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Sediment Yield Dynamics during the 1950s Multi-Year Droughts from Two Ungauged Basins in the Edwards Plateau, Texas

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Abstract

Sediment yield dynamics on the Edwards Plateau region of Texas was dramatically influenced by a multi-year drought that occurred there during the 1950s. To assess the effect of this drought on sediment yield, we used the Soil and Water Assessment Tool (SWAT) to identify the factors that contributed erosion and to propose potential mitigation measures in case of future drought recurrence. The basins of interest to this study were Brady Creek One (BC 1) and Deep Creek Three (DC 3), located in McCulloch County, Texas. Although the streams in these basins are not gauged, the land cover and reservoir sediment budgets have been assessed in a past study. Calibration of SWAT flow simulation was accomplished using parameter transfer from a gauging station located in San Saba River. The results showed that sediment yield from storms above 60 mm was five times more during and immediately after drought period than during continuous wet seasons. Approximately half of the total drought period sediment yield was from five major rainstorms. The multi-year drought coupled with historical high grazing intensity resulted in significant loss of plant cover, which was considered critical in determining erosion and sedimentation rates. To test this hypothesis, the model was run for the periods of high land cover (1990s) using the 1950s multi-year drought data which showed that sediment yield was 24% of that simulated for 1950s land cover. It was concluded that maintenance of surface cover could play a critical role associated with multi-year drought extreme events.

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Keywords

Multi-Year Droughts, Sediment Yield, SWAT, Parameter Transfer, Land Cover, Reservoir Survey

1. Introduction

Droughts are natural disasters that have attracted the attention of environmentalists, ecologists, hydrologists, meteorologists, geologists and agricultural scientists due to the impacts these events may have on natural resources [1]. According to Lott and Ross [2], the associated cost of drought disasters between 1980 and 2005 was 16.7% of the approximately $ 500 billion damages caused by weather disasters in the United States of America. Available historical records and paleoclimatic proxies showed that droughts of twentieth century in the region were probably exceeded several times earlier in the last 2000 years by droughts with longer duration and greater spatial extent [3]-[5]. In the twentieth century, the region experienced a series of droughts, with nine episodes between 1889 and 1957 [6]. The most severe was the "drought of record" of 1950s [3], which persisted for six consecutive years in which the most extreme period between 1954 and 1956 had a cumulative rainfall deficit of more than 500 mm [6] [7]. These droughts reduced the vegetative cover density. The occurrences of droughts impact environmental and socio-economic resources and should stimulate mitigation planning for future recurrence [8].

Recent studies have shown that the droughts increase upland sediment yield dramatically. A basin-scale study by Dunbar and Allen [9] showed that in watersheds without significant land cover change, sediment yield was lowest during the relatively drought free period from 1971 to 2007 and over 70 times higher during the early part of the 1950s droughts. At a plot scale, Allen and Harmel [10] analyzed a legacy database from the 3.4 km^2 Riesel watershed, Texas [11], and concluded that sediment yield per unit runoff during drought was higher than all the observed data in the watershed. This was attributed to the combined effects of changes in cover, soil erodibility, and rainfall characteristics, which varied during drought years as compared to the non-drought years. These studies demonstrate the critical role played by vegetative cover in controlling erosion. In a plot level study Thurow and Blackburn [12] showed that the sediment yield from grazed plots was strongly correlated to vegetative cover. The removal of vegetative cover leaves the soil so vulnerable to erosion that even with decreased rainfall erosivity during drought, erosion rates increase dramatically [9]. It is known that sediment is one of the leading pollutants in the U.S. Rivers (USEPA, 2008) and any increased yields, due to droughts, will exacerbate its impacts on water resources. An assessment of the potential change in the climate is particularly important for agricultural watershed given the ever-increasing demand for food production and water supply.

Hydrologic models are often used to investigate potential effects of climate change and land use on water quantity and quality. For example, Andreadis and Clark [13] used Variable Infiltration Capacity (VIC), macroscale hydrologic model, to reconstruct the impacts of drought history from 1920 to 2003 based on simulated soil moisture and runoff for the continental U.S. This study showed that the most severe events occurred during the multi-year drought of the 1950s. At a basin-scale, Nearing and Jetten [14] used Water Erosion Prediction Project (WEPP) model to simulate the response of soil erosion and runoff to changes in precipitation and cover in the Walnut Gulch, Arizona. They showed that changes in rainfall intensity would likely have greater impacts on runoff and erosion than simply changes in rainfall amount alone. In a continental study, Thomson and Brown [15] combined Hydrologic Unit Model of the United States (HUMUS) and Soil and Water Assessment (SWAT) to simulate the impact of La Niña conditions on water yield across much of the Continental US. They showed that the water yield during an El Niño year increased across the south of the country while declining across the rest of the country. In Lower Republican River, Kansas, Perkins and Sophocleous [16] used SWAT and MODFLOW to simulate a basin hydrology and hydraulic response from interconnected stream aquifer system under drought conditions. From their study, they showed that the influence of drought on base flow was a relatively significant component of streamflow yield in the basin. These studies, however, were all limited by the availability of observed sediment yield data.

Accurate application of hydrological models depends on the quantity and quality of observed data necessary for parameter estimates during calibration [17] [18]. Most river basins are not adequately gauged due to either poor accessibility or lack of foresight regarding the need to have adequate gauging stations [19]. Hence, where observed data is missing, regionalization of parameters may be considered appropriate [20]. Regionalization of parameters is a process whereby parameters are inferred from a basin with data to another basin(s) of interest. In the regionalization process, it is assumed that basins with similar characteristics, such as cover and soil properties, will show similar hydrological behavior and thus can be modeled using similar parameters [20] [21]. There are three options for parameter regionalization and transfer. These are regionalization based on: regression [22], physical similarity [23] and spatial proximity [24]. Past application of SWAT that made use of transferred parameters included studies by Heuvelmans and Muys [25] and Wang and Kalin [24]. Their studies showed that transfer of parameters within the catchment and to a neighboring catchment gives a better performance when compared to an uncalibrated model. However, Heuvelmans and Muys [25] caution against transfer of regional parameters between different land use topography and soil, which tend to lower the performance of model.

