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Floodwater harvesting to manage irrigation water and mesquite encroachment in a data-sparse river basin: an eco-hydrological approach

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Abstract

This investigation attempts to understand the eco-hydrology of, and accordingly suggest an option to manage floodwater for agriculture in, the understudied and data-sparse ephemeral Baraka River Basin within the hyper-arid region of Sudan. Reference is made to the major feature of the basin, that is, the Toker Delta spate irrigation scheme. A point-to-pixel comparison of gridded and ground-based data sets is performed to enhance the estimates of rainfall. Analysis of remotely sensed land use/cover data is performed. The results show a significant reduction of the grassland and barren areas explained by a significant expansion of the cropland and open shrubland (invasive mesquite trees) areas in the delta. The cotton sown area is highly dependent on the flooded area and the discharge volume in the delta. However, the area of this major crop has declined since the early 1990s in favour of cultivation of more profitable food crops. Expansion of mesquite in the delta is problematic, taking hold under increased floodwater, and can only be manged by clearance to provide crop cultivation area. There is a great potential for floodwater harvesting during the rainfall season (June to September). A total seasonal runoff volume of around 4.6 and 10.8 billion cubic metres is estimated at 90 and 50% probabilities of exceedance (reliabilities), respectively. Rather than leaving the runoff generated from rainfall events to pass to the Red Sea or be consumed by mesquite trees, a location for runoff harvesting structure in a highly suitable area is proposed. Such a structure will support any policy shifts towards planning and managing the basin water resources for use in irrigating the agricultural scheme.

KEYWORDS

Baraka River Basin, eco-hydrology, floodwater harvesting, land-cover classification, Mesquite, Toker Delta

1 | INTRODUCTION

Although some old and some relatively new options for African river basin management do exist, they are not without constraints. In arid environments of Africa, rainfall is characterized normally by a limited number of rain events but with high intensities that generate massive short-lasting runoff. Accordingly, spate irrigation, that is, flood diversion and spreading, is practiced involving capturing of storm floods mainly from catchments and ephemeral streams and diversion into croplands (Fadul, Masih, & De Fraiture, 2019; Ngigi, 2003). There is evidence that the criteria for sustainable intensification can be fulfilled by water harvesting since such a practice can, for example, improve water availability, increase agricultural yield, rehabilitate degraded lands with an influx of fertile sediments, and minimize adverse effects on the environment that are induced by the use of external chemical inputs (Dile, Karlberg, Temesgen, & Rockström, 2013; Rockström, Barron, & Fox, 2002; Rockström & Falkenmark, 2015). Ensuring sustainable water supply through evaluation of the potential of large-scale (e.g., river basin) water harvesting and identification of suitable runoff zones/sites for feasible water harvesting structures is on one hand very useful, but on the other hand challenging, for the planners and water resources engineers and managers (Ghebreamlak et al., 2018; Jha, Chowdary, Kulkarni, & al, 2014).

El-Sadek, El Kahloun, and Meire (2008) and Ligdi, El Kahloun, and Meire (2010) argued that determining the eco-hydrological status of a river basin permits integrated water resource management. Derivation of eco-hydrological properties, that is, vegetation, hydrologic, and geomorphic attributes, can support management actions and improve decision-making for ephemeral and intermittent streams (Levick et al., 2018). The principles of eco-hydrology are useful in developing sustainable approaches aiming at managing river floodplain systems and minimizing the flood risk (Kiedrzyńska, Kiedrzyński, & Zalewski, 2015). Moreover, a better understanding of the ecological processes and water management are believed to create multifunctional agro-ecosystems (Gordon, Finlayson, & Falkenmark, 2010). The tight coupling between hydrology and ecology in the world's arid ecosystems is poorly understood; therefore, there is a need for strengthening the research in water-scarce ecosystems (Jackson, Jobbágy, & Nosetto, 2009). However, a major hurdle to progress in addressing eco-hydrological challenges in water-limited environments is “the paucity of data at multiple scales and poor quantification of spatial interactions among hydrological elements”, such as topography, soils, and rainfall (Newman et al., 2006). It is generally accepted that the capability of traditional monitoring networks of capturing the spatio-temporally dynamic and complex eco-hydrological processes is usually low (Krause, Lewandowski, Dahm, & Tockner, 2015), especially in vast and physiographically intricate regions where extensive field measurements and observations are either poor or impossible in practice.

Reflecting on African river basins, it is clear from the above background that the prospects for ultimate success of development planning and management are constrained by the harsh environment, limitations of funding, lack of specialized labor, institutional difficulties, and technological problems (Mather, 1989). These constraints create problems of poor database and inadequacy of monitoring which make planning and management often being based on false assumptions (Barrow, 1998). Advances in monitoring techniques and data analysis linked within an interdisciplinary interpretive framework aid in realizing and addressing the myriad of issues facing the dryland eco-hydrological systems and effectively managing these systems (Wang et al., 2012). As indicated by Levick et al. (2018), under the situation of large geographic extent of a study area and infeasible collection of intensive gauge-based streamflow data, Geographic Information System (GIS)-derived variables and hydrologic modelling can be alternatively utilized.

Sudan is among the African countries where spate-irrigated agriculture is extensively practiced in river basins located within vast arid regions. There, seasonally and episodic heavy floods are exploited to irrigate adjacent agricultural lands (Fadul et al., 2019; Fadul, De Fraiture, & Masih, 2018; Fadul, Masih, De Fraiture, & Suryadi, 2020; Fujihara, Tanakamaru, Tada, Adam, & Elamin, 2020; Ghebreamlak et al., 2018). The system of irrigation in Toker Delta is the most complicated spate (flood) irrigation system in the world, as the amount of land irrigated depends on the available Baraka River flows (van Steenbergen, MacAnderson, & Haile, 2011). The scheme was established by the British colonial administration during the World War I for the primary purpose of irrigated cotton production. Nevertheless, the basin is surprisingly understudied. Many changes have resulted in the deterioration of the irrigation infrastructure of Toker Delta Agricultural Scheme (TDAS)—an over-century old scheme. These changes have eventually decreased the efficiency of the scheme. According to Meybeck (2003), such changes are referred to as syndromes of riverine changes caused by natural conditions and human pressures, such as land-use change (agriculture), irrigation, reservoir construction, and water management types (flood control). Based on interviews with experts of the scheme during a field visit in January 2018 and a literature review (de Nooy, 2010; van Steenbergen, MacAnderson, & Haile, 2011), these syndromes, adapted to the situation in the Barak River Basin, are summarized in Table 1 (also with reference to Figure 1). The scheme development is subject to various constraints. Ensuring proper planning and development of the irrigation infrastructure and water distribution on the floodplain is hindered by a serious lack of meteorological and hydrological information. Another constraint is the lack of effective overall management, including inadequate flood embankment capacity and bunds along the course of the river, inadequate control of mesquite trees, insufficient design and implementation capacity of the TDAS, and exacerbation of drawdown of groundwater wells by increasing pump irrigation. The present work aims at making use of meteorological, hydrological, and land cover data (ground-based, satellite-based, and/or estimated) in an attempt to:

1. understand the current status of the ephemeral Baraka River Basin, with a special focus on the part located in the hyper-arid zone of Sudan to account for the complexity of existing interactions between hydrological and ecological processes.
2. suggest floodwater harvesting as a water management option for the basin in general and the agricultural scheme in Toker Delta in particular with the background understanding of the eco-hydrology of the basin.

TABLE 1 Key syndromes and associated symptoms of Barak River changes in relation to marked influences of humans

Syndrome	Symptoms
Tree invasion	Presence and spread of invasive mesquite trees throughout the delta (Figure 1(a) and (b)) and the river channels and banks, thus blocking or diverting the water.
Sedimentation	Local dune and sand ridge formation forced by erosive winds, which gradually block the flood flow channels. Poor land management by the farmers leading to the creation of uneven topography of small sand and silt hills.
Fragmentation	Inhibition of the movement of sheet flow and irrigation of land when crop residues (sorghum stalks), bushes or other obstacles are not removed. These conditions result from the creation of uneven topography, as described above, and eventually result in uneven water distribution.
Soil erosion	Formation of small gullies and erosion channels.
Natural conditions	Unpredictable nature of Baraka River as regards its course and flood direction, magnitude, timing, and width. See the Tomasay bund in Figure 1(c) which functions as flood protection-works of Toker town and water withholder from the non-cultivable western part of the delta.

