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Research Article

Enhancing flood resilience through mixed forest cover: A case study of the Upper Sabarmati River Basin, Gujarat, India

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ABSTRACT

The forest cover plays an important role in India as well as other countries. The decreasing forest cover in India is one of the major causes of floods in many low-lying areas. Hence, study investigates the novel approach of enhancing flood resilience through strategic augmentation of mixed forest cover in Upper Sabarmati River Basin, Gujarat, India. By leveraging SWAT(Soil & Water Assessment Tool) hydrological model, we explore various land cover change scenarios aimed at increasing mixed forest cover and optimizing plantation types within forested areas. Analyzing land cover data from 1985 to 2017, we introduce three scenarios augmenting mixed forest cover by 3%, 6%, and 9%. Our findings reveal a significant reduction in surface runoff by 4.5%, 7.8%, and 11.6% respectively, highlighting the innovative potential of mixed forest ecosystems in sustainable flood management strategies. This study elucidates the critical role of strategic forest management in mitigating flood risks within river basins, offering valuable insights for environmental policymakers and hydrologists.

Keywords: Flood management, hydrological model, land use land cover, mixed forest, surface runoff

INTRODUCTION

The terrestrial land surface is a fundamental component of our natural environment, sustaining animal and human life through its diverse ecosystems. Among its classifications, forest land cover stands out for its multifaceted benefits, including ecosystem conservation (Chen et al., 2018) and its role as a buffer against atmospheric pollution and flooding (Zhao, et al., 2017). Within watersheds, various types of LULC (Land Use Land Cover) exert distinct influences on water cycle, directing water flow from upstream to downstream regions. These LULC categories encompass a range of landscapes, from croplands to urban areas, each contributing uniquely to hydrological processes. During the monsoon season, substantial surface runoff occurs, leading to soil erosion and water loss. However, forested lands, particularly mixed forests, play a critical role in mitigating these effects (Chen, et al., 2018)(Luo, et al., 2020). Mixed forests, characterized by the presence of diverse tree species, possess exceptional water retention and soil nourishment capabilities (Zhou, et al., 2018), thereby playing a pivotal role in managing watershed dynamics (Andersan, et al., 1976)(Zhou, et al., 2002)(Goeking, et al., 2020). SWAT model emerges as a powerful mechanism for hydrological modelling, offering insights into sediment load, runoff, and nutrient transport based on climatic and spatial data inputs (Arnold, et al., 1998)(Darji, et al., 2022)(Pandey, et al., 2021)(Srinivasan, et al., 1998)(Zhou, et al., 2002).

With its capacity for daily, monthly, and yearly predictions, SWAT facilitates water resource management and scenario analysis (Wang, et al., 2019)(Tufekcioglu, et al., 2017)(Nda, et al., 2020). Complementing SWAT, SWAT-CUP serves as a calibration tool, enabling parameter refinement and sensitivity analysis for enhanced model performance (Arnold, et al., 2012)(Pandey, et al., 2021)(Parikh, et al., 2019). Research aims to evaluate forest cover changes' impact, with a specific focus on mixed forest cover, on surface runoff dynamics utilizing the ARCSWAT model. Leveraging data preparation, analysis, and visualization tools such as MS Office and ArcGIS, we seek to

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elucidate the role of mixed forest ecosystems in shaping hydrological processes within the Upper Sabarmati River Basin, Gujarat, India.

MATERIALS AND METHODS

A. Study area description:

Research region encompasses Upper Sabarmati River basin, extending from Rajasthan to Gujarat, India. Spanning approximately 6,114 square kilometres, the basin stretches across latitudes 23°35' to 24°55' north and longitudes 72°35' to 73°45' east. Geographically, it has been bordered by Aravalli hills to north as well as northeast, Rann of Kutch to west, and an alluvial plain near Ahmedabad to the south. The Sabarmati River, originating at 762meters elevationnear Tepur village in Udaipur district, Rajasthan, meanders through basin before converging into the Gulf of Khambat (Cambay) in the Arabian Sea. River's course spans 108 kilometres from its source to Derol Bridge, marking the study area's southern boundary.