Compared to water quantity, quality related modeling studies are rare. This could be attributed to limited availability of observed data necessary for model calibration and validation. Use of regression equations to estimate erosion rate could be an alternative, but does not account for climate change [26]. One approach is to use reservoir sedimentation data as a time-integrated surrogate for inflow sediment loading. Reconstruction of sedimentation rates requires the use of multi-frequency acoustical surveying techniques and 3-D data modeling to accurately estimate the current volume of reservoir and deposited sediment stratigraphy [27] [28]. The Texas Water Development Board (TWDB) has carried out bathymetric surveys of over 100 reservoirs and has estimated their volume loss over time due to sedimentation [29]. There have also been a large number of smaller, flood-water retention reservoirs surveyed that provide information on erosion in the catchment [26]. Outside Texas Graf and Wohl [30] assessed the sedimentation and sustainability of western American reservoirs. Age dating, for example using Cesium concentration of specific sediment horizons [31], provides an approximate time-scale in which to estimate sedimentation rates in a reservoir. Uses of this reservoir survey technology provide an alternative to mitigate the lack of historical data.

In Edwards Plateau, drought events are common and similar to other areas of North American with a continental climate regime. Ranching is the main land and leading agribusiness on the Edwards Plateau. It is also likely the main cause of the erosion of the thin soils found in the region [32]. Historically, the livestock population density peaked in the early 1900s, mainly stimulated by initial successfully introduction and production in the region mainly from sheep, cattle and goats [33] [34]. In the early 1930s, changes in livestock market and technology development reduced the prominence of ranching with continued declines in active ranching on the plateau to date [35] [36]. The Taylor Grazing Act of 1934 and the creation of the Bureau of Land Management in 1947 also brought about reductions in numbers of grazing animals in many basins [30] [37]. Finally, with decreased number of ranches the density of grazing animals per ranch may have increased as landowners' maximized production per area of land altering the vegetation cover.

Most previous studies of drought, climate change and potential impacts on local hydrology have focused on the impacts of future climate change scenarios where variability of daily to interannual forcing are investigated [38]. In this study, the hydrological simulation using parameter transfer and Normalized sediment yield [9] are based on reservoir sedimentation that was used to assess sediment yields from the 1950s under various observed meteorological and land cover conditions. The overall goal of this project was to identify the main landscape factors that led to the dramatic erosion and sedimentation rates during or immediately after the multi-year droughts of the 1950s. The specific objectives were to: 1) Calibrate SWAT's long term streamflow simulations in San Saba river basin, 2) systematically transfer SWAT hydrologic parameters to two ungauged sub-basins of the San-Saba River, Brady Creek 1 (BC 1) and Deep Creek 3 (DC 3), 3) calibrate SWAT sediment yield simulation using Normalized sediment yield (NA), and 4) study the impacts of different grazing management scenarios in mitigating the impact of droughts on sediment yield.

2. Methodology

An outline of the methodology used in this study is summarized in **Figure 1**. As shown in the figure the three main steps in this study were: 1) input data acquisition; 2) hydrological model calibration and parameter transfer; and 3) scenario modeling. Each of these steps is described in the subsequent sub-sections.

2.1. Study Area—San Saba River, Brady Creek One and Deep Creek Three Basins

The watersheds used for this study were for the San Saba River (HUC 12090109), Brady Creek one (BC 1) and

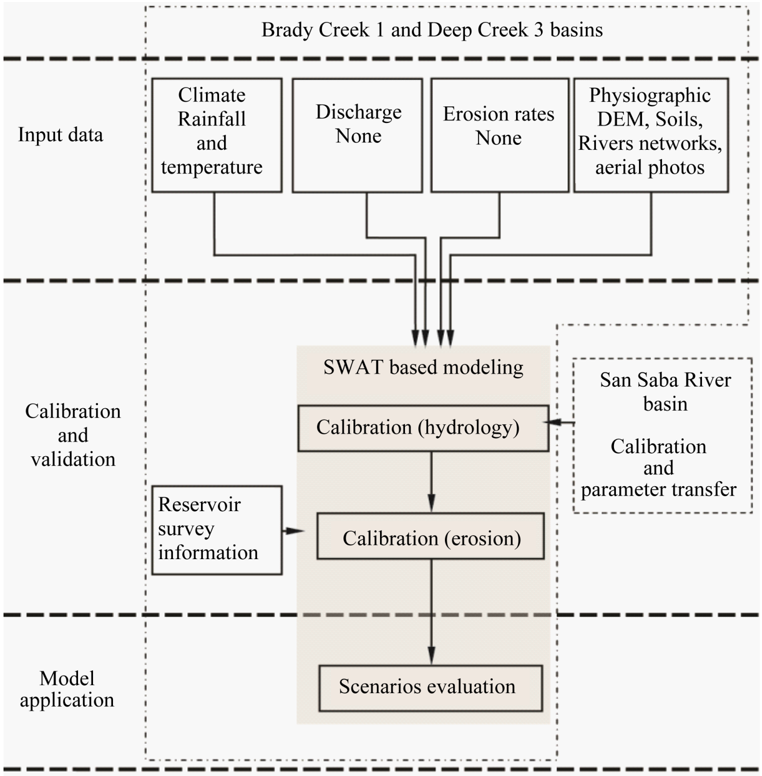

Figure 1. An outline of the methodology used in this study.

Deep Creek three (DC 3) basins (**Figure 2**). The BC 1 and DC 3 are sub-basins of Brady river basin (HUC 12090110) and Middle Colorado (HUC 12090106), respectively. These basins were chosen for study based on availability of observed data and proximity to each other. In addition, the San Saba River had observed streamflow data spanning over 100 years for some of its river gauging stations (RGS). The entire San Saba River watershed partly covers five counties, but a section of the watershed between USGS 08144500, 08145000 and 08146000 (**Figure 2**) was chosen as a parameter donor basin for regionalization of SWAT parameters.

These basins are located on the northern flank of the Edwards Plateau Land Resource Area [9]. Approximately 71% and 21% of the 2940 km^2 San Saba river basin is presently covered by shrublands and herbaceous plants, respectively [39]. The BC 1 and DC 3 basins cover about 25.63 km^2 and the 9.47 km^2, respectively. These two basins have reservoirs, which were constructed during the 1950s multi-year droughts. The location of the two basins is shown in **Figure 2**, whereas **Table 1** summarizes the characteristics of their reservoirs. The BC 1 and DC 3 basins were of interest to this study because Dunbar [40] and Dunbar *et al*. [9] established their normalized sediment yield characteristics, which was used to deduce long term sediment yield.