2 | MATERIALS AND METHODS

2.1 | Study area

The Baraka River Basin (Figure 2), also named Khor Baraka in Sudan, originates from the Eritrean Highlands and covers a catchment area of about 66,400 km^2—most of which is located on the Eritrean side of the basin. It runs for 300 km in the north-west of Eritrea and through Sudan for 200 km, and flows finally to Toker Delta at Shidin before it reaches the Red Sea (de Nooy, 2010). It constitutes the most important ephemeral river in Eastern Sudan. The river channels are dry for most of the year. Baraka's hydrological pattern can be distinguished by high intermittent flood events occurring between June and October (Anderson, 2008; de Nooy, 2010). Even though there are some winter rains in the lower catchments, the Sudanese part of the basin receives most of its water from the runoff generated from the rains falling in the Eritrean part of the basin during the summer. The flow of Baraka River is ungauged. However, two flow measurements made during the early operation of the TDAS in 1912 and 1920 show total annual discharge volumes of 209 and 968 million cubic metres (MCM), respectively (de Nooy, 2010). Since then, no measurements have taken place except some records of flood frequency and duration over the period 2002–2009 (de Nooy, 2010). The available estimates of the number and duration of flood events in Baraka River at Toker Delta are shown in Table S1.

Toker Delta is located in the hyper-arid zone of Sudan (Elagib, 2002), covers an area of 170,520 ha and has its base lying at the Red Sea (Figure 2). The delta receives large river deposits of fertile silt during the flood season of June to September. It is divided into three areas: western, eastern, and central, where the central part represents the main irrigation scheme, that is, the TDAS. Current profitable crops for farmers are sorghum, millet, and vegetables. The total irrigable area is 80,000 ha.

2.2 | Data collection and processing

2.2.1 | Rainfall estimation and evaluation

Due to the limited availability of and access to ground-based meteorological and hydrological observations over the study area, this study utilized mostly open-source data sets for rainfall as will be described below and land cover data. Data on irrigated and cotton sown areas were provided by the TDAS for the period 1900–2016 during the field visit in January 2018. Ground-based meteorological data across the basin are very scarce. In the Sudanese territory of the basin, many of the rain gauges located inside or close to the basin belong to Sudan Meteorological Authority (SMA), but have been out of operation for at least two decades (See Table 2). Rainfall data from six ground rain gauges (see Figure 2) within or near the Sudanese part of the study area were acquired from SMA for different periods (Table 2). In addition, as access to data from the Eritrean site was not feasible, the decision was made to use rainfall estimates. For this purpose, Global Precipitation Climatology Center Full Data Reanalysis Version 8.0 (GPCC V8) of Deutscher Wetterdienst was used due to the temporal coverage needed for the analysis. This updated product of GPCC is a gridded precipitation data set based on data from more than 116,000 rain gauges, and is freely available for the whole world on a monthly basis for the period spanning from 1891 to 2016 (Meyer-Christoffer et al, 2018). It has a spatial resolution of 0.25° and is freely available in the Network Common Data Form (NetCDF) file. Basheer and Elagib (2018) evaluated the previous version of this product (GPCC V.7) in South Sudan. Using several metrics, they ranked GPCC V.7 as the best performing product on monthly, and annual scales based on the linear fit measures, namely lowest intercept (nearest to zero), nearest slope to 1.0 and highest R^2, and smallest errors (mean bias error (MBE), mean absolute bias error (MABE), and root mean square error (RMSE)). In addition, data on the irrigated and cotton-sown areas over 1900–2011 and 1900–2016, respectively, for Tokar Delta were obtained from the TDAS administration in Toker city.

To evaluate the rainfall product, the point-to-pixel method was used to compare the data sets from both the selected available rain gauges and the corresponding pixel of the GPCC product on a monthly basis. This method is commonly used for validating rainfall estimates within East Africa (Basheer & Elagib, 2018, 2019; Gebrechorkos, Hülsmann, & Christian, 2018). Several performance indicators were used to evaluate the agreement of the GPCC product with the rain gauge data, such as the RMSE, the MABE, the MBE, the range of bias error, the slope, and the y-intercept of the linear regression of the two data sets.

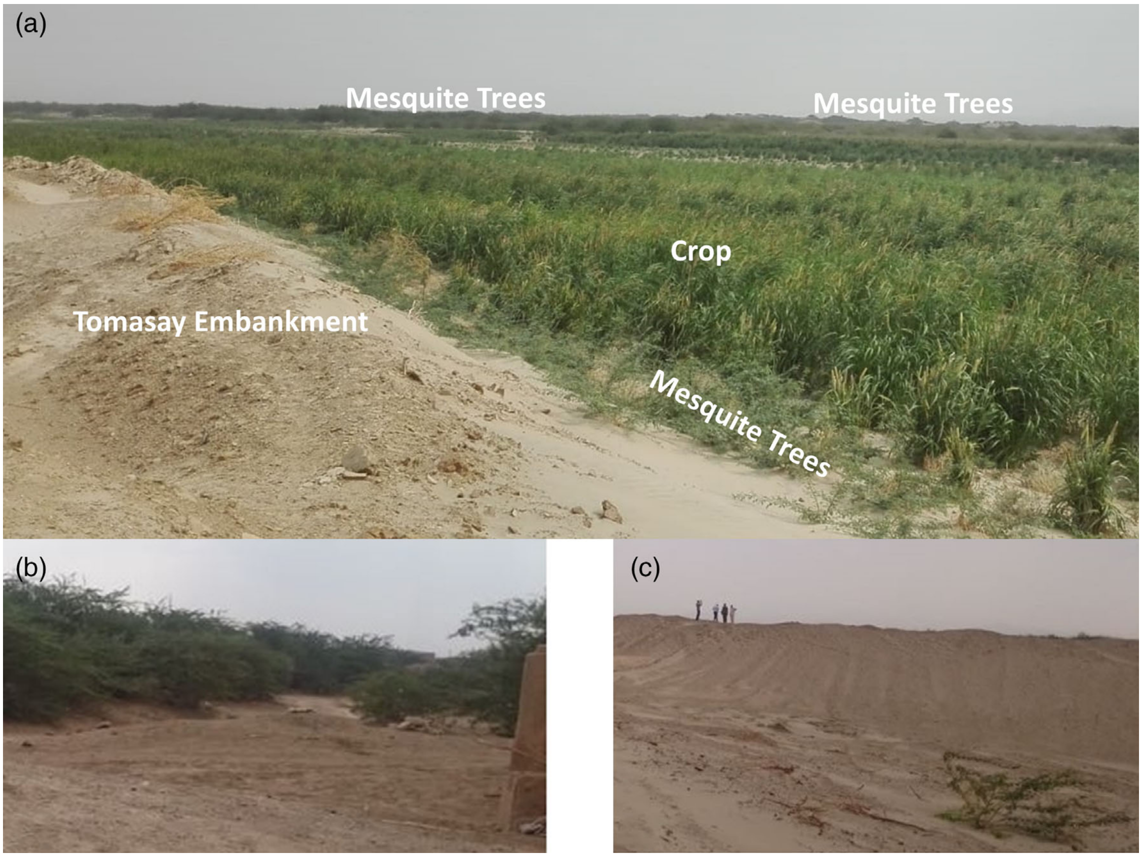

FIGURE 1 Views of Toker Delta: (a) Irrigable and cultivable land downstream the Tomasay Embankment in Toker Delta Irrigated area. Note the spread of the mesquite trees in the irrigated land; (b) Invasive mesquite trees; (c) upstream view of the Tomasay Embankment which provides western and northern limits of the scheme, restricts outflow to the Red Sea, and protects Toker Town from large floods. Photos were taken during the field visit in January 2018 [Color figure can be viewed at wileyonlinelibrary.com]

$$\mathrm{RMSE} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{X_i - X_o}{X_o}\right)^2} \tag{1}$$

$$\mathrm{MBE} = \frac{1}{n}\sum_{i=1}^{n} X_i - X_o \tag{2}$$

$$\mathrm{MABE} = \frac{1}{n}\sum_{i=1}^{n} |X_i - X_o| \tag{3}$$

where X_i and X_o are the estimated and the observed values of rainfall, respectively, and n is the data size.

A regression line of the GPCC data against ground rain gauge data, with a slope closer to 1 and y-intercept closer to zero indicates better performance (Allen, 1996). The other indicators (Equations (1)–(3)) are well known and are used in several studies (Allen, 1996; Armstrong & Collopy, 1992; Bayissa, Tadesse, Demisse, & Shiferaw, 2017; Guo & Liu, 2016; Hyndman & Koehler, 2006; Tan, Ibrahim, Duan, Cracknell, & Chaplot, 2015). The rain gauges were ranked based on each performance metric where a rank of 1 represented the best performance, whereas 6 meant the worst performance. The ranks were summed up to give an overall score; thus, a lower score indicates better overall performance at the given rain gauge.

