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RESEARCH ARTICLE

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Change in low flows due to catchment management dynamics—Application of a comparative modelling approach

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Abstract

Understanding the natural low flow of a catchment is critical for effective water management policy in semi-arid and arid lands. The Geba catchment in Ethiopia, forming the headwaters of Tekeze-Atbara basin was known for its severe land degradation before the recent large scale Soil and Water conservation (SWC) programs. Such interventions can modify the hydrological processes by changing the partitioning of the incoming rainfall on the land surface. However, the literature lacks studies to quantify the hydrological impacts of these interventions in the semi-arid catchments of the Nile basin. Statistical test and Indicators of Hydrological Alteration (IHA) were used to identify the trends of streamflow in two comparatives adjacent (one treated with intensive SWC intervention and control with fewer interventions) catchments. A distributed hydrological model was developed to understand the differences in hydrological processes of the two catchments. The statistical and IHA tools showed that the low flow in the treated catchment has significantly increased while considerably decreased in the control catchment. Comparative analysis confirmed that the low flow in the catchment with intensive SWC works was greater than that of the control by >30% while the direct runoff was lower by >120%. This implies a large proportion of the rainfall in the treated catchment is infiltrated and recharge aquifers which subsequently contribute to streamflow during the dry season. The proportion of soil storage was more than double compared to the control catchment. Moreover, hydrological response comparison from pre- and post-intervention showed that a drastic reduction in direct runoff (>84%) has improved the low flow by >55%. This strongly suggests that the ongoing intensive SWC works have significantly improved the low flows while it contributed to the reduction of total streamflow in the catchment.

KEYWORDS
catchment management, Geba catchment, hydrological processes, low flow, soil and water conservation, Tekeze-Atbara River basin

1 | INTRODUCTION

Low flows are the dry season flow in a river where groundwater is the primary source (Bradford & Heinonen, 2008; Wittenberg, 2003). The magnitude and variance of low flows depend on the seasonal distribution of rainfall as well as inter-seasonal variability (Giuntoli et al., 2013; Pushpalatha et al., 2012). Accurate estimates of low flow characteristics in a catchment are fundamental for water resources development and management (Castiglioni et al., 2011; Laaha & Blöschl, 2006). To this effect, much of the focus on water management particularly, in arid and semi-arid regions has been on finding the balance between the incoming and outgoing water from rivers during the low flow periods (Giuntoli et al., 2013).

Low flow varies in response to natural controls on runoff and anthropogenic disturbances (Gebremicael et al., 2013; Guzha et al., 2018). A combination of human activities including land use/cover change, water abstraction and SWC can modify the low flow of a catchment (Chang et al., 2016; Li et al., 2007). SWC activities can cause visible changes in the dry season flow regimes (Gebremicael, 2019; Mu et al., 2007; Wang et al., 2013). Large scale implementations of such interventions can modify the hydrological processes of a catchment by changing the partitioning of the incoming rainfall at the land surface (Gates et al., 2011). For example, various studies (e.g. Schmidt & Zemadim, 2013; Abouabdillah et al., 2014) reported that the introduction of physical SWC structures can increase the base flow by >50%.

However, there is no distinct understanding of the literature on how the SWC interventions affect the dry season flow. Hengsdijk et al. (2005) and Wang et al. (2013) showed that improving catchments with vegetation cover can increase the dry season flow by enhancing infiltration capacity during the rainy season while other researchers showed a decrease of low flow due to increase in interception and actual evapotranspiration (e.g. Brown et al., 2005; Silveira & Alonso, 2009). In semi-arid catchments, improving vegetation cover can improve green water use efficiency and groundwater recharge at a local level while reducing total surface runoff at a larger scale (Garg et al., 2012; Nyssen et al., 2010). On the other hand, it may enhance subsurface flow which increases dry season flow at the larger scale. Such conflicting results call for further investigation on the impact of SWC interventions on low flows which is vital for improved water management.

The Tekeze-Atbara headwaters are known for the recent integrated catchment management experience (Gebremeskel et al., 2018; Gebremicael et al., 2018). In the last two decades, various land and water management interventions have been implemented to enhance food security and environmental rehabilitation (Gebremeskel et al., 2018; Woldearegay et al., 2018). Integrated catchment management approaches that include physical (e.g. terraces, bunds) and biological (e.g. afforestation) SWC interventions were introduced at different parts of the basins (Nyssen et al., 2014; Woldearegay et al., 2018). These interventions resulted in the restoration of extensive areas with severe land degradation (Gebremeskel et al., 2018; Guyassa et al., 2018).

Upstreams catchment management interventions have increased infiltration of rainwater and the discharge of springs and streams in lower parts of catchments (Gebremeskel et al., 2018; Nyssen et al., 2010). The observed changes are demonstrated by the increasing groundwater levels, decrease of direct surface runoff and emerging of springs (Nyssen et al., 2010). Moreover, these achievements can also be evidenced by the expansion of small-scale irrigation schemes in the basin using dry season river flow (Gebremeskel et al., 2018; Kifle and Gebretsadikan, 2016; Kifle et al., 2017). These literatures revealed that the drivers of these changes were due to the different human interventions in the catchments. However, the literature showed limited studies to quantify the impacts at a larger scale. Results from experimental plots, surveys or micro-watershed levels (<2 km^2) may not be extrapolated to basin-scale (Lacombe et al., 2008). As the impact of SWC interventions is more pronounced on the base flow, improved scientific understanding on the response of low flow to these interventions is critical for effective water management interventions in the basin.

A comparative analysis has been commonly applied to identify the difference in hydrological responses to different human interventions (Worqlul et al., 2018; Zhao et al., 2010). The basic concept behind this approach involves the comparison of hydrological response of two adjacent catchments (one as a control and other as a treatment) or the hydrological response from 'before and after' interventions in a single catchment (Brown et al., 2005; Ssegane et al., 2013). In a comparative catchment modelling approach, it is not necessary that the two catchments are identical, but are comparable in characteristics and in close proximity to each other (Best et al., 2003; Zhao et al., 2010). A comparative analysis using such a modelling approach may ascertain the relative differences in hydrological responses between catchments (Brown et al., 2005; Kralovec et al., 2016; Zhao et al., 2010). Therefore, the purpose of this study was to investigate the low flow responses to catchment management interventions in the Geba catchment of Tekeze basin headwaters using different approaches.

2 | STUDY AREA DESCRIPTIONS

This study was conducted in two comparative catchments; Agula (481 km^2) and Genfel (502 km^2) within the Geba catchment in Ethiopia (Figure 1). The outlets of the two adjacent catchments are close to each other at a distance of <5 km. They are located in northern Ethiopia between 13.54°N, 39.59°E to 14.14°N, 39.80°E in the headwaters of Upper Tekeze-Atbara, a tributary of the main Nile river basin. Table 1 summarizes the characteristics of the catchments. The topographic characteristics such as elevation, size, slope, length of stream network and drainage density of the two catchments are very close to each other. They both have similar features of physical geography and hydrography in the altitude between 1961 and 3070 m.a.s.l. They are also very similar in terms of geological information in which Enticho Sandstone, Adigrat Sandstone, Antalo Super sequence and Metamorphic (basement) rocks are dominant in both catchments