The annual precipitation in this region ranges between 350 and 900 mm [6] with an average of 600 mm [41]. Average annual temperature ranges between 10˚C and 210˚C with summers temperature as high as 380˚C [41]. Ranching and arable farming are the main industry in the area, which supports the economic structure of the counties [41]. These basins, like much of the southern Great Plains of the U.S., experienced the multi-year droughts during the 1950s with catastrophic socio-economic and environmental impacts [42].

2.2. Soil and Water Assessment Tool

Soil and Water Assessment Tool (SWAT) was selected for this study because of its public availability, design philosophy and use for studying agricultural dominated watersheds by other researchers. The model is a physically-based, continuous time and semi-distributed parameter model [43] [44]. SWAT was designed with a flexible architecture that uses readily available data to describe the physical and climatic characteristics of a watershed [45]. The intended use of SWAT is to predict impacts of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils [44]. The spatially distributed

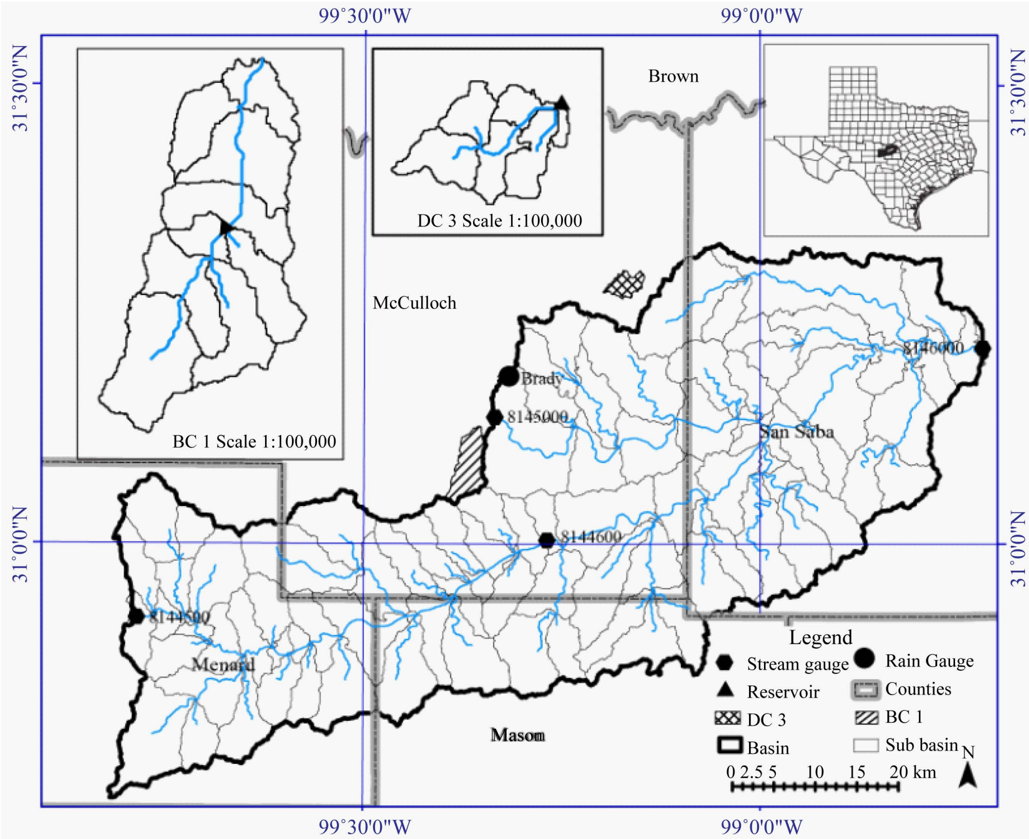

Figure 2. Location, sub-basins and stream networks of San Saba River, Brady Creek one (BC 1) and Deep Creek three (DC 3) basins in the Northern boundary of Edwards Plateau, Texas. The map also shows the location of River gauging stations and Brady weather stations.

Table 1. Name of reservoirs, their upstream watershed area, date of impoundment, year of survey and estimated current volume of the normal pool of BC 1 and DC 3 reservoirs in McCulloch County, TX..

Reservoir	Upstream area (km^2)	Date of impoundment	Year of surveys	Volume of the normal pool (m^3)
BC 1	18.21	1 Jun. 1956	1956, 2007	327,000
DC 3	14.01	13 Nov. 1953	1952, 1960, 1965, 1971, 2007	183,700

nature of SWAT allows a multi-objective evaluation of the impact of spatially varying characteristics and activities on hydrological responses within a watershed [46]. The model has been used worldwide [47]. These uses include assessing Total Maximum Daily Loading (TMDL) of nutrients into river systems [48], Best Management Practices (BMPs) [49] and impact of climate change [50]-[52]. This study integrates management practices and impacts of drought occurrence on sediment yield under low data conditions. It takes advantage of the ability of SWAT to integrate hydro-meteorological conditions and management practices, such as grazing, to simulate sediment yield in a watershed.

2.3. Input Data

The required spatial and time series input data were compiled using databases from various state and federal government agencies. Spatial data included Digital Elevation Model (DEM), streams network; land cover maps and soil information. Time series data required were daily precipitation, temperature, streamflow and annual sedimentation rates. Topographic information of the study basins were based on a DEM, which was obtained from the United States Geological Survey (USGS). A series of historical digital aerial photographs obtained from Texas Natural Resources Information System (TNRIS) for the years 1939, 1953, 1971, 1995 and 2008 were used to generate land cover maps for BC 1 and DC 3 basins. The aerial photographs were preferred over satellite imagery because of their spatial and temporal resolutions. These aerial photographs were classified into land cover maps using ERDAS Imagine and USGS land cover classification system, with an intention of detecting any land cover changes in the basins. The land cover maps of the San Saba basin was also obtained from TNRIS. The soils information including the necessary data for running SWAT were extracted from the 1:24,000 soil survey geographic (SSURGO) databases. All these spatial data were obtained as either grid or shapefiles, which were processed using the ArcGIS based graphical user Interface (GUI) of SWAT called ArcSWAT. In addition, the stream's channel cross-sectional characteristics were measured in the field at three representative locations in BC 1 and DC 3.

