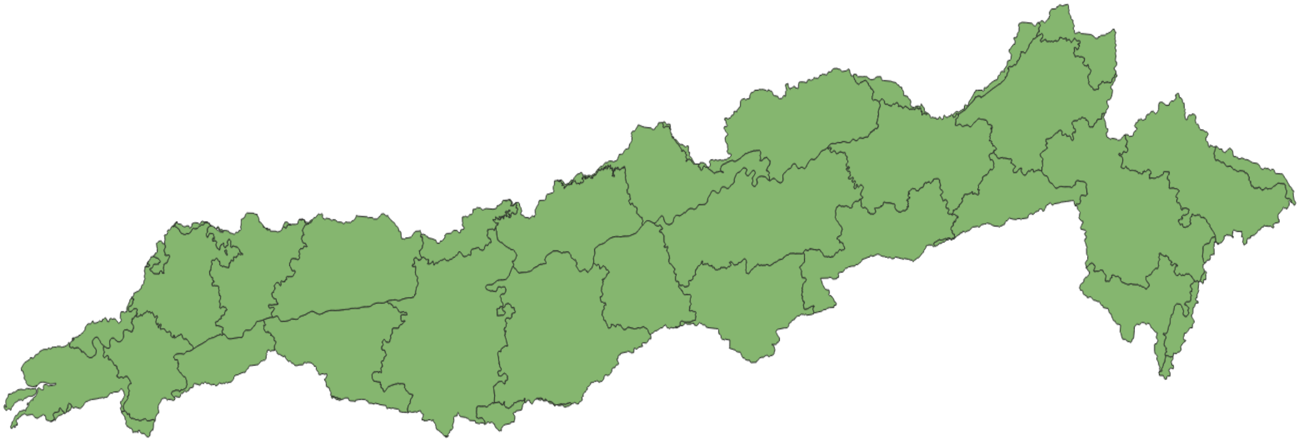
National River Conservation Directorate
Ministry of Jal Shakti, Department of Water Resources,
River Development & Ganga Rejuvenation
Government of India

Water Balance/ Accounts/Budget as per delineated administrative and natural boundaries



December 2025

Water Balance/ Accounts/Budget as per delineated administrative and natural boundaries

National River Conservation Directorate (NRCD)

The National River Conservation Directorate (NRCD), under the Department of Water Resources, River Development & Ganga Rejuvenation, Ministry of Jal Shakti, supports state governments in the conservation and rejuvenation of India’s rivers. Through the Centrally Sponsored Scheme of the National River Conservation Plan (NRCP), the NRCD provides financial and technical assistance for pollution abatement, ecosystem restoration, and capacity-building initiatives aimed at ensuring the long-term health of rivers across the country.

www.nrcd.nic.in

Centres for Narmada River Basin Management and Studies (cNarmada)

The Centre for Narmada River Basin Management and Studies (cNarmada) serves as a knowledge and research hub dedicated to the sustainable management of the Narmada River Basin. Established in 2024 through a collaboration of IIT Gandhinagar and IIT Indore under the supervision of cGanga at IIT Kanpur, cNarmada integrates scientific research, technological innovation, and community-based approaches for effective river basin management.

www.cnarmada.org

Centres for Ganga River Basin Management and Studies (cGanga)

cGanga, formed under the aegis of the National Mission for Clean Ganga (NMCG), functions as India’s leading think tank for river science and basin management. Headquartered at IIT Kanpur, cGanga’s mandate includes the development of innovative frameworks, technologies, and policy tools to address complex water management challenges, and to position India as a global leader in river restoration.

www.cganga.org

Acknowledgment

This document is the result of a collaborative effort between IIT Gandhinagar (Lead Institute) and IIT Indore (Partner Institute) under the guidance of cGanga, IIT Kanpur, and with the support of the National River Conservation Directorate (NRCD). We extend our gratitude to government agencies, local stakeholders, and scientific experts whose inputs and insights have shaped the design of this pilot.

Team Members

Pranab Kumar Mohapatra, cNarmada, IIT Gandhinagar
Bhanu Parmar , cNarmada, IIT Gandhinagar
Akash Yadav , cNarmada, IIT Gandhinagar

PREFACE

The Narmada River, one of India's most revered and significant rivers, has long been the lifeline of central India, sustaining a complex web of ecological systems, human settlements, and cultural traditions. Flowing majestically across the states of Madhya Pradesh, Gujarat, Maharashtra, and Chhattisgarh, the river provides water for agriculture, industry, and domestic use, while simultaneously supporting rich biodiversity, sacred landscapes, and a cultural heritage that dates back centuries. For countless communities, the Narmada is more than a river—it is a living entity, deeply interwoven into their spiritual and everyday lives. Yet, in recent decades, the pressures exerted on this vital resource have intensified at an unprecedented pace. Expanding industrial corridors, unplanned urbanization, over-extraction of water, unsustainable farming practices, deforestation in catchment areas, and the unpredictable impacts of climate change have combined to degrade the river's health. The consequences of these stresses are evident in declining water quality, reduced flows, biodiversity loss, and an increasing vulnerability of the basin to droughts, floods, and other extreme events.

Recognizing the urgency of these issues, the Narmada River Monitoring Protocol (2025) laid out a comprehensive scientific and community-oriented framework to observe, assess, and understand the river's condition. While this protocol provided the technical foundation for monitoring key indicators of river health, it also highlighted a critical gap: the need for an adaptive mechanism that not only gathers information but also uses it effectively to guide timely action. Traditional monitoring approaches often remain limited to data collection and periodic reporting, lacking the feedback systems required to respond dynamically to changing conditions. In an era where environmental challenges evolve rapidly and unpredictably, a static system of observation is no longer sufficient. What is needed is a framework that transforms data into actionable knowledge, integrates the voices of local stakeholders, and ensures that management practices are continuously refined to meet emerging challenges.

This report responds to that need by presenting a pilot framework for initiating a Monitoring and Feedback (M&F) system for the Narmada River Basin. The pilot is envisioned as a dynamic, adaptive model designed to bridge the persistent gap between policy formulation and on-ground realities. By combining cutting-edge technologies for real-time data collection with participatory processes that involve local communities, this pilot seeks to demonstrate how collaborative monitoring can drive effective decision-making and lead to tangible improvements in river health. It represents an important shift—from viewing monitoring as a purely technical exercise to recognizing it as an inclusive governance process that empowers people, strengthens institutions, and builds resilience within the basin.

A central feature of this pilot is its commitment to integration and adaptability. It aims to unify diverse sources of information—from automated sensor networks and satellite imagery to community observations and institutional data—into a coherent system that can provide timely insights. It emphasizes transparent reporting, enabling policymakers, researchers, industries, and citizens alike to access and use the information generated. Equally important, it fosters ownership among local communities by valuing their traditional knowledge and involving them as active participants in the stewardship of the river. By embedding structured feedback loops into every stage of the monitoring process, the pilot ensures that interventions can be adjusted promptly, resources can be allocated more efficiently, and successes as well as shortcomings can be openly shared for collective learning.

This document is therefore more than a technical guideline; it is a vision for how rivers in India can be managed in the 21st century. It calls for a transition from fragmented, reactive approaches to integrated, proactive, and inclusive strategies that safeguard the ecological, social, and cultural integrity of river systems. The lessons learned from this pilot will inform the development of a full-scale Monitoring and Feedback system for the entire Narmada Basin and serve as a replicable model for other river basins facing similar challenges across the country. Through this effort, we aspire to ensure that the Narmada continues to flow as a living, thriving river—one that sustains ecosystems, nourishes communities, and carries forward a legacy of resilience and reverence for generations to come.

