock units with areal coverage less than 50 × 50 m were not considered for mapping. Similarly, soils with depths less than 0.5 m were not mapped because they were considered to have little effect on groundwater dynamics at watershed level. For rocks, the lateral and vertical distributions, thickness, degree of fracturing, and degree of weathering was described from surface exposures, river/stream sections, and road cuts. Test pits with variable depths (ranging from 1.0 to 4.0 m) were excavated to determine the subsurface conditions of the area. A total of 18 soil samples were collected for measurement of texture in the laboratory. The saturated hydraulic conductivity of the unconsolidated deposit was determined in the field with the inverse auger-hole method (Kessler & Oosterbaan, 1974). In areas with very rapid fall of water in the auger-hole (in sandy/gravely soils) the saturated hydraulic conductivity of the soils was estimated from gradation curves using the empirical equation proposed by Hazen (1911). Evaluation of the overall hydrogeology of the area was done based on hydraulic properties of soils, degree of fracturing of rocks, distribution (lateral and vertical) of the major soil and rock units, and assessment of the hydraulic connectivity of the different units and the overall recharge-storage-discharge conditions in the watershed.

2.3. Assessment and evaluation of implemented interventions

The technologies implemented, the approaches followed and the implementation phases of the interventions prior to 2012 were assessed based on: (a) review of previous works from various sources which include published papers, unpublished reports (from government offices, NGO's and donors), and (b) discussions with local communities and decision makers at various government levels. For the interventions implemented after the year 2012, a fully participatory approach of technology selection, assessment and evaluation was adopted.

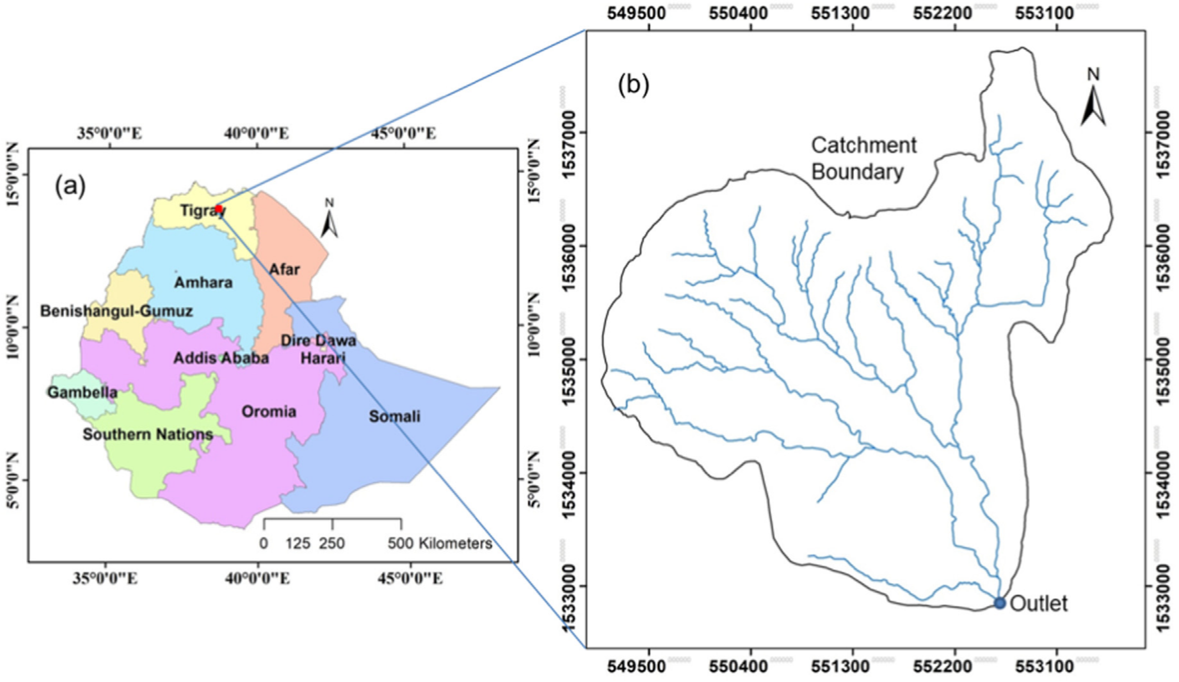

Fig. 1. Location of the study area: (a) regional states of Ethiopia, (b) Gule watershed.

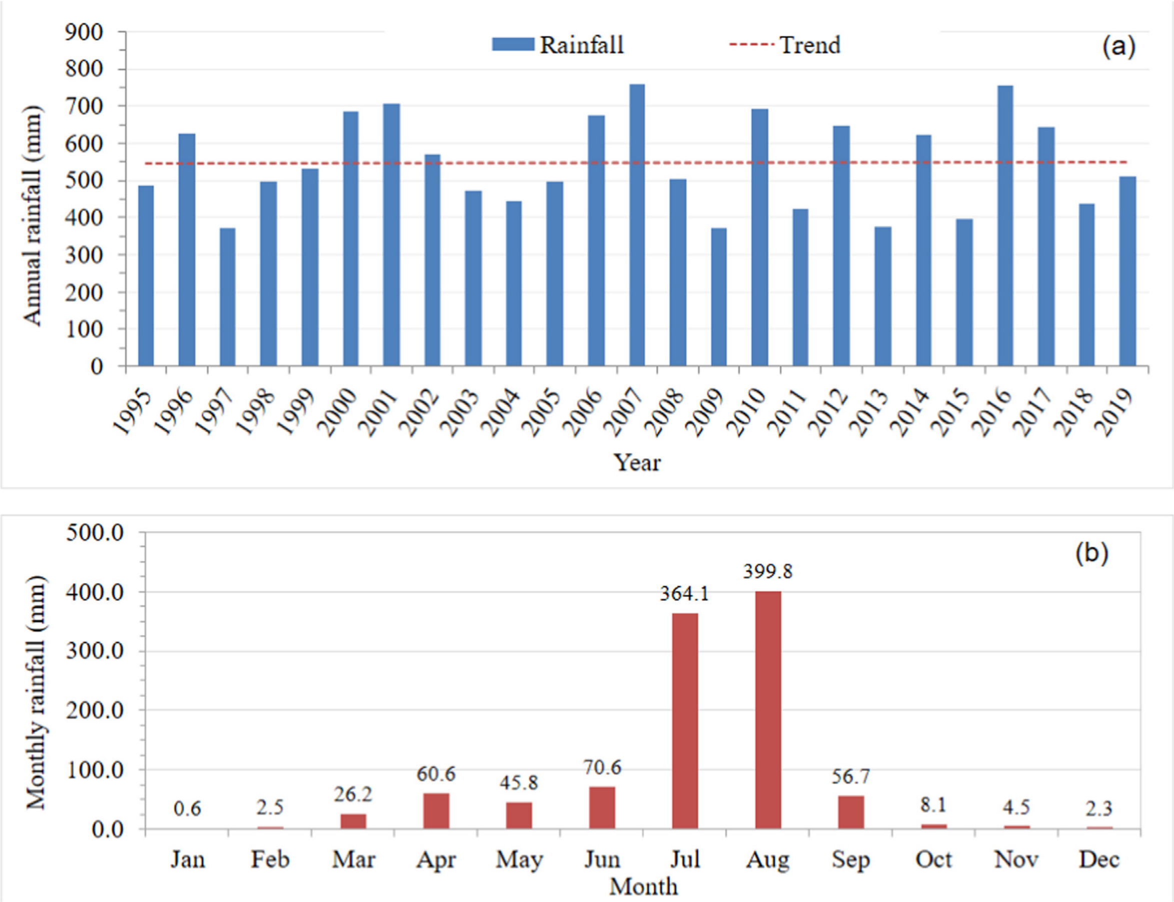

Fig. 2. Rainfall of the study area (from Wukro station) for the years 1995-2019 (ENMSA, 2020): (a) Annual rainfall (mm) and its trend; (b) Monthly rainfall (mm).

Knowledge-based participatory stakeholder involvement in SWC and WH allows for semi-quantitative assessment (Fleskens et al., 2014; Schwilch et al., 2012) and combines modern approaches with indigenous traditional knowledge and instils cultural identity (and hence social cohesion) through the process of participation (Schwilch et al., 2012; Stringer & Reed, 2007). With this approach, four rounds of participatory stakeholder workshops were organized at the study site with different objectives: to identify the major watershed management related problems, prioritize areas of interventions, select appropriate technologies and share responsibilities for further implementation (Round 1; year 2012); to evaluate the performances of interventions implemented in 2012–2014, as part of the co-learning and knowledge sharing process (Round 2; year 2014); to evaluate the performance of the interventions implemented in the previous years and their effect in addressing the worst drought of 2015/2016 (Round 3; 2016); and to identify key intervention areas for further agricultural intensification and livelihood diversification as well as evaluate the long-term sustainability of the interventions implemented before this year (Round 4; 2018). In addition to stakeholder workshops, focus group discussions were carried out with elders and other people who have good knowledge on the long-term hydrological history of the watershed.

The WH structures were inventoried individually while the SWC measures were inventoried as areal coverage. These were implemented for various purposes: (a) stone bunds, deep trenches, percolation pits: to enhance the dual function of sediment retention and groundwater recharge (Grum et al., 2017), and (b) exclosures: for the rehabilitation of degraded land, production of grass for fodder and thatching, wood for fuel and construction and non-wood forest products such as honey (Babulo et al., 2008; Desta et al., 2005). In Gule watershed, several types and sizes of check-dams have been implemented across streams and rivers: these are structures built across a channel or gully to interfere with flows in channels and are used to meet a variety of objectives such as to reduce sediment delivery, conserve floodwater, decrease the channel slope gradient and allow water percolation to recharge aquifers (Hassanli & Beecham, 2010).

In this study, check-dams (stone or gabion) with sizes less than 0.5 m height are considered as part of the in-situ moisture conservation measures and are not inventoried individually. Percolation structures with storage capacity of less than 10 m^3 were considered as in-situ SWC measures and were not inventoried individually. Data pertaining to the purposes, dimensions/sizes, landscape positions and their functionalities were documented for the implemented SWC and WH interventions.

Gule watershed is a typical example of watersheds in Tigray whereby SWC and WH interventions were implemented through trial and error in earlier phases but in well planned, participatory and evidence-based projects in later phases. A summary of the different phases and the major technologies implemented is presented in Table 1.

2.4. Monitoring the level, quality and yield of groundwater

The relationship between watershed management and groundwater recharge is an emerging concept for climate change adaptation. Groundwater recharge is the downward flow of water reaching the water table, forming an addition to the groundwater reservoir (Lerner et al., 1990). It is derived from precipitation

Table 1
Summary of the soil and water conservation (SWC) and water harvesting (WH) implementation phases in Gule watershed.

Phase	Major activities implemented in the watershed	Reference
Phase I (1994–1995)	A groundwater well was developed in the downstream part of the watershed to a depth of 65 m and was monitored for one year, but later was abandoned because of its low yield (less than 0.5 L s^{-1}). The static water level (before pump test) was 45.3 m. There were no SWC and WH interventions in the watershed at the time.	CoSAERT (2002); Woldearegay (2009)
Phase II (1996–2000)	Some isolated SWC interventions (pits and terraces) were implemented in the watershed as demonstrations (mainly at plot level and some sections of the landscape).	Personal communication with local people
Phase III (2001–2008)	As part of the wider landscape restoration in Tigray, several interventions such as deep trenches, terraces, gabion check-dams were implemented by the government, mainly in the northern (upper) and western parts of the watershed. There was little attention on gully control and WH.	TBoARD (2009)
Phase IV (2009–2012)	More focus was given to WH using flood diversions and check-dam ponds. Two spate diversions were constructed: one in 2009 and another in 2011. Moreover SWC (mainly deep trenches with bunds) were implemented in the whole catchment. In addition, the government (in collaboration with NGO's) implemented two check-dam ponds for water storage.	TBoARD (2011); REST (2012); Woldearegay (2009)
Phase V (Early 2013)	Several partners collaborated and agreed to align their activities in the Gule watershed: Mekelle University (supported by WAHARA project), Wukro Saint Mary College, Relief Society of Tigray (REST) and local communities. Facilitated by the WAHARA project, the partners developed a comprehensive plan with clear roles and responsibilities for the different partners whereby Mekelle university took the lead for research and capacity building while the other partners took the lead for implementation on the ground. Previous interventions were evaluated and various technologies were selected for implementation.	WAHARA (2013)
Phase VI (2013–2016)	The planned and agreed interventions were implemented. This involved joint implementation, monitoring and evaluation of the interventions. The implementation, participatory monitoring/evaluation as well as capacity building components were supported by the WAHARA project which ended in 2016. In this period, Gule became a learning watershed and paved a way for further up-scaling initiatives by other projects.	Grum et al. (2017); Woldearegay et al (2015a)
Phase VII (2017–2019)	Different interventions continued to be implemented including constructions of sand dams. The site also became an up-scaling site for the "Africa RISING" project with more focus on agricultural intensification and livelihood improvement. Implementing partners, mainly Wukro Saint Mary college and REST, continued their interventions. Mekelle University and Center for Tropical Agriculture (CIAT) continued supporting the project through research and capacity building with finance from the "Africa RISING" project.	TBoARD (2019); Woldearegay et al. (2019)

recharge which may consist of piston flow and preferential flow (Huang et al., 2020). Precipitation infiltration could be dominated by fast pathways of influent flow, such as through fissures, worm burrows and root channels (Cai & Ofterdinger, 2016).