The time series input weather data *i.e*. precipitation, maximum and minimum temperature were obtained from the National Climatic Data Center (NCDC) for a weather station (Cooperative ID 411017) in Brady, Texas (**Figure 2**). No other weather stations near the study sites had rainfall data at the frequency and quality required for the model. A summary of the meteorological data used in this study is given in **Table 2**. The percent of missing data in the table gives an indication of data quality in terms of gaps in the records. Where daily total rainfall was missing, it was generated from sum of 24 hourly values for that day. If both daily and hourly data were missing for a given date, the previous day weather data values were used. The rainfall data were analyzed to identify the occurrence of multi-year droughts. Since the historic record of precipitation was generally available at a point, in this study drought analysis is confined to meteorological droughts. A constant value based on long-term mean of annual rainfall amount was derived as threshold for drought occurrence. A similar thresholds for meteorological drought [53] [54] was used by Bonacci [55] and Hisdal and Tallaksen [56]. The advantage of using precipitation based indicators over hydrological or water supply indicators is that the records are not influenced by human or environmental factors [4] [57]. In this study any year with a negative deviation from this threshold was considered a drought year.

The density of grazing livestock was estimated from USDA's National Agricultural Statistics Service (NASS) data. The data for McCulloch County were used as the base data where available. If the county data was missing, it was estimated from the state of Texas livestock data using 1%, a percentage of the number of sheep in McCulloch County when compare to the total in Texas. The sheep data were used because it is the most available in both the Texas and McCulloch County databases. From these data, it also was determined that the average ratio of populations of sheep to cattle to goats was 2:1:1. Hence, for modeling purposes, the sheep populations (**Figure 3**) were doubled to represent the total number of livestock in the County. In this study it was assumed that the percentage of sheep in McCulloch County to the total number in Texas and the average ratio of sheep, cattle and goats in the county were constant over the entire period of study. These data were used to determine the average population density of livestock in the basin over time and consequently approximate the amount of biomass removed via grazing.

Streamflow data were obtained from four USGS river gauging stations (RGS) in San Saba River basin (**Table 2**). In addition, limited streamflow data were measured from selected sites in BC 1 and DC 3 watershed using Hobo pressure transducers for a period of one year. Rating curves for the streamflow monitoring sites in BC 1 and DC 3 were developed using WinXSPRO [58]. The rating curves were then used to convert the mean daily stage height derived from Hobo transducer to discharge rates. Sediment yields for the watershed were derived

Table 2. A summary of weather and streamflow data used in this study.

Gauge No.	Name	Parameter	Period	Percent of missing data
411017	Brady	Rainfall (hourly, mm)	1940-2009	50
411017	Brady	Rainfall (daily, mm)	1991-2010	33
411017	Brady	Maximum and minimum temperature (daily, ˚C)	1921-2010	20
08144500	San Saba River at Menard, TX	Streamflow (daily, m^3/s)	1915-2011	4
08145000	Brady Creek at Brady, TX	Streamflow (daily, m^3/s)	1939-2011	20
08146000	San Saba River at San Saba, TX	Streamflow (daily, m^3/s)	1915-2011	18

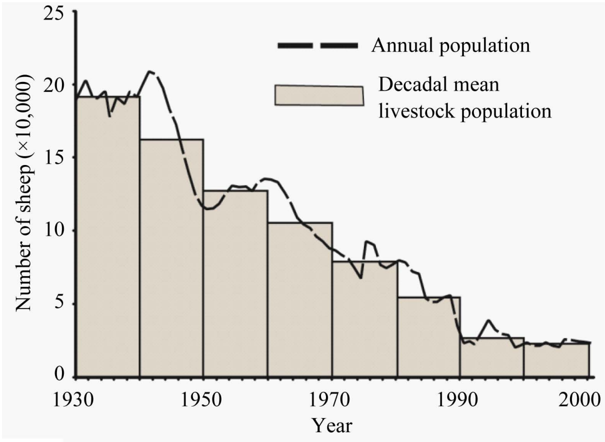

Figure 3. Annual number of sheep in McCulloch County, TX, reconstructed from USDA's National Agricultural Statistics (NASS) database, the bars gives the decadal mean population used in the model simulation.

from normalized sediment yield [9] [40] for the region. The monthly and annual mean values of these time series data were aggregated from their mean daily values where available.

2.4. Model Setup

Literature and default values of various parameters were used in the model set up. The Initial curve number (CN) values in each HRU in San Saba River watershed were estimated based on a combination of land cover and soil hydrologic groups. These estimates were counterchecked with values in Neitsch, Arnold [44]. All other SWAT calibration parameter values were based on their default values and adjusted during the subsequent calibration exercise. The RGS 08144500 and 08145000 (**Figure 2**) were used as basin inlets and their streamflow data used to account for the upstream inflow. Calibration and validation processes were implemented using split-sample test [59], where the model was calibrated against one half of the observed streamflow data and subsequently validated against the remaining half.

A manual calibration procedure was used to calibrate the model to predict streamflow in San Saba river basin. The default and range of parameters, which were adjusted during calibration, process are given in **Table 3**. Calibration of the model was accomplished against both drier and wetter period (1945-1970) years to avoid simulation bias to either dry or wet season. The years between 1940 and 1944 were used as the warm-up years. Subsequently, the model was validated using data from 1971 to 1980. Statistical and graphical techniques described by Moriasi and Arnold [60] were used to evaluate the performance of SWAT in the calibration and validation exercise. The specific statistics used were coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE) and Percent bias (PBIAS).

2.5. Parameter Transfer from San Saba River Watershed to BC 1 and DC 3

Parameter transfer was a derived metric to extend parameters derived from the San Saba River watershed calibration to the BC 1 and DC 3 watersheds. The values of this metric were based on step-by-step screening of potential donor HRUs in San Saba watershed for each recipient HRU. The metric gave priority to similarity in HRUs based on land cover types, soil types, location and proximity. Land cover type in the donor and recipient HRUs were compared for similarity and this gave a number of potential donor HRUs. The selection of HRUs based on land cover types was followed by soils types. From the HRUs selected based on land cover types, those with similar soils types were selected to form a new set of potential donors. The next step considered location of the selected sub-basins in the flow route. Selection of a donor HRUs based on location prioritizes those in a most upstream sub-basin. This eliminates any influence of upstream inflow on a sub-basin's parameters. From the pool of HRUs selected based on land cover and soils, those that were upstream sub-basin were selected from this pool. However, if no suitable upstream HRUs were available, those receiving upstream inflow were also

Table 3. Calibration parameters, their default values and range of variations.