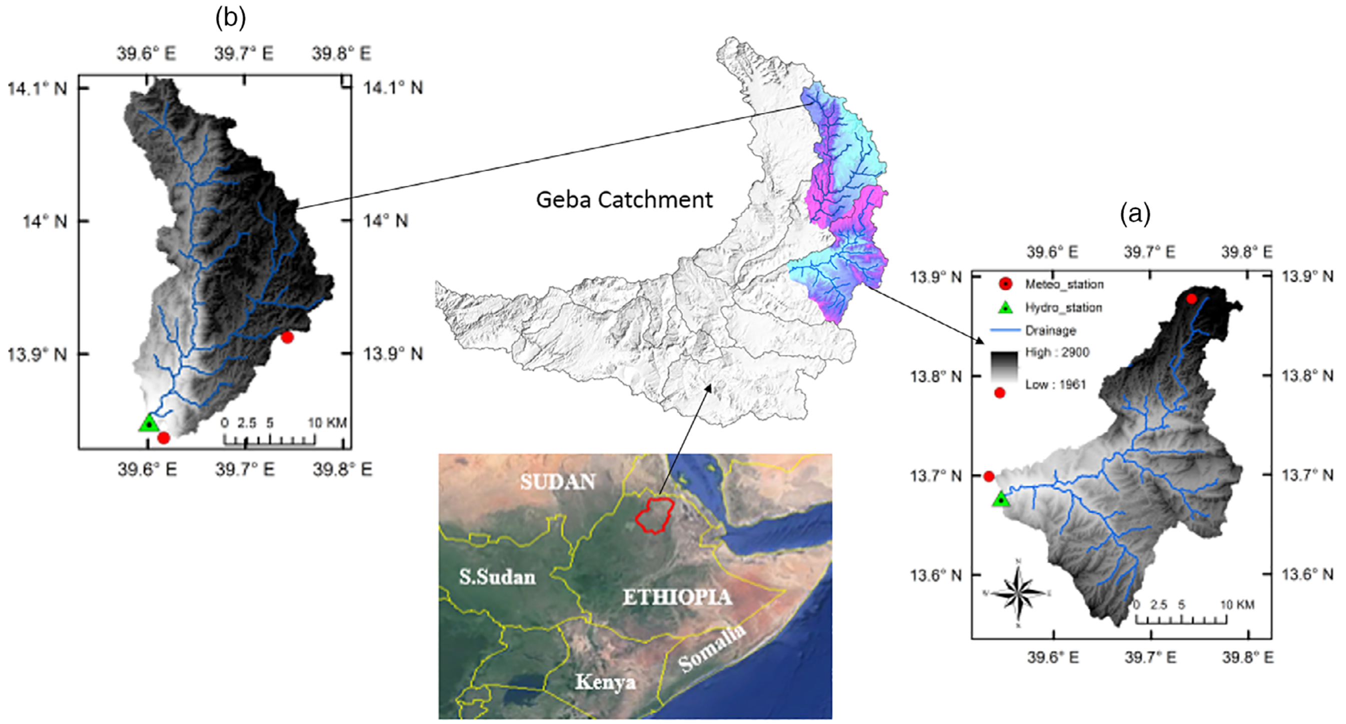

FIGURE 1 Location of the study area, meteorological and hydrological monitoring stations, (a) Agula and (b) Genfel

(Gebreyohannes et al., 2013). However, the major difference is depicted by the average annual discharge and coverage of SWC measures (Table 1).

The two catchments are characterized by a semi-arid climate in which the majority of the rainfall occurs from June to September after a long dry season (Gebremicael et al., 2017). More than 80% of the total rainfall falls in July and August only (Gebremicael et al., 2017). Rainfall over the two catchments is highly variable mainly associated with the seasonal migration of the intertropical convergence zone (ITCZ) and the complex topography (Gebremicael et al., 2017). However, they have almost the same mean annual rainfall and temperature. The land use/cover of the two catchments are also comparable. The same agricultural systems are practised in the two catchments wherein farmers use a mixed subsistence farming based on crops and livestock production.

Cambisol, Luvisol and Leptosol are the dominant soil type in both catchments, i.e. 33%, 25% and 25% in Agula and 36%, 30% and 18% in Genfel, respectively. In general, weathered soils are found in the uppermost plateaus, rocky and shallow soils in the vertical scarps, coarse and stony soils in the steep slopes, finer-textured soils in the undulating pediments and most deep alluvial soils are found in the alluvial terraces and lower parts of the alluvial deposits (Gebreyohannes et al., 2013).

In summary, whereas both catchments are very similar, they differ in the proportion of land management that was subject to catchment rehabilitation interventions and annual discharge. This allows for a comparative study since hydrological response can differ due to the difference in land management interventions. The government and NGOs have given strong attention to rehabilitating the degraded land with different watershed management interventions in different locations of the Geba catchment where the two comparative catchments are located. Starting from the mid-2000s, an integrated approach of SWC interventions including physical and biological measures have been introduced in the catchments (Figure 2). Compared to the Genfel, Agula catchment is known for its intensive and most successful implementations of SWC in the region (Table 1). These intensive management interventions were implemented from around 2005/2006 (Gebremeskel et al., 2018; Woldearegay et al., 2018). Detailed descriptions of these interventions, including types of intervention, how, when and who implemented these interventions can be found in our previous works (Gebremeskel et al., 2018; Gebremicael et al., 2018).

3 | DATASETS AND METHODS

The low flow responses to catchment management interventions in the study area were analysed using different approaches. To understand how the interventions changed the low flows in the catchment, first, the relationships of the observed flows from before and after the interventions were quantified using different Indicators of Hydrological Alteration (Mathews and Richter, 2007) parameters, and Pettitt (Pettitt, 1979) and Mann–Kendall (MK; Kendall, 1975) statistical tests. However, these methods do not show how SWC interventions influence the overall hydrological processes of the catchments. To infer the physical mechanisms behind the changes, if

TABLE 1 Physical characteristics of the two comparative catchments

Catchment characteristics	Agula	Genfel
Catchment area (km^2)	481	502
Maximum elevation (m.a.s.l.)	2900	3070
Minimum elevation (m.a.s.l.)	1961	1988
Average slope (%)	17.3	19.8
Area with slope > 30% (km^2)	16.5	14.9
Drainage density (km/km^2)	1.93	2.05
Agro-climatic zone	Semi-arid	Semi-arid
Length of major riverine (km)	41	46
Mean annual temperature	21.6	21.3
Annual average discharge (m^3/s)	1.1	0.6
Average dry season flow (m^3/s)	0.6	0.2
Mean annual rainfall (mm/year)	550	560
Potential evapotranspiration (mm/year)	1430	1432
Aridity index (–)	0.39	0.39
Moisture index (%)	−59	−59
Major soil types	Leptosol, Cambisol, Luvisol	Leptosol, Cambisol, Luvisol
Major crops	Teff, wheat, barley, maize, tomato, potato	Teff, wheat, barley, maize, tomato, potato
Proportion of land use/cover types (%)		
Rain fed agriculture	30	34.2
Irrigated agriculture (from 2016)	1.4	0.8
Forest land	2.5	1.2
Bushes and shrubs	26.4	19
Wood land	11.7	8.4
Plantations (eucalyptus trees)	5.9	7.5
Bare land	8.4	17.6
Grass land	13	10.9
Urban areas	0.6	0.3
Water bodies	0.2	0.1
SWC coverage (%)	49.6	15.4

any, a comparative catchment modelling analyses was introduced. A spatially distributed hydrological model based on Wflow-PCRaster/python framework are developed to simulate and compare the overall hydrological responses and in particular the low flow from the two catchments.

3.1 | Datasets

3.1.1 | Static datasets

Land use/cover, Digital Elevation Model (DEM), soil, Local Drainage Direction (LDD) and river maps are the main static input datasets required to develop a distributed hydrological model in a Wflow_PCRaster/Python framework environment (Gebremicael et al., 2019; Schellekens, 2014). The land use/cover maps of 2003 and 2014 were developed for both catchments (Figure 3). These years were selected considering intensive watershed management interventions in the catchments from around 2005/2006 (Woldearegay et al., 2018). Landsat7 and 8 images for 12/03/2003 and 23 March 2014, respectively, were obtained from the US Geological Survey (USGS) centre for Earth Resources Observation and Science (EROS). Ancillary data including field observations, topographic maps and secondary literature were collected from different sources to enhance classifications.

Ground truth points (200 each) used for classification and accuracy assessment of classified images were collected during field survey (September–November 2018) and our previous study (Gebremicael et al., 2018). The same procedure as described in Gebremicael et al. (2018) was applied to the pre-processing of images and identifying the different land-use types shown in Figure 3. Both supervised and unsupervised classification approaches were applied to classify the images and the final classified LULC maps were evaluated using independent ground truth data. Soil maps of the two catchments obtained from our previous study (Gebremicael et al., 2019) were used in this study. Produced LULC and soil maps were used as inputs for the development of a distributed hydrological model. Input data formats needed for the Wflow model were created from the DEM, land cover, soil and hydrological gauge locations with a pre-preparation step1 and step2 of the WFlow model (Gebremicael et al., 2018).

3.1.2 | Dynamic datasets

Daily precipitation (P) and potential evapotranspiration (PET) is the main dynamic input data to force the hydrological model. Satellite-based rainfall and evapotranspiration products were used in this study as there is not enough ground observed climatic data in both catchments. The Climate Hazards group InfraRed Precipitation with Stations (CHIRPS) and PET from the Famine Early Warning System Network (FEWS NET) which are found at a spatial resolution of 5 and 11 km, respectively, were used as model input. Performance of CHIRPS over the study area was evaluated in our previous study (Gebremicael et al., 2019) and showed a better agreement with ground measurements compared to the other eight products. These data are available at daily from 1981 and 2001 to present for CHIRPS and PET, respectively. All static and dynamic input maps were projected to WGS-84-UTM-zone-37 N and resampled to a resolution of 50 m for the model inputs.