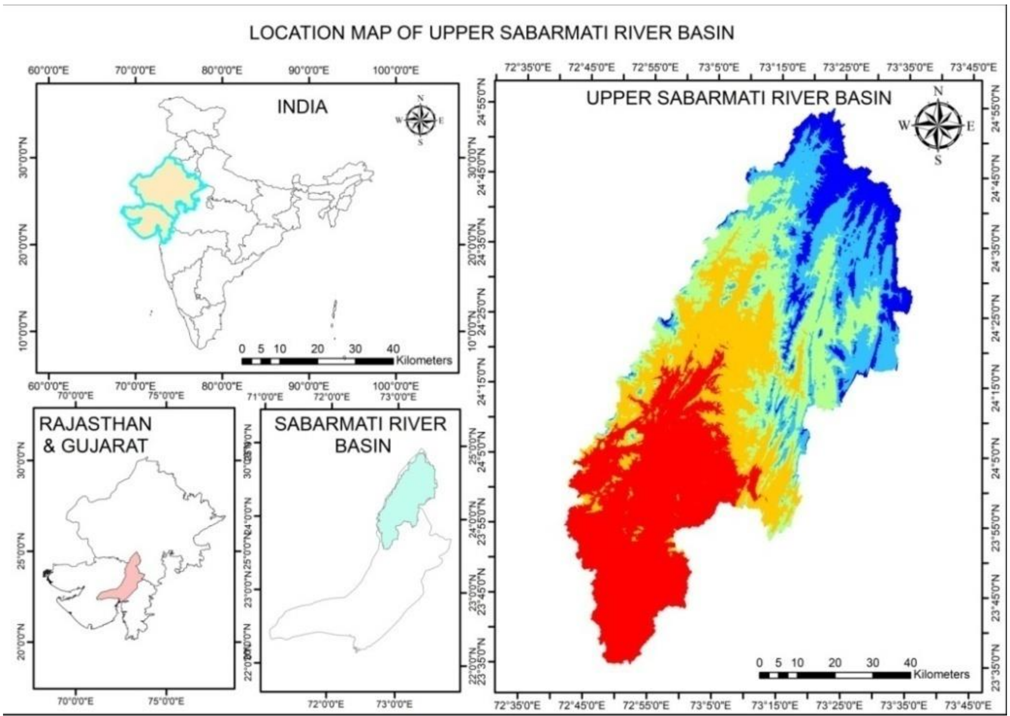

Figure 1 Location map of Upper Sabarmati River basin

B. Influence of Mixed Forest Cover on Surface Runoff Dynamics

Mixed forests, characterized by their diverse array of tree species and root structures, play a pivotal role in shaping surface runoff patterns. The intricate composition of mixed forests contributes to soil stability and enhances the soil's water absorption capacity, thereby mitigating surface runoff. Research indicates that mixed forest stands, such as those comprising Cunninghamia lanceolata and Phyllostachys heterocycla, exhibit higher levels of soil organic matter compared to monoculture stands of C. lanceolata alone. This elevated organic content enhances the soil's water retention capacity, effectively reducing runoff. Additionally, the varied structure of mixed forests facilitates greater canopy interception of rainfall, leading to increased water capture and subsequent evaporation, thereby minimizing runoff volumes.Moreover, mixed forests create a more stable microclimate, characterized by reduced temperature fluctuations, which can influence evapotranspiration rates and subsequently impact runoff dynamics. Furthermore, their inherent resilience to pests, diseases, and climate variations positions mixed forests as robust ecosystems capable of maintaining their runoff-regulating function amidst changing environmental conditions. While both mixed and single-species forests play indispensable roles in runoff control, the diversity inherent in mixed forests provides additional benefits, making them vital components in sustainable watershed management strategies.

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C. Data Collection and Preparation

Rainfall Data

Rainfall data spanning a 30-year period (1990 to 2019) from three rain gauge stations (Jotasan, Kheroj, and Derol), situated around the Dharoi reservoir, were sourced from the Central Water Commission (CWC) and NASA Agro Climate websites (Table 1). Additionally, daily temperature data for the same period and stations were obtained from NASA for the analysis and comparison of monthly maximum and minimum temperatures (Fig2).

Table 1. Rain gauge stations along with locations

Sr no	Rain gauge station's names	Latitude	Longitude	Elevation (m)
1	Derol	23.588	72.808	94.000
2	Kheroj	24.247	73.016	215.000
3	Jotasan	24.355	73.168	288.000

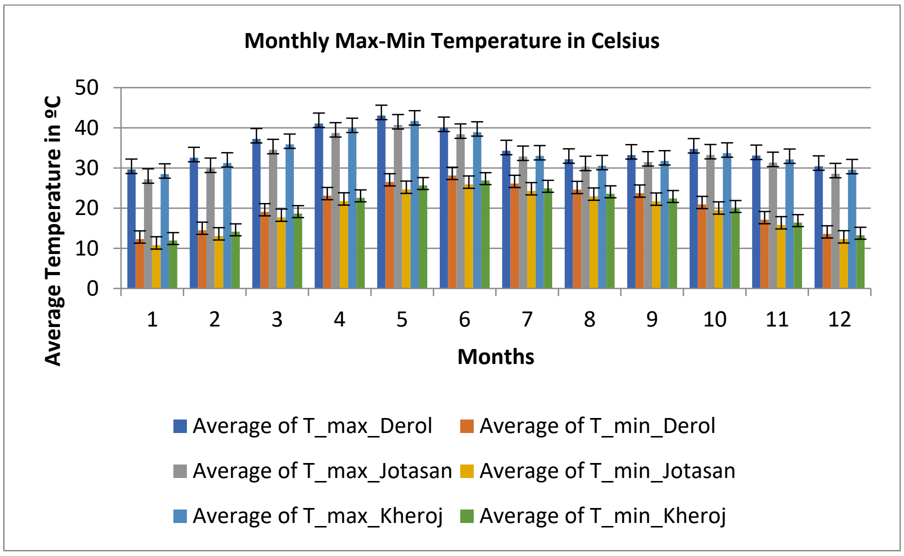

Figure 2. Mean monthly max-min temperature distribution of three rain gauge stations

Figure 2 illustrates the mean monthly max as well as minitemperatures, accompanied by their standard deviations, over 30-year period for the three stations. During the summer season, temperatures fluctuate between 38°C and 48°C, while in winter, they range from 10°C to 15°C. May typically experiences the highest temperatures, making it the hottest month, whereas January is characterized by the lowest temperatures, marking it as the coldest month. On average, max as well as mini temperatures across the year are34°C along with 20°C, respectively.

Elevation Data

Elevation data were collected from topo-sheets and the Aster DEM (Digital Elevation Model) of USGS(US Geological Survey). The study basin exhibits varying elevations, with the highest point at 782 meters (Aravalli Hills, Rajasthan) and the lowest at 53 meters (Gujarat Plain) above mean sea level (Fig. 3(a)).

Soil Data

The Upper Sabarmati basin comprises various soil types, including loamy, clay loamy, loamy sand, heavy clay, and rock (areas with thin soil cover). Soil characterization is based on texture, hydrological group, and the percentage of clay, silt, and sand (Fig. 3(b), Table 2).