2.2.2 | Digital elevation model and soil data

Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model—developed by the National Aeronautic and Space Administration (NASA's Land Processes Distributed Active Archive Center [LP DAAC]) with 30-m resolution—was downloaded from the United States Geological Survey (USGS) portal (https://lpdaac.usgs.gov/data/). It was used to generate the slope and drainage networks and delineate the basin boundary. Soil data from the Harmonized World Soil Database with a 30 arc-second raster was obtained from the Food and Agriculture Organization (FAO, 2008).

2.2.3 | Land cover

For the purpose of floodwater harvesting (FWH) analysis, a readily available long-term average land-cover released in 2010 for global coverage with a spatial resolution of 300 m from the European space agency (ESA) was used in this study (ESA, 2010). This product has been used in many studies around the world (e.g., Eberenz et al., 2016; Herold, See, Tsendbazar, & Fritz, 2016). However, to obtain long-term annual land-cover data, which were needed to

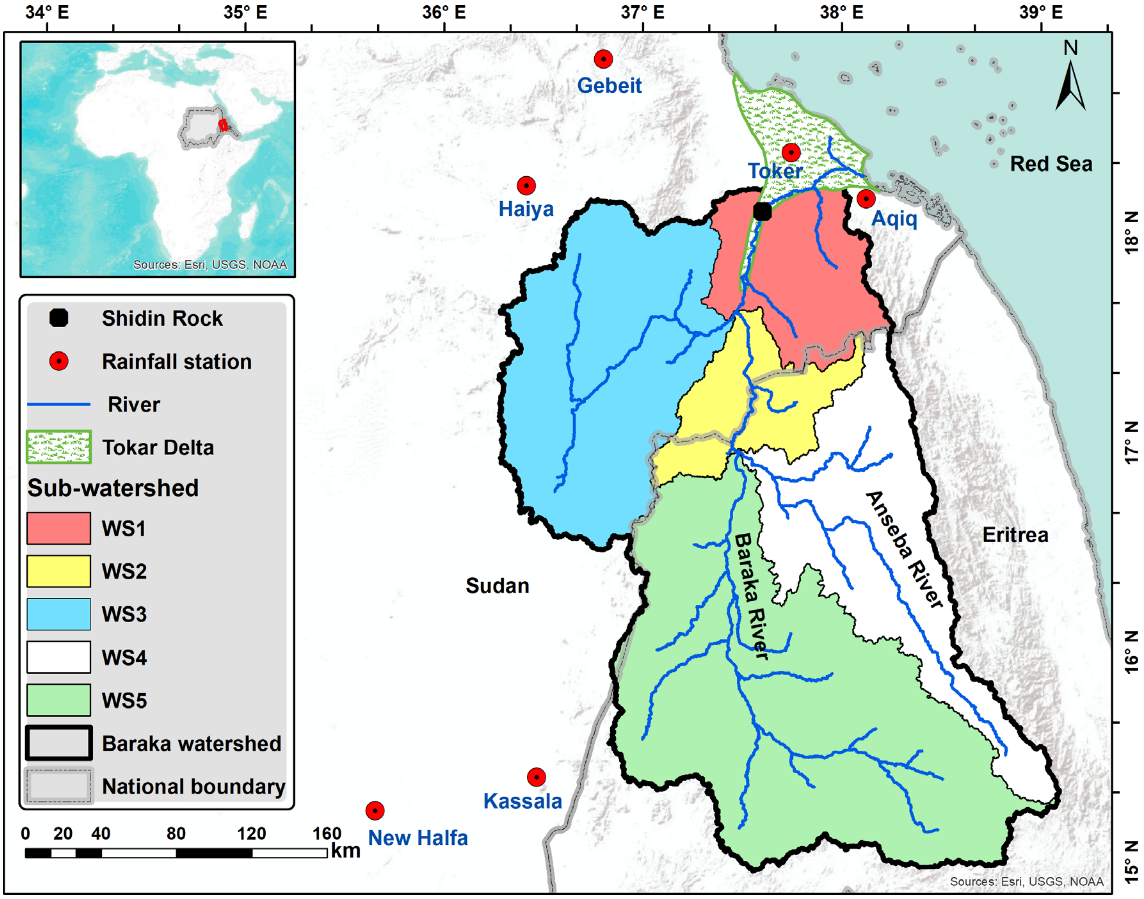

FIGURE 2 Overview map of the study area, location of Toker Delta and rain gauges under consideration. Note: WS = Watershed [Color figure can be viewed at wileyonlinelibrary.com]

detect the land cover change in the study area, the Terra and Aqua combined Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type (MCD12Q1) Version 6 data were used. This product is a global land cover data set that contains eight different land cover classification schemes, including the Geosphere-Biosphere Programme (IGBP) (Sulla-Menashe & Friedl, 2018). The use of this version is advantageous in that the data set was derived using supervised classifications of MODIS Terra and Aqua reflectance data (Friedl & Sulla-Menashe, 2015). The MCD12Q1-IGBP classification scheme has 75% overall land cover classification accuracy (Friedl et al., 2010) and has been utilized in many studies worldwide (e.g., Weber, Sadoff, Zell, & de Sherbinin, 2015; Zhang & Roy, 2017). In addition, Khalifa, Elagib, Ribbe, and Schneider (2018) and Al Zayed, Elagib, Ribbe, and Heinrich (2015) used a previous version of the MCD12Q1-IGBP in different areas in Sudan. Therefore, the IGBP scheme was selected and used in the current study. The grid data have a 500-m spatial resolution and an annual time step. MCD12Q1 data were retrieved from the National Aeronautics and Space Administration (NASA) Land Data Products and Services website (NASA Earthdata, 2018) in Hierarchical Data Format (HDF) for the available period of record 2001–2018.

To classify the land cover in Toker Delta using MCD12Q1 land cover data, a new raster data set for each year was extracted and converted into Tagged Image File Format (TIFF) using Extract sub-dataset tool in ArcGIS 10.4.1 software (ESRI, 2018). The land cover for the delta was extracted by utilizing the Extract-by-Mask tool in GIS and projected into a Projected Coordinate System with Universal Transverse Mercator (UTM) WGS84 datum. Using the Tabulate-Area tool, the corresponding area for every land cover class was determined. The non-parametric Kendall-tau rank correlation test (Kanji, 1997) was used to examine the significance of trends of the time series of land-cover classification areas. Linear regression was also employed to establish eco-hydrological relationships between land-cover areas and irrigated areas or discharge volumes.

2.3 | Runoff estimation

In areas with no runoff data or inadequate historical discharge records to validate rainfall-runoff models, the best way to overcome this problem is by using a method requiring few parameters. Therefore, the Soil Conservation Service-Curve Number (SCS–CN) method (NJDEP, 2004) that was developed by the Natural Resources Conservation Services (NRCS) of the United States Department of Agriculture (USDA) was selected for the area under study. It is considered as

TABLE 2 Performance indicators of GPCC V8 seasonal rainfall data at the ground rain gauges (upper entry) and corresponding rank† (lower entry) among the stations

Station	Period	No. of years used	r	r^2	RMSE (mm)	MBE (mm)	Range of bias error (mm)	MABE (mm)	Slope	y-intercept	Overall score	Final ranking among stations †
Gebeit	1908–1986	65	0.97	0.95	22.1	9.4	−53.1 to 87.3	15.9	1.28	−12.58		
				1	4	4		4	6	4	23	4
Haiya	1950–1979	29	0.97	0.94	15.4	10.2	−8.7 to 37.4	11.3	1.00	10.06		
				3	3	5		3	1	3	19	3
Aqiq	1921–1989	60	0.97	0.94	2.9	−1.6	−7.6 to 4.2	2.1	1.04	−1.82		
				2	1	2		1	2	1	9	1
Tokar	1913–1993	71	0.95	0.91	4.2	−0.2	−111.8 to 95.9	3.1	1.12	−2.79		
				4	2	1		2	5	2	16	2
Kassala	1901–2015	111	0.92	0.85	42.3	−22.4	−15.3 to 10.1	33.6	1.07	−41.33		
				5	5	6		5	3	6	30	5
New Halfa	1966–2013	30	0.87	0.76	56.0	3.0	−205.7 to 150.9	34.8	0.92	22.80		
				6	6	3		6	4	5	30	5