No.	Parameter	Default value or range	Change after calibration
1	Curve number (CN)	61 - 84	−15.00
3	Plant uptake compensation factor (EPCO)	0.00	+0.75
4	Soil available water capacity (SOL_AWC)	0.050 - 0.017	+0.03
5	Baseflow alpha factor (Alpha_BF)	0.05	−0.002
6	Threshold depth of water in the shallow aquifer for "revap" or percolation to the deep aquifer to occur (REVAPMN)	1.00	+310
7	Threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN)	0.00	+550
8	Groundwater "revap" coefficient (GW_REVAP)	0.02	+0.13
9	Manning's "n" value for the main channel (CH_N2)	0.01	+0.02
10	Effective hydraulic conductivity in main channel alluvium (CH_K2)	0.00	+5.00

Source of names Neitsch *et al*. [44].

considered. Finally, proximity to the recipient HRU was taken into consideration. Based on the principal of regionalization by spatial proximity, the donor HRU closer to a recipient HRU was selected. The donor HRUs that satisfied all or most of these criteria was used. The calibration parameters of recipient HRU were varied from default values based on how much they were changed after calibration in the donor HRU. This parameter transfer procedure was repeated for each HRUs for the BC 1 and DC 3 basins and their effect on simulated streamflow was checked against the monitored streamflow data.

2.6. Sediment Yield Dynamics in BC 1 and DC 3 Basins

For the BC 1 and DC 3 watershed, SWAT was calibrated to predict sediment yield in the BC 1 and DC 3 basins against data from normalized sediment yield for McCulloch County as developed by Dunbar and Allen [9]. The units of Normalized Sediment yield (NA) were in t/ha/yr/unit K/unit LS, which was converted to sediment yield (t/ha) for a sub basin using the USLE K, USLE LS and area. This sediment yield was summed for each sub basin to generate a value for the entire basin. Calibration of SWAT to predict sediment yield was done using procedure in Neitsch and Arnold [61]. The land cover maps, (for the year 1939, 1953, 1971, 1995 and 2008), were each used to represent land cover spanning the period halfway to the next map e.g. the map of 1953 represented the period between 1946 and 1962. In addition, the removal of biomass through grazing was accounted for since it plays a critical role in the basins. The mean population of livestock per decade was used as an input. The amount of biomass removed by the livestock was a sum removed by goats, sheep and cattle.

The effects of rainfall storms during a drought period or in the year after a drought period were compared to those in a continuously wet season. This was achieved by simulating daily sediment yield for the dry period (1957 to 1959) and comparing to the simulated yield from a storm of similar amount in the wet period (1968 to 1970). This analysis could be done with any other periods as well. To evaluate the impact of droughts and factors in this study the "drought record" of 1950s was used as a base case. Then, the land cover scenario coupled with the prevailing mean decadal grazing intensity (**Figure 3**) were compared to the base case while using the same time series data *i.e.* rainfall and temperature as model inputs. These analyses showed the impacts of varying cover due to drought coupled with grazing intensity.

3. Results and Discussion

3.1. Land Cover and Rainfall Trends in the Study Area

The trend of land cover in BC 1 and DC 3 from analysis of historical aerial photos is given in **Table 4**. The table gives the percentage of each land cover class between 1939 and 2008. Classification of the aerial photos confirmed that agricultural land is one of the main cover types of the two basins. Field survey conducted as part of this study agree with the findings of DeBord [41], and Dunbar and Allen [9], that the agriculture is composed of

Table 4. Percentage of land cover extent over time in BC 1 and DC 3 basins, in McCulloch County, TX.

Basin	Land Cover	Percentage of Land cover				
		1939	1953	1971	1995	2008
BC 1	Agricultural lands	30	28	30	31	28
	Bare and paved surface	2	6	3	3	2
	Herbaceous grasslands	31	16	16	19	23
	Open water	0	4	1	1	1
	Pasture	24	27	23	22	20
	Shrubs and brush rangelands	15	20	26	25	27
DC 3	Agricultural lands	0	15	8	11	23
	Bare and paved surface	10	11	20	11	6
	Deciduous forests	5	7	6	21	8
	Herbaceous grasslands	26	28	31	10	28
	Open water	0	2	4	10	0
	Pasture	38	14	32	33	12
	Shrubs and brush rangelands	21	24	0	5	24

improved pasture, small grains, cotton, peanuts, and grain sorghum. Bare and paved surfaces identified in the classified data were attributed to roads, household compounds and bare fields. Open water surfaces within the watersheds consist of the two reservoirs and stock ponds. Pasturelands were dominated by various native and non-native grass species, whereas shrub and brush rangeland consisted of junipers (*Juniperus erythropcara*), live oaks (*Quercus fusiformis*) and mesquite (*Prosopis glandulosa*). Slight variation in land cover over time was observed in this study was attributed to the difference and quality of aerial photographs used. These results support our conclusion that no significant change in land cover over the last 60 years has occurred for the BC 1 and DC 3 basins. Similar results were shown by Dunbar and Allen [9] based on their sediment budget study of reservoirs located in these watersheds.

Annual rainfall data between 1940 and 2007 are shown in **Figure 4**. The long-term mean annual rainfall in the figure was the threshold used to identify incidences of possible drought between 1940 and 2007. **Figure 4** shows how the mean annual rainfall deviated from the long term mean in the region, which we considered a drought year in this study when the deviation was negative. The 1950 periods corresponds to the multi-year droughts shown in **Figure 4**. This analysis supports past analysis such Stahle and Cleaveland [62] which shows that the worst drought with the longest duration occurred between 1949 and 1956 with severe impacts on the socio-economic activities and the environment. It is also consistent with observation by Andreadis and Lettenmaier [63] that more recent droughts have become shorter, less frequent, less severe over the last century in most parts of the contiguous US.

3.2. Sediment Yield Dynamics in BC 1 and DC 3 Basins

The results of calibration and validation of SWAT in San Saba River basin are given in **Figure 5** and **Table 5**. The transferred parameters between HRUs in San Saba River basin and those in either BC 1 or DC 3 basins are given in **Table 6**. The characteristics of simulated streamflow with and without transferred parameters in BC 1 and DC 3 basins are summarized in **Table 7**.