Understanding the groundwater response (level, quality and yield) to watershed management interventions (SWC and WH) is considered to be an instrument for addressing challenges due to rainfall variability. Proper evaluation of the interactions between watershed management and groundwater recharge could help to provide evidence on the significance of such processes for future design and implementation of better climate adaptation practices.

Two types of wells have been developed in the area: shallow open hand-dug wells and tube wells. The open hand-dug wells are mostly circular in shape (with top diameter up to 8 m) and are supported by masonry to avoid collapse and developed mainly for small-scale irrigation purposes. The shallow tube wells are mainly developed for domestic uses. The main source of recharge for these wells is subsurface flow from areas upstream of the wells; no recharge is expected from other adjacent catchments to the groundwater system in Gule watershed. Generally, there are no surface runoff flows into the wells. In the open hand dug wells some recharge, though not the main factor, is expected from direct precipitation.

The level and quality of groundwater varies with season depending on the rate of abstraction and recharge. One of the major challenges in groundwater monitoring was lack of baseline data before the interventions. In this research, 4 groundwater wells, namely W1–W4 (Fig. 3) were considered for monitoring as there was some data (before the interventions) from previous work (Woldearegay, 2009, 1998). Static groundwater level measurements were carried out every month (mid of month: mostly between day 14–18) in wells using measuring tapes. The measured data was compared with previously recorded groundwater levels.

The quality of groundwater was monitored in order to assess any change due to the interventions. Groundwater samples were collected from the wells and analyzed in the laboratory for total dissolved solids (TDS) using gravimetric method and compared with records of groundwater quality before the interventions. The groundwater sampling period for TDS determination was adopted based on the data presented by Woldearegay (2009) whereby he monitored the groundwater quality of 48 wells in Tigray for one year and found higher TDS values when the groundwater level has the lowest level and lower TDS values when the water level rises to its maximum level. Based on this TDS measurement was carried out in May (for higher concentration) when the static water level is low, and October (for low concentration) when the static water level reaches its highest level. This was validated by taking monthly measurements of the TDS values of two wells for the years 2010, 2016 and 2018 which gave similar results to previous findings: higher TDS in the months May to June and lower TDS in the months October to December.

Out of a total of 68 groundwater wells inventoried in the watershed in 2016 (Fig. 3), yield evaluations were carried out on 24 representative wells (including the monitored ones). The evaluation was carried out in April to May 2016, when the area was affected by drought. For open hand dug wells ($n = 20$), a sludge test method (Bouwer & Rice, 1976) was applied, and for the tube wells ($n = 4$) pumping test method (Kruseman & de Ridder, 1994) was used. For the monitored wells, the yields after the watershed management intervention was compared with previous records before the interventions.

2.5. Monitoring spring discharge

Spring discharge is expected to vary with season as it is recharged from rainfall. A total of 7 springs were inventoried in the watershed. Springs were classified based on the work of Meinzer (1923) for their characteristics of points of issue and lithology of

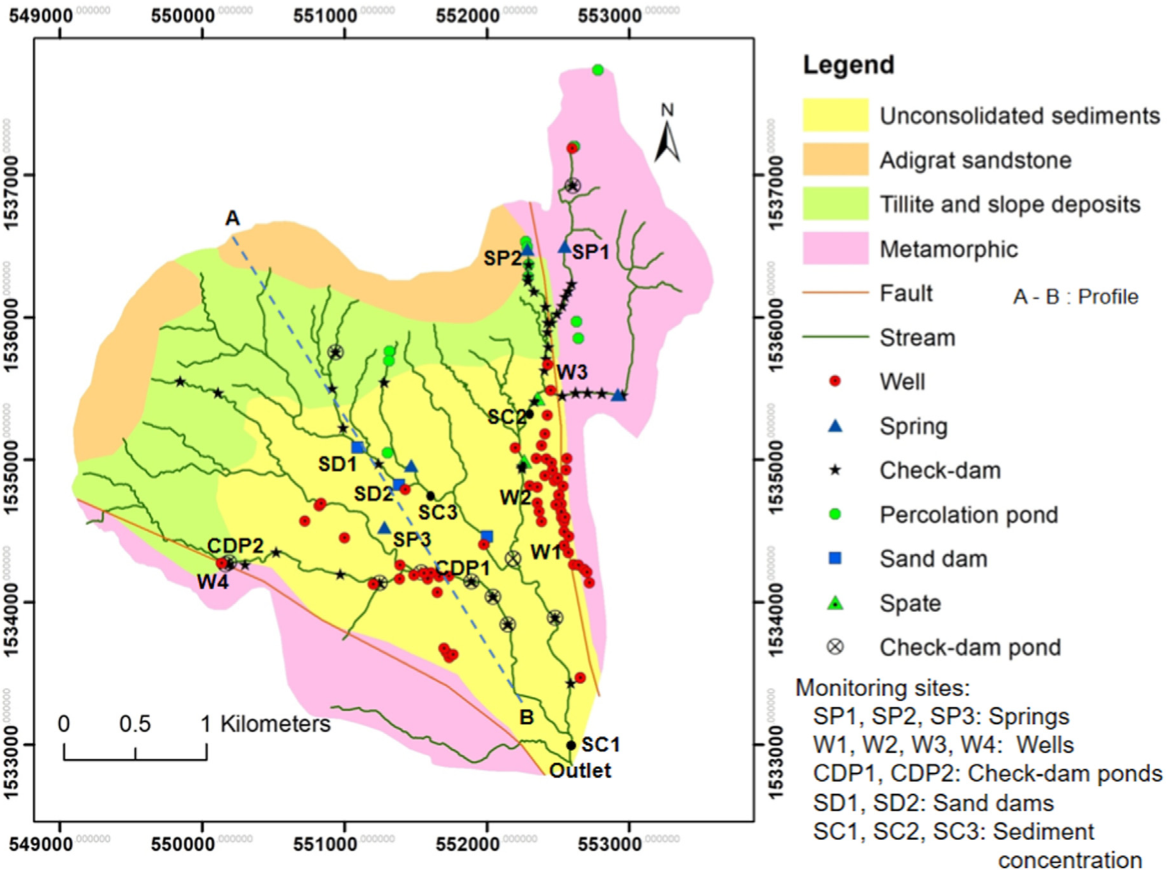

Fig. 3. Major soil and rock types, implemented water harvesting technologies and hydrological monitoring sites in the Gule watershed.

aquifer. Out of these, only 3 were monitored as there was baseline information. The discharge was measured monthly (mid of month) using the bucket method (Inversin, 1986) which involved recording the amount of time required for the discharge to fill a bucket. This method is recommended to be applied for discharges less than about 4 L s^{-1} (Inversin, 1986). The measured discharges of the springs were compared with previous records.

2.6. Monitoring sediment concentration

One of the expected effects of watershed management and other WH practices is reduction in sediment concentration of surface runoff. Three sites were considered for monitoring as there was prior information (before the intervention) on the sediment concentration. Water samples were collected with a storm-chasing approach, where more samples were taken when water level and turbidity were rapidly changing and up to three samples were collected from each flood. The samples were analyzed for suspended sediment concentration (SSC) in the laboratory using the evaporation method (Guy, 1977). The SSC in g L^{-1} of each sample was determined as the mass of suspended sediment divided by the sample volume. The maximum SSC value for each year is used to compare variations in SSC over the years.

3. Results

3.1. Major types of interventions implemented in Gule watershed

As can be noted from Table 2, the SWC measures inventoried include stone bunds, deep trenches, percolation pits, and exclosures. Deep trenches were constructed from the upslope to the lower sections of the watershed. The inventoried check-dams are categorized into two: gabion check-dams which were implemented mainly as erosion control measures, and check-dam ponds which were implemented mainly to store water for different purposes. Other WH inventoried in the study site are spate irrigation systems in which flood water is emitted through normally dry wadis and conveyed to irrigable fields (Mehari et al., 2007). Moreover, several percolation pits and ponds as well as groundwater wells and springs were inventoried. A summary of the different SWC and WH interventions is presented in Table 2 and examples of the different interventions implemented at various levels of the landscapes are shown in Fig. 4.

3.2. Hydrogeology of the watershed

The major rocks in the area include (EGS, 2002; Kazmin, 1972, 1975; Mohr, 1967; Mohr & Zanettin, 1988): metamorphic rocks, Edaga Arbi Tillite, Adigrat Sandstone, and unconsolidated sediments (Table 3; Fig. 3).

Results of the detailed hydrogeological characterization of the rocks and soils of Gule watershed revealed that the area is generally favourable for groundwater recharge and storage for several reasons (Table 3; Fig. 5).

- Concave nature of the terrain whereby surface and sub-surface flow converges into the flat downstream area which is dominated by unconsolidated deposits.
- Presence of moderate to high permeability and infiltration capacity of rocks and soils at the upper part of the watershed

Table 2
Major soil and water conservation (SWC) and water harvesting (WH) technologies implemented in Gule watershed.

Type of technology	Purpose	Areal coverage (ha%)/Quantity (n)	Size/dimension	Landscape position	Year of implementation
SWC	Reduce erosion and enhance soil moisture	1.4% of the catchment		Along the whole landscape	2001 to 2015
Exclosures	Vegetation growth/ natural regeneration	2.5% of the catchment		Along the whole landscape	2001 to 2019
Gabion check-dams	Gully treatment and groundwater recharge	56	Crest length: 2–7 m; height: 2.1–4 m	Gully affected streams/rivers	12 prior to 2012; 44 in the years 2013–2019
Check-dam ponds	Surface water storage	12	Crest length: 18.3–25.5 m; height: 2.7–3.5 m.	Streams at lower part	2009–2013
Spate diversion	Flood diversion	2	Crest length: 14.2 m–21.5 m; height: 3.6–3.7 m	Streams at middle and lower part	2009–2012
Percolation ponds	Surface water storage	12	Width: 8–18; length: 12–18 m; depth: 1.8–3.5 m	Where there is space for pond construction	2009–2019
Sand dams	Store sand and groundwater	3	Crest length: 25–32 m; height: 2.5–3.2 m	Streams at lower part of the landscape	2018–2019
Shallow groundwater wells	Irrigation, livestock and domestic use	74	Depth of tube wells: 37–52 m; depth of hand dug wells: 6–15 m.	Areas with good potential for groundwater (mainly at lower areas)	Started in 1995. More productive wells developed since 2010.
Springs	Irrigation, livestock and domestic use	7		Areas where springs have emerged	Non-perennial springs observed since 1995

Note: SWC include all in-situ WH technologies such as stone bunds, deep trenches, percolation pits. n = number of structures.

Fig. 4. Examples of the interventions at different parts of the landscapes: (a) SWC at upper sections of the landscapes, (b) gabion check-dam integrated with biological measures, (c) sand dams for sediment and groundwater storage and recharge, and (d) shallow groundwater wells developed at lower parts of the landscapes.

Table 3
The hydrogeological properties of rocks and soils in the Gule watershed (modified after EGS, 2002).