†Rank: 1 = best performing; 6 = worst performing.

the most widely used method for calculating runoff volumes and peak discharge values, requiring mainly the precipitation depth and the Curve Number (CN) value (NJDEP, 2004). This method is also recommended for arid and semi-arid regions and has been applied in Sudan to calculate the runoff generated from a rainstorm for rainwater harvesting applications (Mahmoud, Elagib, Gaese, & Heinrich, 2014). It can be summarized as follows:

$$Q_s = \frac{(P-I_a)^2}{(P-I_a)+S}\,(\mathrm{P} \geq \mathrm{I\,a}) \tag{4}$$

where Q_s is the surface runoff (discharge) in mm, P is the rainfall in mm, I_a is the initial abstraction in mm, and S is the potential maximum retention in mm after rainfall has begun. The initial abstraction concerns the early losses before runoff has begun, and S is related to the soil type and is a function of CN. Both I_a and S can be calculated using the following two empirical equations (USDA, 2010):

$$I_a = 0.2 \times S \tag{5}$$

$$S = \frac{25400}{CN} - 254 \tag{6}$$

In this study, the CN was determined for each sub-watershed according to its specific soil type, land use, and vegetation cover characteristics (USDA, 1972) using GIS. It was then applied in Equation (6) to calculate S. The estimated maximum potential runoff in each watershed was calculated for different rainfall reliabilities using Equation (4).

As outlined in Section 2.1, the amount of land irrigated in Toker Delta depends on the amount of discharge that flows into the delta from Baraka River. With this background, and due to the unavailability of measured discharge data for the basin, the estimates of runoff obtained herein were validated indirectly by understanding the eco-hydrology of the basin and delta, that is, the relationship between both the ground-based cotton sown area and the satellite-based shrubland area and the estimated discharge.

2.4 | Development of floodwater harvesting potential map

In this study, the Multi-Criteria Decision Rules (MCDR) in GIS, namely the Weight Linear Combination (WLC) and the Boolean techniques, were used for integrating and analyzing thematic layers. The latter was introduced by Robinove (1986) and was used in this study to obtain a constraints map using the variables "true or false". This method was used to eliminate some sites that are considered unsuitable for FWH. The FWH structures can only be located within the river channels to collect floodwater. Therefore, in this study, a buffer zone of 1 km on each side of the selected rivers was suggested as an Effective Distance (ED) for floodwater availability. All suitable areas for FWH site selection in the study area were determined to lie within this ED for each river. Areas outside the ED, including areas where the 1 km buffer zone extends beyond national borders, were considered as constraints for FWH. Thus, a value of 1 was assigned to the area located inside the ED and a 0 if it was otherwise. The WLC method involved classifying each factor map and assigning a score to each class depending on its suitability to allocate a FWH structure. Once all the required data were obtained, organized, and formulated, ArcGIS 10.4.1 was used to analyze the data and produce suitability thematic layers for FWH site selection in the study area using different functions and decision rules. The main criteria adopted in this study for selecting suitable sites for FWH were rainfall, soil type, slope, land cover, and drainage density. Each one of these criteria was assessed individually. Thematic layers were created for each suitability component, which was ranked in classes and weighted based on their importance to the selection of the FWH sites (Table S2). The weighting system used was based on the available literature (Gavade & Patil, 2011; Kahinda, Lillie, Taigbenu, Taute, & Boroto, 2008) and common practices in Sudan (Khidir; personal communication, 2017). Then, the weights were normalized using the pairwise comparison matrix (Table S3).

All the generated thematic layers were overlaid based on their normalized weights from the pairwise comparison (Table S3) using the WLC method, and with the aid of Equation (7), a final FWH suitability map was created with four classes of potential water harvesting suitability within the ED in the Sudanese part of the study area. These classes included low suitability, moderate suitability, high suitability, and very high suitability for water harvesting.

$$GS_i = \sum_{i=0}^{n} W_i * Y_i \tag{7}$$

where GS_i is the grid cell suitability value, W_i is the criteria normalized weight, and Y_i is the criteria grid cell.

2.5 | Rainfall frequency analysis and reliable discharges

Using the SCS-CN method and the runoff parameters (Table S4), sub-watershed discharge at different probabilities of exceedance (reliabilities) were estimated. Because Baraka River flows only for a short period during the rainy season (June to September), the analysis of runoff was based on seasonal rainfall during this part of the year using the GPCC data over the period extending from 1976 to 2016. To this end, the rainfall probability curves were plotted by attempting different transformation functions to eliminate the skewness and retain a (near) normal distribution of the data (Mansell, 2003; Shaw, 1994). The runoff in mm generated from each sub-watershed was estimated for reliability values of 50, 67, 80, and 90% and transformed into discharge volumes in MCM. FAO (1991) recommended the use of design rainfall of 67% reliability for agricultural purposes to account for rainfall variability and, accordingly, design a runoff harvesting system that can meet the irrigation demand.

3 | RESULTS

3.1 | Rainfall estimates and variation across the basin

Based on point-to-pixel scatter plots of the June-September monthly rainfall for the nearest six rain gauges to the basin in the Sudanese territory, all the comparative performance indicators, together with the corresponding rank, are shown in Table 2. The variations in rainfall between the GPCC and the rain gauges are mostly explainable by the results for the rain gauges located north, or in the northeast, of the basin. This performance is demonstrated by coefficients of determination (R^2) of ≥.91. At the rain gauges located far from the Red Sea, that is, the two located southwest of the basin in the arid zone of Sudan (Elagib, 2002), the GPCC explains 76% and 85% of the variations in the rain gauge data. All the error metrics, that is, MBE, RMSE, and MABE, together with the y-intercept (closest to zero) indicate the best performance of GPCC at the rain gauges located in Toker Delta. An opposite performance is exhibited by the two rain gauges located in the arid area (Kassala and New Halfa). The overall score (smallest) demonstrates the best performance of GPCC at the rain gauges situated inside the Delta. It can be inferred from the results presented in Table 2 that the GPCC data could be used reasonably to estimate the seasonal (June to September) rainfall in the inner part of the basin, especially in view of the current state of unavailability of rainfall data.

The intra-annual rainfall behavior over the different watersheds of the Baraka River Basin is shown in Figure 3. It is noticeable in general that rainfall reduces from the watersheds located in the Eritrean Highlands towards those situated in the Sudanese territory, reaching its smallest amount in Watershed 1 at the border of Toker Delta. Most of the rainfall contributing to the runoff of Baraka River occurs within the season extending from June to September with the peak reached in August. The total rainfall received during this period has a median of 68.1 mm (Watershed 3) to 259.5 mm (Watershed 5). This rainfall contributes about 56% (Watershed 2) to 79% (Watershed 5) of the annual rainfall. Rainfall over the watershed bordering Toker Delta occurs during November to January (median is only ~42 mm); thus, this amount does not contribute to the runoff of Baraka River. Only ~11 mm of rain fall over this watershed from June to September of the year thus representing only 16% of the total annual rainfall. Rainfall is also highly variable during the year. The seasonal (June to September) rainfall has a coefficient of variation of 37% for Watershed 5 to 66% for Watershed 3.

3.2 | Runoff estimates and variation for different sub-watersheds

The estimated values of runoff parameters used in calculating the discharge on each sub-watershed are shown in Table S4. The results reveal appreciable amount of seasonal (June to September) discharge, varying between 4.6 and 10.8 billion cubic metres (BCM) with 90% and 50% reliabilities, respectively, as estimated at the outlet of the