Centres for Narmada River Basin Management and Studies (cNarmada)
IIT Gandhinagar, IIT Indore

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ABBREVIATIONS AND ACRONYMS

CGWB – Central Ground Water Board

cNarmada – Centre for Narmada River Basin Management and Studies

CWC – Central Water Commission

DEM – Digital Elevation Model

ET – Evapotranspiration

FRL – Full Reservoir Level

GSI – Geological Survey of India

HFL – Highest Flood Level

IMD – India Meteorological Department

LULC – Land Use / Land Cover

MMK – Modified Mann–Kendall Test

NCA – Narmada Control Authority

NDMA – National Disaster Management Authority

NDRF – National Disaster Response Force

NHDC – Narmada Hydro Development Corporation

OSL – Optically Stimulated Luminescence

PCA – Principal Component Analysis

RCP – Representative Concentration Pathway

SRTM – Shuttle Radar Topography Mission

SSD – Sardar Sarovar Dam

SSNNL – Sardar Sarovar Narmada Nigam Limited

SWAT – Soil and Water Assessment Tool

VIC – Variable Infiltration Capacity Model

WRIS – Water Resources Information Syste

Introduction

Water is a critical natural resource that sustains ecosystems, agriculture, industry, and human livelihoods. Increasing pressure from population growth, land-use change, climate variability, and unplanned development has intensified stress on freshwater resources, particularly in large river basins. Accurate assessment of water availability, distribution, and utilization through systematic water balance and water budgeting is therefore essential for sustainable water-resources planning and management.

The water balance approach provides a quantitative framework to account for the inflow, outflow, and storage components of the hydrological cycle within a defined spatial boundary. Water balance components such as precipitation, evapotranspiration, surface runoff, groundwater recharge, and baseflow collectively determine the availability of water in a watershed. Estimation of these components at watershed, sub-basin, and administrative levels is crucial for effective allocation, conservation planning, and policy formulation.

The Narmada River Basin, extending across the states of Madhya Pradesh, Maharashtra, and Gujarat, is one of the most significant river systems in central India. The basin exhibits wide spatial variability in physiography, climate, land use, and hydrological response, ranging from forested uplands and hilly terrains to intensively cultivated plains. These variations strongly influence the spatial and temporal distribution of water resources across the basin. Rapid agricultural expansion, reservoir development, and climate-induced changes in rainfall patterns have further increased the need for basin-scale water accounting.

Water budgeting at the watershed scale, aligned with both natural (hydrological) boundaries and administrative boundaries, provides valuable insights into regional water availability and demand. Such integrated assessments support decision-making related to irrigation planning, drinking-water supply, reservoir operation, groundwater management, and drought mitigation. Delineation of watersheds and sub-watersheds allows for a distributed analysis of hydrological processes, enabling identification of water-surplus and water-deficit regions within the basin.

Hydrological models and geospatial tools play a vital role in water balance assessment for large river basins. Models such as the Soil and Water Assessment Tool (SWAT) offer a physically based, semi-distributed framework to simulate hydrological processes over long time periods. SWAT divides a basin into sub-basins and further into Hydrologic Response Units (HRUs) based on land use, soil characteristics, and slope, enabling spatially explicit estimation of water balance components. The model has been widely applied for hydrological assessment, climate and land-use impact studies, and watershed-scale water-resources evaluation.

In the present study, a water balance and water budget analysis is carried out for the Middle Narmada River Basin using a watershed-based modeling framework. The analysis incorporates multiple datasets, including Digital Elevation Model (DEM), land use/land cover, soil data, and climatic variables such as rainfall and temperature. The modeling process involves watershed delineation, hydrological simulation, and estimation of key water balance components across delineated natural and administrative units

The results of this study provide a comprehensive understanding of spatial water availability within the Narmada Basin and serve as a scientific basis for sustainable water-resources planning, watershed management, and policy development. The water budget outcomes can support efficient water allocation, conservation strategies, and long-term management of surface and groundwater resources in central India.

Objective

The primary objective of this study is to conduct a comprehensive, multi-scale watershed analysis of the Narmada River Basin—extending from its headwaters at Amarkantak to the Gulf of Khambhat—using the Soil and Water Assessment Tool (SWAT) to systematically quantify sediment yield and map spatial variations in soil erosion. The research aims to delineate the entire 1,312 km basin into approximately 150–200 Hydrological Response Units (HRUs) to identify "Critical Source Areas" by evaluating the synergistic influence of high-intensity monsoon rainfall, steep topographic gradients of the Satpura and Vindhya ranges, and the high erodibility of predominant Black Cotton (Vertisol) and Red-Yellow soils. By segmenting the study into the Upper, Middle, and Lower reaches, the analysis evaluates reach-specific challenges, such as headwater deforestation in the Upper reach, intensive agricultural runoff within the fertile Middle alluvial belt, and reservoir siltation in major structures like the Bargi and Sardar Sarovar dams in the Lower reach. Furthermore, the study seeks to bridge the gap between hydrological science and policy application by aligning sub-basin modeling results with Administrative Boundaries across Madhya Pradesh, Gujarat, and Maharashtra. This integration ensures that the resulting soil erosion risk maps and SWAT-derived data provide an actionable framework for district-level authorities to implement targeted "Ridge-to-Valley" conservation measures, manage nutrient loading, and mitigate the long-term impacts of land degradation across the diverse landscape of the Narmada Basin.

Study Area

The present study has been undertaken over the entire Narmada Basin, one of the major river basins of central India. The Narmada River is a prominent west-flowing river, originating from the Amarkantak Plateau in Madhya Pradesh at an elevation of approximately 1,057 m above mean sea level. From its source, the river flows westward for about 1,312 km, traversing the states of Madhya Pradesh, Maharashtra, and Gujarat, before draining into the Arabian Sea near Bharuch.

The total drainage area of the Narmada Basin is approximately 98,796 km², encompassing diverse physiographic, climatic, and hydrological conditions, ranging from the forested uplands of the eastern highlands to the alluvial plains and coastal regions in the west. In the present study, the entire Narmada Basin was first considered as a single integrated hydrological unit. Subsequently, for detailed hydrological modeling and to account for administrative and regional variability, the basin was subdivided into three major sub-regions: Upper Narmada Basin, Middle Narmada Basin, and Lower Narmada Basin

Each of these sub-basins was analyzed independently using the SWAT (Soil and Water Assessment Tool) model, enabling a more refined assessment of spatial heterogeneity in hydrological processes, land use characteristics, and climatic influences within the basin. This hierarchical approach—combining basin-wide analysis with sub-basin-level modeling—provides a comprehensive framework for understanding hydrological dynamics and supporting effective water resource management across the Narmada River Basin.