Lithology	Description
Metamorphic rocks	Metamorphic rocks are dominantly metavolcanic type, with thin intercalations of meta-sediments. Meta-sediments are black/graphitic or variegated colored, fine grained, highly foliated (spacing 0.07—0.4 m), jointed (spacing 0.13—0.85 m) slates/phyllites with some calcareous sediments. The meta-volcanics are green to purple colored, fine to medium grained, jointed (spacing 0.3—1.7 m). These metamorphic rocks have variable degree of fracturing depending on topography: in steeper terrains they are fractured to about 10 m depth and in flat terrains they are fractured up to 30—40 m depth.
Tillites with slope deposits	Tillites display high variation in their properties and are generally represented by grey to black sand-silt-clay matrix, interbedded with thin layers (thickness 0.06—0.18 m) of silty limestone, and poorly sorted pebbles and boulders (measured size up to 4.5 m diameter). The weathered and fractured Tillites have moderate permeability while the less weathered ones (at depth) have low permeability. Overlying the Tillites are slope deposits (coluvials and debris deposits) which are highly heterogeneous materials (silt, sand, gravel and boulders) and their overall permeability is considered to be high. At greater depth, the permeability of these rocks is low.
Adigrat sandstone	These rocks are cliff forming and are exposed at the upper part of the watershed and are characterized by red to brown, medium to coarse-grained, slightly to moderately weathered, horizontally bedded (thickness 0.5m-2.8 m), jointed (spacing 0.7—3.5 m) rock with characteristic block size varying between 0.8 and 12.5 m^3. The major joints in these rocks are vertical or sub-vertical. During rainy season, springs emerge at the contact between the cliff forming sedimentary rocks and the underlying Tillites. The geomorphological expression of Adigrat sandstone is ridge forming and it acts as recharge zones to the downstream areas.
Unconsolidated deposits:	These are mapped in the flat areas of Gule watershed. As confirmed from grain-size analysis of samples collected from different locations, these soils are dominantly silty sand to sandy silt with silty clay and sandy clay in limited cases. The measured thickness of the soils (from groundwater well logs, gully sections and test pit excavations) vary from 0.50 m to 12 m. Permeability of these unconsolidated soils was found to range between 2.5×10^{-3} to 4.7×10^{-5} cm s^{-1} which indicate moderate to high permeability. The unconsolidated deposits are in most areas underlain by Tillites and Metamorphic rocks.

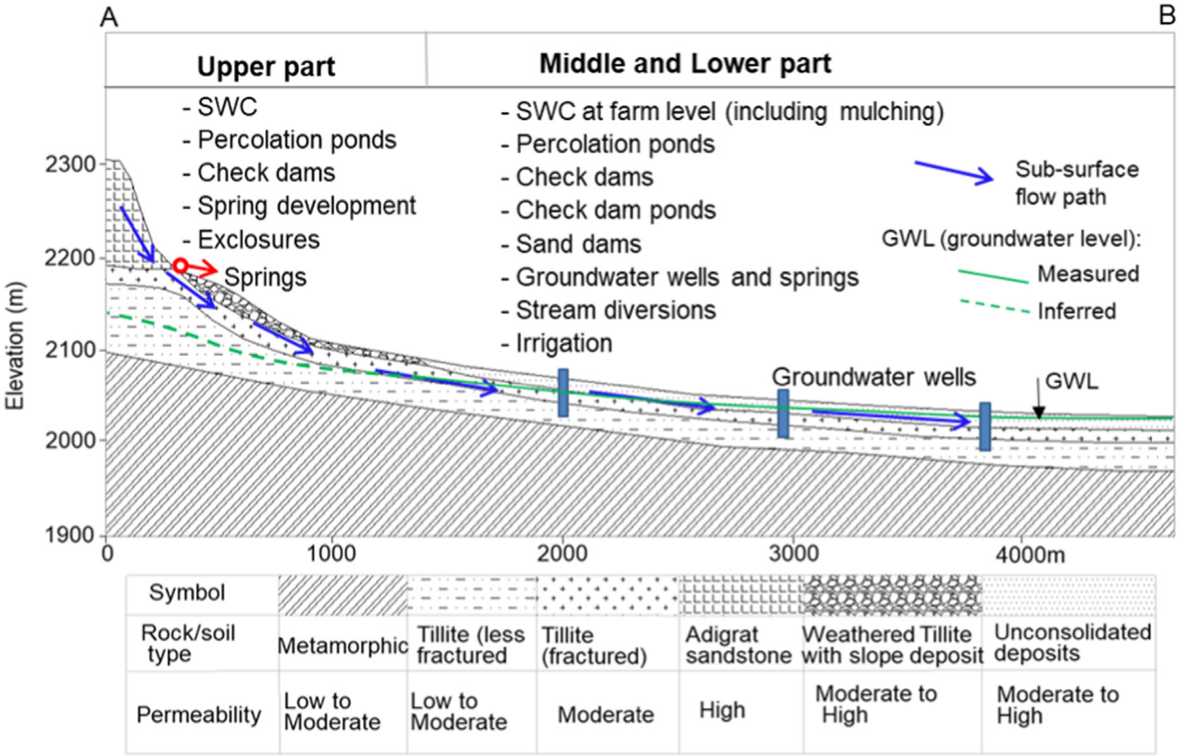

Fig. 5. Hydrogeological profile along A-B (Fig. 3), major interventions along the landscape and sub-surface flow path in Gule watershed (Modified after Grum et al., 2017). SWC: soil and water conservation. GWL (groundwater level) was measured in the months of April to May 2016 (worst drought period).

(mainly fractured Adigrat sandstone, the weathered Tillites with slope deposits, and weathered Metamorphic rocks) which act as recharge zones to the downstream areas.

- The presence of moderate to high permeability and infiltration capacity of soils and rocks at downstream areas favour water storage. The unconsolidated deposits have thicknesses of up to 12 m and are predominantly silty sand to sandy silt (with silty clay) with moderate to high permeability values.
- Presence of less fractured and low permeability rocks (Tillites and Metamorphic rocks) underlying the more permeable media which retard the deep infiltration and percolation of water and enhance groundwater storage at shallow depth.
- Implementations of different SWC and WH interventions at various parts of the landscapes which contribute to groundwater recharge at different scales.

3.3. *Effects of the interventions on shallow groundwater*

As confirmed through the hydrogeological evaluations, the soils and rocks at the lower areas of the watershed (unconsolidated sediments and the underlying fractured/weathered rocks) are acting as storages for shallow groundwater. Therefore several groundwater wells have been developed in these areas for different purposes: domestic use, small-scale irrigation and livestock watering. Due to increased water availability in the area, the average distance from homesteads to water points has decreased from 4.5 km in 1998 to 0.8 km in 2018 (TBoARD, 2017; Woldearegay, 2017). Furthermore, Teka et al. (2020) have reported improvements in water quality and health conditions of local communities.

Results of the yield tests (sludge and pumping tests) of 24 groundwater wells in the study area revealed that the yield varied from 1.4 to 4.5 L s^{-1} with a mean value of 2.5 L s^{-1}. All these groundwater wells remained productive during the year 2016 despite a major drought in the region.

In order to evaluate the long-term groundwater dynamics in the watershed, four shallow groundwater wells (W1–W4) were monitored for over ten years. Because the groundwater in the different wells has shown a similar response, results of two wells (W1 and W4) are discussed in detail and a summary is given for the others as presented below. Lithological logs of the four wells (EIGS, 1996; TBoWR, 2010) are presented in Fig. 6.

3.3.1. *Groundwater dynamics in well 1 (W1)*

In the year 1994/1995, a well was drilled to a depth of 65 m in the lower part of Gule watershed for rural water supply and was monitored monthly until January 1995; the well was found to be non-productive (yield less than 0.5 L s^{-1}) (Woldearegay, 1995). As part of a pre-feasibility study for dam construction in the Gule watershed (in the same location), groundwater was monitored for the year 2002 though the dam project was not implemented. In 2010, the groundwater monitoring resumed again in the area for assessing the potential of shallow groundwater wells for irrigation. Since 2013, continuous monitoring was carried out until 2019 as part of the long-term groundwater monitoring.

As can be noted from Fig. 7, in 1995 the maximum static water level was at 45.3 m in June and at a depth of 24.2 m in December. Monthly rainfall for some characteristic years (1995, 2002, 2015, 2016, 2018, 2019) (Fig. 8) show that though the rainfall was variable over the years (with most of rain being in the months June to September), the raise in groundwater level occurred in the months November to December. The groundwater response in the different years has been different: lower until 2010 and relatively higher after 2013. The recharge between 1995 and 2010 is believed to be the combined effect of the interventions implemented in phase III (Table 1). Since 2013, the groundwater level has risen significantly to 2.6 m below the surface during the dry period and about 1 m during the rainy season. With regard to yield, W1 has improved from non-productive (less than 0.5 L s^{-1}) in 1994/1995 to 3.5 L s^{-1} in 2016 (during the worst drought in the region).

Groundwater quality, described by TDS, was found to vary with seasons and with interventions over the years (Fig. 9). In the year 1995, TDS was 1230 mg L^{-1} in May (when the water level was lower) and 890 mg L^{-1} in October (when the water level was high due to recharge of the preceding rainy season). With increase in the various SWC and WH interventions, TDS has continued to decrease

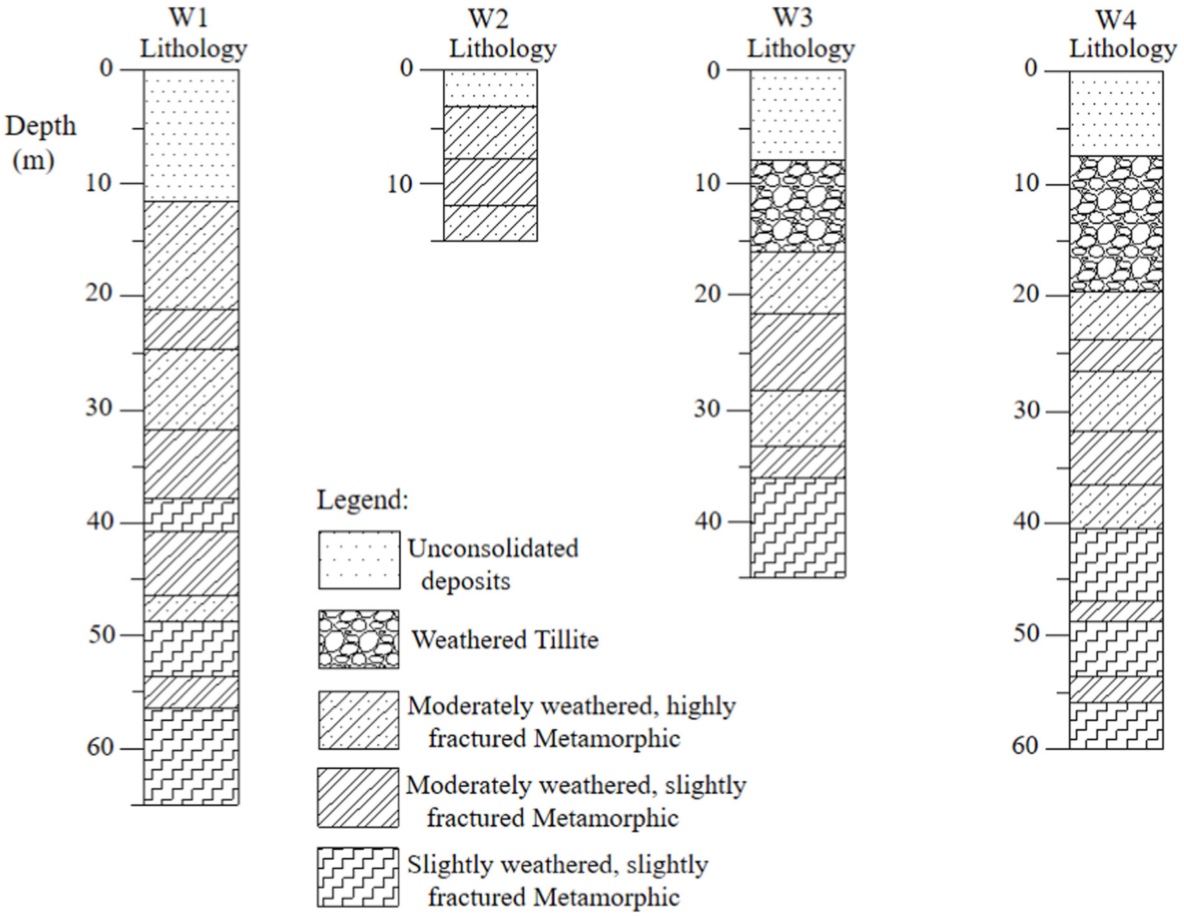

Fig. 6. Geological logs for the different monitored wells (W1-W4) in Gule watershed: W1 (EIGS, 1996); W3 & W4 (TBoWR, 2010).