A visual comparison of the simulated and observed monthly streamflow hydrographs (**Figure 5**) in San Saba River basin showed that calibration substantially improved the performances of SWAT. The model slightly over predicts the low and mid-flows and underestimates the high flow. Statistically, as shown in **Table 5**, there was a better model correlation in the model predictions during the calibration period than during the validation period. Based on the threshold of model performance given by Moriasi *et al*. [60] the NSE values lower than 0.50 could

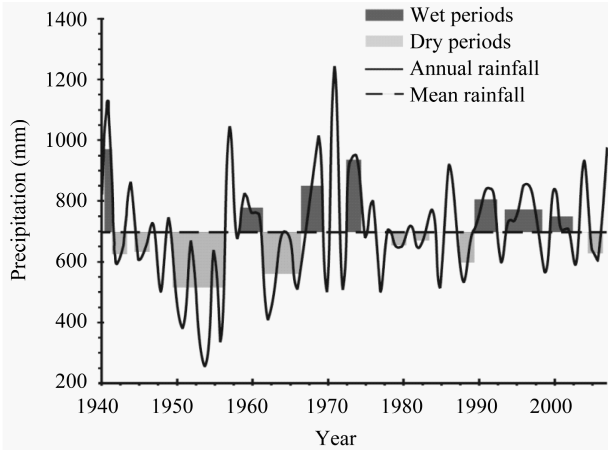

Figure 4. Long-term precipitation plot showing the multi-year droughts of 1950s and subsequent short dry and wet seasons based on data from Brady weather station in McCulloch County, TX.

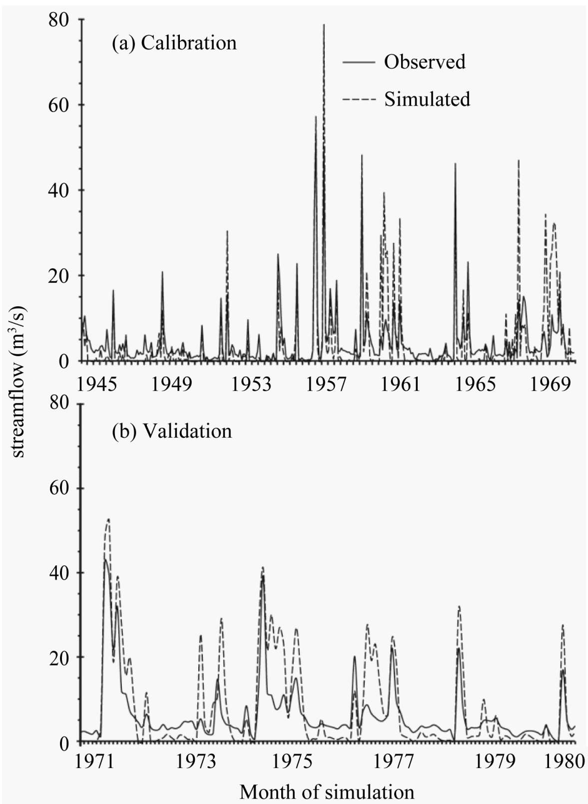

Figure 5. Typical observed and simulated monthly streamflow hydrographs for (a) calibration period (1950-1955) and (b) validation period (1971-1980) for San Saba River basin.

be unsatisfactory although the R^2 and PBIAS values of 6.48% are in the satisfactory range. This performance was attributed to the use of a single precipitation station for the three basins, which might have been insufficient to capture the critical spatial variations associated with localized convective thunderstorms events that produce intense precipitation within a few hours common during dry periods for this locality [64]. Furthermore, distributed models, like SWAT, generally suffer from a poor simulation and prediction performance in the dry periods [65] [66]. Therefore, for SWAT calibration to capture both the wet and dry period one has to compromise

Table 5. A summary of weather and streamflow data used in this study.

Period	Coefficient of determination (R^2)	Nash-Sutcliffe efficiency (NSE)	Percent bias (PBIAS)
Calibration period (1945-1970)	0.64	0.25	6.48
Validation period (1971-1980)	0.71	0.21	−22.92
Thresholds (good)	>0.5	0.65 < NSE < 0.75	±10 < PBIAS < ±15
Thresholds (satisfactory)		0.50 < NSE < 0.65	±15 < PBIAS < ±25

Table 6. The area, land cover and soils types of parameter recipient and corresponding donor HRUs.

Recipient					Donor			
Basin	Sub-basin	Area	Land cover	Soil	Sub-basin	Area	Land cover	Soils
BC 1	1	186.9	Range-Grasses	TAC	39[a]	143.8	Range-Grasses	TAC
	2	204.3	Range-Grasses	TKC	59	9219.2	Range-Brush	Ta
	3	705.0	Range-Grasses	TKC	59	9219.2	Range-Brush	Ta
	4	231.2	Pasture	MeB	70[a]	5706.0	Range-Brush	Ta
	5	111.1	Range-Grasses	OTE	3a	9675.0	Range-Brush	SmF
	6	302.7	Range-Grasses	CMB	24	3782.0	Range-Brush	RgD
	7	795.6	Range-Grasses	TAC	39[a]	143.8	Range-Grasses	TAC
DC 3	1	28.7	Water	W	None			
	2	126.3	Range-Brush	OTE	8	2711.9	Range-Brush	TAC
	3	165.9	Range-Brush	ToB	1	26868.1	Range-Brush	NCF
	4	225.2	Range-Brush	OTE	8	2711.9	Range-Brush	TAC
	5	189.5	Range-Brush	BUE	3[a]	9675.0	Range-Brush	RgD

[a]Non-upstream sub basin.

Table 7. Effect of transferred parameters on predictions of mean monthly streamflow in BC 1 and DC 3 based on a one year of measured data.

Basin	Statistics	Simulated streamflow with defaults parameters	Simulated streamflow with transferred parameters	Observed streamflow
BC 1	Average	0.1519	0.1523	0.1272
BC 1	R^2	0.0108	0.0504	
BC 1	NSE	−0.0524	−0.155	
DC 3	Average	0.0441	0.0001	0.0266
DC 3	R^2	0.0172	0.0001	
DC 3	NSE	−0.084	−0.219	

between these two extremes.

The transferred parameters did not have significant impacts on the model performance when it was evaluated against the limited available streamflow data from monitoring sites in BC 1 and DC 3 as shown in **Table 7**. The single year of observed streamflow data collected was insufficient to conclusively evaluate the model performance in comparison to long-term data in San Saba river basin. The mean simulated and observed monthly streamflow was almost the same but there was no correlation. Ideally, SWAT should be calibrated against long term observed streamflow data (more than three years), however; this study evaluates the model performance with a limited data collected over one year. Wang and Kalin [24] showed that the SWAT performance improved with the parameters transfer, but also cautioned on the use of long term calibration parameter with a short term application. This is a typical situation when using a hydrological model with limited data source. In such a situation, one has to make a judicious decision whether to accept or reject the results despite the poor correlation statistics between the observed and simulated results. Since SWAT tends to overestimate dry period flow, it is worth considering the simulation results of this study as an upper bound of sediment yield.