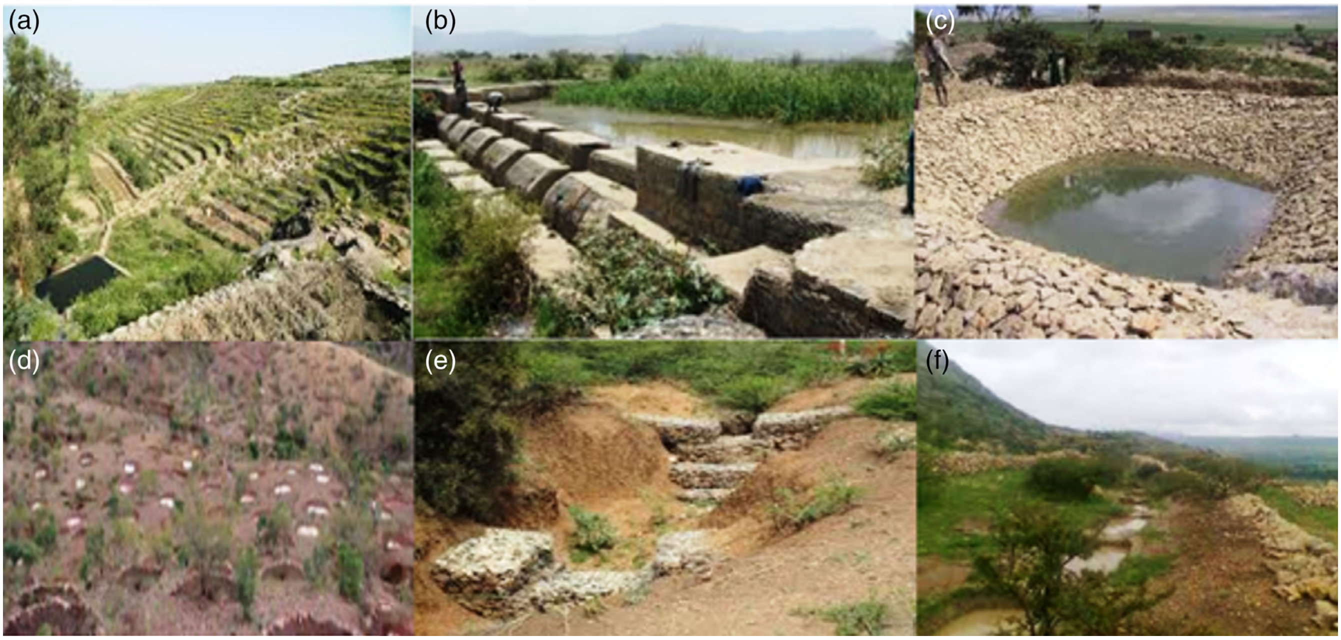

FIGURE 2 Physical SWC interventions in the Geba catchment of the Tekeze-Atbara headwaters: (a) terraces, (b) check dams, (c) water harvesting structures, (d) percolation ponds at the top of hills, (e) gully rehabilitation using gabion and (f) deep trenches at the bottom of hills (sources: Woldearegay & Tamene 2017; Yosef & Asmamaw, 2015)

Streamflow data at the outlets of the two catchments were collected from the Ethiopian Ministry of Water Resources for calibration and validation of the model. Descriptions and quality of these data are presented in Gebremicael et al. (2017). However, since around 2010/2011, irrigated agriculture in the two catchments has significantly increased and hence the low flow in the rivers has been reduced due to abstraction for irrigation consumption (Gebremicael et al., 2019). In this study, it was necessary to naturalize the observed streamflow from actual evapotranspiration (AET) derived from remote sensing. Actual evapotranspiration from irrigated pixels of the study areas was generated using Landsat information and PySEBAL model (UNESCO-IHE, 2018; Jaafar & Ahmad, 2019). The PySEBAL model was developed based on Python open-source platform and it is capable of semi-automatic processing of selected satellite images (Bastiaanssen et al., 2005; Van Eekelen et al., 2015). The PySEBAL translates raw satellite measurements into maps of actual evapotranspiration at 30 x 30 m spatial resolutions (Van Eekelen et al., 2015). The detailed information on the algorithm embedded in PySEBAL is found in Bastiaanssen et al. (2005). The time step of 16 days with 30 m spatial resolution of Landsat images was used to estimate the AET fluxes during the irrigation seasons from 2011 to 2016. This time step is limited by the availability of Landsat products.

The final estimated AET at 16 days interval were interpolated into daily time step using linear interpolation and converted to daily discharge at the two catchment outlets. The naturalized discharge at the catchment outlets was obtained by adding the observed and the estimated river withdrawal for the irrigated agriculture and this data was used for the calibration and validation of the model.

3.2 | Methodology

3.2.1 | Hydrological model development

A distributed hydrological model based on Wflow_PCRaster/Python framework was developed to simulate hydrological responses in the two catchments. Wflow is an open sources software developed by the Deltares OpenStreams project which simulates catchment runoff in both limited and rich data environments (Schellekens, 2014). This model was derived from the CQFLOW model (Köhler et al., 2006) and is programmed in the PCRaster-Python environment (Karssenberg et al., 2010). A detailed description of the model is given in Gebremicael et al. (2019) and hence only a brief description is given here.

Hydrological processes in the model are represented by three main routines. Interception is represented by Gash model (Gash et al., 1995) and uses PET to drive actual evapotranspiration based on the soil water content and land cover types. Runoff generation is calculated by the TOPOG_sbm (Vertessy & Elsenbeer, 1999). River drainage and overland flows are modelled using kinematic wave routing. The soil in Wflow_sbm is considered as a simple bucket model which assumes an exponential decay of the saturated hydraulic conductivity (Ksat) depending on the depth (Schellekens, 2014). The model is fully distributed and the runoff is calculated for each grid cell with the total depth of the cell is divided into saturated and unsaturated zones (Gebremicael et al., 2018; Vertessy & Elsenbeer, 1999). The hydrological processes are described by different parameters which are linked to the model by a PCRaster look-up table.