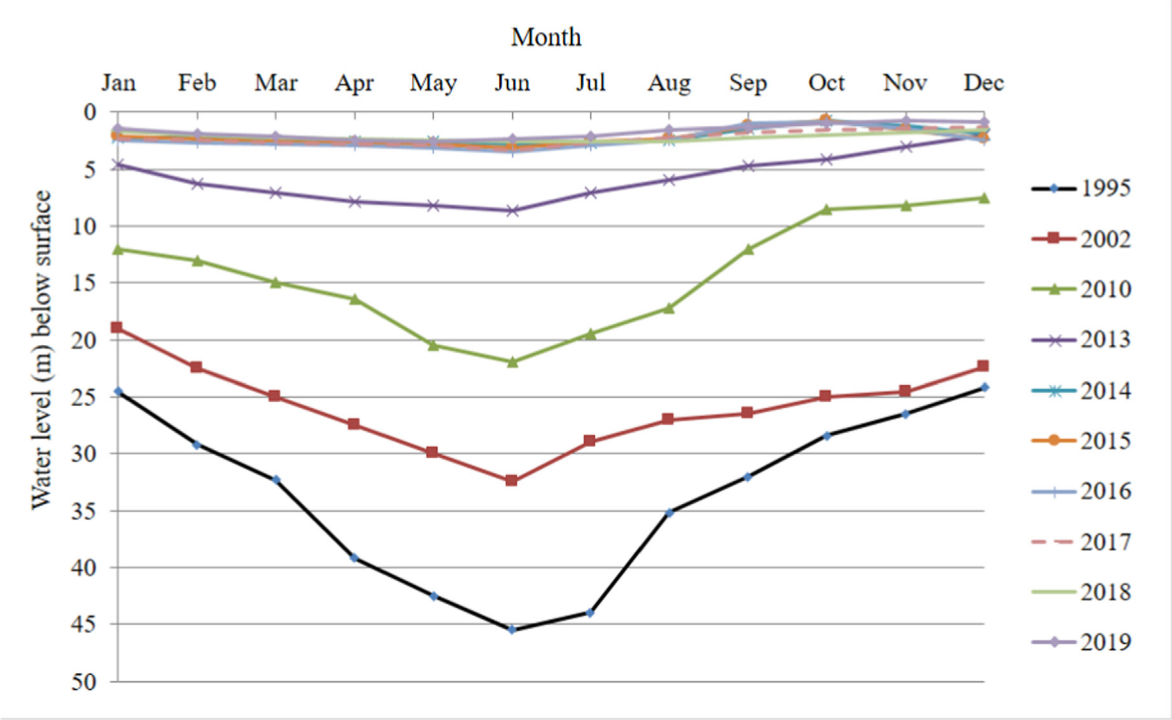

Fig. 7. Variation in groundwater level (W1) for the years 1995, 2002, and 2010-2019 in Gule watershed.

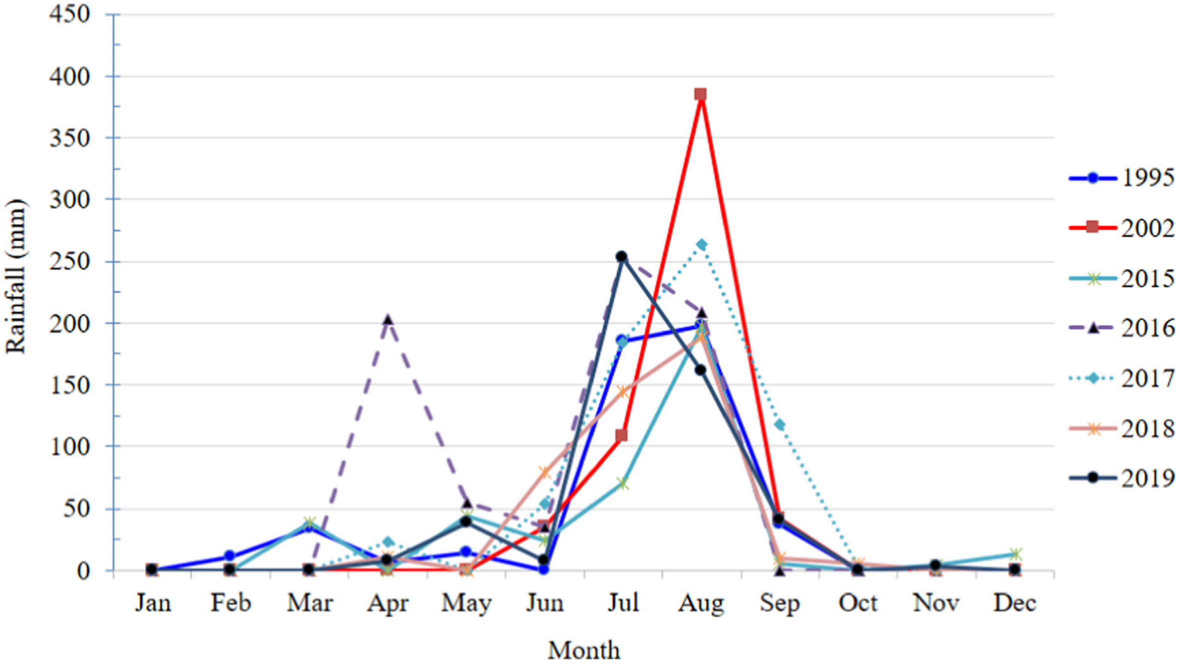

Fig. 8. Daily rainfall for characteristics years (1995, 2002, 2015, 2016, 2018, 2019) for the study area (from Wukro station (ENMSA, 2020).

over the years. In the year 2019, TDS was measured to be 630 mg L^{-1} in May and 550 mg L^{-1} in October. The decrease in TDS concentration is believed to be due to an increase in groundwater recharge in the area.

3.3.2. Groundwater dynamics in well 4 (W4)

Well 4 (W4) was drilled in 2010 to a depth of 60 m and the first water strike was at 50 m. The well was left undeveloped because of its low yield (0.5 L s^{-1}) and only one measurement of groundwater level was taken in 2010. In 2014, a check-dam pond 2 (CDP2) was constructed close to the well in order to store surface water for livestock and small-scale irrigation. In the same year, the check-dam pond was totally silted-up and hence acted as a sand dam (Fig. 10). Monitoring of groundwater level showed an improvement in 2014. Additional interventions continued in the years 2015–2017 upstream of the check-dam pond mainly through construction of

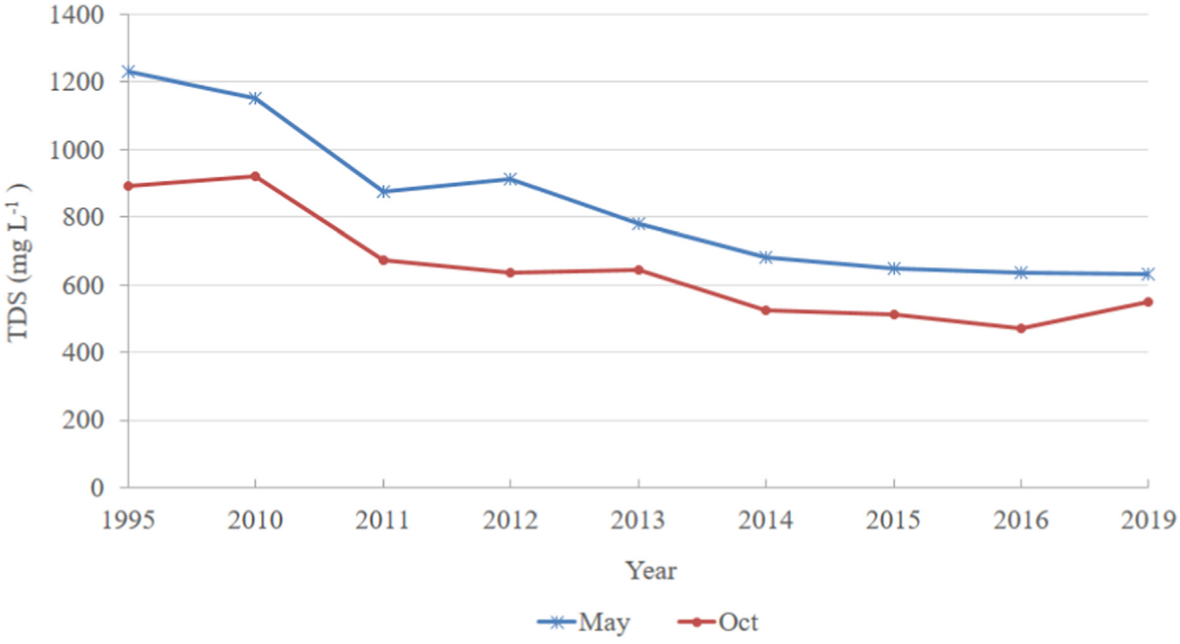

Fig. 9. Variations in TDS of W1 for the years 1995, 2010-2016, and 2019 in Gule watershed.

deep trenches and percolation pits. Due to the combined effects of the interventions (construction of check-dam pond and upstream intervention), the static groundwater level in W4 has risen from 50 m in 2010 to 14.5 m in 2018 (in the dry season) (Fig. 11). Moreover, the yield for W4 has improved from 0.5 L s^{-1} in 2010 to 4.1 L s^{-1} in 2016 (during the drought period).

3.3.3. Groundwater dynamics for other monitored wells (W2 and W3)

W2 has a depth of 15 m and the static water level during excavation in 2007 was at 10 m below the surface. In the year 2009, a spate diversion structure was constructed upstream of this well. Improvement in groundwater level was observed after the construction of the spate diversion though the major recharge was found to be after 2013 when several check-dams and percolation ponds were constructed upstream of this well. In 2019, the maximum groundwater level was found to be 5.2 m below surface during the dry season and the minimum water level (below surface) was 2 m during the rainy season. The water quality has also improved from 1120 mg L^{-1} during the month of May in 2008 to 834 mg L^{-1} during the same month in 2019. Similarly, TDS has decreased from 910 mg L^{-1} in October 2008 to 520 mg L^{-1} in October 2019. In relation to yield, W2 has improved from 0.7 L s^{-1} in 2007 to 2.8 L s^{-1} in 2016 (during the worst drought).

For W3 drilling was carried to a depth of 45 m (with first water strike at 42.5 m) in 2010. Result of the pump test showed the well to be non-productive and only one measurement was taken in the year 2010. With implementations of several SWC and WH upstream of the well, the groundwater level has improved remarkably until the year 2019: to 8.4 m during May and to 4.2 m during December. TDS has also improved as a result of the interventions: from 1070 mg L^{-1} in May 2013 (low groundwater level) to 815 mg L^{-1} in May 2019. Similarly, the TDS has decreased from 715 mg L^{-1} in October 2013 to 566 mg L^{-1} in October 2019. In terms of yield, W3 has improved from dry condition in 2010 to 2.5 L s^{-1} in 2016 (during the worst drought).