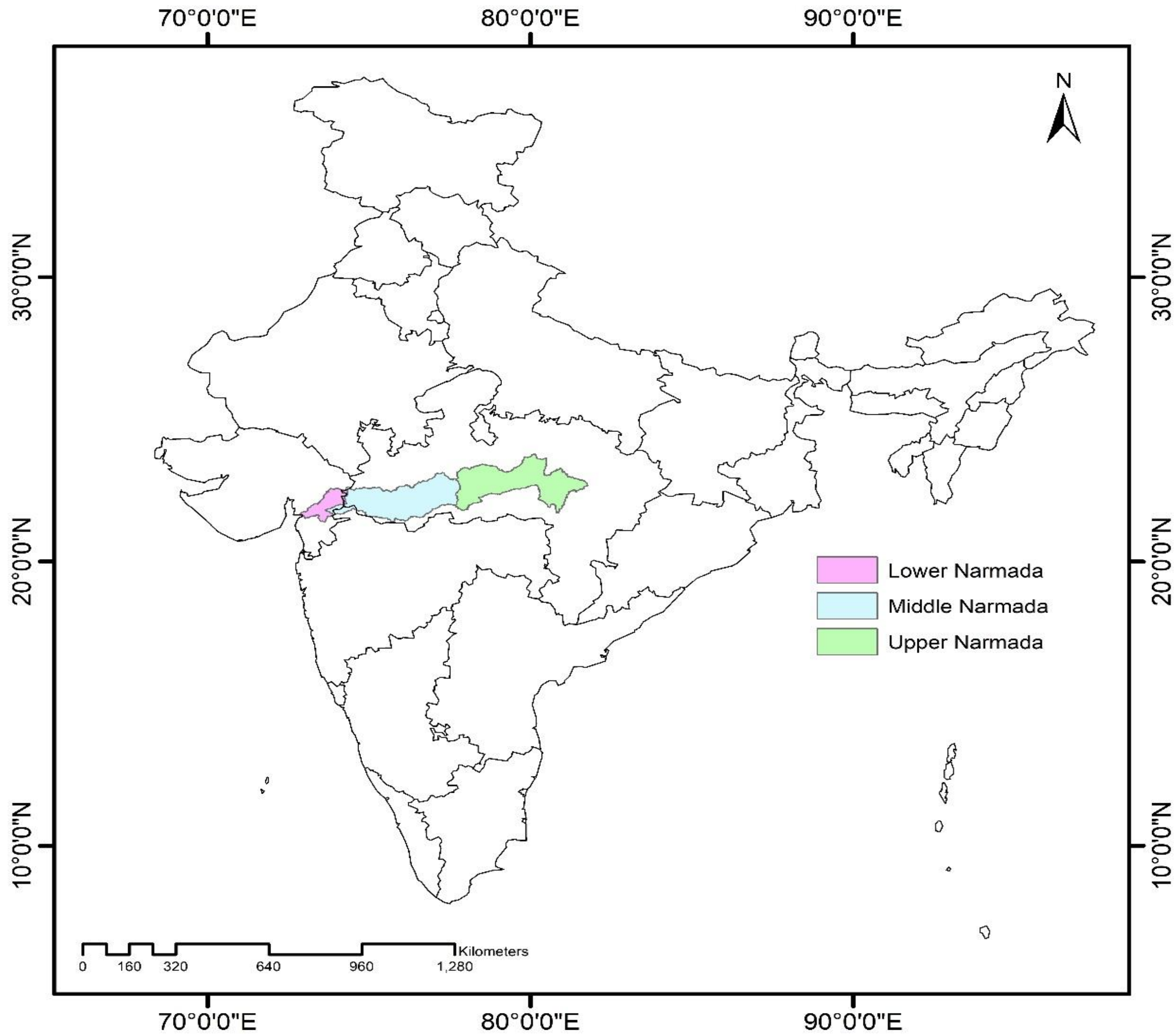


Figure 1: Narmada basin in India map

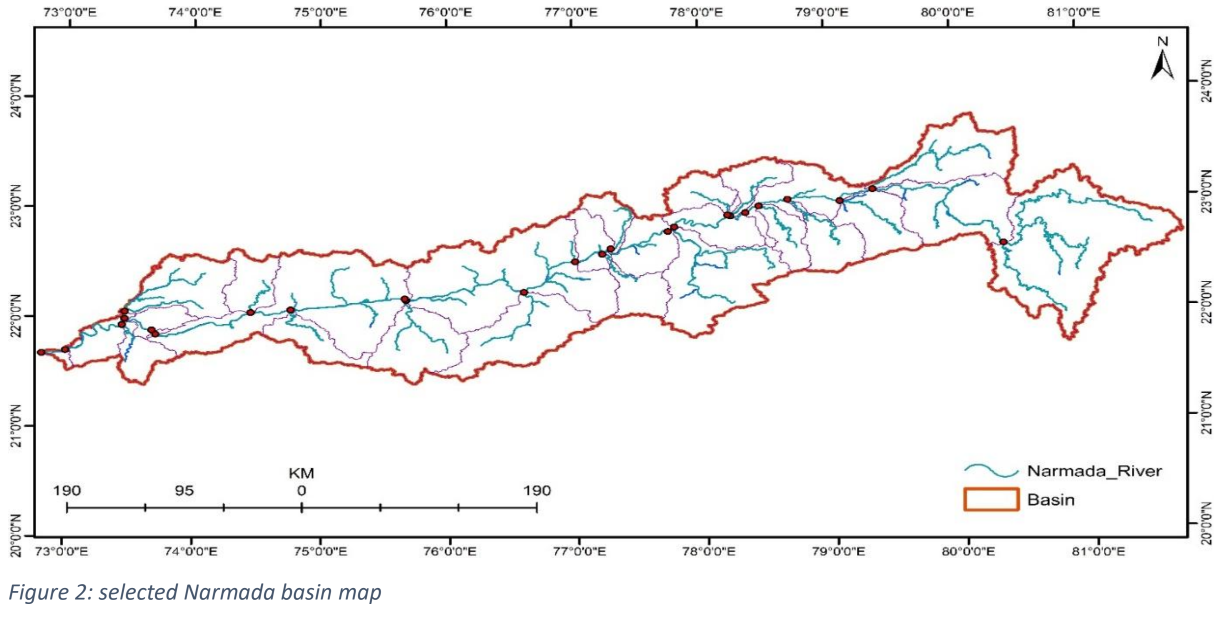


Figure 2: selected Narmada basin map

Significance of Selecting the Study Area

The Narmada Basin constitutes a hydrologically and geomorphologically significant river system in central India, characterized by complex drainage patterns and dynamic surface processes across its spatial extent. The basin encompasses a dense and hierarchically organized network of tributaries, including major rivers such as the Tawa, Ganjal, Dudhi, and Hiran, which contribute to pronounced spatial variability in runoff generation, flow accumulation, and sediment transport processes. Variations in topography, soil characteristics, and rainfall regimes across the basin result in differential erosion potential, with relatively higher erosion susceptibility observed in regions with steeper slopes, fragile soil formations, and frequent high-intensity precipitation events. These interacting factors collectively influence sediment yield, channel morphology, and hydrological response at multiple scales, rendering the Narmada Basin highly sensitive to land-use dynamics and climatic variability. From a technical and modeling perspective, the basin offers a comprehensive framework for investigating watershed-scale hydrological processes, erosion dynamics, and the performance of soil and water conservation and river basin management strategies under diverse physiographic and hydro-climatic conditions.

Database and Methodology

The present study utilizes multiple datasets obtained from various reliable national and international sources. The details of the data used, including their formats, sources, and spatial or temporal resolutions, are summarized in Table 1.

Table 1 : List of spatial/nonspatial data used in the present study

Parameters	Data format	Source	Resolution / scale
SRTM DEM	Raster	United States Geological Survey (USGS) [2000]	30 m
LULC	Raster	ESRI, Sentinel-2 Land Cover Explorer [2023]	10 m
Soil Map	Vector	FAO (DSMW)	1:5000000
Temperature, Relative Humidity, Rainfall, Wind Speed	CSV	NASA POWER (DAV) [2022-23]	Daily
Observed Discharge Data	CSV	WRIS Time Series Data	Daily

Reference : Kushwaha, A. P., Tiwari, A. D., Dangar, S., Shah, H., Mahto, S. S., & Mishra, V. (2021). Multimodel assessment of water budget in Indian sub-continental river basins. Journal of Hydrology, 603, 126977.