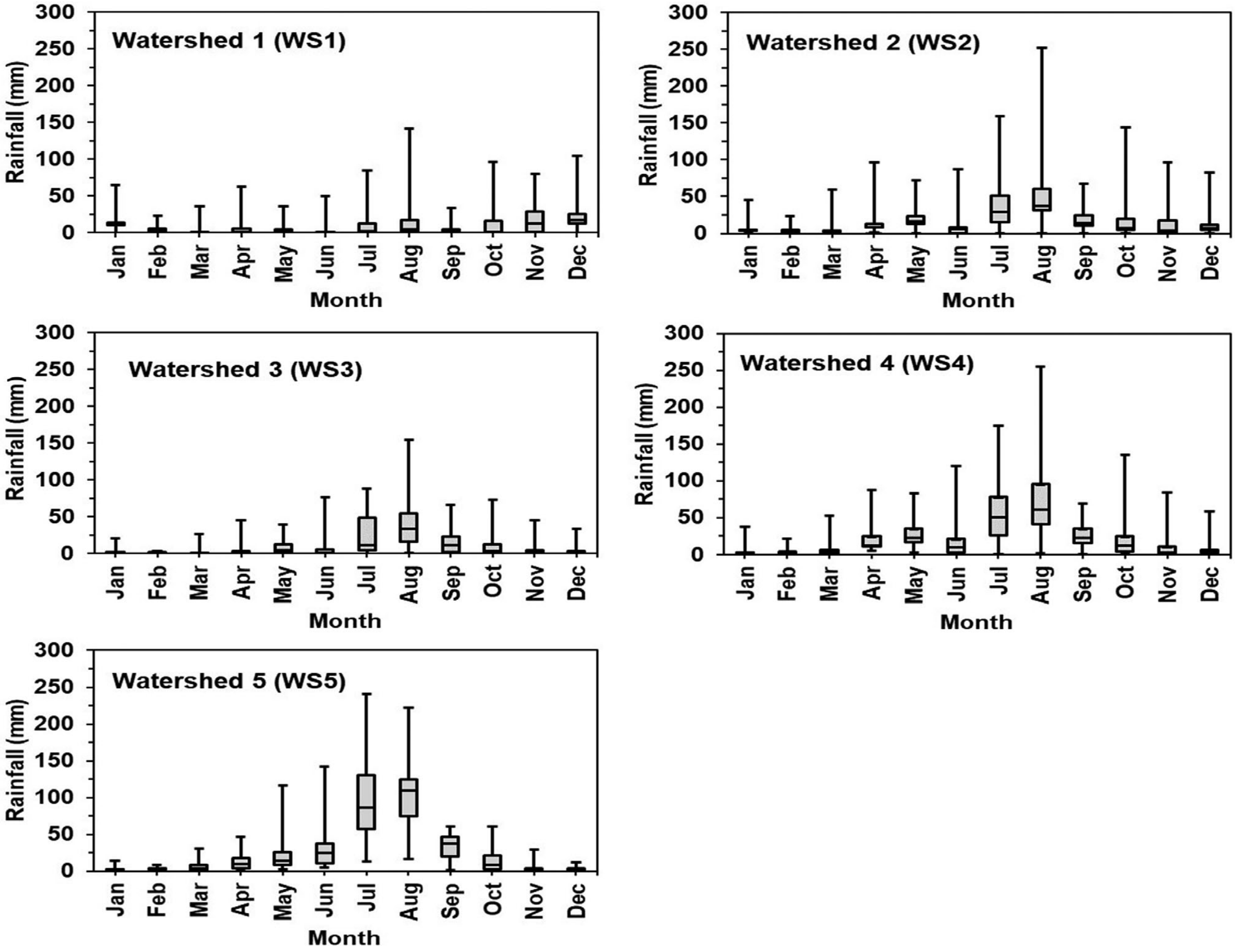

FIGURE 3 Median and standard deviation of sub-watershed areal monthly rainfall across Baraka Basin

basin (Table 3). The majority of this runoff is generated in the upper part of the basin in the Eritrean Highlands on Watersheds 4 and 5 where most of the rain falls. It contributes to the river flow that is generated on Watersheds 3, 2 and 1 in the Sudanese part of the basin, and ultimately reaches Toker Delta (Figure 2). A discharge volume of about 10.6 BCM, which corresponds to the recommended design rainfall reliability of 67%, could be harvested before entering the delta. These values show a great potential of the seasonal discharge of Baraka River for utilization in irrigation and other purposes under appropriate management practices.

3.3 | Eco-hydrological process in Toker Delta

The temporal and spatial variations of the land-cover areas detected across Toker Delta during the period 2001–2018 are shown in Figure 4. Over the common period of both hydrological and land-cover area data sets (2001–2016), the Kendall tau test shows highly statistically significant trends existing for all the land-cover classification areas (Figure 4(a)). Both the grassland and the barren areas decreased (Kendall tau = –0.750; p = 0.000) in favour of increasing areas of both open shrubland (mesquite) and cropland (Kendall tau = 0.933 and 0.551 with p = 0.000 and 0.007, respectively). The most remarkable feature about the time series of the land cover areas in Figure 4(a) is the sudden rises of the area occupied by cropland despite the inconsistent location of these areas in space in the delta, especially during the last 5 years (see the blue pixels in the zoomed areas in Figure 4(b)). Understanding of this variabtion of the cropland area could be attained in view of Table 1. Where to cultivate and how much area the cultivation activities can cover in the delta are attributes governed by the syndromes and symptoms presented in Table 1. In 2018, it is clear that the area of shrubland decreased and that of the cropland increased, as shown in the south-eastern part of the delta. The practice of expanding cropland to the eastern side of the delta is in line with the recommendation offered by de Nooy (2010) that priority should be given to flood the eastern section and build up its level, which is below that of the central portion.

To understand the ecohydrological processes in Toker Delta, Figure 5 shows the interactions between these land covers and the hydrology of the delta. High inter-annual variability in the water volume, irrigated area, and cotton area can be seen in Figure 5(a) and (b). Irrigable and sown cotton areas reached their peak during the season of

TABLE 3 Results of the estimated potential seasonal runoff on Baraka River watersheds with different rainfall reliabilities

Rainfall reliability (%)	Sub-watersheds rainfall amount P (mm) and estimated discharge Q (mm) at different reliabilities†											Estimated seasonal discharge volumes at the outlet (MCM)
	WS5		WS4		WS3		WS2		WS1		Outlet	
	P	Q	P	Q	P	Q	P	Q	P	Q	Q	
50	330.5	283	274.1	206	120.5	55	122	25	37.8	1	569	10,792
67	283.1	232	215.7	144	86.2	44	83.3	19	15.4	0.1	439	10,587
80	239.7	160	162.4	108	54.7	22	48	15	0	1	305	7,010
90	192.2	110	103.9	86	20.3	11	9.2	4	0	1	212	4,654

†The entries are organized in the direction from the source to the outlet, that is, beginning with the upper part of the basin in the Eritrean Highlands (WS5 and WS4) and ending with the outlet in Sudan.

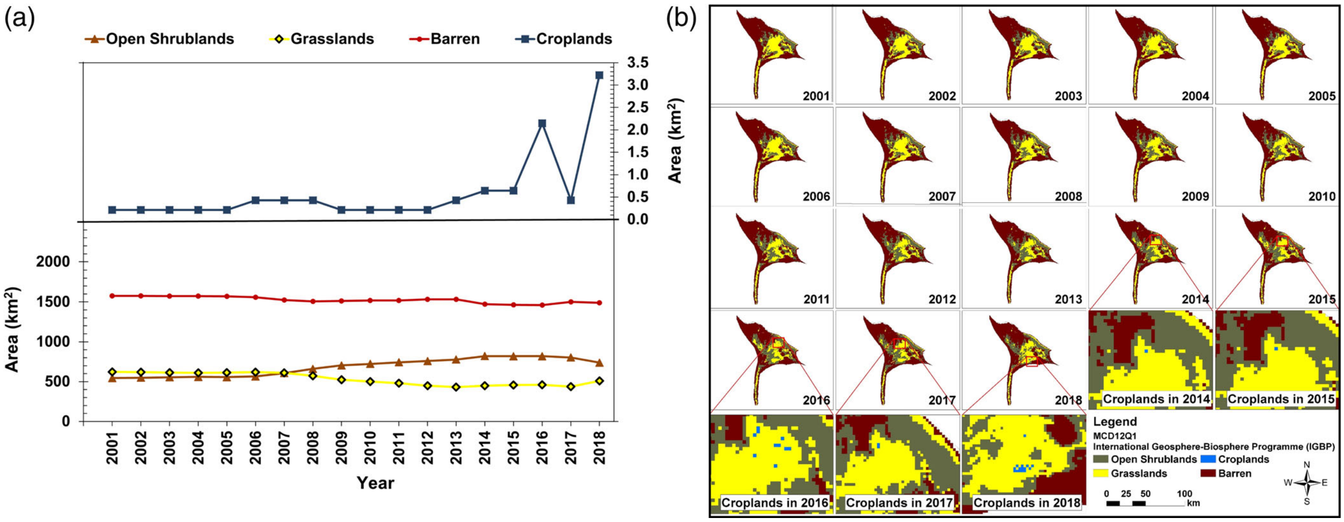

FIGURE 4 Change in land cover area in Toker Delta during the period 2001–2018. (a) Temporal and (b) spatial. Changes in cropland area for 2014–2018 are shown in the zoomed map sections [Color figure can be viewed at wileyonlinelibrary.com]

1961–1962 (~90,000 and 52,000 ha, respectively). However, both areas seem to have been declining, especially the cotton area since the farmers have become more inclined to plant other profitable crops and vegetables in terms of marketing (see Section 2.1).