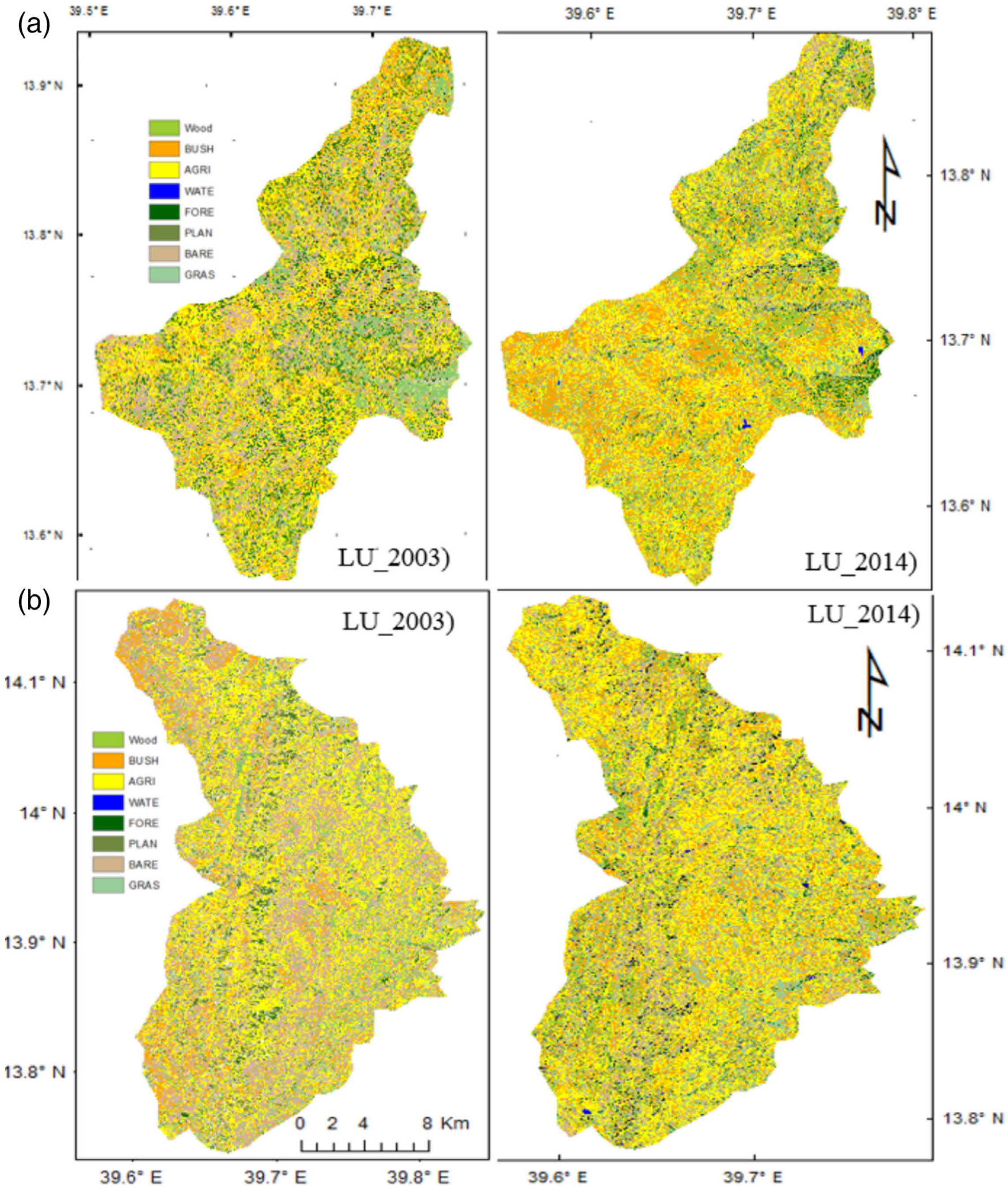

FIGURE 3 Land use/cover maps used as for model inputs, (a) Agula catchment and (b) Genfel Catchment

3.2.2 | Model calibration, uncertainty analysis and validation

Climatic and hydrologic datasets of 2001 to 2006 and 2011 to 2016 were used for the calibration and validation of models during the before and after interventions comparisons, respectively. The first 3 years were used for calibration while the remaining 3 years were used for validation of the models in each period. Initial parameter values were taken from our previous work (Gebremicael et al., 2018), field observation and laboratory analysis.

Model parameters are subject to different sources of errors during calibration and hence uncertainty analysis is essential to improve the modelling results. The uncertainty of model parameters was analysed using Global Likelihood Uncertainty Estimation (GLUE) method which was implemented in the Python programming language. Detailed procedures and equations of GLUE are found in Beven and Binley (1992). A randomly 20 000 parameter sets were employed through the Monte Carlo simulations to constrain the parameters in feasible parameter space. The Nash Sutcliffe (NSE) objective function was employed to constrain the model parameters and to evaluate the performance of the model during calibration and validation processes. Model performance was acceptable if NSE > 0.5 and PBIAS value within ±25% (Moriasi et al., 2007).

3.2.3 | Analysis and comparison approach

First, Pettitt and MK tests and IHA method were applied to understand if there is a significant change in the naturalized streamflow of the adjacent catchments by considering before and after the interventions. The statistical test was used to identify if there is an abrupt change of streamflow after the interventions while the IHA method was used to assess the alteration of low flows. The statistical tests and IHA method demonstrated the change in streamflow of the catchments, without however identifying the physical causes behind the changes. To establish such causality, the response of the low flows to human interventions such as large-scale catchment management implementation programs were analysed using comparative catchment modelling approach.

A comparative analysis of two independent catchments (with and without interventions), comparison of hydrological responses from pre- and post-catchment interventions were done to understand the impacts. Water balance models focusing on the low flow from before and after interventions within each catchment were compared. Comparison of calibrated model parameters from the two catchments was also analysed in order to verify whether the differences in catchment management interventions are reflected in the low flow responses.

4 | RESULTS

4.1 | Analysis of change in streamflow

The Pettitt and MK tests ($P < 0.05$) and IHA methods were applied to the observed annual, wet and dry season streamflow of the period 1996 to 2016 for the two catchments. The pattern and comparison of streamflow in the two catchments are given in Figure 4 and Table 2. The annual and wet season (June–September) streamflow of the two catchments significantly reduced for the given period (Figure 4). The dry season flow of Genfel has significantly decreased; by contrast, the dry season flow of Agula has significantly increased for the same period of analysis. The result from the MK test is also consistent with the Pettitt test that both annual and wet season flow showed a decreasing trend in both catchments (Table 2). Positive (negative) values of Z statistics associated with the computed probability (P-value) indicate an increasing (decreasing) trends of the flow.

To understand how the interventions modified the low flows in the catchment, the relationships between the flows before and after the interventions were quantified using different IHA parameters (Figure 5). In agreement with the statistical test, the result from IHA ascertained that there was a significant change in hydrological variables after the SWC works in the Agula catchment. The median monthly flow during the dry winter, spring and autumn seasons increased by 78%, 54% and 67%, respectively (Figure 5a). In contrast, the median monthly flow during the wet summer season declined by >50% after the intensive SWC interventions. Similarly, all indicators for the low flow of annual conditions exhibited a significant change in magnitude and duration between the two periods. The summary of annual flow conditions for Agula catchment is presented in Figure 5 whereas, for the Genfel catchment, it is given as supplementary file in

TABLE 2 Summary results of MK test on streamflow trends. Negative (positive) Z value indicates a decreasing (increasing) trend and statistically significant trends at 5% confidence level are shown in bold ($Z = \pm 1.96$)

Station name	Annual flow	Wet season flow	Dry season flow
Agula	**−4.4**	**−3.4**	**3.2**
Genfel	**−3.8**	**−2.4**	**−2.1**

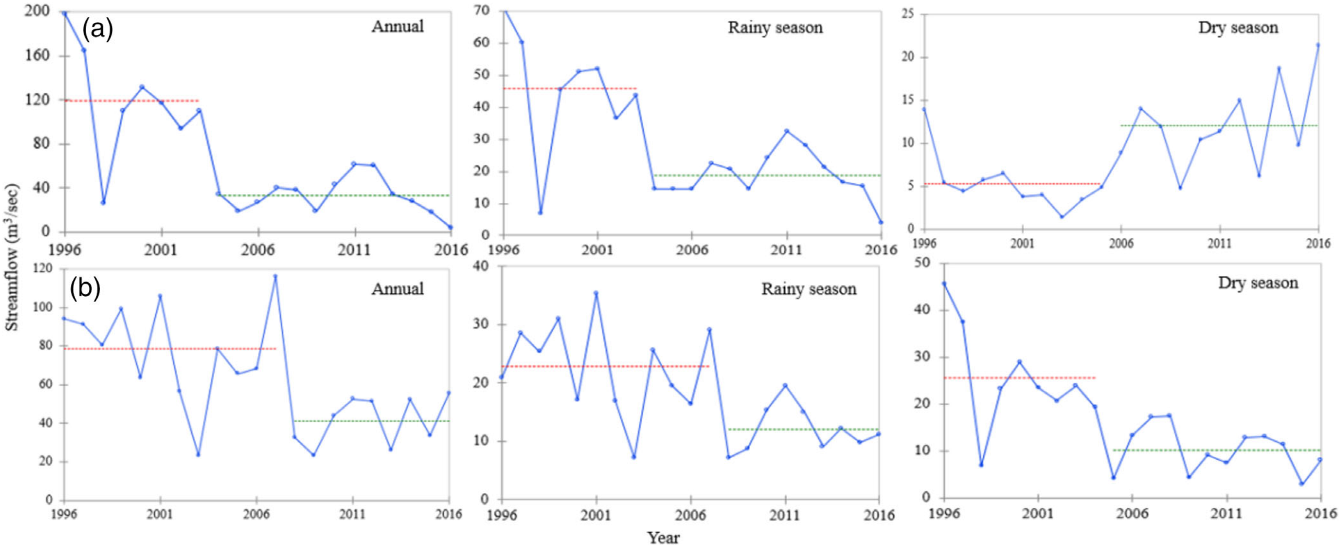

FIGURE 4 Homogeneity test of annual and seasonal naturalized streamflow in the paired catchment, (a) Agula and (b) Genfel