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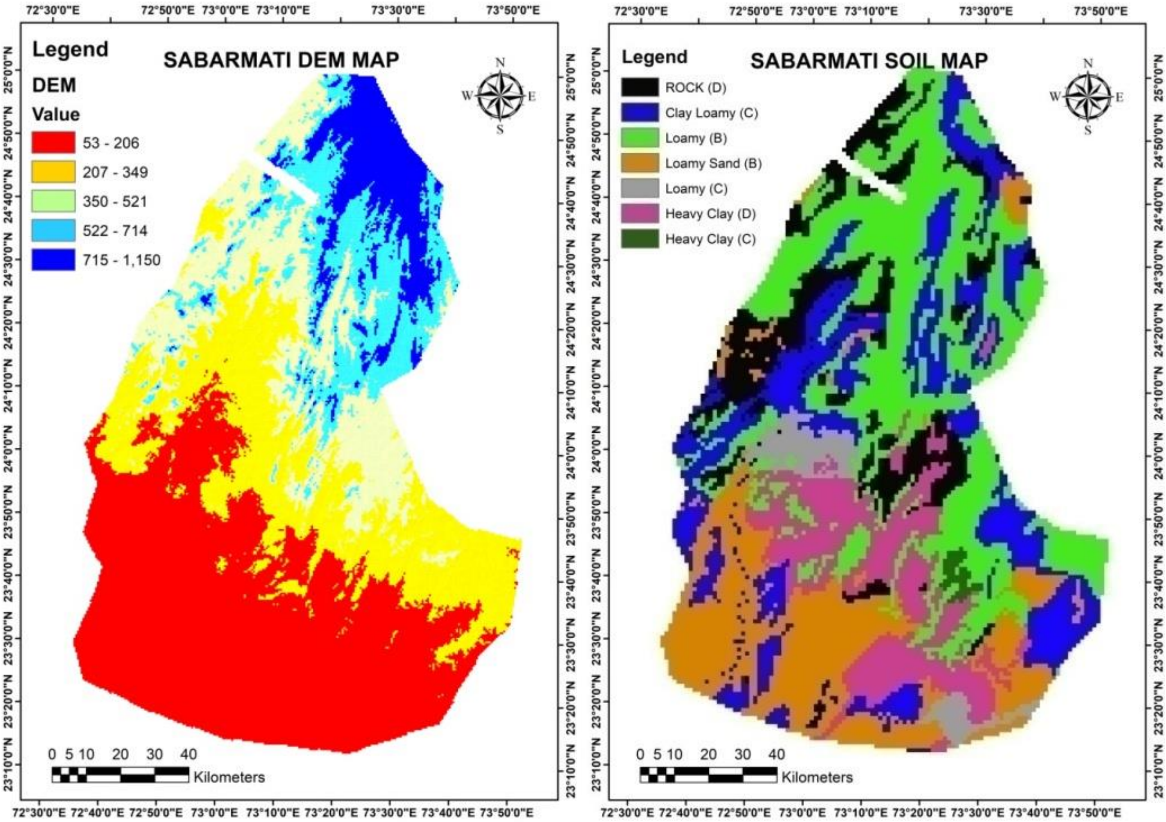

Figure 3 (a) Elevation and (b) soil map of the Upper Sabarmati basin

Table 2 Soil types in the Upper Sabarmati basin

Sr no	Soil Name	Texture	Hydrological Groups (HYD)	Clay %	Silt %	Sand %	Rock %
1	A039_2b_4	Loamy	C	22	31	46	0
2	Bc9_2b_8	Clay loamy	C	32	26	43	0
3	Bd31_2c_11	Loamy	B	22	38	40	0
4	Kh1_1ab_3990	Loamy sand	B	10	10	80	0
5	Rock_193	Rock	D	5	25	70	90
6	Zg6_3a_3326	Heavy clay	D	65	11	24	0

Land Use and Land Cover Maps

LULC maps had beengathered from Decadal Maps of India website moreover were further refined using satellite imagery and Google Earth images (Table 3, Fig. 4).

Table 3. Satellite images used for the development of LULC maps

Data period	Satellite type	Sensor used	Resolution of data
1984-1985	Landsat 4	MSS	56 m
1994-1995	Landsat 5 & IRS 1B	TM & LISS-I	30m&72m
2004-2005	Landsat 5 &Resourcesat	ETM+ & LISS-III	30 m
2016-2017	Landsat 8	L8 OLI/ TIRS	30 m

Source: Website Earth data, daac.ornl.gov/decadal lulc of India.

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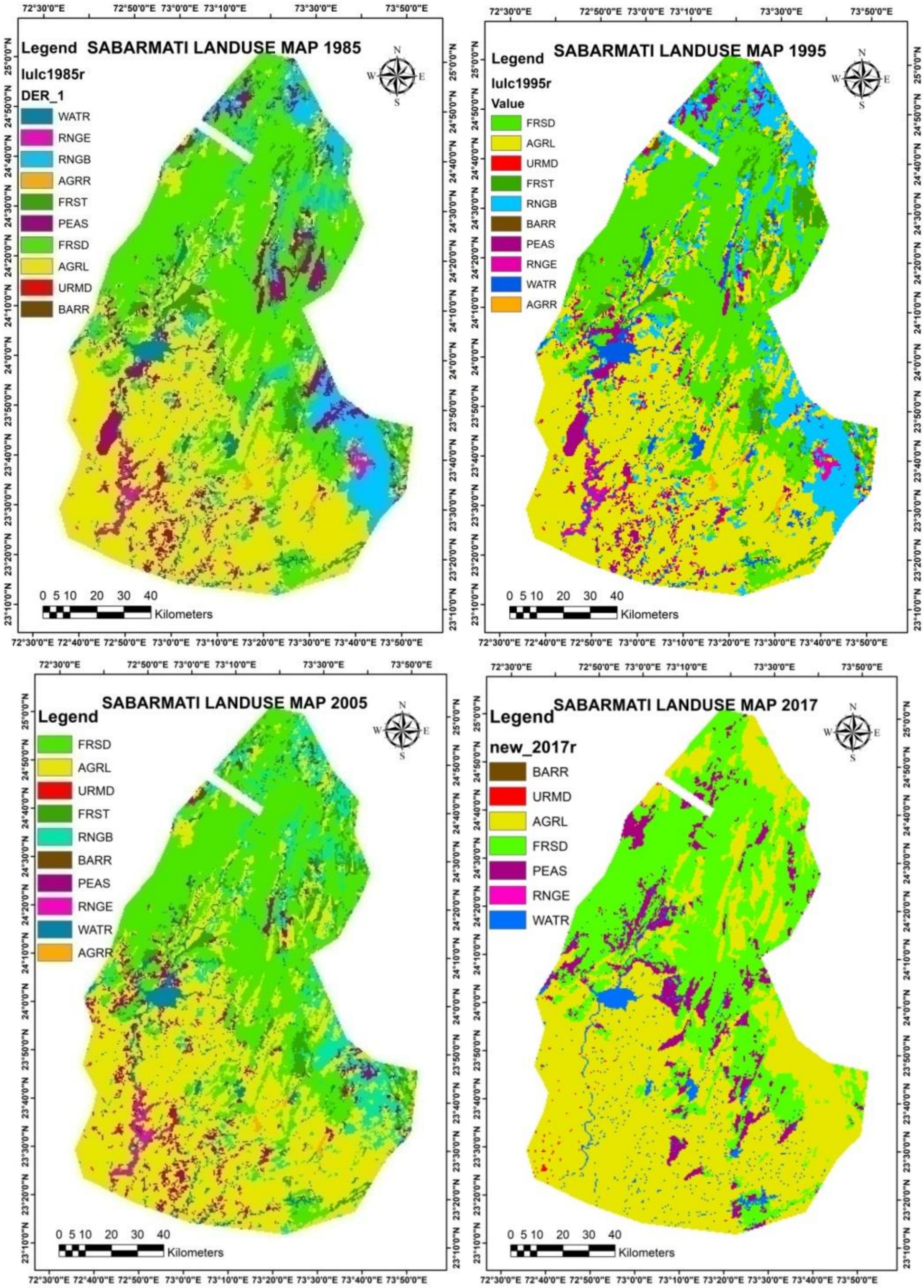