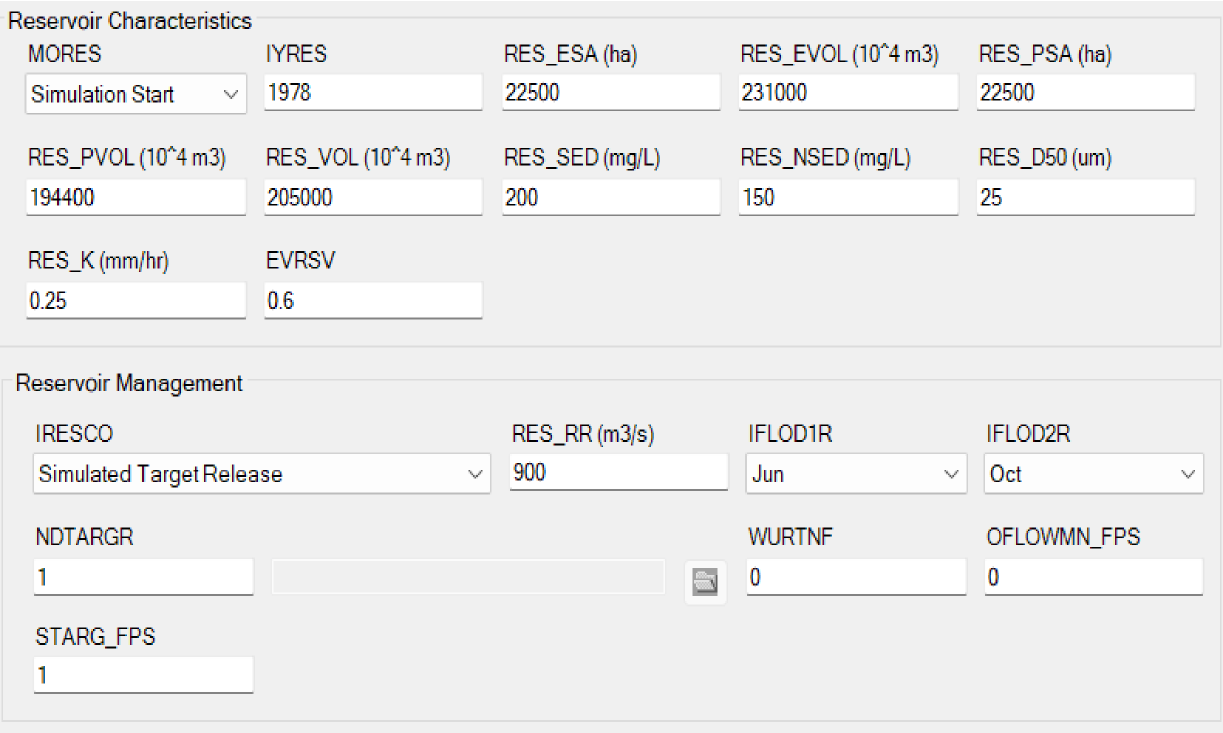
Dataset Description

Dataset Description for dams reservoir

Upper Narmada Basin Dataset

The Upper Narmada Basin dataset was developed to support SWAT-based hydrological modeling and water budgeting. This section includes major reservoirs:, Barna Dam, Bargi Dam and Tawa Dam. For these reservoirs, daily storage data were collected and processed to capture temporal variations in water availability.

The dataset incorporates reservoir storage fluctuations, inflow-outflow relationships, and catchment response characteristics. These inputs are essential for calibrating the SWAT model in upstream regions, where flow regulation significantly influences downstream hydrology.



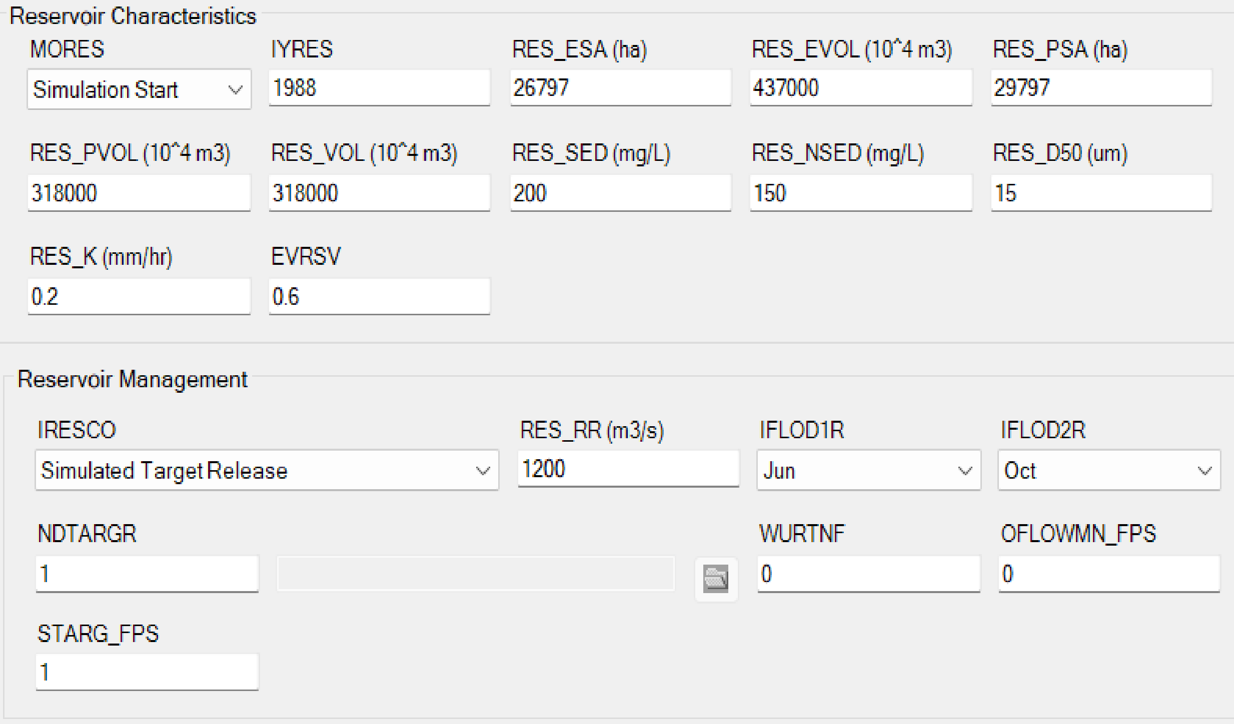
Reservoir Characteristics

MORES: Simulation Start
IYRES: 1978
RES_ESA (ha): 22500
RES_EVOL (10^4 m3): 231000
RES_PSA (ha): 22500
RES_PVOL (10^4 m3): 194400
RES_VOL (10^4 m3): 205000
RES_SED (mg/L): 200
RES_NSED (mg/L): 150
RES_D50 (um): 25
RES_K (mm/hr): 0.25
EVRSV: 0.6

Reservoir Management

IRESCO: Simulated Target Release
RES_RR (m3/s): 900
IFLOD1R: Jun
IFLOD2R: Oct
NDTARGR: 1
WURTNF: 0
OFLOWMN_FPS: 0
STARG_FPS: 1

Figure 3: dam dataset in swat for Barna dam



Reservoir Characteristics

MORES	IYRES	RES_ESA (ha)	RES_EVOL (10^4 m3)	RES_PSA (ha)
Simulation Start	1988	26797	437000	29797

RES_PVOL (10^4 m3)	RES_VOL (10^4 m3)	RES_SED (mg/L)	RES_NSED (mg/L)	RES_D50 (um)
318000	318000	200	150	15