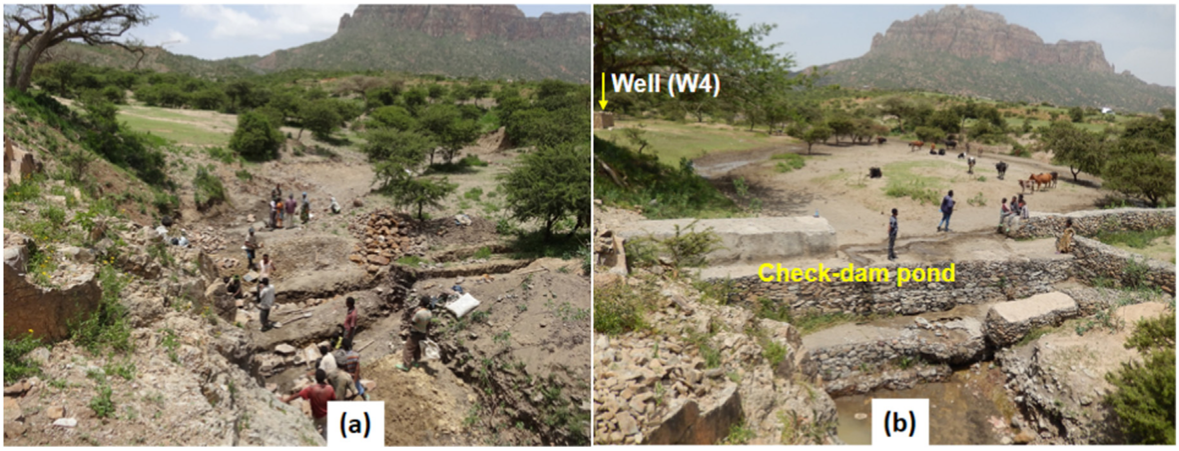

Fig. 10. Check-dam pond constructed in 2014 to store surface water: (a) during construction (cut-off trench excavation), and (b) after construction (silted-up) and acting as sand dam.

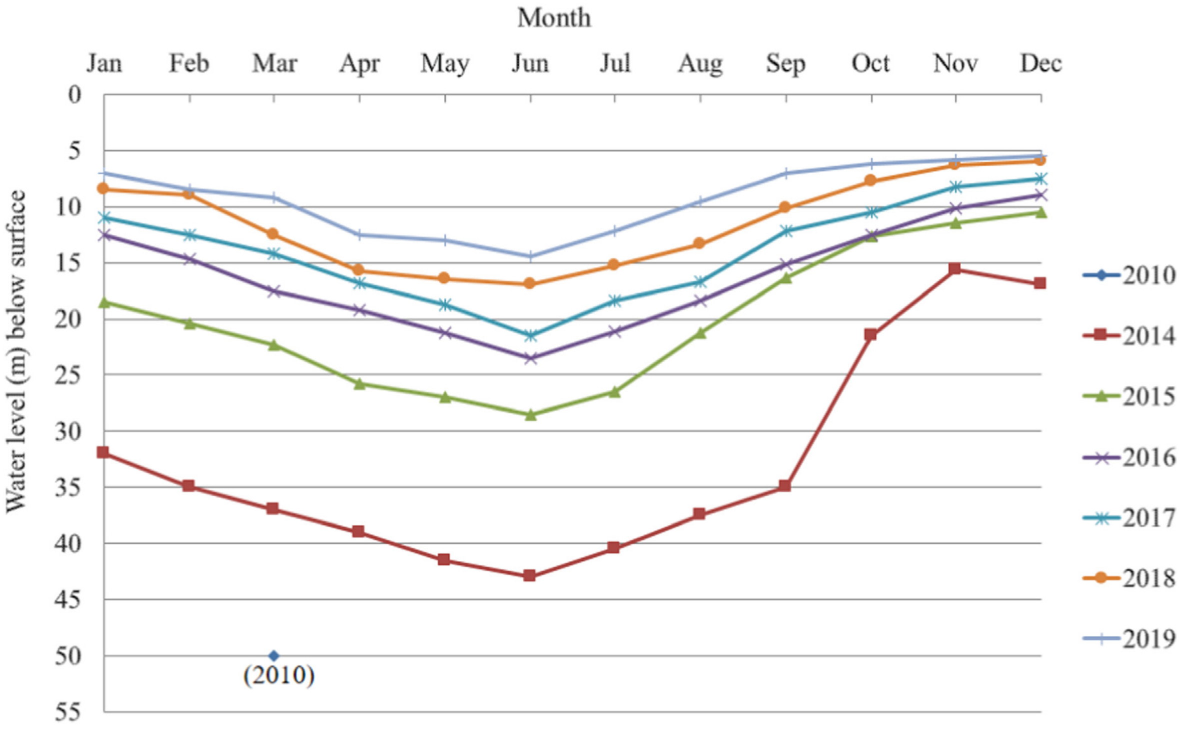

Fig. 11. Variation in groundwater level in well 4 (W4) for the years 2010 and 2014-2019.

3.3.4. *Variation in groundwater response of the wells to watershed management*

The four monitored wells (W1—W4) have shown variations in the rate of increase in groundwater levels over the years. Though the main rainy season in the study area occurs from June to September, maximum raise in groundwater level of the wells was recorded in October to November, which is similar to what was recorded in other watersheds (Woldearegay et al., 2018). With regard to groundwater quality, all the wells have shown higher TDS values in the dry seasons (when the water level is low) and lower values when the water level attains a higher level which is believed to be due to recharge.

The monitored four wells are located at different parts of the landscapes (Fig. 3): W1 is located downstream of all the monitored wells followed by W2 and then W3. Annual average groundwater levels in the different wells (Fig. 12) show improvements in groundwater level after the interventions though the rate of recharge seems to vary: higher improvements in W1 followed by W2. The variations in the rate of groundwater recharge in the various wells could be due to one or a combination of, among others, the following factors: (a) the size of the recharging area: W1 is believed to be receiving more recharge from a larger area followed by W2, (b) variations in hydraulic conductivity of the subsurface media (soil and rock) and the connectivity of the wells to the recharging water, and (c) locations, types and effectiveness of the interventions on enhancing recharge to the wells.

The groundwater responses of the wells (especially W2—W4) show that shallow groundwater systems quickly respond to recharge if appropriate technologies are selected and properly implemented. Shallow groundwater recharge could therefore be considered as time and scale independent: (a) it could be recharged for a single well or at watershed scale, and (b) the response could be fast (few months) for a single shallow well or longer for recharge at watershed level.

With regard to the effects of rainfall, despite its variability over the years, the groundwater level have significantly increased due to the watershed management interventions. However, with the same watershed management intervention, the groundwater level was found to positively correlate with the amount of rainfall in the preceding months. Higher rainfall has resulted in slightly higher recharge and lower rainfall has resulted in slightly lower recharge following the rainy period, though the groundwater level of the wells is still higher than the level before the watershed management interventions. This could indicate that though rainfall amount in preceding months have some influence on groundwater recharge, the dominant factor is the intervention implemented.

3.4. *Effects of the interventions on spring discharge*

Implementation of SWC and surface water storage could enhance spring discharge in downstream areas. During the rainy seasons, emergence of springs is common in Gule watershed, especially in areas with topographic breaks and in sites where soils and rocks with lower permeability underlay higher permeability ones. Based on Meinzer's (1923) classification, out of the 7 springs inventoried in the watershed, 5 are contact springs and 3 are depression springs. For the purpose of monitoring, only three springs were considered because for these there were historical data and because they have significant discharge which was used for off-season and supplementary irrigation. Results of the monitoring for the three springs are discussed below.

3.4.1. *Dynamics in discharge of spring 1 (SP1)*

SP1 is one of the most significant springs in Gule watershed. In the year 1995, the spring was mainly used for drinking purposes especially for communities living in the upstream part of the watershed. SP1 used to be dry in April to June. Monitoring was carried out for the years 1995, 2007 and 2013 to 2019 (Fig. 13). Several SWC measures were implemented upstream of SP1 in the years 2001—2008 and 2011 to 2013 which included deep trenches, percolation pits/ponds. As a result, significant improvement in spring discharge was observed in the year 2015. Realizing the

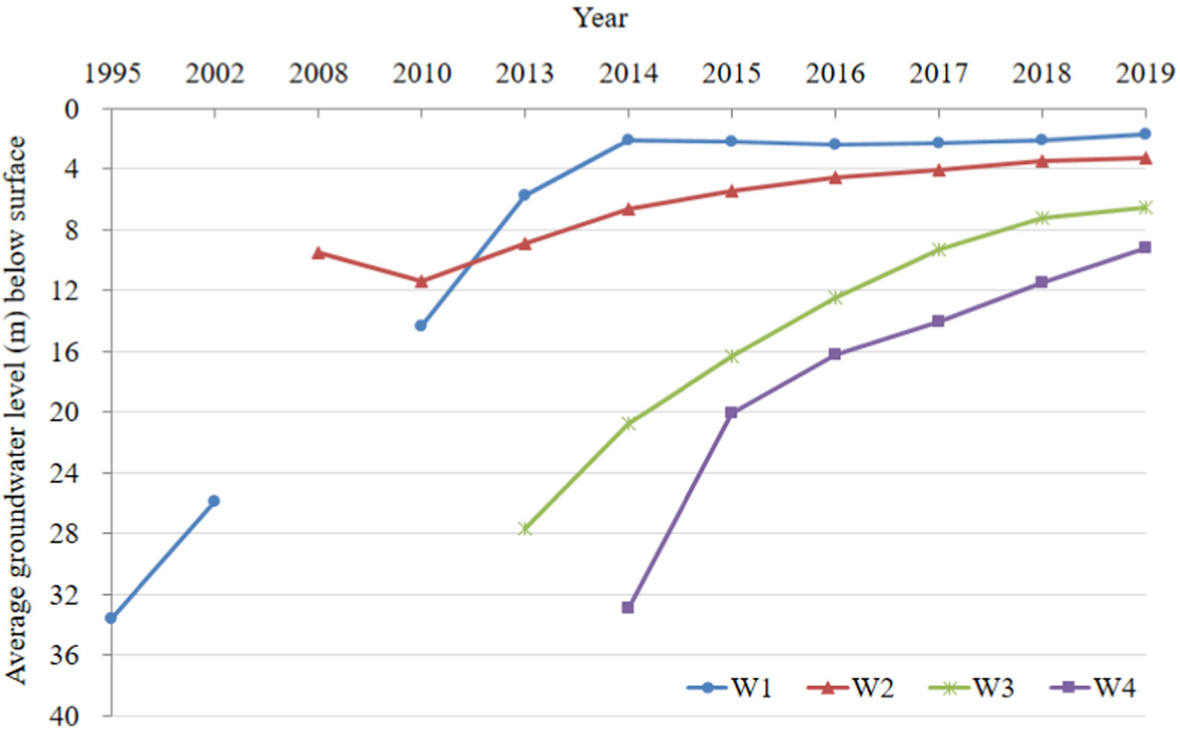

Fig. 12. Average annual groundwater level in the four monitored wells.

importance of constructing upstream recharge systems for enhancing spring discharge, as there was still excess runoff from upstream areas, two check-dam ponds were constructed upstream of SP1 in 2015 (February to May). This has further enhanced the discharge of SP1 in the years 2016–2019. Due to the effects of the interventions on SP1, this spring discharge increased to over 75 L min^{-1} in 2019. As a result, irrigation is being promoted with water from the spring by integrating appropriate water management interventions which includes construction of night storage structures and lining of irrigation canals. In 2019, for example, 1.5 ha of land was irrigated (off-season) in the upper part of Gule watershed with water from SP1 only.