Figure 4. Various decadal (a) LULC1985, (b) LULC1995, (c) LULC2005 and (d) LULC2017 maps of study area

Land Use and Land Cover Analysis

LULC alterationanalysis utilized remote-sensing data from four decadal thematic maps: LULC 1985, LULC 1995, LULC 2005 (Chourushi, et al., 2019), and LULC 2017 (Fig. 5). Analysis reveals a consistent increase in deciduous broadleaf forest and cropland areas by 4% and 9% respectively (Table 4). Conversely, the coverage of mixed forest exhibits a steady decline of approximately 0.50% from 1985 to 2017 (Fig. 6).

Table 4. Change detection analysis of four LULC maps

Sr. No.	LULC Codes	LULC types	Area in percentage			
			LULC 1985	LULC 1995	LULC 2005	LULC 2017
1	FRSD	Deciduous broadleaf forest	32.89	31.38	32.10	36.17

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2	AGRL	Cropland	40.32	42.03	44.14	53.43
3	URMD	Built up land	0.16	0.16	0.18	0.19
4	FRST	Mixed forest	3.92	4.81	4.16	0.00
5	RNGB	Shrub land	10.70	10.78	9.33	0.00
6	BARR	Barren land	0.50	0.41	0.65	0.00
7	PEAS	Fallow land	6.44	4.80	4.39	7.26
8	RNGE	Waste land	0.93	0.93	0.74	0.02
9	WATR	Water bodies	3.80	4.39	3.95	2.93
10	AGRR	Plantations	0.33	0.33	0.35	0.00

Source: https://daac.ornl.gov/VEGETATION/guides/Decadal_LULC_India.html

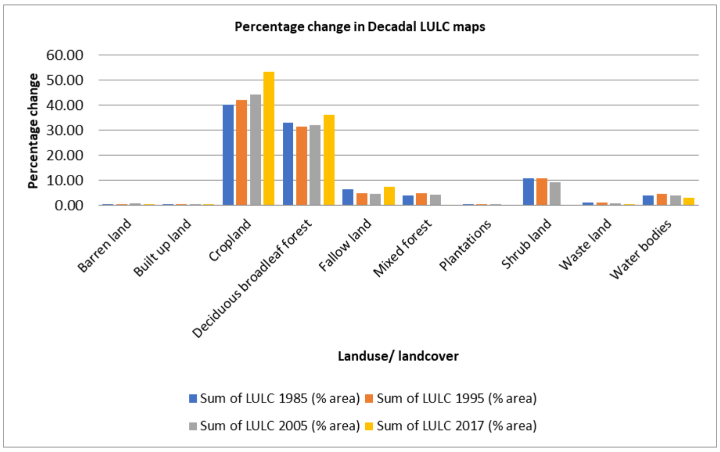

Figure 5. Percentage change in decadal LULC maps (1985, 1995, 2005 & 2017 maps)

Figure 5 illustrates the distribution of various LULC types, with cropland occupying the maximum land use, accounting for over 40% during all four years under consideration. Deciduous broadleaf forests have been 2nd most prevalent, covering more than 30% of the area. Fallow land ranks 3rd, encompassing between 4% to 7% of the total watershed area. Minimal changes are observed in barren land, wasteland, and plantation areas (Table 3 and Fig. 7). Literature review suggests that forest cover diminishing by0.7% can lead to surface runoff's substantialrise by 45% (Guzha, et al., 2018)(Garg, et al., 2019)(Vojtek, et al., 2016).

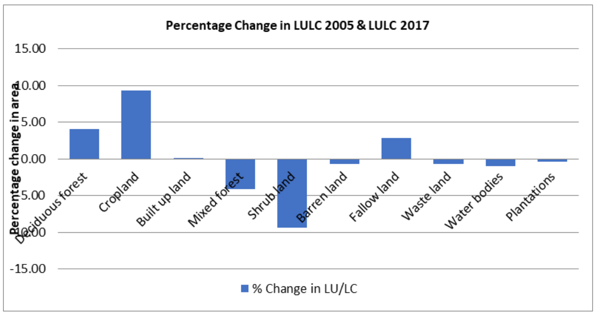

Figure 6. Percentage change detection in LULC 2005 & LULC 2017 maps

Table 5. Various model scenarios of the Sabarmati River basin

Model Scenarios	Landuse scenarios				Hypothetical situations		
	S1	S2	S3	S4	S5	S6	S7
LULC Maps	Lulc 1985	Lulc 1995	Lulc 2005	Lulc 2017	Lulc 2017 modified	Lulc 2017 modified	Lulc 2017 modified