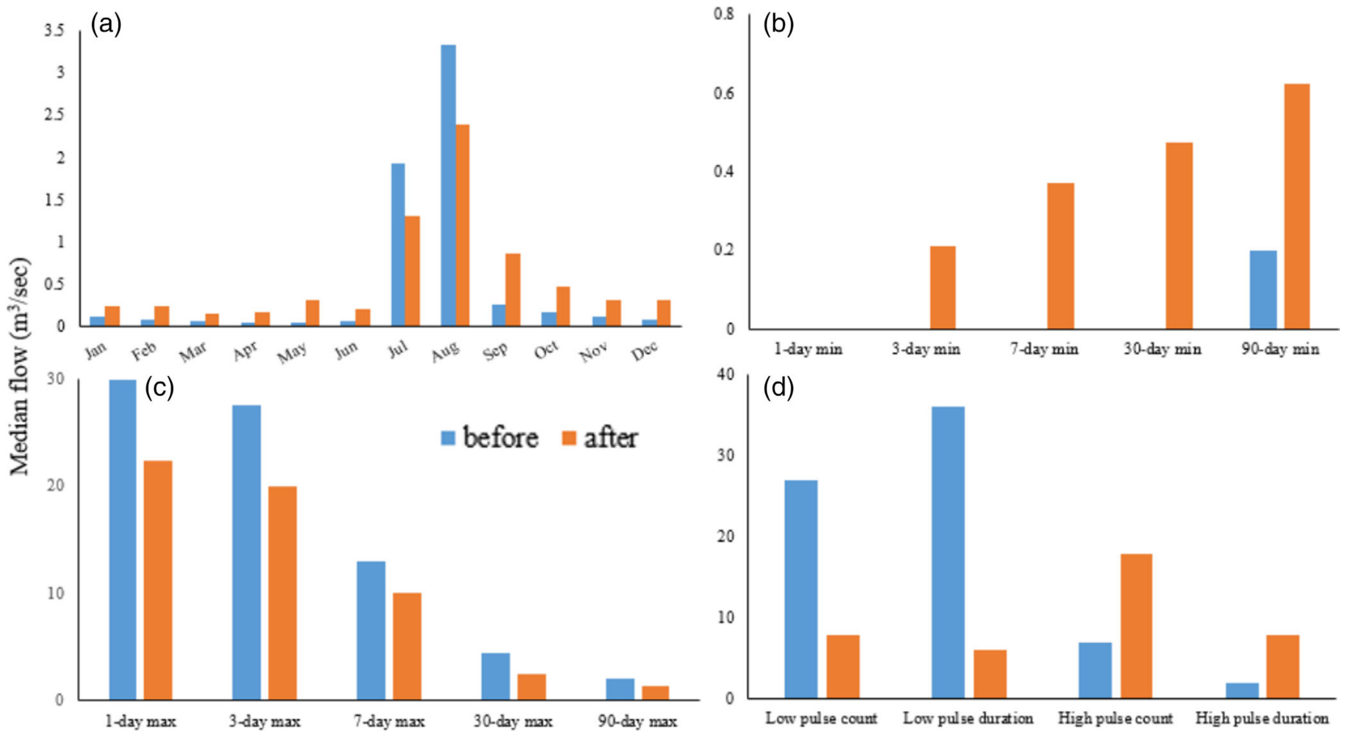

FIGURE 5 Comparison of hydrological responses in Agula catchment before and after catchment management interventions using indicators of hydrological alteration parameters: (a) Magnitude of average median monthly flow; (b) Magnitude of median annual average minimum flows; (c) Magnitude of median average annual maximum flows and (d) Frequency and duration of average high and low pulses

Figure S2. The values of all except the 90-day annual minima parameters were negligible before interventions while increased up to 0.6 m^3/s after the interventions (Figure 5b). All maxima parameters moderately declined in the post-treatment period (Figure 5c). The decrease in annual maxima and annual minima parameters between the two periods show the influence of management interventions in the catchment. The base flow index, i.e. the ratio of 7-day minimum flow to the mean flow of the year increased from 0 to 0.11 m^3/s between the two periods. This indicates that the contribution of subsurface flow to the stream has increased after SWC development in Agula catchment.

Assessment of the alteration of frequency and duration of low pulses indicates that their magnitude and duration were higher in the pre-treatment compared to the post-treatment (Figure 5d). This shows the low flow in the Agula catchment is becoming constant after the implementation of SWC measures. This, in turn, reflects that the rainfall contribution to the groundwater increased in the catchment. In contrast, the high pulse count above and below the given threshold during the pre-treatment period demonstrates the hydrological response of the catchment was flashier. The number of high and low flow pulses is associated with the rise and fall rates and gives evidence on how the low flow response is increasing after the physical SWC interventions. The median rise rate (positive differences between two consecutive daily values) and fall rate (negative difference) has decreased from 0.15 and 0.25 m^3/s to 0.08 and 0.11 m^3/s, respectively. This denotes that the frequent fluctuation of low flows during the pre-treatment period has decreased and more stable flow is contributed from the catchment after the interventions.

4.2 | Model calibration and validation result

Daily streamflow hydrographs during the two calibrations (2001–2003 and 2011–2016) and validations (2004–2006 and 2014–2016) periods are given in Figures 6 and 7, respectively. Results presented in these figures generally indicate a good agreement between the simulated and observed streamflow in the two catchments. The models of the two catchments were able to capture the daily hydrographs both for the peak and low flows. The simulated and observed hydrographs have very similar trends in Agula and Genfel catchments in both simulation periods. However, there is a consistent slight overestimation of streamflow in both catchments. The consistent overestimation of streamflow could be related to the coarse resolution of evapotranspiration from the satellite products or due to model structure errors. The statistical indicators for the evaluation of model performance are presented in Table 3, showing a satisfactory model performance. The NSE value at both catchments are <0.8 while values of PBIAS and RMSE are below 20% and 10%, respectively. This indicates that our model performance is acceptable both for the calibration and validation periods during 2001–2006 and 2011–2016 simulation periods.

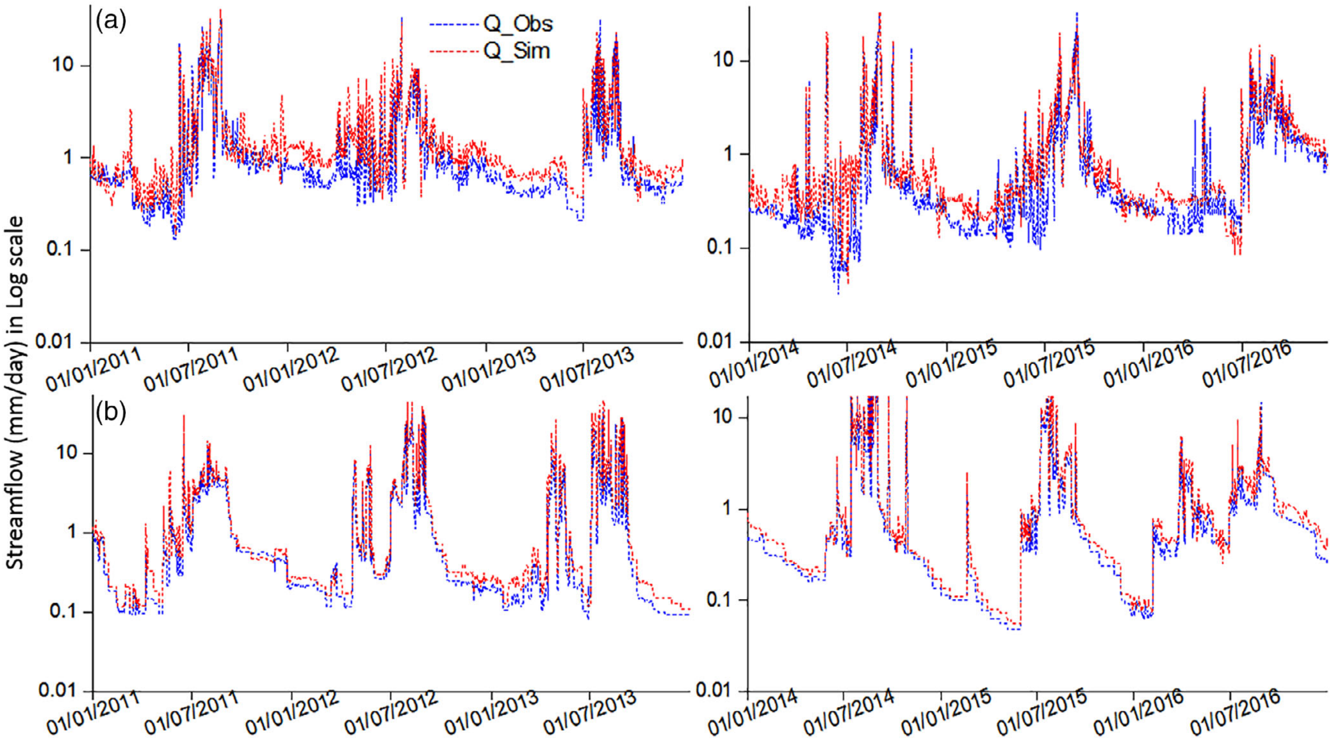

FIGURE 6 Calibration (left) and validation (right) of the Wflow-sbm hydrological model at Agula (a) and Genfel (b) during the 2011–2016 period