RES_K (mm/hr)	EVRSV
0.2	0.6

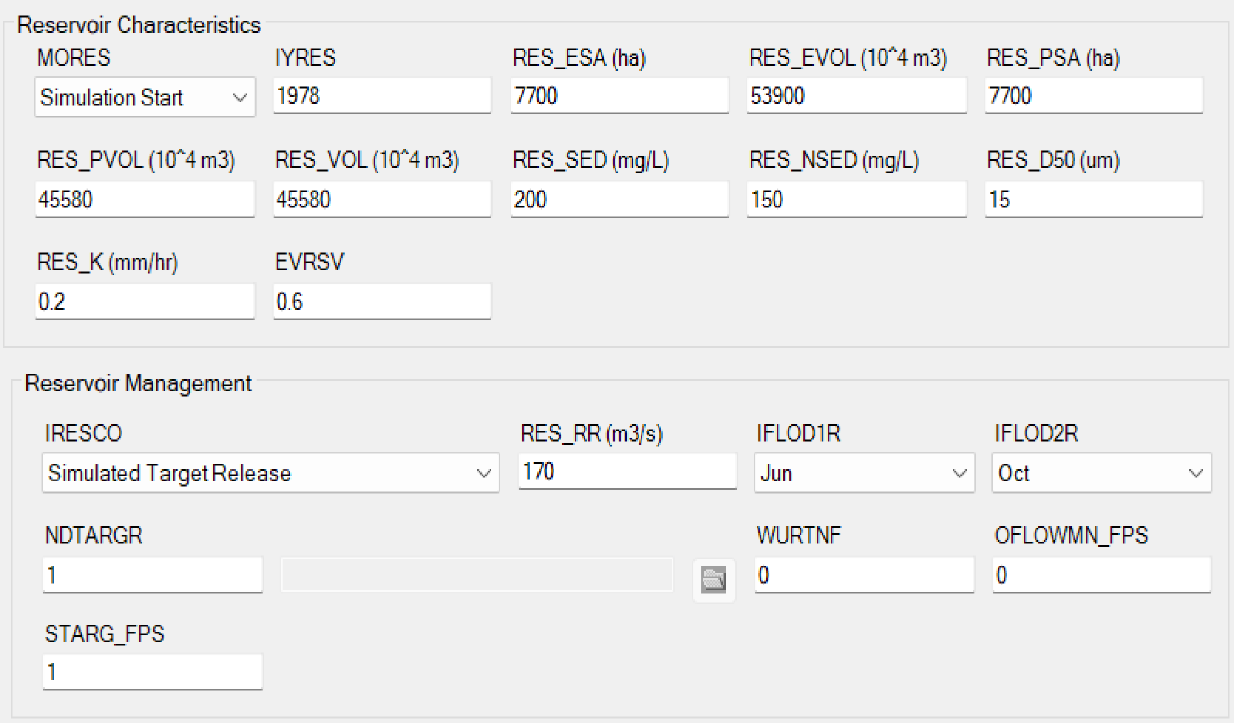
Reservoir Management

IRESCO	RES_RR (m3/s)	IFLOD1R	IFLOD2R
Simulated Target Release	1200	Jun	Oct

NDTARGR	WURTNF	OFLOWMN_FPS
1	0	0

STARG_FPS
1

Figure 4:Dam dataset in swat for Bargi dam



Reservoir Characteristics

MORES	IYRES	RES_ESA (ha)	RES_EVOL (10^4 m3)	RES_PSA (ha)
Simulation Start	1978	7700	53900	7700

RES_PVOL (10^4 m3)	RES_VOL (10^4 m3)	RES_SED (mg/L)	RES_NSED (mg/L)	RES_D50 (um)
45580	45580	200	150	15

RES_K (mm/hr)	EVRSV
0.2	0.6

Reservoir Management

IRESCO	RES_RR (m3/s)	IFLOD1R	IFLOD2R
Simulated Target Release	170	Jun	Oct

NDTARGR	WURTNF	OFLOWMN_FPS
1	0	0

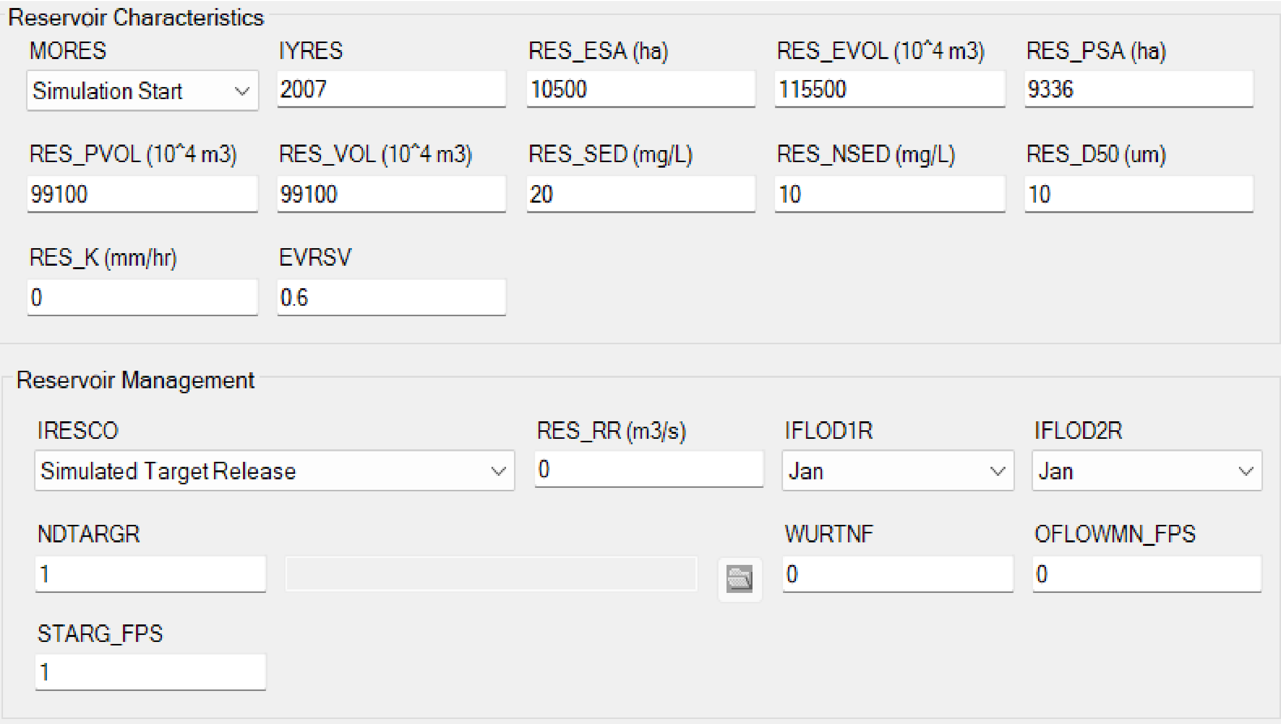
STARG_FPS
1

Figure 5:Dam dataset in swat for Tawa dam

Middle Narmada Basin Dataset

The Middle Narmada Basin dataset focuses on key hydraulic structures, namely Omkareshwar Dam and Indira Sagar Dam. Similar to the upper basin, daily reservoir storage data were used as primary inputs for SWAT modeling.

This dataset plays a critical role in representing regulated flow conditions in the midstream section of the basin. It captures the impact of large-scale water storage and release patterns on river discharge, enabling accurate simulation of water balance components within the SWAT framework.