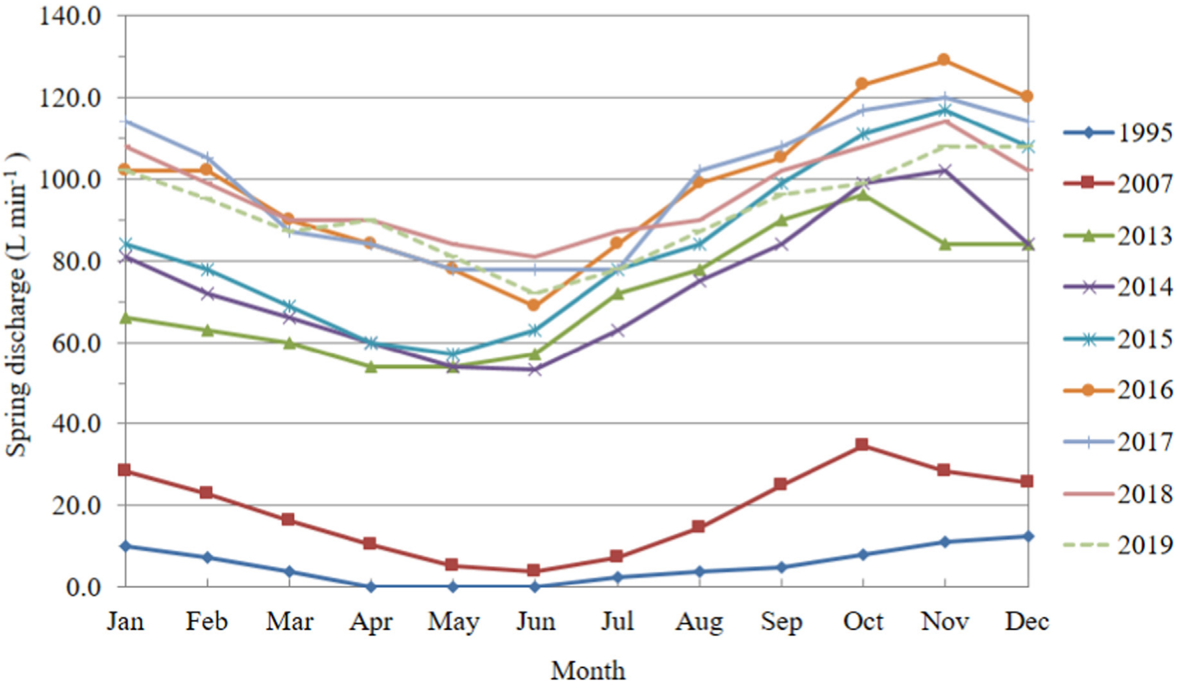

Fig. 13. Variation in discharge (L min^{-1}) of spring 1 (SP1) in Gule watershed.

3.4.2. *Dynamics in discharge of spring 2 (SP2)*

Before 2013, spring 2 (SP2) used to be dry from January onwards. In May to June 2013, two percolation ponds were constructed upstream of SP2. The discharge of SP2 has significantly improved starting in September of the same year (Fig. 14). In the years 2014–2015, some SWC interventions were constructed upstream of SP2. The effects of the interventions have enhanced the discharge of SP2 and this has created an opportunity for smallholder farmers to practice small-scale irrigation.

3.4.3. *Dynamics in discharge of spring 3 (SP3)*

SP3 is one of the springs used for small-scale irrigation and drinking. Results of monitoring for the years 2012–2019 showed significant improvements in spring discharge (Fig. 15). Unlike SP1 and SP2, no intervention was implemented which specifically targeted recharge of SP3. The effects of the various interventions which were constructed in upstream areas which include SWC, percolation ponds, and sand dams are nevertheless believed to have contributed to enhancing the discharge of SP3. SP3 used to dry in April and May until 2012 but has become productive after 2014. After 2016, the discharge during the dry period has not reduced below 30 L min^{-1} despite high rainfall variability in the area.

3.4.4. *Variation in discharge of the monitored springs due to watershed management*

In all monitored springs, discharge was found to vary with season: higher discharge was recorded in October to November and lower during the late dry season (May to June). Before the interventions, the monitored springs used to dry or have very low yields during the dry seasons (April to May). Results of the monitoring show that spring recharge could be carried out at any scale and duration. For example, a SP2 was recharged by two percolation ponds and deep trenches in one rainy season. The discharge of the springs has shown an overall increase despite some variability. This indicates the importance of implementing appropriate recharge systems for enhancing spring discharge at various scales for addressing challenges related to rainfall variability.

The monitored three springs showed variations in their response to rainfall variability, with higher discharge variability for SP2 than for SP1 and SP3. The recharge area for the three springs is variable with a smaller area for SP2 than for the others. The high variability in spring discharge for SP2 is believed to be due to the relatively smaller recharge area and hence a higher sensitivity to rainfall variability. On the other hand, SP1 and SP3 have relatively larger recharge areas and this is believed to be contributing to the relatively lower sensitivity to rainfall variability as compared to SP2.

In relation to the effects of rainfall, despite its variability, the discharge of the springs have significantly increased due to the watershed management interventions. However, with the same watershed management intervention, the discharge of each spring was found to positively correlate with the amount of rainfall in the preceding months. Higher rainfall has resulted in slightly higher spring discharge and lower rainfall has resulted in slightly lower discharge following the rainy period, though the discharge of the springs is still higher than before the watershed management interventions. This indicates that though rainfall amount in preceding months have some influence on the spring discharge in the months that follow, the dominant factor is the watershed management intervention implemented.

3.5. *Effects of the interventions on sediment concentration*

One of the expected effects of watershed management and other WH practices is reduction in sediment concentrations in surface runoff. In this regard, three sites were considered for monitoring as there was prior information (before the interventions) on the sediment concentration in these locations.

3.5.1. *Sediment concentration at the outlet (SC1)*

The maximum sediment concentration at the outlet (SC1) has changed over the years (Fig. 16). The measured sediment concentrations in the years 2010 and 2012 were 55.2 and 58.3 g L^{-1} respectively. In 2013, sediment concentration had reduced to 28.2 g L^{-1} and since

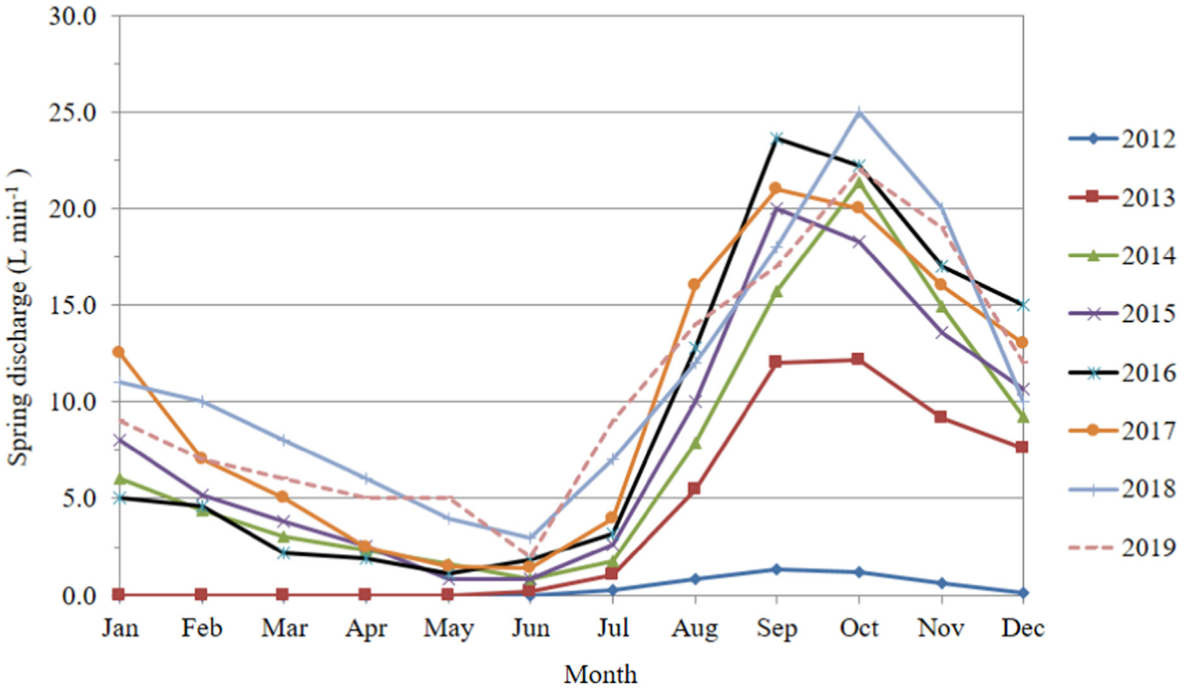

Fig. 14. Variation in discharge (L min^{-1}) of spring 2 (SP2) in Gule watershed.

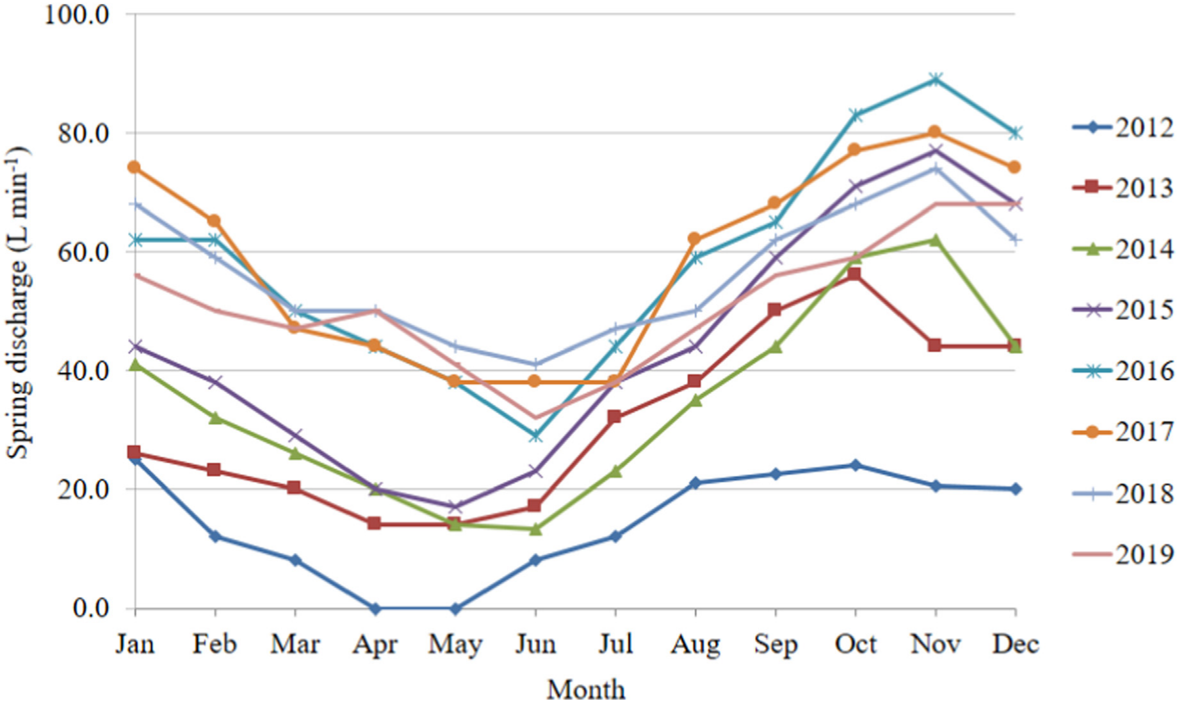

Fig. 15. Variation in discharge (L min^{-1}) of spring 3 (SP3) in Gule watershed.

then sediment concentration has varied between 38.9 and 20.5 g L^{-1}. This is in similar order to the magnitude of average SSC (27.2 g L^{-1}) reported by Grum et al. (2017) at the watershed outlet for the years 2014 and 2015. SSC in high floods has been reduced by up to 65% since 2013 compared to the years before 2013.

The reduction in sediment concentration since 2013 is considered to be due to the extensive SWC and WH interventions which have been implemented since 2013 and which continued until 2020. The reduction in sediment concentration is also manifested in reduction of sediment yield from the watershed. Grum et al.