A scatter plot of cotton area versus direct-flood irrigated area reveals a highly significant correlation using the full records (Figure 5 (c)). An even higher correlation was found with Kendall tau value of 0.810 ($p < 0.0001$) for the data up to 1992. In addition, the cotton area declined thereafter in a non-matching pattern with that of the irrigated area (Figure 5(b)). Thus, the correlation became insignificant for the last two decades of overlapping data (1993–2012). The shrubland decreases with increasing sown cotton area (Figure 5(d)) since shrubs are removed to make the area available for crop cultivation. The planted cotton area increases as water discharge volume increases (Figure 5(e)), a relationship confirmed by the dependence of the cotton area on the irrigated area as explained above.

Shrublands seem to decrease non-linearly with increasing water discharge volume until a certain discharge value of ~13,450 MCM is reached (Figure 5(f)), probably because the water is used for crop cultivation. However, if the discharge increases beyond this threshold, the shrubland area starts to increase since the excess water allows shrubs to grow in inaccessible/uncultivated areas. During the years 2014–2016, the area covered by mesquite reached up to 820,000 ha (see triangular points), thus becoming independent of the volume of surface water made available in the delta. A possible explanation of this remark is depicted in Figure 4(b) where the shrublands expanded during the period 2014–2016 to the western part of the delta. The above relationships and, thus, understanding of eco-hydrology give great confidence in the validity of the discharge estimates obtained from the SCS-CN method.

3.4 | Baraka River Basin water management in Sudan

Based on the thematic layers for the development of the site suitability map for seasonal floodwater harvesting (Figure S1), the final FWH site suitability map in the Sudanese part of the basin was developed as shown in Figure 6. The site suitability for FWH is very high, high, and moderate in 13%, 41%, and 35% of the area within the ED, respectively, while the areas with low potential represent only around 11%. Therefore, the study areas can be said to have a great potential

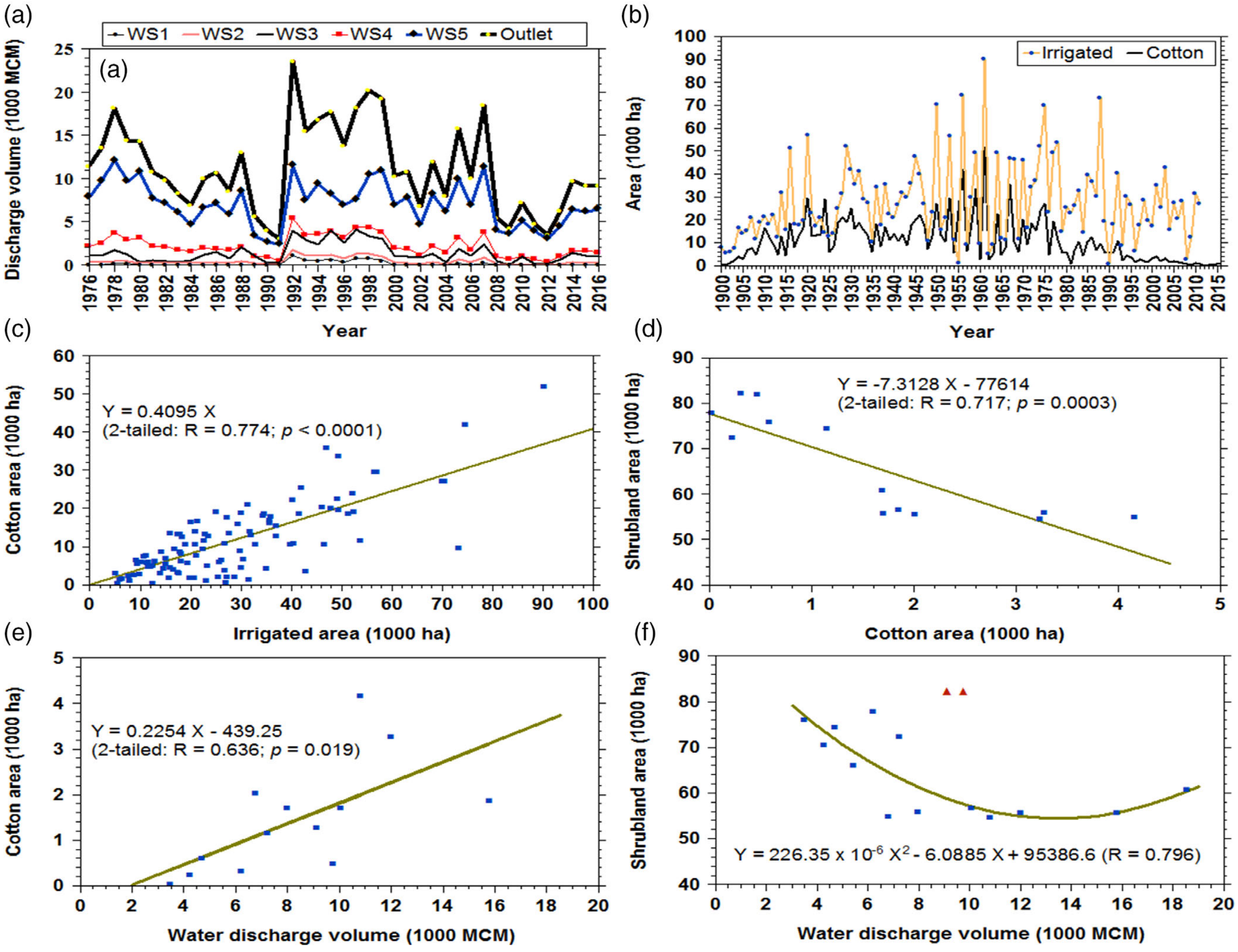

FIGURE 5 Hydrological and land use/cover changes and their interactions in Toker Delta. The outlet in (a) represents the total water discharge volume from the five watersheds and entering the delta. Figures (d) to (f) are constructed using the data for 2001–2016; however, the equation in (f) excluded the triangular points which represent the large areas under shrub recorded in 2014–2016 (see explanation in the text) [Color figure can be viewed at wileyonlinelibrary.com]

for FWH. This conclusion is in line with that drawn by Kadam, Kale, Pande, Pawar, and Sankhua (2012) for remote areas, where less secondary data are available, that integration of SCS-CN and MCDR method in GIS proves effective in identifying suitable rainwater harvesting sites.

According to de Nooy (2010, p. 12), "*The main system of flood management on the Tokar Delta is to construct seasonal dams in the bed of the Baraka River at the head of the Delta and divert the flow across the Middle and Eastern Delta. [This technique will allow the water to penetrate…] the cultivable areas rather than being lost to the Red Sea*". Based on the above results and recommendation, we propose a site for FWH as shown in Figure 6 to be located at the entrance of Toker Delta, 14 km upstream of the Iron Bridge near Shidin rock. This site is highly suitable for FWH and is close to the outlet where the discharge volume reaches the largest magnitude. It also considers the possibility of utilizing the proposed storage structure for regulating the river flows into the irrigation scheme. In addition, it can also act as water storage for use in irrigation during the dry spells rather than being left to pass to the Red Sea or lost for use by mesquite trees. This way of exploiting the available water resource will help increase the agricultural productivity of the scheme. Building dams for water harvesting in India, for instance, proved effective in playing a crucial role in farming by overcoming water scarcity during the summer irrigation season (Balooni, Kalro, & Kamalamma, 2008). The proposed structure herein will also contribute to the flood control of the river, which is characterized by high discharge during a short runoff period.