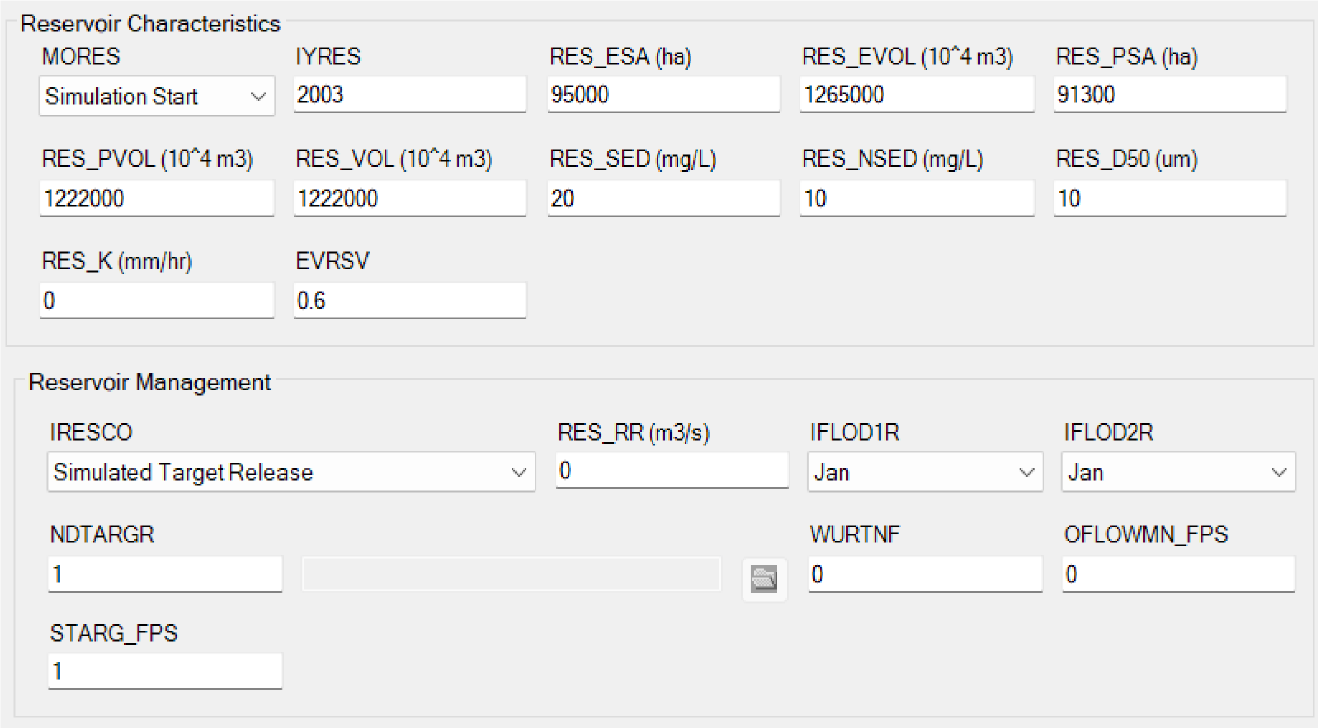
Reservoir Characteristics

MORES	IYRES	RES_ESA (ha)	RES_EVOL (10^4 m3)	RES_PSA (ha)
Simulation Start	2007	10500	115500	9336
RES_PVOL (10^4 m3)	RES_VOL (10^4 m3)	RES_SED (mg/L)	RES_NSED (mg/L)	RES_D50 (um)
99100	99100	20	10	10
RES_K (mm/hr)	EVRSV			
0	0.6			

Reservoir Management

IRESCO	RES_RR (m3/s)	IFLOD1R	IFLOD2R
Simulated Target Release	0	Jan	Jan
NDTARGR		WURTNF	OFLOWMN_FPS
1		0	0
STARG_FPS			
1			

Figure 6:Dam dataset in swat for omkareshwar dam



Reservoir Characteristics

MORES: Simulation Start
IYRES: 2003
RES_ESA (ha): 95000
RES_EVOL (10^4 m3): 1265000
RES_PSA (ha): 91300
RES_PVOL (10^4 m3): 1222000
RES_VOL (10^4 m3): 1222000
RES_SED (mg/L): 20
RES_NSED (mg/L): 10
RES_D50 (um): 10
RES_K (mm/hr): 0
EVRSV: 0.6

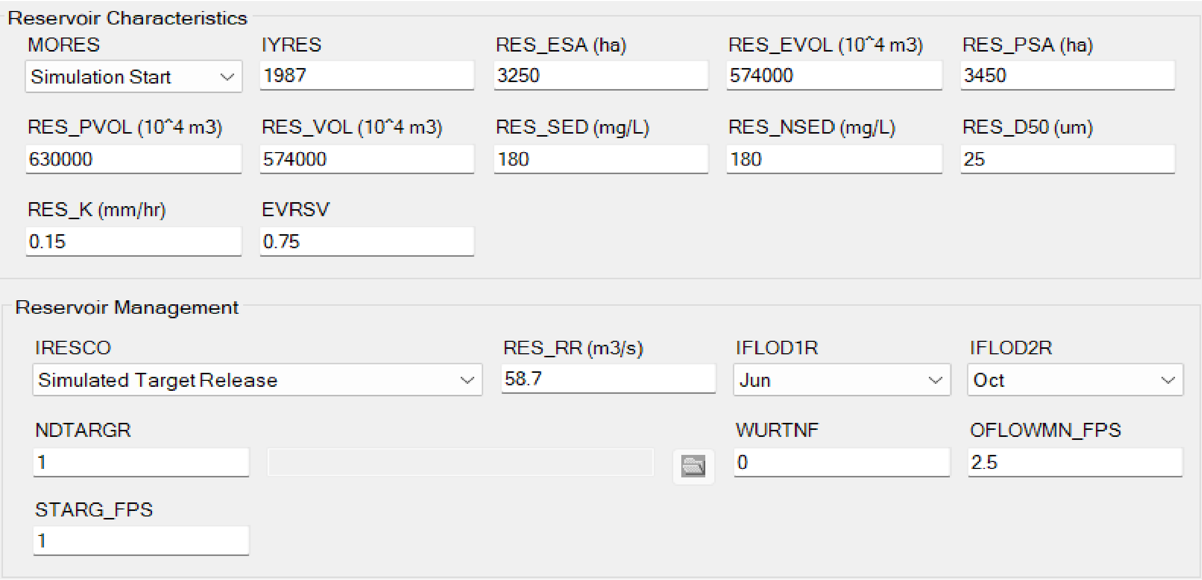
Reservoir Management

IRESCO: Simulated Target Release
RES_RR (m3/s): 0
IFLOD1R: Jan
IFLOD2R: Jan
NDTARGR: 1
WURTNF: 0
OFLOWMN_FPS: 0
STARG_FPS: 1

Figure 7:Dam dataset in swat for Indira sagar

Lower Narmada Basin Dataset

The Lower Narmada Basin dataset includes Sukhi Dam, Karjan Dam, and Sardar Sarovar Dam, which are critical for downstream water management and distribution. Daily storage datasets were compiled for all reservoirs to represent real-time storage dynamics in SWAT simulations.