Changes in scenarios	4 % FRST	5 % in FRST	4 % in FRST	0 % in FRST	+3 % in FRST	+6 % in FRST	+9 % in FRST

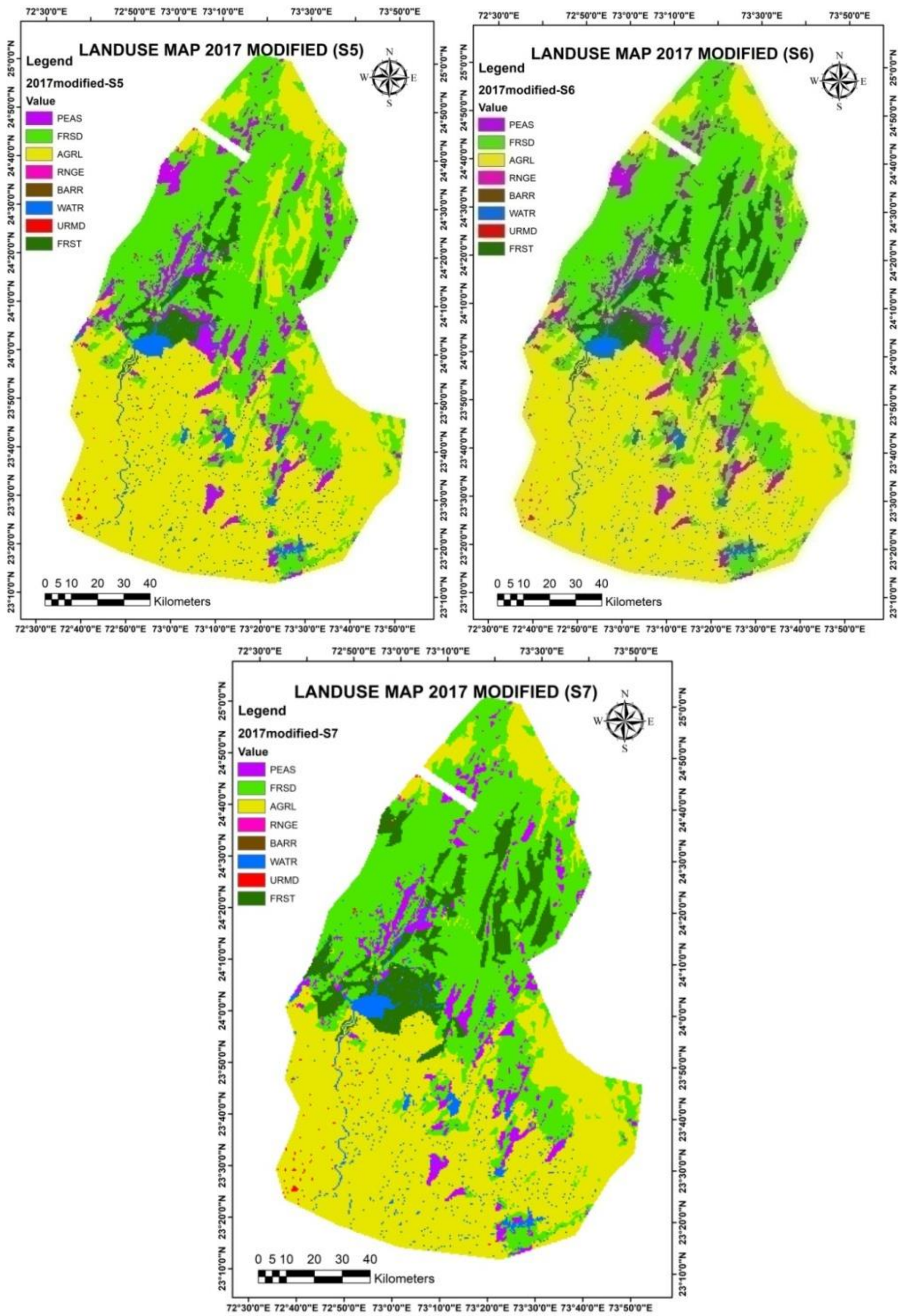

Figure 7. Hypothetical Land use land cover scenarios S5, S6 and S7

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Comparing LULC data from 2005 to 2017, notable shifts are observed. Cropland and deciduous forest areas saw an increase of 9% and 4% respectively, while mixed forest and shrubland experienced a decrease of 4% and 9% respectively. Additionally, fallow land witnessed an increase of 3%.

Creation of Different LULC Scenarios to Assess Impact on Runoff
2017 LULC map served as baseline for different scenariogeneration using ARCMAP software. A total of three scenarios (S5, S6, & S7) were developed utilizing the Land Use classification method in ARCMAP. The specific modifications for each scenario are detailed in Table 6.