3.3. Drought and Sediment Yield in Edwards Plateau, Texas

Figure 6 shows the simulated sediment yield in the BC 1 and DC 3. Alongside these results is the calibration data from Dunbar and Allen [9]. **Figure 7** gives a plot of annual sediment yield against the simulated streamflow and compares the effects of prevailing rainfall storms during the wet and dry period. Finally, **Figure 8** shows the impacts of land cover scenario on sediment yields into the two reservoirs in BC 1 and DC 3.

It was not easy to compare the trends of simulated and observed sediment yield data in the two basins. This is because of the time interval of the surveys as shown in **Figure 6** and summarized in **Table 1**. The SWAT model output was at an annual time step whereas the observed sediment yield data from Dunbar and Allen [9] were based on results of two and five surveys, (between 1952 and 2007), in BC 1 and DC 3, respectively. The simulated long-term sediment yield in BC 1 was 44% more than the observed data whereas in DC 3 it was 2% less than the observed data. On annual basis (**Figure 7(a)**), the impact of the drought is not easily discernable. This is probably due to averaging on annual data. However, when daily data is considered the impact of the individual storm become clears. It is observable that the prevailing storms events during or immediately after the multi-year drought season generated more sediment than during the wet season as shown in **Figure 7(b)**. For example,

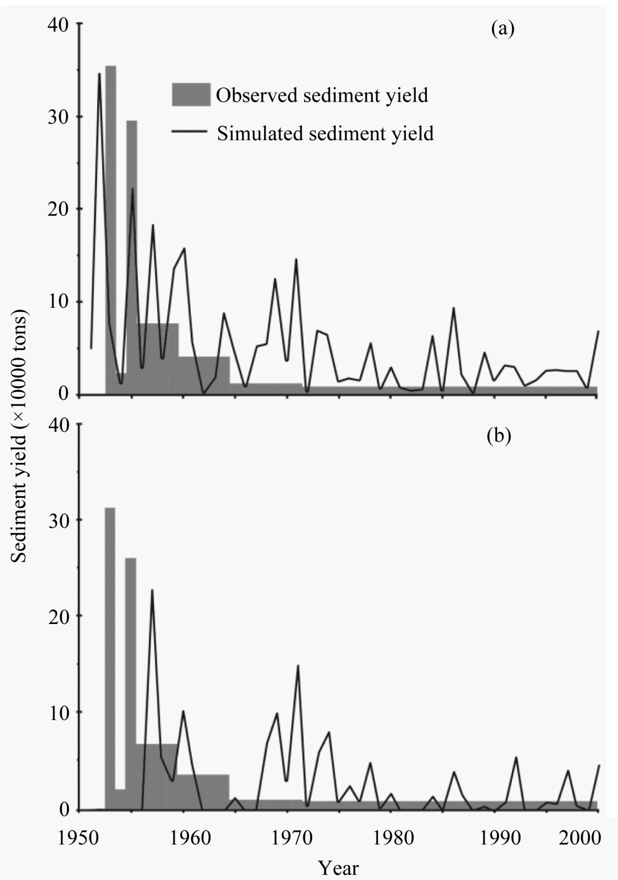

Figure 6. Comparison of simulated annual sediment yields into (a) BC 1 and (b) DC 3 to the trends of observed data from Dunbar *et al*. (2010).

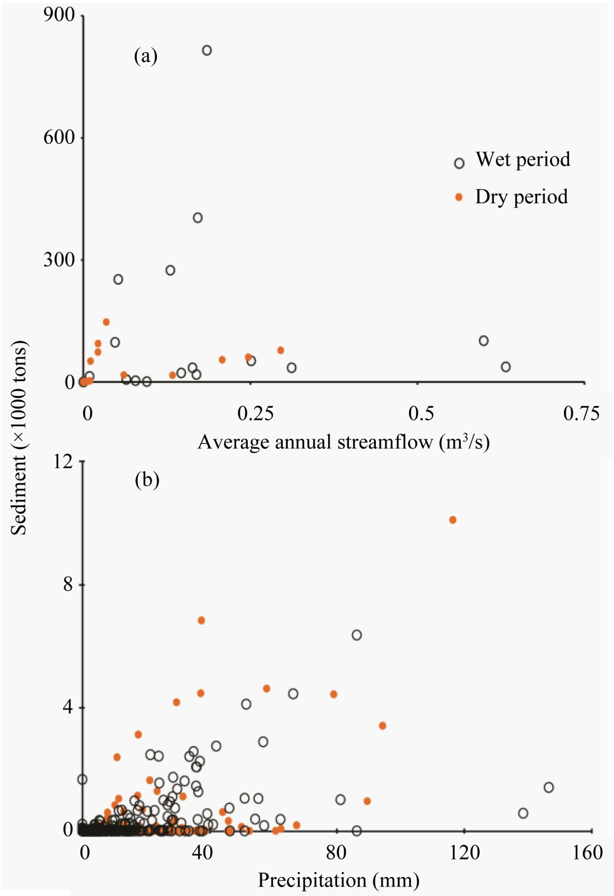

Figure 7. A plot of (a) simulated annual sediment yield against average streamflow and (b) simulated daily sediment yield due to rainfall storms, into BC 1and DC 3, in multi-year drought and non-drought periods.

a 60 mm storms occurring in or immediately after multi-year drought period generated about five times more sediment yield as compared to a similar storms in the wet period. Further analysis showed that approximately half of the sediment yields in the multi-year drought were only due to five major storms. Grazing intensity in the study sites also had significant impact on the sediment yields. Scenario comparison of grazing intensity (**Figure 8**) shows that the current stocking rate could have reduced sediment yield by a factor of 4 and 3.5 in BC 1 and DC 3 basins, respectively. Livestock, mainly cattle, sheep and goats grazing also contribute to plant biomass removal. The high number of livestock (**Figure 3**) in the 1950s in the County could have exacerbated the effects of droughts, which predisposed the soils to agents of erosion.