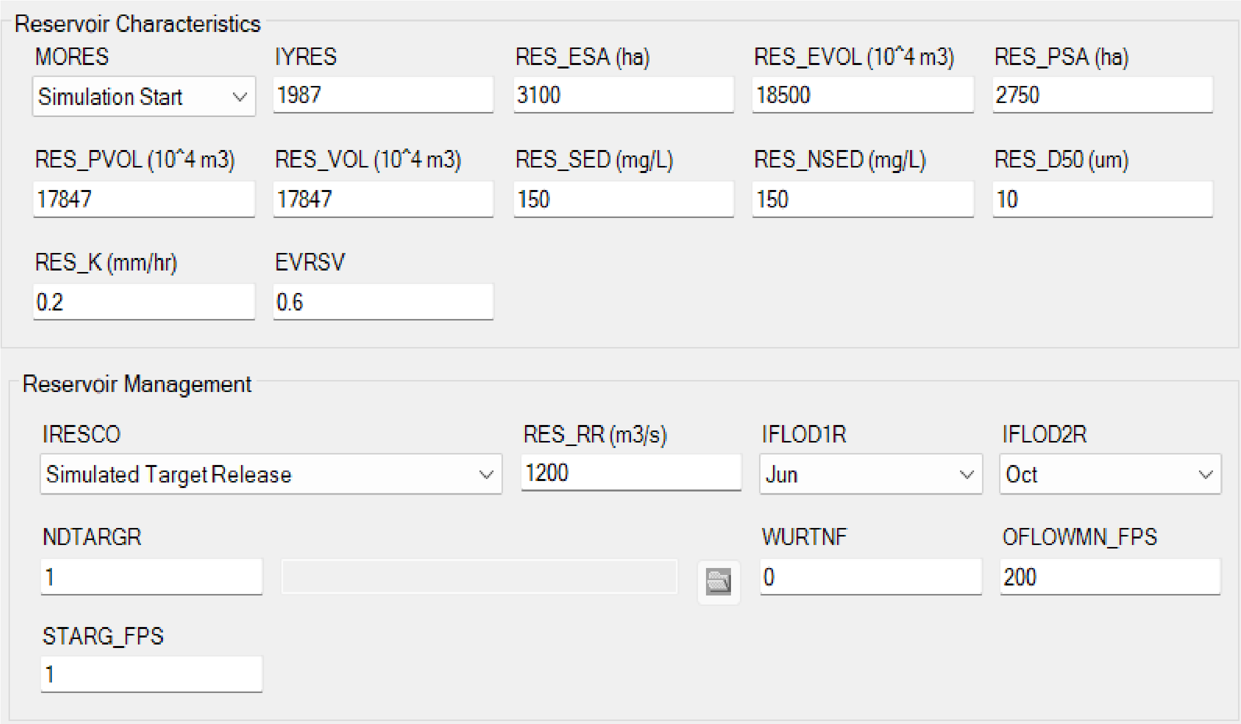
Reservoir Characteristics

MORES: Simulation Start
IYRES: 1987
RES_ESA (ha): 3250
RES_EVOL (10^4 m3): 574000
RES_PSA (ha): 3450
RES_PVOL (10^4 m3): 630000
RES_VOL (10^4 m3): 574000
RES_SED (mg/L): 180
RES_NSED (mg/L): 180
RES_D50 (um): 25
RES_K (mm/hr): 0.15
EVRSV: 0.75

Reservoir Management

IRESCO: Simulated Target Release
RES_RR (m3/s): 58.7
IFLOD1R: Jun
IFLOD2R: Oct
NDTARGR: 1
WURTNF: 0
OFLOWMN_FPS: 2.5
STARG_FPS: 1

Figure 8:Dam dataset in swat for sukhi dam



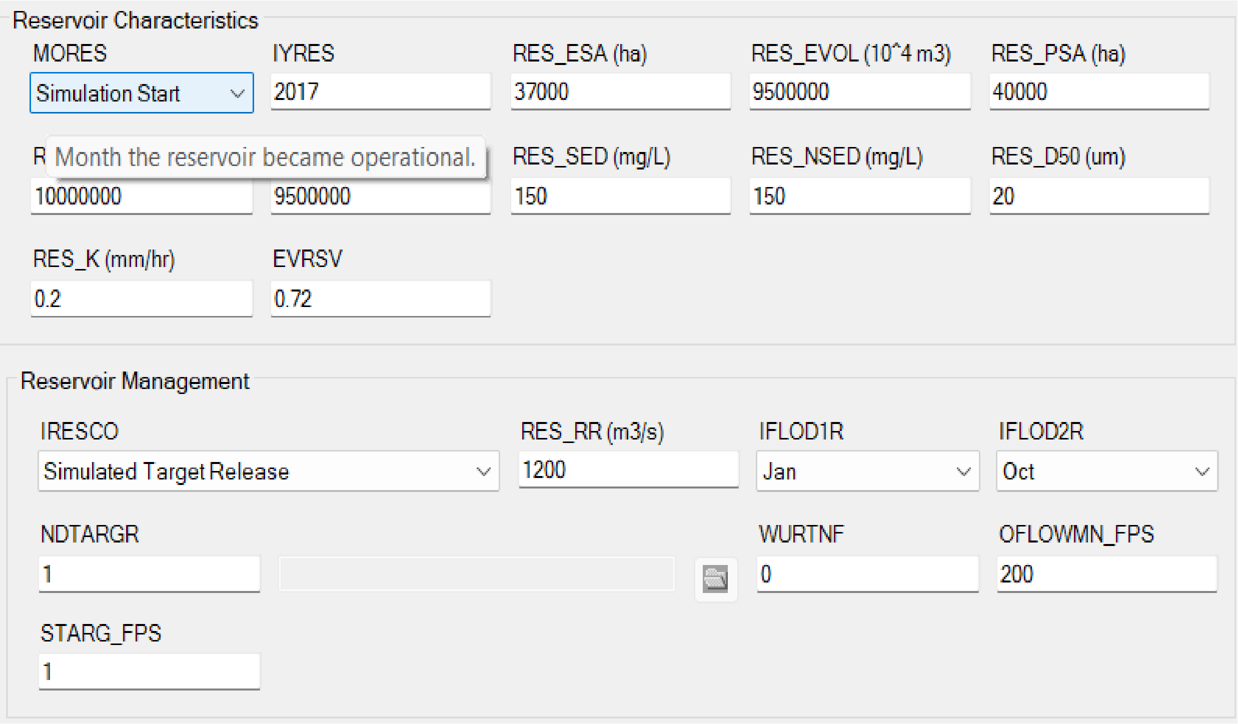
Reservoir Characteristics

MORES	IYRES	RES_ESA (ha)	RES_EVOL (10^4 m3)	RES_PSA (ha)
Simulation Start	1987	3100	18500	2750
RES_PVOL (10^4 m3)	RES_VOL (10^4 m3)	RES_SED (mg/L)	RES_NSED (mg/L)	RES_D50 (um)
17847	17847	150	150	10
RES_K (mm/hr)	EVRSV			
0.2	0.6			

Reservoir Management

IRESCO	RES_RR (m3/s)	IFLOD1R	IFLOD2R
Simulated Target Release	1200	Jun	Oct
NDTARGR		WURTNF	OFLOWMN_FPS
1		0	200
STARG_FPS			
1			

Figure 9:Dam dataset in swat for sardar sarovar dam



Reservoir Characteristics

MORES	IYRES	RES_ESA (ha)	RES_EVOL (10^4 m3)	RES_PSA (ha)
Simulation Start	2017	37000	9500000	40000
R	Month the reservoir became operational.	RES_SED (mg/L)	RES_NSED (mg/L)	RES_D50 (um)
10000000	9500000	150	150	20
RES_K (mm/hr)	EVRSV			
0.2	0.72			

Reservoir Management

IRESCO	RES_RR (m3/s)	IFLOD1R	IFLOD2R
Simulated Target Release	1200	Jan	Oct
NDTARGR		WURTNF	OFLOWMN_FPS
1		0	200
STARG_FPS			
1			

Figure 10:Dam dataset in swat for karjan dam

Description of SWAT Model Methodology

The SWAT (Soil and Water Assessment Tool) model uses a combination of spatial and climatic input data to simulate hydrological and erosion processes in a watershed. The model requires three primary datasets: Digital Elevation Model (DEM) for terrain and watershed delineation, Soil and Land Use/Land Cover data for defining surface characteristics, and Climate data including wind speed, relative humidity, rainfall, and temperature for hydrological simulations.

Using these inputs, the watershed is delineated into sub-watersheds, and Hydrologic Response Units (HRUs) are created based on unique combinations of land use, soil type, and slope. The SWAT model then performs simulation runs to estimate soil erosion (Figure2). Model outputs are further subjected to calibration and validation using observed data to ensure accuracy.

Finally, a soil erosion map is generated to identify erosion-prone areas within the watershed.