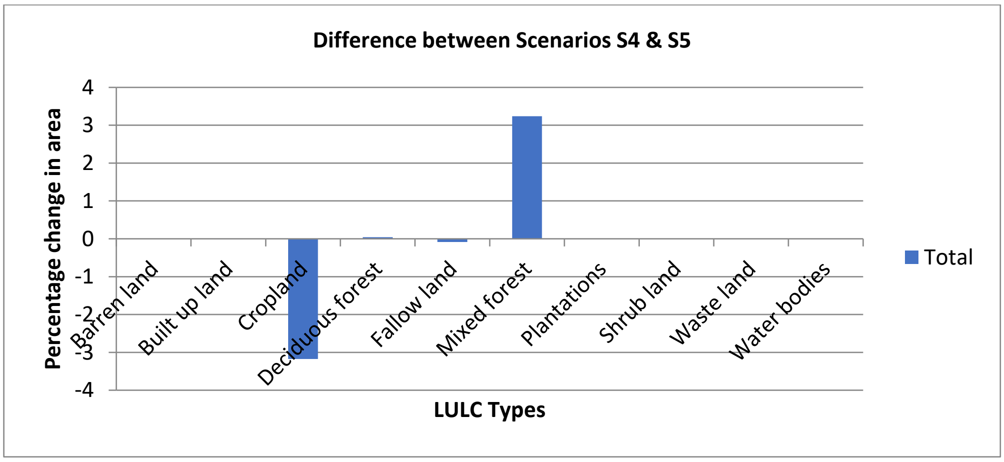

Figure 8. Graph showing percentage change in area of S4 & S5

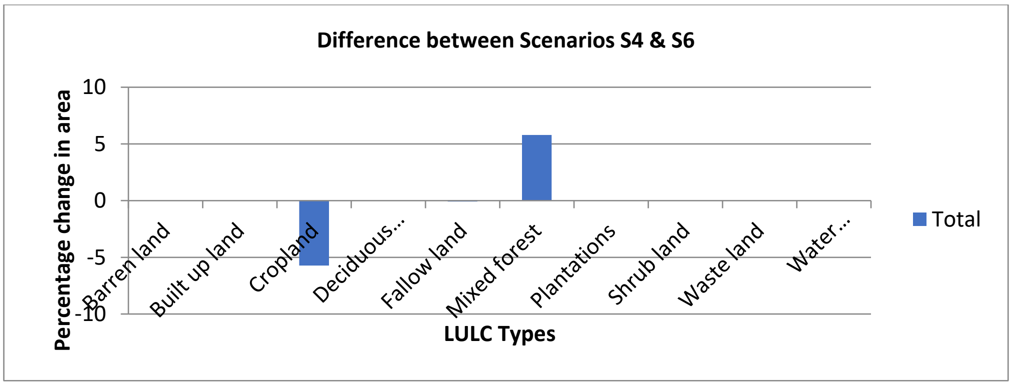

Figure 9 Graph showing percentage change in area of S4 & S6

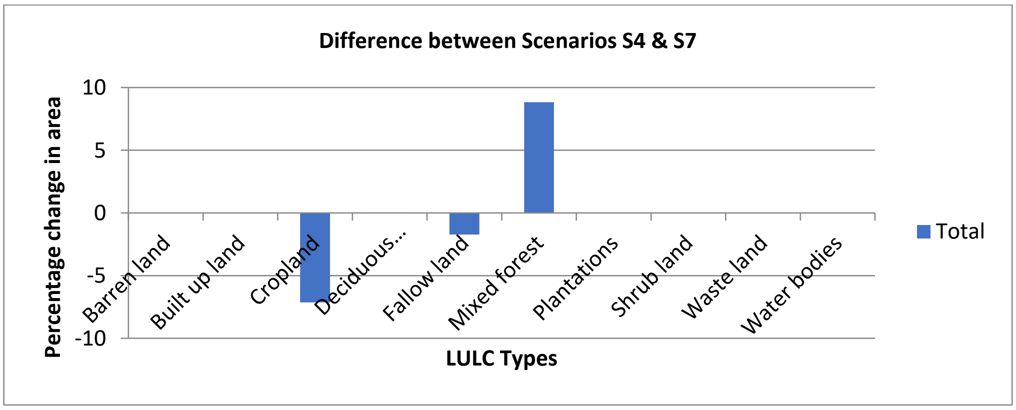

Figure 10 Graph showing percentage change in area of S4 & S7

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Figure 8 illustrates a 3% rise in mixed forest area along with a corresponding 3% cropland decreasein LULC Scenario 5 (S5) compared to LULC Scenario 4 (S4). Similarly, Figure 9 depicts a 6% mixed forest area increase as well as 6% cropland decrease in LULC Scenario 6 (S6) relative to LULC S4. Lastly, Figure 10 shows a 9% increase in mixed forest area, a 7% decrease in cropland, and a 2% decrease in fallow land in LULC Scenario 7 (S7) when compared to LULC S4.

D. ARCSWAT Model Study

Model Simulations

Research integrates four observed LULC scenarios: LULC 1985 (S1), LULC 1995 (S2), LULC 2005 (S3), and LULC 2017 (S4). These decadal scenarios (S1, S2, & S3) were employed for trend analysis of surface runoff. Additionally, three hypothetical scenarios (LULC S5, S6, and S7) were constructed by modifying the percentage of mixed forest cover in the model simulation to evaluate their potential impact on surface runoff.

Calibration and Validation Analysis

SWAT-CUP, the SWAT Calibration and Uncertainty Program, is utilized in CV(Calibration and Validation), along with sensitivity analysis of the ARCSWAT model. Observed discharge data from 1987 to 2004, acquired from the Derol gauge station courtesy of CWC as well as SWDC(State Water Data Center), Gandhinagar, was utilized for calibration. Highest peak discharge occurred in 1994 at the Derol gauge station.

SWAT-CUP software incorporates SUFI-2(Sequential Uncertainty Fitting- Version-2)process for CV. Twelve critical parameters influencing research area had been selected for simulation. CVhad been conducted using discharge data from3 rain gauge stations: Jotasan, Kheroj, along withDerol, over five years (1990 to 1994).

Table 6 List of parameters utilized in SWAT modelcalibration

S. no.	Parameters	Description	Range
1	CN2	SCS runoff curve number	35 to 98
2	ALPHA_BF	Base flow alpha factor (days)	0 to 1
3	GW_DELAY	Groundwater delay (days)	0 to 500
4	GWQMN	Shallow aquifer's threshold water depth needed for return flow to occur(mm)	0 to 5000
5	GW_REVAP	Groundwater “revap” coefficient	0.02 to -0.2
6	ESCO	Compensation factor for soil evaporation	0 to 1
7	CH_N2	For main channelManning’s “n” value	-0.01 to 0.3
8	CH_K2	Hydraulic conductivity efficiency in main channel alluvium	-0.01to500
9	ALPHA_BNK	Alpha factor for base flow in bank storage(days)	0to1
10	SOL_AWC	Soil layer's available water capacity	0to1
11	SOL_K	Saturated hydraulic conductivity	0to2000
12	SOL_BD	Moist bulk density	0.9to2.5

Table 6 outlines the 12 critical parameters identified, with statistical measures including Percentage of observed data used (P-factor), R-factor(Thickness of 95% prediction uncertainty), R^2(Coefficient of determination), along with NSEcoefficient (Nash-Sutcliffe efficiency).