4 | DISCUSSION

The efforts intended for managing and developing the African river basins are inherent with difficulties associated with observing, measuring and recording unpredictable hydrometeorological

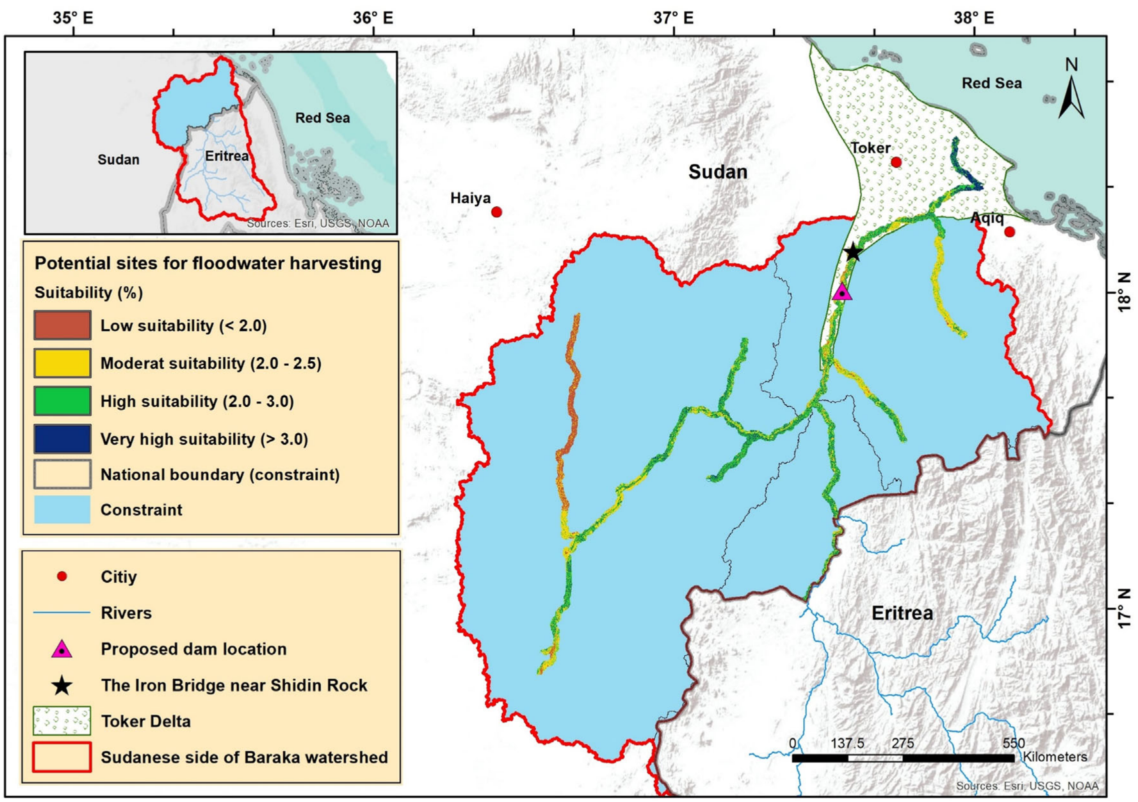

FIGURE 6 Final site suitability map for floodwater harvesting in the Sudanese part of Baraka River Basin [Color figure can be viewed at wileyonlinelibrary.com]

characteristics, especially in remote and harsh regions (Mather, 1989). Problems of poor databases and inadequacy of monitoring beset the African river basins and hinder the understanding of the structure, functions and exploitation opportunities of the basins (Molle, Wester, & Hirsch, 2010). However, the present study has presented an approach to overcome this troublesome scarcity of data. The approch integrates observed and estimated rainfall data, satellite-based land cover data, a flexible rainfall-runoff method and a field visit to collect useful data and information to understand the bidirectional land use-water interactions. Therefore, an option for managing the vast, dynamic, and data-scarce river basin under study has been suggested. As emphasized by Krause et al. (2015), real-time monitoring and research enhance our knowledge about the complexity of spatially and temporally dynamic eco-hydrological systems. It is argued that the umbrella of eco-hydrology provides a means to embrace diverse topics at the interface between hydrology, ecosystem science and the human activities found in different settings (Bonell, 2002; Nuttle, 2002). In catchment eco-hydrology research, the spatial distribution of vegetation is often presumed as a signature of the status of water availability in a catchment (Thompson, Harman, Troch, Brooks, & Sivapalan, 2011). The eco-hydrology principle "enhances the resilience of the river basin against climate and anthropogenic change", flood safety and ecosystem services for society (Kiedrzyńska et al., 2015). Therefore, the eco-hydrological approach proposed in this study can be framed in Figure 7 for replication in similar river basins. For instance, unavailability of data is a typical constraint to the understanding of the actual conditions of similar spate irrigation schemes in Sudan, such as the Gash Delta in the east of the country (Fujihara et al., 2020).

Management of river basin water and treating water as an economic good are considered as two of three policy prescriptions for sustainable water management (Wester & Warner, 2002). The present study area relies heavily on highly variable rainfall amounts and a short rainy season that is fundamental to the generation of runoff, which is in turn a key source of water for the land uses and vegetation growth in the basin, particularly in Toker Delta. Although mesquites are highly resistant to harsh environments and are a source of fuel and animal food, their eco-hydrological impacts are formidable. Shrubland encroachment at the expense of other land covers can cause hydrological alterations and imbalance with remarkable consequences on the ecosystem structure and function (Wang et al., 2012). A study carried out by Yasuda et al. (2014) in an arid environment in Khartoum North (Al Kadaru) showed that, due to roots that extend deep into the aquifers, the type of invasive mesquite in Sudan alters subsurface water dynamics. As indicated earlier, the growth of mesquite in the irrigable part of Toker Delta is one of the major challenges. Hence, we expect that a similar negative effect is taking place in the study area, although no data are available to confirm this effect. The field visit highlighted important information. This kind of trees was introduced to Toker Town in 1960 and 1980 as windbreakers and sand dune stabilizers. In the delta, mesquite trees and seeds have spread across the agricultural land by floodwater and animals. Expansion of mesquite trees causes water depletion at the expense of irrigation water for crops. Any land left uncultivated can quickly be overtaken by mesquite vegetation. In order to cultivate the lands, farmers clean their plots of mesquites every year. The control of mesquite in the irrigable area was an important component in the rehabilitation of the Toker Delta by the local authorties during the last two decades. Clearance of mesquite was employed manually; however, the large-scale eradication plan was halted due to the high cost of the cleaning process.

As concerning agricultural management in African, production is always beset by low soil fertility (Tittonell & Giller, 2013). A recent study found a positive correlation between the crop yield and frequency and quantity of fertilization in an underperforming irrigated scheme within the Nile River basin in Sudan, thus emphasizing the importance of soil properties in determining crop productivity (Khalifa, Elagib, Ahmed, Ribbe, & Schneider, 2020). Drawing on the TDAS, it is recommended not to pursue any flood irrigation plans in the inappropriate western delta due to its characteristic sand and silt dunes (de Nooy, 2010).

Reforms for future river basin management are thought to be grounded on a couple of approaches. These approaches are identified by Molle et al. (2010) as the water development approach for the human benefit through water infrastructure and the approach that promotes restoring and maintaining ecosystems. However, Molle et al. (2010) argue that river basin management in developing countries, where poverty is widespread, will need a strong development dimension. This viewpoint is clearly reflected in the present study through the need for a water harvesting structure, the purpose of which will be to control the flood and at the same time to make better use of the scarce, seasonal water received in the basin.

5 | CONCLUSIONS

This study has attempted to account for complex factors that will be required to improve our understanding of, and ability to predict, the eco-hydrological processes in dryland agro-ecosystems, such as the ephemeral Baraka River Basin in the hyper-arid zone of Sudan. The present research has succeeded in integrating ground-based, remotely-sensed and hydrological data and the assessment of floodwater harvesting potential to achieve this goal. Due to the unavailability of up-to-date gauge rainfall records, a global rainfall product was validated with past rain gauge data within and around the basin to give an overview of the rainfall pattern. This rainfall product was then employed to estimate the discharge volume over the basin sub-watersheds using the SCS-CN method, also due to unavailable rainfall-runoff data. The use of estimates of rainfall and discharge volume, together with the classification of remotely-sensed land-cover areas and ground-based data on irrigated and major crop sown areas, has been successful in establishing and improving the understanding of the underlying eco-hydrological processes in Toker Delta. Hydro-meteorological estimates and GIS techniques were utilized to facilitate locating the sites suitable for FWH within the study area. The eco-hydrological approach adopted herein has proved useful for enhancing the understanding of a complex river basin in a hyper-arid zone. Hannah, Wood, and Sadler (2004) recommended that for eco-hydrology to be a truly interdisciplinary science, this scientific paradigm should explicitly include five aspects. These aspects are the bidirectional hydrological–ecological interactions and feedback mechanisms, the fundamental process understanding, the embracement of natural and human-impacted water-dependent ecosystems, the spatiotemporal scales of process interactions, and the interdisciplinary nature of the research to ensure integrative science. This study has shown how floodwater availability and distribution determine the vigour of the mesquite and the crop area. At the same time, possible