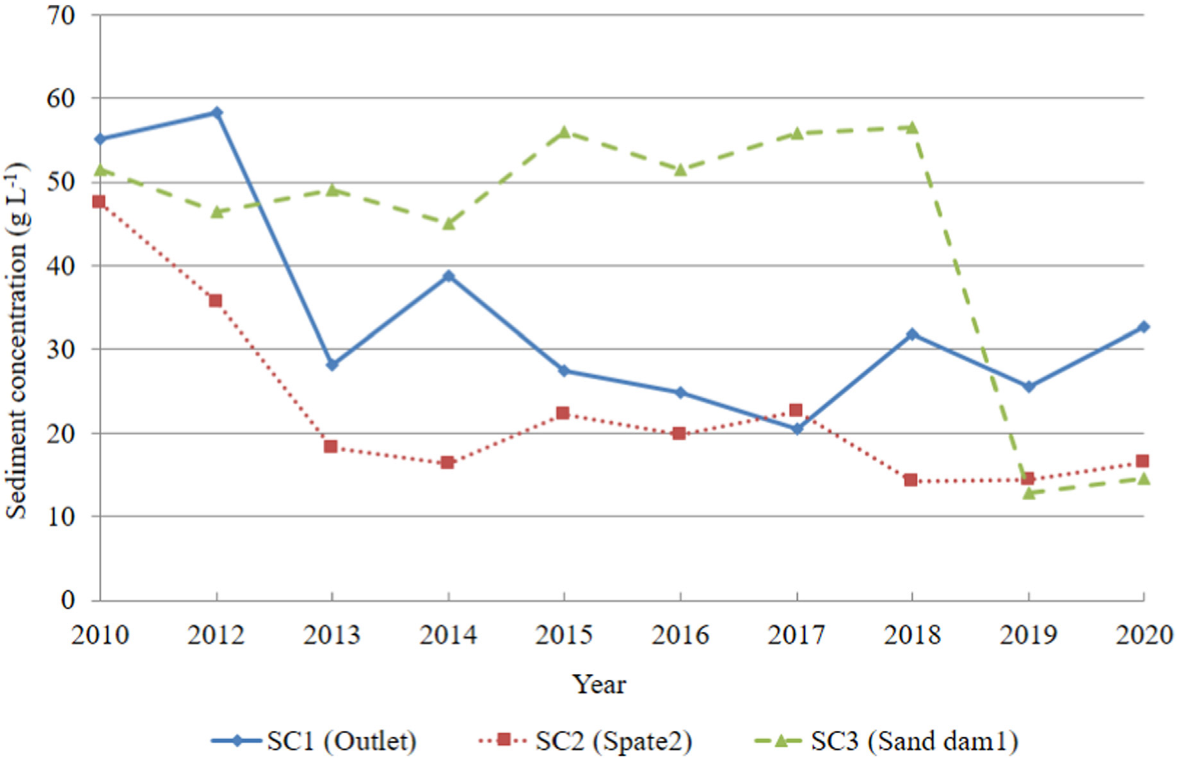

Fig. 16. Maximum sediment concentration (g L^{-1}) at the three monitoring sites in Gule watershed. SC1: catchment outlet; SC2: Downstream of Spate 2 (construction was completed in 2012); SC3: Downstream of sand-dam (sand-dam was constructed in February to May 2019).

(2017) reported that the implementation of WH techniques in the Gule watershed decreased sediment yield at the catchment outlet by 61%. Although SWC and WH measures might have long-term effects of reducing erosion in the uplands, it is often the case that the performance of a one-time intervention is short lived: it could only reduce sediment concentration until the implemented structure gets silted-up. Taye et al. (2015) also reported that the effectiveness of some WHTs in reducing sediment yield declines over time due to the infilling of the structures with sediments.

3.5.2. Sediment concentration downstream of spate 2 (SC2)

Downstream of Spate 2 (SC2), sediment concentration was monitored for the years 2010 and 2012–2020 (Fig. 16). In 2010, the maximum sediment concentration was 47.5 g L^{-1} while in 2012 the concentration was 35.6 g L^{-1}. In 2013, sediment concentration reduced to 18.3 g L^{-1} and remained relatively low (with values in the range 16.3–22.5 g L^{-1}) until 2020 despite rainfall variability. This reduction in sediment concentration is believed to be due to the several interventions implemented upstream of the spate structures which included SWC (e.g., gabion check-dams with biological measures) and WH (e.g., recharge ponds and check-dam ponds) since 2013, which have continued until 2020.

3.5.3. Sediment concentration downstream of sand dam (SC3)

The sand dam was constructed in the period February to May 2019 and got silted up in the same year. Downstream of the sand dam site, sediment concentration was measured both before and after the sand dam construction. Highest sediment concentrations of 55.8 g L^{-1} and 56.6 g L^{-1} were recorded for the years 2017 and 2018 respectively. In the rainy season of 2019 (June to September), the lowest sediment concentration was recorded (12.8 g L^{-1}) as the sediment which was transported from upstream areas accumulated in the reservoir area of the sand dam. At the end of September 2019, the sand dam got completely filled-up with sediments. In same year (2019), biological measures were implemented in the reservoir area of the sand dam. In the rainy season of 2020 (June to September), sediment concentration has slightly increased (to 14.5 g L^{-1}) but was lower than the condition before the construction of the sand dam. This is believed to be due to the biological measures in the treated sand dam which acted as traps to sediment transport in floods.

3.6. Implications of SWC and WH for drought resilience

Implementation of watershed management which incorporates both SWC and WH has enhanced groundwater and spring recharge as well as availability of surface water (in ponds and check-dam ponds) for irrigation, domestic water supply and livestock watering in Gule watershed. Runoff harvesting from roads was mainly from culverts and road side ditches as promoted in recent years by various researchers (van Steenbergen et al., 2018; Woldearegay et al., 2015b). As a result, both off-season and supplementary irrigation practices have been promoted with water from shallow groundwater wells, springs and water harvested from road catchments. As can be noted from Fig. 17, irrigated area has increased in Gule watershed from less than 3.5 ha in 2002 to 166 ha in 2019 (41.3 ha supplementary and 124.5 ha off-season irrigation) despite high rainfall variability over the years. In the year 2015/2016, Tigray region in general was hit by the worst drought in 50 years (TBoARD, 2017). However, the watershed remained resilient to droughts: availability of water for irrigation, domestic water supply and livestock watering was not affected by the drought. Woldearegay, 2009 inventoried watersheds in Tigray which remained resilient to the 2015/2016 droughts and Gule watershed was one of the least affected ones and even acted as source of water for drinking and livestock watering for communities in adjacent watersheds.

Results of the participatory assessments (interviews with local farmers and stakeholder workshops) revealed that crop harvest frequency has increased to up to 3 times a year and yield has increased by up to 100%. The dominant crops grown in the watershed include: (a) maize, wheat, teff, millet, beans and lentil during rainfed season, and (b) onions, peppers, tomatoes, maize, fruits and vegetables during off-season irrigation. Stakeholders attributed this increase to the availability of water and use of better agricultural inputs (fertilizer). Farmers indicated that the availability of water is an incentive to invest on additional inputs; they feel guaranteed that there will be no crop failure as there is water available for agriculture. Moreover, stakeholders indicated an improvement in water availability for domestic use: the average distance from homesteads to water source has decreased from over 4 km in 1995 to about 1 km in 2018, and the increased availability of water in the watershed has improved their livelihoods (better income, nutrition, health and education). In terms of land use, though no major change was observed between the years 2006 and 2019 (as evaluated by digitizing high spatial resolution of Google Earth images), a slight increase in woodland cover (0.38%) was observed and the re-emergence of Faidherbia albida is common in the watershed. Faidherbia albida trees are reported to have the capacity to increase crop yields (Kamara & Haque, 1992; Poschen, 1986) and the potential to mitigate climate change effects (Haskett et al., 2019).

4. Discussion

Implementation of proper watershed management practice (SWC and WH) is found to be key for enhancing water availability and addressing rainfall variability related challenges. According to Thomas et al. (2018), scaling involves eight critical actions for success: (a) plan iteratively; (b) fund consistently; (c) select options for scaling based on best available evidence; (d) identify and engage with stakeholders at all scales; (e) build capacity for scaling; (f) foster institutional leadership and policy change to support scaling; (g) achieve early benefits and incentives for as many stakeholders as possible; and (h) monitor, evaluate, and communicate. Similar actions were taken in Gule watershed, as discussed below.

4.1. Proper planning, design and implementation of appropriate watershed management interventions

SWCs are often perceived as practices which could be planned and designed by local experts and communities as many of the interventions are small-scale - especially the in-situ WHs. The effects of such interventions at watershed level, especially on groundwater (quality and level), is often overlooked. In watershed management, the overall hydrogeological system of the watershed and its potential for groundwater recharge and storage is often not evaluated. What was observed in Gule watershed fully aligns with the recommendation by Rockstrom et al. (2010) for: (i) a new and widened approach of planning which considers green and blue water resources, and (ii) catchment scale interventions as these offer the best opportunities for water investments to build resilience in small-scale agricultural systems and to address trade-offs between water for food and other ecosystem functions and services. The well planned and participatory implementation of SWC and WH in Gule watershed, at later stages, have indicated the need to consider the following for further up-scaling: (a) select appropriate technologies at suitable locations of the landscapes, (b) predict the expected impacts of the interventions at various scales, (c) implement the interventions following proper steps so that each new intervention complements the functionality/sustainability of the earlier ones, and (d) support the implementation through evidence generation and adapt to any design modifications when required.

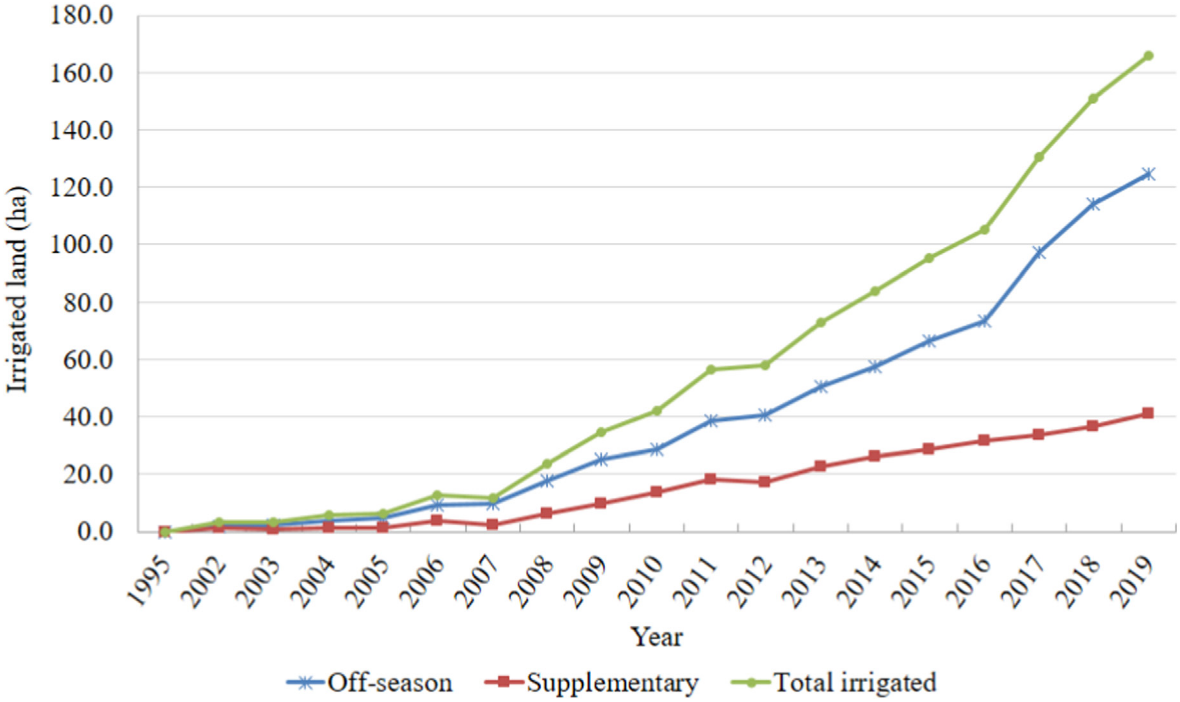

Fig. 17. Off-season and supplementary irrigation development in the years 1995 and 2002- 2019 in the Gule watershed.

4.2. *Learning from past and looking for simple but smart solutions*

Prior to 2012, many of the interventions implemented in Gule watershed had several problems, mainly due to siltation and scouring/erosion. Most of the check-dam ponds (8 out of 12) and all the spate diversions were constructed before 2012. The sandy silt to silty sand texture of the soils in the area coupled with high sediment load from the upper catchment has resulted in siltation problems of these WH structures. As a result, in recent years (especially after 2016), three options were considered to mitigate these problems: (a) implementation of small check-dams with biological measures targeted at reducing downstream scouring/erosion, (b) design of check-dams ponds targeted at groundwater recharge and surface water storage in areas where siltation hazard is low, and (c) introduction of sand dams.

The promotion of small check-dams with biological measures included the design and implementation of solutions to prevent collapse from downstream scouring/erosion and hence stabilize the existing check-dams, check-dam ponds and spate diversions through constructions of simple, smart and nature based solutions. Constructing small gabion check-dams, with spillway levels equal to the apron levels of the structure to be treated (Desta et al., 2005) integrated with biological measures have saved these structures from collapse. These check-dams, check dam ponds and spate diversion structures are critical for buffering moisture and recharging groundwater systems in Gule watershed.