Table 7. Statistical classifications based on NSE and R Square values

R Square values	NSE values	Classifications of statistics
0.75 to <=1.00	0.75 to <=1.00	Very Good
0.60 to <=0.75	0.60 to <=0.75	Good
0.50 to <=0.60	0.36 to <=0.60	Satisfactory

Source: Rafael et al (2018)

Table 8. Final summary of validationas well as calibration output in SWAT-CUP

Iteration	P-factor	R-factor	R Square	NSE
Calibration	1.00	0.79	0.73	0.71

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Validation	0.96	0.58	0.70	0.63

CVoutput meets standards outlined in Tables 7 and 8, with satisfactory R Square and NSE values. Figure 11 depicts a comparison between observed and calibrated values, establishing an R2 relationship. Similarly, Figure 12 illustrates a comparison between observed and validated values, with corresponding formulas indicating model performance.

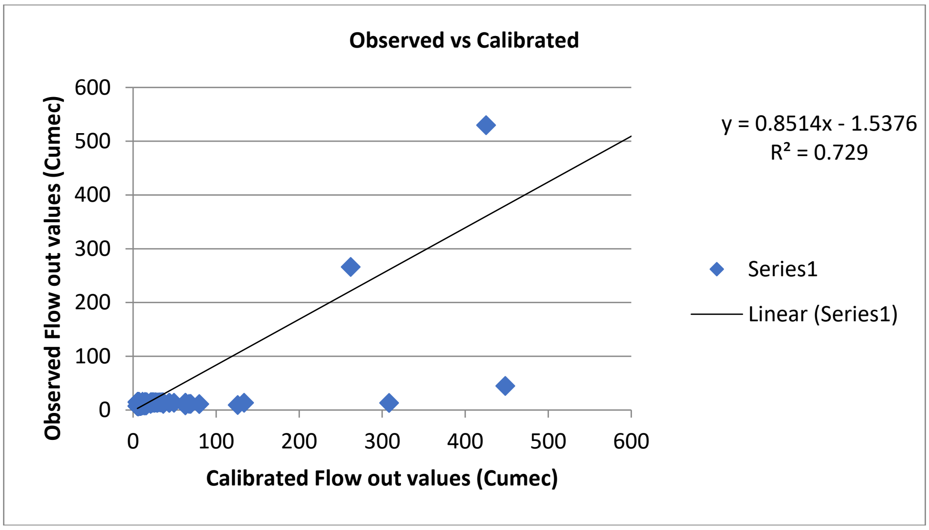

Figure 11. Observed Vs Calibrated Flow out values

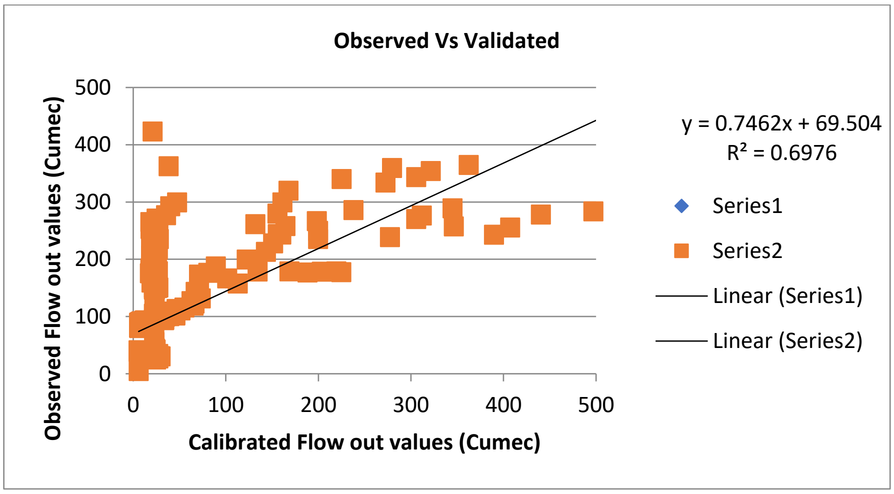

Figure 12. Observed Vs Validated Flow out values

In Figures 11 and 12, although data points beyond the 500-1000 range are not excluded due to their scattered distribution, additional data points will be incorporated in subsequent model studies to further validate findings.

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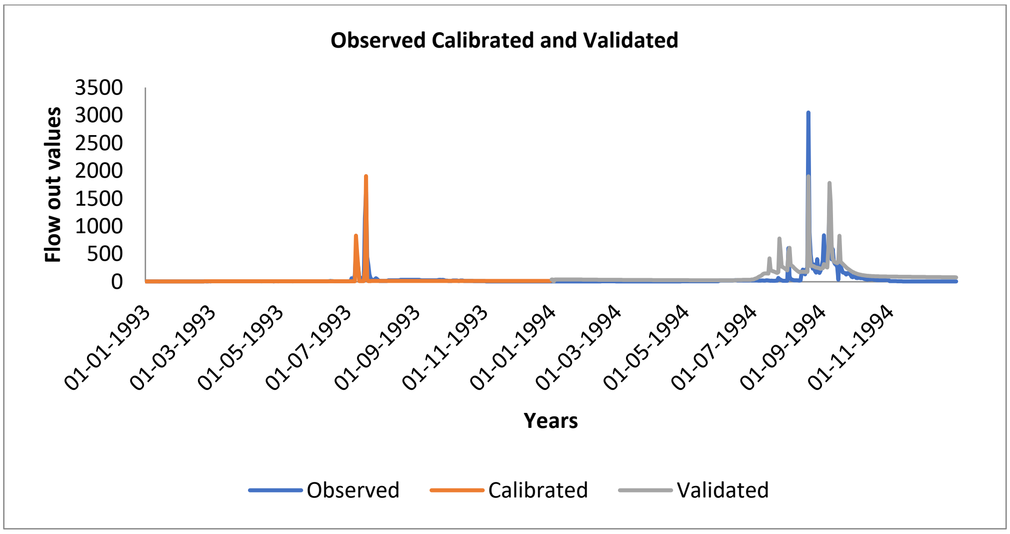

Figure 13. Graph showing observed, calibrated and validated flow-out values

Figure 13 displays observed flow-out values alongside calibrated and validated values, incorporated into the ArcSWAT model for further analysis.