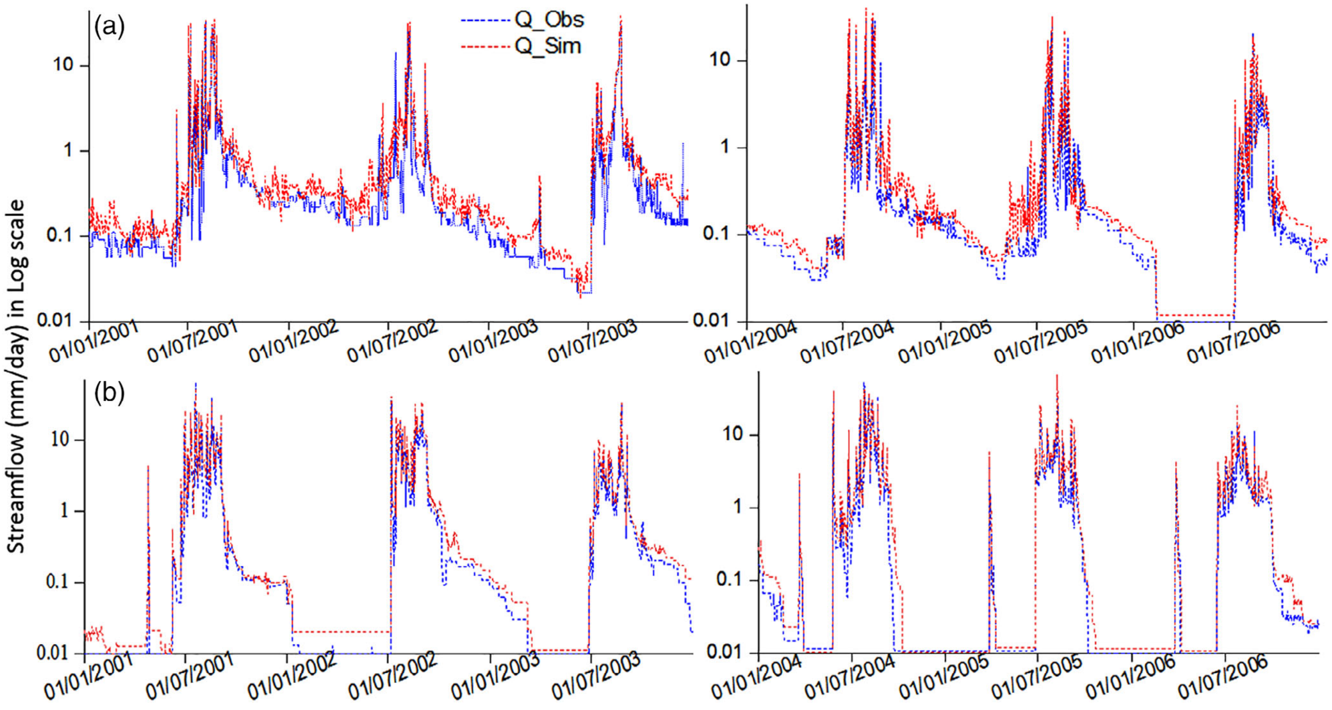

FIGURE 7 Calibration (left) and validation (right) of the Wflow-sbm hydrological model at Agula (a) and Genfel (b) during the 2001–2006 period

Uncertainty analyses of the model parameters were done using the whole time series data for calibration and validation processes (Figure 8 and Table 4). The dotty plots presented in Figure 8 show the goodness of fits and the distribution of each model parameter within their dimensions. These dotty plots indicate that parameters such as CanopyGapFraction (free throughfall coefficient), Ksat (Saturated conductivity of the store at the surface), M parameter (Soil parameter determines how Ksat decreases with depth), ThetaS (Water content at saturation) are well identifiable. Relatively less definable are RootingDepth (depth of the vegetation) and EvorR (Gash interception model parameter), which may possibly be attributed to model structure errors. The statistical summary (Table 4) from the posterior distribution also demonstrates the variability of optimal parameter values in the 20 000 Monte Carlo simulation and indicates optimal values of all parameters are around the mean with relatively small variance and skewness. Overall, the good identifiability of model parameters and better agreement between simulated and observed streamflow indicates that the Wflow-sbm distributed hydrological model is applicable for the analyses of hydrological processes in the catchments. The calibrated optimum parameters value used in this study are shown in Table S1.

4.3 | Water budget analysis from the two comparative catchments

The average water balance and proportion of each hydrological component of Agula and Genfel catchments are presented in Table 5. The average absolute value differences between the water balance components of Agula (treated) and Genfel (control) is provided for the comparison. On average, both catchments received the same amount of precipitation and they evaporate similar proportional amounts of water. However, Genfel catchment exhibited higher runoff volume (32%) than Agula catchment (13%), while the reverse is true for the base flow (the base flow index BFI is here used as a proxy) and soil water storage. The annual average streamflow of Agula was greater than that of Genfel, as shown Table 1, but this has changed after

TABLE 3 Evaluation performance of the hydrological model during calibration and validation

		Catchments					
		Agula		Genfel			
Simulation periods		NSE	PBIAS	RMSE	NSE	PBIAS	RMSE
2011–2016	Calibration	0.92	8	2.3	0.89	7	4.2
	Validation	0.89	11	5.8	0.87	14	6.8
2001–2006	Calibration	0.87	12	5.1	0.84	19	7.0
	Validation	0.85	17	6.3	0.82	21	10

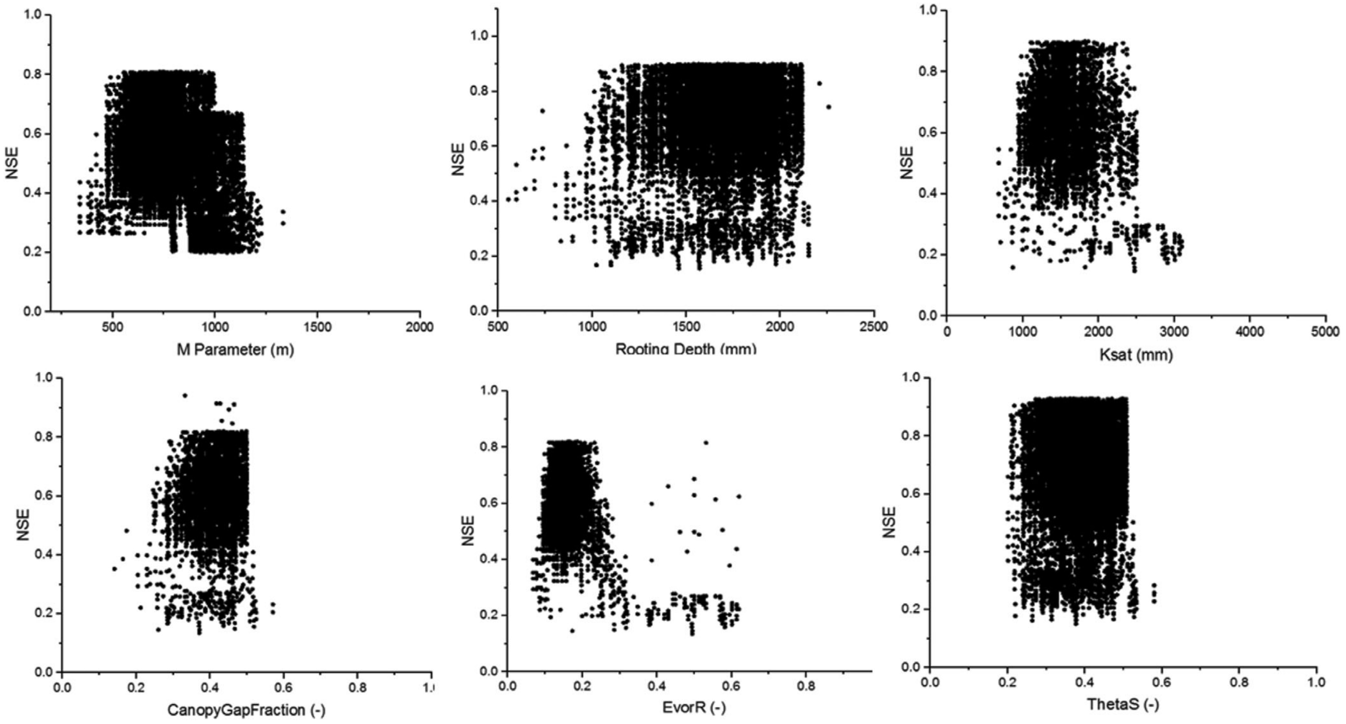

FIGURE 8 Dotty plots for the most important parameters during uncertainty analyses