The other option considered was the introduction of sand dams in appropriate locations with proper design and implementation. Since there is still excess runoff and sediment load in streams in the watershed and the soil is sandy, these sand dams are favoured over check-dam ponds until sedimentation hazard is limited. The unconsolidated deposits in the lower areas of the watershed have high to moderate permeability and could be recharged by construction of sand dams. As a result, three sand dams were constructed in 2018–2020 and more are expected to be implemented as part of the upscaling.

4.3. *Enhancing groundwater availability using multi-functional recharge systems*

Chernet (1993) and EGS (2002) have mapped the groundwater resources potential of northern Ethiopia. These authors categorized the Gule watershed and its surrounding as an area with low groundwater resources. The non-productive nature of the groundwater well drilled in Gule watershed before the interventions in 1995 (Woldearegay, 1995) has confirmed the low productivity of the area. However, the SWC and WH interventions which were implemented in Gule watershed over recent years have not only enhanced soil and water conservation but also resulted in significant improvements in groundwater availability in the area. As confirmed through monitoring of groundwater wells and springs, a watershed which was mapped as having low groundwater potential has been changed into a landscape which is resilient to rainfall variability. Groundwater has the potential to act as the foundational resource to underpin regional development by enabling irrigated agriculture, urban and rural water security, and drought resilience (Cobbing & Hiller, 2019). When there is excess surface runoff in other watersheds in similar environments with suitable hydrogeological conditions for groundwater storage, there is scope to tap the potential for shallow groundwater development through better investments in implementation of appropriate and multi-functional recharge systems at different scales as demonstrated in the Gule watershed.

4.4. *Promoting social learning*

Social learning describes the process whereby individuals learn about a new and uncertain technology from the decisions and experiences of their neighbors (Munshi, 2008). It includes (Kilvington, 2014; Pahl-Wostl, Gupta, & Petry, 2008): learning and thinking; group participation and interaction; and social and institutional arrangements. In Gule watershed, successful interventions were implemented for several reasons: (a) the technologies and approaches implemented/adopted were proven to work in the local context where the interventions were planned by and addressed the priorities of the local communities/users, (b) focus was given to experience sharing visits, field demonstrations, and formal/informal trainings, (c) the interventions were oriented towards income/profit generation (short-term, medium term and long-term), (d) proper institutional/governance settings were established to support up-scaling – especially through collaboration between government, NGO's and research institutions, and (e) joint involvement of local communities, development agents and decision makers in all phases (including planning, implementation, monitoring and feedback).

4.5. Watershed management intervention beyond project horizon

The intervention processes, implemented technologies and their hydrological effects in Gule watershed indicate that watershed management is a process which demands the following major components: (a) having proper understanding of the watershed characteristics and the technologies to be implemented (what, where, how and when) by all stakeholders, (b) learning from the implementations of the previous interventions (approaches, performances, etc.), (c) upgrading/design modifications when necessary, (d) maintenance of implemented interventions, and (e) evidence generation for further improvements and learning. This implies that watershed management is not a one-time practice which could be completed in one project period of often less than 5 years. It is therefore important to consider watershed management as a continuous process and beyond a single project life time. The monitoring results from Gule watershed clearly show the need to integrate watershed management implementation, evidence generation and learning as integral parts of long-term watershed development in order to enhance drought resilience and promote better climate change adaptation practices. In this line, it is highly recommended to consider and integrate simple monitoring systems as part of watershed management intervention.

4.6. Towards implementing complementary/linked interventions

The different interventions implemented in Gule watershed, especially those introduced prior to 2012, were planned and implemented for specific objectives. For example: percolation ponds and check-dam ponds were mainly designed to store surface water. However, these structures have a great role in recharging groundwater systems which was not the main purpose of their design and construction. Embaye et al. (2020) evaluated various WH structures on agricultural productivity in Tigray and concluded river diversion was the most productive technology in the region. This could be the case for specific sites. In the case of Gule watershed, however, most of the diversions and check-dam ponds have failed to achieve their initial aim but have contributed to drought resilience through acting as sand dams and as groundwater recharge systems. In the planning, design, construction, operation and evaluation of SWC and WH interventions, it is important to look at the complementarity of the interventions (including surface and sub-surface hydrological dynamics) at watershed level in order to capture the multi-dimensional effects and benefits of the interventions to the overall performance of the watershed.

4.7. Towards integrated blue and green water management for drought resilience

The main rainy season in Gule watershed and in most parts of Tigray is June to early September. In periods with early cessation of rainfall, moisture stress was a challenge during maturation of crops (September to October) in the area. After the SWC and WH interventions, the groundwater levels in the lower flat areas rose to about 1–2 m below surface during the months of September to November. The unconsolidated sediments in the lower part of the watershed are predominantly sandy silt to silty sand and the capillary rise in such soils could vary between 0.5 and 1 m (Lohman, 1972). The combined effects of SWC, WH, maximum rise in groundwater levels (in the months of September to November) and capillary rise has enhanced soil moisture in the lower flat areas of Gule watershed especially during early cessation of rain. This scenario is similar to the characteristics of drought resilient landscapes identified by Woldearegay (2017) in which he indicated depth of groundwater as one determinant factor; areas with shallow groundwater levels during maturation of crops are found to be more resilient to moisture stresses. The recommendation by Rockstrom et al. (2010) to move towards integrated green and blue water resources management is in line with the findings from Gule watershed whereby integrated SWC and WH interventions at catchment level have played a key role to enhance water availability in the landscape. This has avoided crop failures in rainfed seasons, promoted off-season irrigation (up to two times a year) and enhanced water availability for domestic and livestock uses despite rainfall variability; a lesson for promoting drought resilience.

4.8. Towards upscaling groundwater recharge for climate change adaptation

This study has shown the importance of groundwater recharge for enhancing availability of water, including during drought periods. Since there is still excess runoff leaving the watershed catchment, there is a potential to further implement interventions that enhance groundwater recharge. Lessons learned from Gule watershed is believed to have an implication for promoting groundwater recharge as climate change adaptation strategy in Tigray, other parts of Ethiopia and beyond. This concept is aligned with the recommendations by different authors (e.g. Stigter et al., 2023; Taylor et al., 2022) who promoted groundwater recharge as a climate change adaptation option. There is therefore a strong need to further upscale groundwater recharge (linked with surface water management) that considers: (a) proper understanding of the hydrogeological setting, (b) selections of appropriate recharge systems, (c) evaluation of surface-ground water interactions and dynamics, and (d) climate variability and change.

5. Conclusion

Comprehensive evaluation of soil and rock properties is necessary for successful implementations of soil and water conservation (SWC) and water harvesting (WH) at various spatial scales. The presence of high permeability rocks and soils in the upstream part of Gule watershed has enabled recharge to downstream areas. High permeability unconsolidated deposits and weathered Tillites in downstream areas act as a storage. The low permeability rocks (Tillites) underlying the unconsolidated sediments act as a retarding media for deep percolation of groundwater and hence enhance lateral movement of water to downstream areas. This combination of factors has favoured shallow groundwater occurrence in Gule watershed.

In relation to their initial design objectives, some of the technologies implemented in Gule watershed such as check-dam ponds and spate diversions have failed to achieve their purposes due to siltation problems. Check-dam ponds were supposed to store surface water while spate structures were constructed to divert floods to farmlands. Such structures have, however, acted as sand dams and contributed positively to groundwater recharge and storage (upstream, laterally and downstream). The high permeability of the deposited sediment (sand to silty sand soil) behind the check-dam ponds and spate diversions have favoured groundwater storage and recharge.

Since Gule watershed is dominated by silty sand and sandy silt types of soils, moisture stress was a challenge for rainfed agriculture in the area – especially during early cessation of rain. Groundwater monitoring has revealed that SWC and WH have resulted in higher groundwater tables during September to November. This condition is believed to have improved the soil moisture (through capillary rise) which could be considered as reverse irrigation especially in the flat and lower part of the watershed where the groundwater reaches close to surface (about 1 m below surface) during September and October; a critical season for moisture stress in soils for rainfed agriculture in Tigray.

Before the interventions, Gule watershed was one of the most drought prone areas in Tigray with high level of land degradation (especially gully erosion), low water tables and periodically dry springs. With proper SWC and WH interventions, the landscape has become resilient to rainfall variability, even to the worst drought of 2015/2016. In addition, irrigated area in the watershed has increased from less than 3.5 ha before 2002 to 166 ha in 2019.

The dominant interventions in Gule watershed have been physical measures with limited biological treatments. Since the soils in the watershed are dominantly sandy silt to silty sand, erosion is still a challenge unless special focus is given to biological solutions. There is therefore a need to promote bio-solutions at all scales and levels of the landscape continuum for a sustainable land and water management.

The interventions in Gule watershed have proven the benefits of linkages among watershed management, groundwater recharge and drought resilience. If there is excess runoff leaving a catchment and a suitable hydrogeological setting, there is a potential for groundwater recharge and for creating landscapes that are resilient to rainfall variability. It is therefore highly recommended to promote climate change adaptation practices through better investments in: (i) proper understanding of the resources (water and land), (ii) evaluations of hydrogeological conditions, (iii) design of appropriate SWC, WH and other groundwater recharge systems, (iv) introduction of low cost groundwater well development and water lifting technologies, and (v) promotion of better water management for improving productivity of applied water.

Declaration of competing interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Appendix 1. Monthly rainfall for Wukro station for the years 1995–2019 (Ethiopian National Meteorology Service Agency, 2020)

Year	Month												Annual rainfall (mm)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1995	0	11.3	33.5	6.5	14.5	0	184.9	198.1	37.6	0	0	0	486.4
1996	0	0	55.6	20.5	73.5	66.8	130.8	264.7	0	0	12.4	1	625.3
1997	0	0	31.7	72.2	10.8	21.4	203.3	5.3	23	4.7	0	0	372.4
1998	0	0	3.1	10	49.1	19.3	415.5	0	0	0	0	0	497
1999	0	0	0	0	0	0	167.3	352.5	13.6	0	0	0	533.4
2000	0	0	0	30	0	67	215.7	365.7	1.1	4.5	0	0	684
2001	0	0	69.5	48.8	83	115.4	385.6	0	4.6	0	0	0	706.9
2002	0	0	0	0	0	35.4	107.7	384.4	41.3	0	0	0	568.8
2003	0	4.9	0	40.7	0	14.3	156.6	237.1	11.1	1.9	0.6	5.7	472.9
2004	2	0	0	14.5	42	67.2	129.3	171.5	4.8	14	0	0	445.3
2005	0	2.8	12.6	61.7	1.3	9.5	183.4	206.3	18.1	0	0	0	495.7
2006	0	0	4.3	42.7	34.5	66.2	155.5	299.6	36.1	35.4	0	0	674.3
2007	0	7.5	6.9	25.2	13.3	94.1	273.2	267.9	69.7	0	0	0	757.8
2008	2.5	0	0	11.5	24	37.1	245.4	152.1	29.9	0	0	0	502.5
2009	0	0	0	9.1	1.6	5.2	118.9	223.8	3.9	0	4.7	3.1	370.3
2010	0	0	4.9	52.7	15.7	12.6	197.2	368	34.5	6.5	0	0	692.1
2011	0	0	49.1	27.5	21	29	153	144	0	0	0	0	423.6
2012	0	0	5	18	34	41.6	249	275	12	7	5	0	646.6
2013	0	0	2	35	0	28	214	90	6	0	0	0	375
2014	0	0	25	0	14.1	26.1	114.1	280.3	152.1	2	7	0	620.7
2015	0	0	38.1	0	44.1	24	70.2	197.1	5	0	4	13.1	395.6
2016	0	0	0	203.2	55.1	35	254.1	208.3	0	0	0	0	755.7
2017	0	0	0	23.2	0	54	183.8	263.7	118.5	1.8	0	0	645
2018	0	0	0	10.4	0	79.8	144.2	188.5	9.3	5.2	0	0	437.4
2019	0	0	0	7.7	38	7.2	253.3	161.1	41.1	0	3.6	0	512

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