Table 9. Comparison of ArcSWAT model run for all land use map scenarios

Sr no	Descriptions	S1	S2	S3	S4	S5	S6	S7
1	Average Curve number	63.17	63.26	63.55	64.21	63.28	62.6	62.01
2	Precipitation (mm)	785.4	785.4	785.4	785.4	785.4	785.4	785.4
3	Evaporation & Transpiration (mm)	261.6	263.3	292.2	259.7	267.4	274.5	285.4
4	PET (mm)	1900.2	1900.2	1910.8	1900	1900.1	1900.1	1900.3
5	Surface runoff (mm)	158.25	158.46	155.44	165.16	157.73	152.33	146.03
6	Lateral flow (mm)	66.31	65.4	65.04	61.25	62.72	62.47	62.7
7	Return flow (mm)	288.05	287.03	279.63	287.66	286.32	284.95	280.55

Table 9 provides a comparative analysis of the calibrated model run using seven different scenarios of land use cover. Among these scenarios, S7 emerges as the most effective in reducing maximum surface runoff (146.03mm) under the same precipitation conditions (785.4mm).

RESULTS AND DISCUSSIONS

Our study unveils a nuanced relationship understanding among mixed forest cover as well as surface runoff dynamics in Upper Sabarmati River Basin. Through comprehensive analysis, we demonstrate that increasing mixed forest cover leading notable surface runoffdepletion, thus mitigating downstream flooding. The observed correlation between mixed forest cover expansion and reduced surface runoff underscores the pivotal role of forest ecosystems in flood regulation. Notably, our findings indicate that as the proportion of forest cover increases, the watershed's runoff production diminishes, emphasizing the effectiveness of mixed forest cover in flood mitigation efforts. Furthermore, our analysis highlights the influence of mixed forest cover on runoff quality, presenting opportunities for enhancing water resource management practices. Figure 14 illustrates a consistent decrease in the average Curve Number (CN) with increasing mixed forest cover, indicative of reduced surface runoff. Figures 15 and 16 further elucidate the tangible impact of mixed forest cover expansion on surface runoff reduction across different land use scenarios. The novel contribution of this study lies in its demonstration of the effectiveness of strategic forest management, particularly through mixed forest cover expansion, in mitigating flood risks within river basins. By elucidating these findings, we provide valuable insights for informing evidence-based flood management policies and practices.

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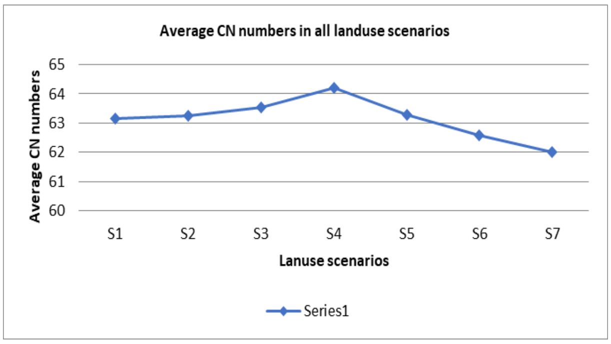

Figure 14. Graph showing a comparison of average CN numbers on various land use scenarios

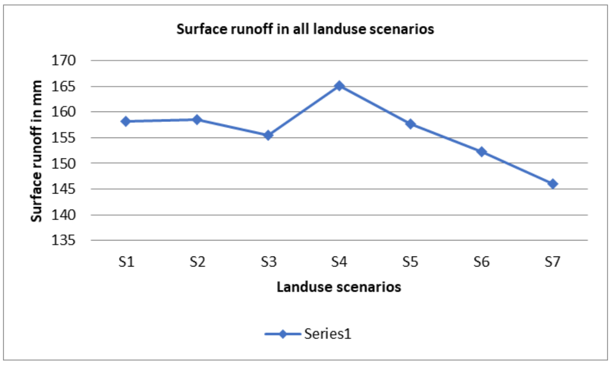

Figure 15. Graph showing a comparison of Surface runoff on various land use scenarios

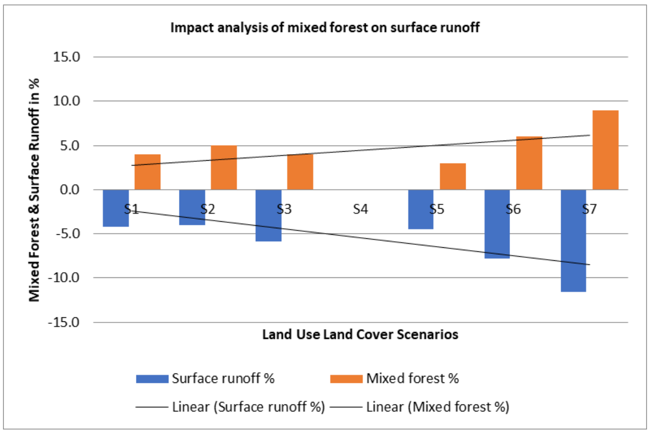

Figure 16. Graph showing Mixed Forest and Surface runoff in percentage in all Land Use Land Cover model scenarios

CONCLUSIONS

In conclusion, our study underscores the critical importance of mixed forest cover in enhancing flood resilience and mitigating downstream flood risks in the Upper Sabarmati River Basin. While our findings offer promising avenues for sustainable flood management, this has been important for acknowledging various limitations inherent in our research. 1stour evaluation depends upon modeling assumptions and data limitations, which may introduce uncertainties into our results. Additionally, future studies could explore the socio-economic implications of implementing mixed forest cover expansion strategies and evaluate long-term interventionsustainability. Even after these limitations, our research contributes valuable insights into potential of mixed forest ecosystems as a natural solution for mitigating flood risks within river basins. Moving forward, concerted efforts toward promoting mixed forest cover expansion could offer an eco-friendly and effective approach to building resilience to future hydrological challenges.

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