TABLE 4 Statistical summary on the posterior distribution of parameter values within their parameter space

Statistics	EvorR [–]	M parameter [m]	CanopyGap Fraction [–]	Rooting [–]	Ksat [mm]	ThetaS [–]
Minimum	0.1	0.0	0.1	554.3	680	0.2
Maximum	0.6	1330.9	0.6	2257.7	3099	0.6
Mean	0.2	776.1	0.4	1693.1	1613	0.4
Median	0.2	757.0	0.4	1700.3	1563	0.4
Skewness	13.4	18.1	14.7	13.0	23	15.2
CV (%)	3.6	0.4	−0.4	−0.5	0.7	−0.1

TABLE 5 Average water balance components of the paired catchment during 2014–2016 simulations and their difference (after catchment management interventions)

	Agula catchment		Genfel catchment		
Water budget components	Average	%	Average	%	Difference
Annual precipitation (mm/year)	642	100	634	100	8
Actual evapotranspiration (mm/year)	385	60	355	56	30
Deep percolation (mm/year)	116	18	43	7	73
Change in storage (mm/year)	57	9	33	5	24
Annual total flow (mm/year)	84	13	203	32	−119
Dry season flow (mm/season)	37	6	27	4	10
Wet season flow (mm/season)	47	7	176	28	−129
Runoff coefficient (–)	0.13		0.32		−0.19
Base flow index (BFI)	0.53		0.28		0.25

catchment management interventions when the annual flow of Agula significantly declined compared to Genfel (Table 5). Despite the similarities in climatic characteristics, the ratio of runoff volume in Genfel is higher than Agula by >80%, while the amount of precipitation contributed to base flow is lower by >60%.

The ratio of base flow to the total discharge in Agula is almost double that of Genfel, suggesting more of the incoming rainfall is contributing to the groundwater recharge. The proportion of soil storage to the total incoming rainfall Agula is more than double compared to Genfel catchment. The result is very important because the amount of incoming rainfall to both catchments are almost the same (Table 5) with similar seasonal variations.

The hydrological processes in the two catchments were further analysed by looking into seasonal hydrological variability. The proportion of runoff fluctuated depending on the amount of rainfall and seasons. The greater differences in runoff proportion between the two catchments were in the wet season (June–September) when >80% of the annual rainfall occurred. In contrast, the lowest values and smallest differences were found during the dry season (October–May). The runoff proportion in Agula is lower than in Genfel catchment by >120% during the rainy season which suggests more of the input rainfall in Genfel is going to runoff production compared to Agula catchment. On the other hand, large parts of the seasonal rainfall in Agula is infiltrated into groundwater which later contributes to streamflow during the dry seasons. This is also ascertained by the large difference in water storage (38%) between the two catchments during the driest months (January–May). Moreover, a noticeable difference in streamflow is also observed during Fall (October–December), i.e. the recession flow in Agula is higher than in Genfel by >20%.

The relationship between the hydrological components before catchment management interventions were also compared for the two catchments (result given in Table S2). The results indicate that the remarkable differences in the hydrological response of the two catchments during the period from 2014 to 2016 were not visible before the intervention (2004–2006) programs. With almost the same precipitation inputs (≈1% difference), surface runoff, evapotranspiration and base flow responses did not show substantial differences between the two catchments. An interesting result is that unlike after the intervention programs, the base flow index of Genfel was greater than Agula by 18%. This implies that the two adjacent catchments had the same hydrological response during the 2004–2006 period. This proves that the observed large differences in the hydrological fluxes during the 2014–2016 simulation period could be attributed to the large scale physical SWC structure implementation programs which have significantly influenced the partitioning of incoming precipitation and soil storage.

4.4 | Analysis of hydrological response using a model to model comparison approach

The model-to-model (pre- and post-treatment) comparison approach compares the hydrological response of the catchments with parameter

TABLE 6 Comparison of rainfall-runoff relationships before and after catchment management interventions (difference is given as post-treatment minus pre-treatment)

	Agula catchment			Genfel catchment		
Water budget components	**Pre-treatment**	**Post-treatment**	**Difference**	**Pre-treatment**	**Post-treatment**	**Difference**
Annual precipitation (mm/year)	540	642	102	536	634	98
Actual evapotranspiration (mm/year)	222	385	163	214	355	141
Deep percolation (mm/year)	43	116	73	38	43	5
Change in storage (mm/year)	−9	57	66	−14	33	47
Annual total flow (mm/year)	284	84	−200	298	203	−95
Dry season flow (mm/season)	22	37	15	36	27	−9
Wet season flow (mm/season)	262	47	−215	262	176	−86
Runoff coefficient (–)	0.53	0.13	−0.40	0.56	0.32	−0.24
Base flow index (BFI)	0.15	0.53	0.38	0.18	0.28	0.10

sets calibrated before and after management interventions. Results shown in Table 6 indicate that Agula catchments experienced an increase in low flows and soil storage while a decrease in surface runoff following environmental rehabilitation programs. Unlike in Agula, the low flow in Genfel catchment showed a decreasing pattern after the intervention.

A total reduction in naturalized streamflow by 70% is observed between the pre- and post-treatment periods (Table 6). The significant reduction in total streamflow is due to the increase in actual evapotranspiration (73%) and significant soil storage enhancements after physical and biological SWC interventions. Surface runoff contribution to the river discharge of Agula has significantly reduced (82%) between the two model validation periods (2004–2006 and 2014–2016). In contrast, low flows during the dry season have increased up to 68% after the interventions. Improvement in catchment characteristics in Agula contributed to a radical reduction in runoff coefficient (75%) and increased the BFI between the two periods (Table 6). Analysis of hydrological fluxes response between the pre- and post-treatments of the comparative catchments behaves consistently (Table 6). However, the magnitude of the changes is incomparable between the two catchments. For example, the reduction in surface runoff and runoff coefficients from Agula is more than double compared to Genfel catchment. Similarly, the base flow index in Agula increased by >250% whereas the increment in Genfel was only 56%. Such large differences in the magnitude of changes are attributed to the differences in the level of catchment interventions.

4.5 | Comparison of model parameters between the two catchments

The optimum values of calibrated model parameters were compared to infer if the possible changes in hydrological fluxes are attributed to the surface characteristics of the catchments (Table S1). Parameter values related to canopies such as CanopyGapFraction and the ratio of average wet canopy evaporation rate over average precipitation rate (EovR) are proportional for the two catchments, suggesting that there were no significant differences in the vegetation cover improvements between the two catchments. This implies that the observed differences in hydrological responses between the two catchments cannot be due to differences in vegetation covers. This was also demonstrated by the observed small differences in actual evapotranspiration rates between the two catchments (Tables 5 and 6). In contrast, the values of parameters related to soil and surface characteristics such as saturated hydraulic conductivity (Ksat), infiltration capacity of the soil (InfiltCapSoil), water content at saturation or porosity (thetaS) and soil parameter determining the decrease in Ksat with depth (M) varied between the two catchments. The value of Ksat, InfiltCapSoil, M parameter and thetaS parameters in Agula are higher than that of Genfel catchment.