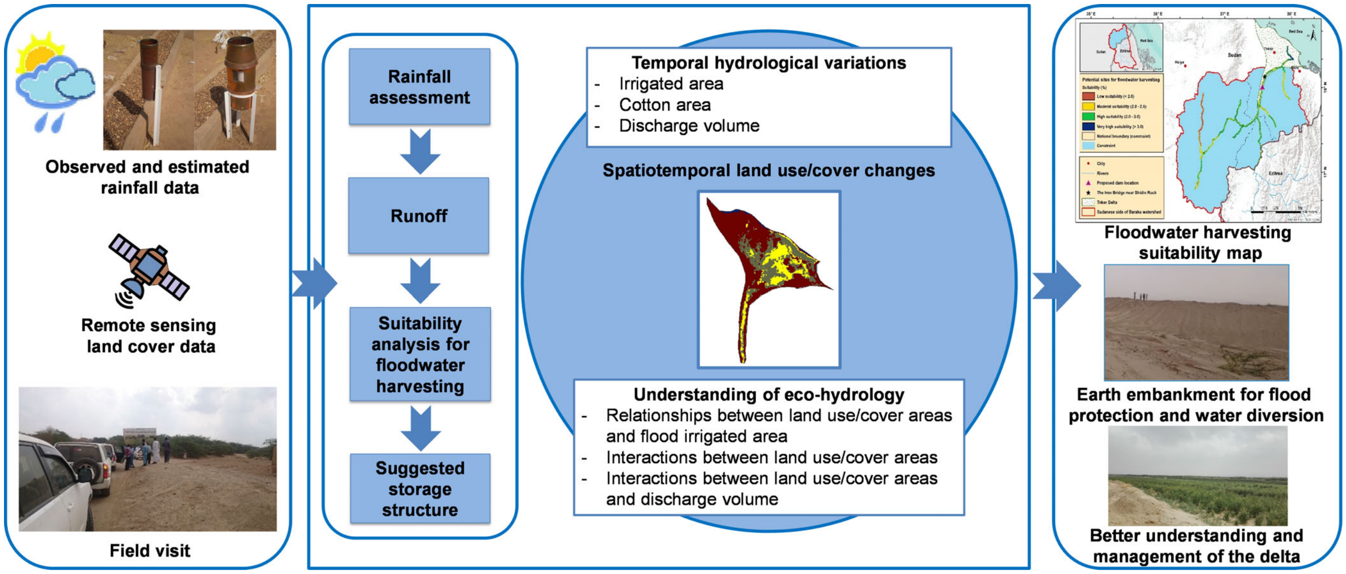

FIGURE 7 Framework of the eco-hydrological approach proposed for enhancing the understanding of a complex and data-sparse river basin such as Baraka River Basin [Color figure can be viewed at wileyonlinelibrary.com]

effects of the mesquite on the water availability for cultivation has been discussed. Finally, the study has proposed a floodwater harvesting structure to manage the basin water for the benefit of the farming activities and to constrain the invasion of mesquite in the delta.

The Sudanese watersheds of the basin receive most of their rainfall during a short period of June to September with a median of ~11 to 91 mm, a mean of ~38 to 122 mm and a standard deviation of ~52 to 89 mm for the period 1976–2016. The amount water available for irrigation determines the type of crop that can be grown and the potential area for irrigation. However, invasive mesquite competes for land and water resources in the delta, and thus negatively influences the farming activities. These results demonstrate marked climatic, hydrological, ecological, and land use associations.

The analysis performed for the study area reveals that 41% of the area within the ED in the Sudanese side of the basin has considerable suitability for FWH. More than half of this area has high to very high potential for implementing FWH structures. If the FWH proposed as a measure of water management in the present research is effectively implemented, it could become central for improving the basin management at large and the ongoing human activities within the delta particularly. A seasonal (June to September) discharge volume of ~4.7 BCM was estimated with a reliability of 90% and could rise to 10.8 BCM with a 50% reliability. A key recommendation to offer herein is the need to enhance the quality of climatic, hydrological, and ecological data and information infrastructures, which are either sparse or completely lacking, to permit a better way for managing the basin challenges and resources and, in turn, to balance the resource uses for generating livelihood among the different beneficiaries.

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CONFLICT OF INTEREST

None.

DATA AVAILABILITY STATEMENT

Data sharing Data subject to third party restrictions: The data that support the findings of this study are available from [Ministry of Agriculture, Livestock and Fisheries, Red Sea State Water Directorate, Sudan] and [Sudan Meteorological Authority, Sudan]. Restrictions apply to the availability of these data, which were used under license for this study. Data are available [from the authors] with the permission of [Ministry of Agriculture, Livestock and Fisheries, Red Sea State Water Directorate, Sudan]. Data derived from public domain resources: The data that support the findings of this study are available in [DEM: Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM); NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC)] available at the USGS Earth Resources Observation and Science (EROS) Center portal (https://lpdaac.usgs.gov/data/); Version 3. [Soil: Food and Agriculture Organization] at [http://www.fao.org/geonetwork/srv/en/metadata.show?id=37139], [Land cover: European Space Agency] at [http://due.esrin.esa.int/page_globcover.php], [Soil: Food and Agriculture Organization] available at [http://www.fao.org/geonetwork/srv/en/metadata.show?id=37139/]; [GPCC V8: Global Precipitation Climatology Centre at Deutscher Wetterdienst (DWD)] at [http://gpcc.dwd.de/], (Geosphere-Biosphere Programme (IGBP): Sulla-Menashe D, Friedl M A. 2018. User Guide to Collection 6 MODIS Land Cover (MCD12Q1 and MCD12C1)] at [https://lpdaac.usgs.gov/documents/101/MCD12_User_Guide_V6.pdf]Data citation [DEM data] National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI)); 2013, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM); NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC) available at the USGS Earth Resources Observation and Science (EROS) Center portal (https://lpdaac.usgs.gov/data/); Version 3. [Land cover data] European space agency (ESA); 2010; Global Land Cover Map; ESA portal (http://due.esrin.esa.int/page_globcover.php); Version 2.3. [Soil data] Food and Agriculture Organization (FAO); 2008; Soil data from the Harmonized World Soil Database with a 30 arc-second raster; FAO.org portal: (http://www.fao.org/geonetwork/srv/en/metadata.show?id=37139).[MODIS Land Cover Type (MCD12Q1) data:]Sulla-Menashe D, Friedl M A; 2018; User Guide to Collection 6 MODIS Land Cover (MCD12Q1 and MCD12C1) Product; Retrieved from: https://lpdaac.usgs.gov/documents/101/MCD12_User_Guide_V6.pdf, Accessed on 26 January 2020; Version 6. [GPCC data:] Meyer-Christoffer A, Becker A, Finger P, Rudolf B, Schneider U, Ziese M; 2015; GPCC climatology version 2015 at 0.25: Monthly land-surface precipitation climatology for every month and the total year from rain-gauges built on GTS-based and historic data; Global Precipitation Climatology Centre at Deutscher Wetterdienst (https://www.dwd.de/EN/ourservices/gpcc/gpcc.html); Version 8; DOI: 10.5676/DWD_GPCC/CLIM_M_V2018_025.

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DATA CITATION

[DEM data] National Aeronautics and Space Administration (NASA) and Japan's Ministry of Economy, Trade, and Industry (METI); 2018, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) digital elevation model (DEM); NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC) available at the USGS Earth Resources Observation and Science (EROS) Center portal (https://lpdaac.usgs.gov/data/); Version 3.

[Land cover data] European space agency (ESA); 2010; Global Land Cover Map; ESA portal (http://due.esrin.esa.int/page_globcover.php); Version 2.3.

[Soil data] Food and Agriculture Organization (FAO); 2008; Soil data from the Harmonized World Soil Database with a 30 arc-second raster; FAO.org portal: (http://www.fao.org/geonetwork/srv/en/metadata.show?id=37139).

[GPCC data] Meyer-Christoffer A, Becker A, Finger P, Rudolf B, Schneider U, Ziese M; 2018; GPCC climatology version 2015 at 0.25: Monthly land-surface precipitation climatology for every month and the total year from rain-gauges built on GTS-based and historic data; Global Precipitation Climatology Centre at Deutscher Wetterdienst (https://www.dwd.de/EN/ourservices/gpcc/gpcc.html); Version 8; DOI: 10.5676/DWD_GPCC/CLIM_M_V2018_025.

[MODIS Land Cover Type (MCD12Q1) data:] Sulla-Menashe D, Friedl M A; 2018; User Guide to Collection 6 MODIS Land Cover (MCD12Q1 and MCD12C1) Product; Retrieved from: https://lpdaac.usgs.gov/documents/101/MCD12_User_Guide_V6.pdf; Version 6.

SUPPORTING INFORMATION

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

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