The results accentuate the significance of soil cover in mitigating sediment yield e.g. [14] even in multi-year drought conditions. In multi-year droughts conditions there is extreme soil desiccation by scorching sun, slow plant cover growth and animals browsing on remaining plant cover and reduced infiltration rates results in increased surface runoff. This increased surface water yield coupled with reduced cover results in an increase in sediment yields. The more total rainfall in a given day, the more runoff occurs, because of the exponential decrease in infiltration rate during rainfall as the surface layer of soil wets downwards [67]. Therefore, the erosion that occurs by runoff before the plant cover is reestablished can be dramatic. Runoff tends to recover in response to precipitation more quickly than soil moisture [13]. Therefore, erosion before plant establishment to reduce runoff will have already generated dramatic. Results of this study (**Figure 8**) showed that the removal of surface cover as opposed to rainfall storms increases erosion and increase sediment yield in a basin under multi-year drought conditions. The land cover scenario of the 1950s caused the most sedimentation, whereas the current cover in the basin yielded the least sedimentation. The simulation for 1990 to 2000 showed a 76% reduction in

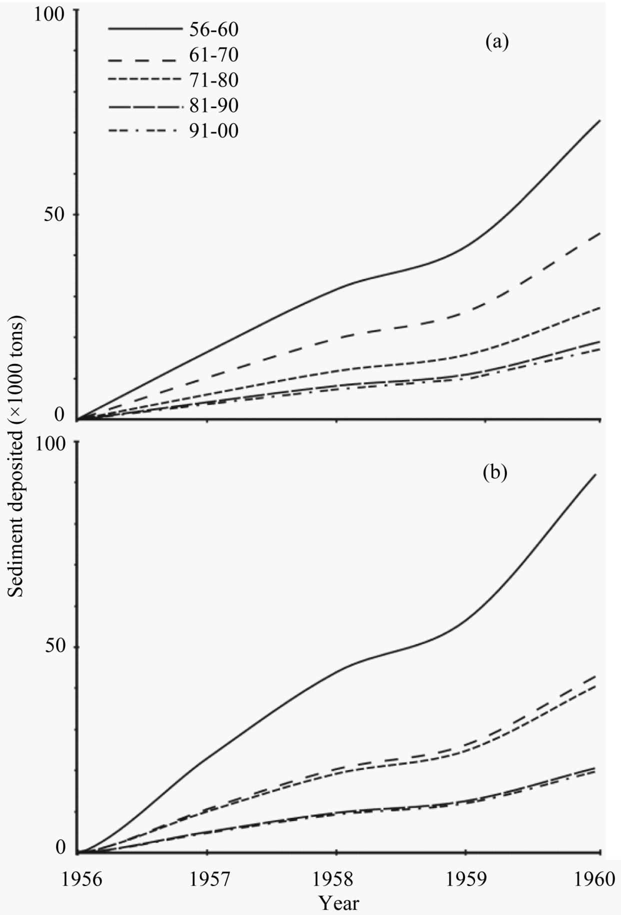

Figure 8. Comparison of sediment yields for land cover simulation scenarios and 1950s weather data only (a) BC 1 and (b) DC 3.

sedimentation rate compared to the 1950 drought that we attribute to higher plant cover and minimum livestock grazing. If land cover and grazing conditions similar to the 1990 to 2000 simulations were sustained, then the estimated reservoir lifespan, based on sediment loading, would be approximately four times longer than the initially projected 50 years. Such sensitivity to land use characteristics, curve number and soil properties was also shown by Osterkamp and Friedman [68]. The frequent low rainfall is not enough to sustain the vegetation but the less frequent high peak result is high enough to generate the dramatic sediment yields. Other studies have shown that vegetation cover removal such as from prescribed fires have similar results. For example water yield from study plots in Guthrie, Oklahoma showed that plant cover removal by burning increased the water yield tremendously from about 0.9 to 100 m^3 per acre [69].

Given the cyclical nature of climate pattern, there is a possibility of future recurrence of multi-year droughts of the same magnitude, or even worse, as the one experienced in the 1950s. From this study, maintaining surface cover plays a critical in role in controlling sedimentation associated with such extreme event. To maintain cover one approach is to significantly reduce the grazing intensity since it is known that livestock compacts the soil, reduces infiltration rates and increases erosion [70]. Moderate grazing increases soil infiltration index which decreases significantly with increase grazing intensity [71]. In rangeland unlike the agricultural lands, mechanical intervention measures like terraces are seldom used; hence, deliberate land cover maintenance effort such as reduced grazing intensity could be the best intervention. One approach could be to fence off the riparian zone from grazing. This could build up plant cover and like filter strips in cropland could reduce soil loss due to erosion. In some instances, maintaining soil cover in such extreme conditions might not be possible; hence one could use mechanical interventions to serve the same purpose. These interventions should slow down the peak flow and thus reduce the delivery of sediment into reservoirs and erosion from uplands.

4. Conclusion

The multi-year drought of the 1950s, six consecutive years of drought often referred to as the "drought of record" [62], caused severe damages to the farming community of Edwards plateau and the wider State of Texas. The community lost not only their sources of livelihood but also the rich top soil in their farms. In this study, SWAT was used to simulate sediment yield during this drought and to show that surface cover was significant to reduce sediment yield after the drought in two basins in Central Texas. Calibration and evaluation of the model in the nearby San Saba basin showed that the performance of the model was satisfactory. Parameter transfer using derived metric, which was based on a combination of spatial proximity and physical similarity, was successfully used to extend parameters derived from the San Saba calibration to the BC 1 and DC 3 basins. The model was then calibrated to predict sediment yield in the watershed using normalized sediment yield [9]. The simulated sediment yield was 44% more and 2% less than the observed values in BC 1 and DC 3, respectively. The difference in performance was attributed to the frequency of the observed data. Given this performance, the model was accepted and used to simulate sediment yield under multiyear drought. Analysis of the modelling results showed that storm sediment yield was about five times higher during or immediately after the multi-year drought as compared to a continuous wet season. Decadal land cover scenario showed that increased land cover tremendously reduced the sedimentation by a factor of 76%. This change in sediment yield was mainly due to a constant grazing intensity, despite the prevailing drought conditions. The reduction in sedimentation is likely to result in a longer increased reservoir lifespan by about four times when evaluated based on sedimentation only. This study showed that the maintenance of plant cover was critical to mitigate the impact of extreme drought in a basin. Grazing intensity should be significantly reduced during multi-year droughts so as to decelerate the loss of plant cover. The use of reservoir survey data, parameter transfer and hydrological models provides a synergy to study ungauged or low data basins, which are common worldwide.

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