5 | DISCUSSION

The impacts of catchment management interventions on the streamflow, in particular, the low flows were analysed using statistical tools (Mk and Pettitt, IHA) and comparative modelling approaches. The statistical tools depicted the total annual and wet season flows of the two catchments significantly declined in both catchments. In contrast, the dry season flow in Genfel (control) and Agula (treated) catchments has significantly decreased and increased, respectively. The changes in streamflow without significant change in rainfall over the study areas (Gebremicael et al., 2017); Fenta et al., 2017) indicates factors other than rainfall are the main drivers of the change in the streamflow of the two catchments. The decline in annual and wet season flows is attributed to an increase in groundwater recharge which subsequently contributes to streamflow during the dry seasons (Gebremeskel et al., 2018; Woldearegay et al., 2018). The observed differences in the dry season flow of the two catchments suggest that the enhanced dry season flow in Agula catchment could be attributed to the modifications of catchment responses through SWC practices. Furthermore, IHA parameters showed a very high (>60%) alteration in low flow between the two periods (before and after interventions) which reveals the impact of SWC practices implemented in the period between the mid-2000s and mid-2010s. The overall change in the hydrological alteration parameters elucidates the modification of the flow regimes of the catchment.

However, the statistical tools demonstrated the change in streamflow of the catchments without identifying the physical mechanisms behind these changes. The results of hydrological responses from the comparative modelling analysis and pre- and post-treatment comparisons revealed that the ongoing integrated environmental rehabilitation programs strongly affected the hydrological processes in the region. It is explicitly shown in the analysis that the hydrological behaviour of Agula catchment changed more dramatically compared to Genfel catchment. This may be attributed to the much more extensive physical SWC interventions in the catchment as compared to the control (Genfel) catchment (Table 1). The higher percentage of differences during the dry season indicates the contribution of groundwater flow is greater in Agula than that of Genfel (Tables 5 and 6). This implies that the streamflow in Agula is distributed more homogeneously among the different seasons compared to Genfel which >80% of the total flow comes from the rainy season (July–September) only. The observed differences in the hydrological components must be related to the catchment management interventions and overall storage properties in the catchment.

Moreover, the observed differences in the average value of model parameters (Table S1) between the two catchments indicate that the differences in physical catchment characteristics were responsible for the hydrological response variability between the two catchments. All changes in parameter values were towards a slow hydrological response in Agula compared to Genfel catchment. An increase in values of soil related parameters (Table S1) in Agula catchment suggests that a larger proportion of the incoming rainfall is contributed to infiltration and groundwater instead of going to direct runoff generation in Agula than in Genfel catchment. The modified soil and surface parameter values of Agula catchment is plausibly due to the large proportion of physical SWC interventions. Change in model parameters value between two models signifies there is a difference in catchment hydrological response behaviour between two catchments (Gebremicael et al., 2019, 2013; Tesemma et al., 2010). Seibert and McDonnell (2010) and Gebremicael et al., (2019) underlined that the comparison of calibrated model parameters value is a powerful tool to distinguish the change in hydrological response of changing environments. However, it should be noted that this method is not straight forward as different parameter values might be equally possible.

The introduced physical SWC structures in Agula catchment contributed to the reduction of hill-slope runoff and increased concentration time of the flows (Alemayehu et al., 2009; Gebremeskel et al., 2018; Nyssen et al., 2010; Woldearegay et al., 2018). The different types of terraces and deep trenches constructed across the slopes that follow the contour of the field enhanced soil infiltration capacity of the catchments. Most of the terraces in the catchment constructed in hillslopes and plateau have significantly reduced overland flow and increased the soil moisture (Haregeweyn et al., 2015; Gebremeskel et al., 2018; Guyassa et al., 2016). These structures are the main explanatory candidate for the increased low flow proportion during the dry seasons. At the same time, soil bunds and deep trenches constructed in gentle slopes and agricultural lands have enhanced soil infiltration capacity, reduced peak runoff, and increased groundwater recharge (Alemayehu et al., 2009; Gebremeskel et al., 2018; Huang & Zhang, 2004; Wang et al., 2013). Generally, the introduced physical SWC structures affected the hydrological regimes of Agula catchment which resulted towards a uniform dry-season flow compared to Genfel Catchment.

Our finding is in agreement with previous studies from around the world (Abouabdillah et al., 2014; Gates et al., 2011; Lacombe et al., 2008; Schmidt & Zemadim, 2013; Wang et al., 2013). These studies evidenced that physical SWC structures made an important contribution in decreasing surface runoff during the peak rainy season and increasing the low flow during the dry months. The overall hydrological processes of a catchment can be modified through the introduction of SWC structures which can change the partitioning of incoming rainfall on the land surface (Gates et al., 2011; Gebremeskel et al., 2018). A number of local studies (e.g. Alemayehu et al., 2009; Haregeweyn et al., 2015; Gebremeskel et al., 2018; Guyassa et al., 2016; Nyssen et al., 2010) has also shown that implementation of SWC structures in watersheds resulted in a decrease of surface runoff volume and enhanced availability of water during the dry months. Similarly, some studies (Gebreyohannes et al., 2013, 2018; Taye et al., 2015) support the finding of this study that groundwater has significantly increased in the previously degraded lands of the region. However, these studies were focused either at experimental plot level (e.g. Alemayehu et al., 2009; Descheemaeker et al., 2006; Negusse et al., 2013; Nyssen et al., 2010) or on very small watersheds and survey studies (Belay et al., 2014, Gebremeskel et al., 2018, Woldearegay et al., 2018), from which it is problematic to extrapolate and infer basin-wide implications of SWC interventions. This study uniquely integrate statistical tools (MK and Pettitt) to investigate the pattern of streamflow before and after implementations of SWC activities, indicators of hydrological alterations to identify fluctuations of hydrological parameters due to the interventions and finally hydrological simulations to understand the difference in the hydrological processes of a comparative catchments that have different level of SWC interventions. This study combines different approaches and unequivocally demonstrates the impacts of catchment management interventions on the low flows with a better understanding at catchment scales.

6 | CONCLUSION AND RECOMMENDATIONS

Integrated catchment management interventions have been intensively implemented in the Agula and Genfel catchments since the mid-2000s but in different degrees. This study aimed at understanding the impact of these measures on the overall hydrological processes, particularly the low flow modification in the catchments. The relationships between the observed flows from before and after the interventions were quantified using different Indicators of

Hydrological Alteration parameters and statistical tests. A comparative modelling approaches including; comparison of hydrological responses from two adjacent catchments, one with intensive SWC intervention (Agula) and control with fewer interventions (Genfel) and a model-to-model (pre- and post-treatment) comparisons were applied to investigate causes of changes in the low flows of the catchments.

The results confirmed that the treated catchment (Agula) has experienced a significant change in the overall hydrological processes after the implementations of SWC structures. Our study demonstrated that the low flow of Agula catchment increased substantially more than the control catchment. Significant differences in the partitioning of incoming rainfall were observed after the intervention periods. The annual runoff volume in Genfel (32%) was greater than Agula (13%) after the intervention Table 5. This has resulted in a larger difference of dry period flows between the two catchments. The ratio of base flow to the total discharge in Agula was almost double that of Genfel which explicitly explains that more of the incoming rainfall in Agula contributes to groundwater recharge. This was also ascertained by the observed large differences in the percentage of the dry season flow. The annual flow in Agula is distributed more homogeneously among the different seasons compared to Genfel catchment. Furthermore, analysis of low flow between the two catchments before and after the SWC measures indicates that the remarkable differences in the dry season flows of the two catchments during the post-treatment period were not visible before the rehabilitation programs.

The large differences in the magnitude of changes in the base flow of the two catchments are attributed to the differences in the level of ongoing SWC interventions that have strongly affected the partitioning of incoming precipitation and soil moisture storage. Implementation of physical SWC structures in the catchment contributed to the interception of runoff water and enhanced soil infiltration capacity of the catchments and hence improved water availability in the dry season. However, although the low flow in the dry season significantly increased, the total flow of the catchment has declined significantly following implementations of large scale SWC works. The decrease in the total flow of the stream could be attributed to the expansion of small-scale irrigation schemes and increase of evapotranspiration in the catchments. The key finding of this study is that although the SWC works can enhance the availability of water resources at the local level, it may also reduce the downstream total flows. This suggests that catchment management implementation strategies should be strengthened and substantiated with research to ensure availability of water at different spatial scales and benefit-sharing from the achievements.

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DATA AVAILABILITY STATEMENT

In this study, the authors acquired data from remote sensing, Ethiopian meteorological Agency and Ethiopian Ministry of Water Resources, Irrigation and Energy and field data. Some of the data that support the findings of this study are available from governmental offices and restrictions apply to the availability of these data, which were used under license for this study However, the original data are presented in the manuscript in the form of tables and graphs. The authors had full access to all remaining data and take responsibility for the integrity of the data and the accuracy of the data analysis.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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