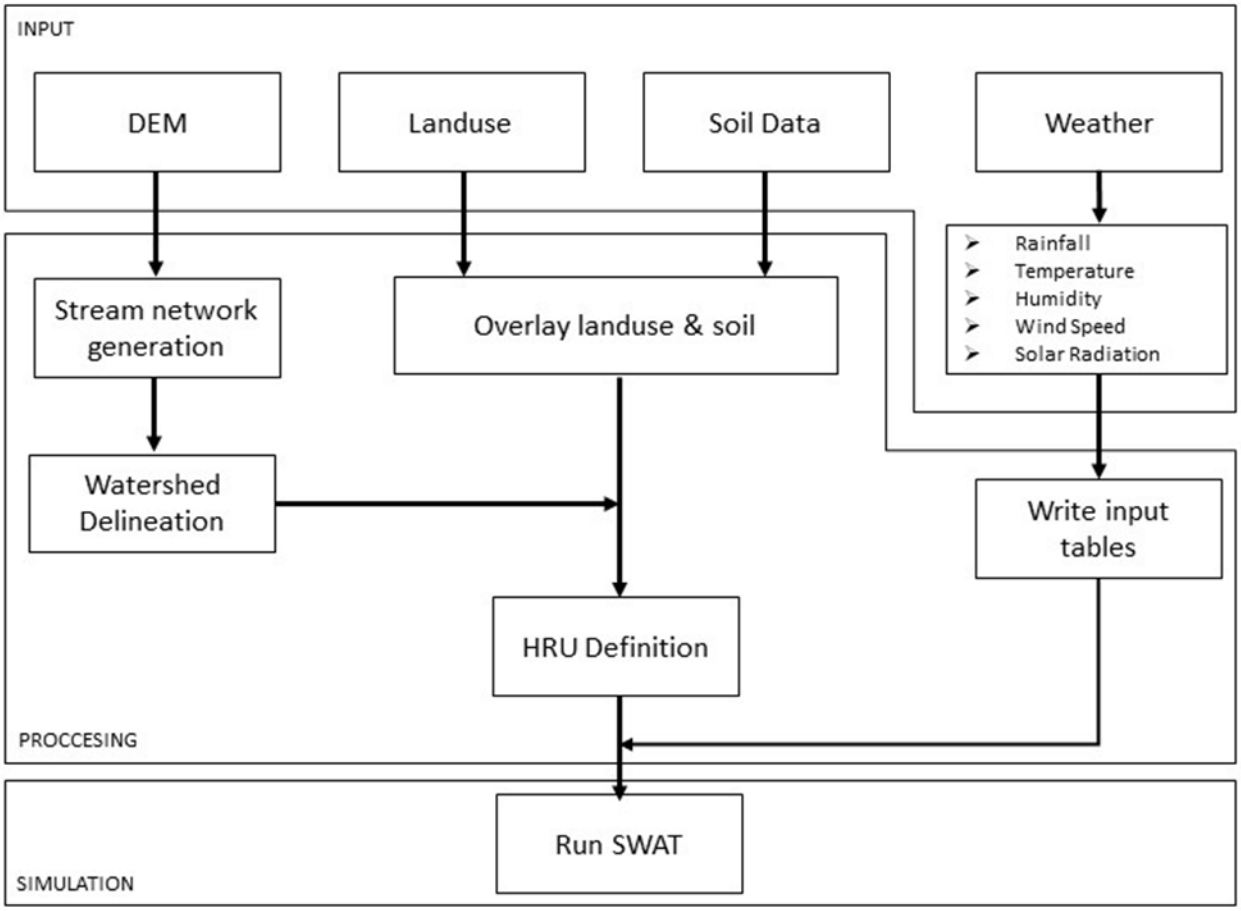


Figure 11: SWAT model Workflow

Modelling in SWAT

- SWAT Project Setup
- Create a new project and define the working directory
- Watershed Delineation
- DEM Setup Stream Definition Stream Network Outlet Definition
- Calculation of Sub-basin Parameter
- HRU Analysis
- Land use Land Cover, Soil, Slope data Definition and Overlay
- Weather Data Definition
- Rainfall Data
- Temperature data Relative Humidity data Wind Speed data
- Solar Radiation data
- SWAT Simulation
- SWAT Calibration

Results and Discussion

Watershed Delineation Narmada basin

Basin–Wise Quantitative Water Budget Analysis

Upper narmada

Watershed Delineation upper Narmada basin

Based on the topographic and hypsometric analysis of the Upper Narmada Basin (Subbasins #1–14), the watershed exhibits a pronounced and structurally controlled elevation gradient, ranging from a minimum of 277 m to a maximum of 1,333 m, resulting in a total vertical relief of approximately 1,056 m. This substantial altitudinal range reflects the basin's location within the complex tectonic and geomorphic framework of the Vindhyan and Satpura ranges, which exerts a primary control on drainage organization, slope processes, and hydrological response dynamics.

Statistical characterization of the elevation data reveals the Upper Narmada as a moderate- to high-relief basin with a distinctly non-uniform elevation distribution. The mean elevation of 526.69 m lies significantly below the midpoint of the elevation range (~805 m), indicating a disproportionate concentration of the basin's area within lower and mid-elevation zones. This asymmetric distribution is characteristic of a landscape in an active stage of fluvial incision and denudation, where erosional processes are progressively reducing higher elevations while expanding the extent of valley slopes and intermediate surfaces. The high standard deviation of 166.49 m confirms considerable internal topographic variability, driven by differential uplift, lithological resistance, and fluvial dissection, which enhances drainage density and promotes rapid runoff convergence during monsoon events.

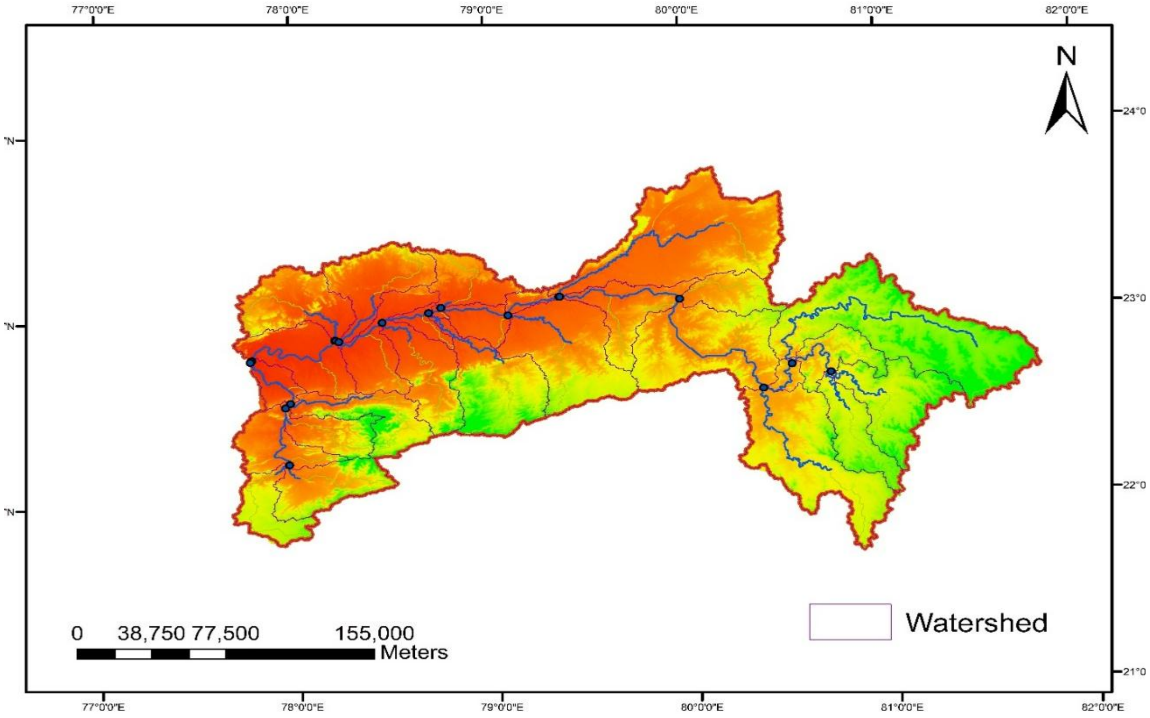


Figure 12: upper narmada basin watershed image

Hypsometric analysis delineates distinct elevation zones that govern the spatial distribution of contributing area and hydrological functionality across the basin. The lowest elevation ranges (<300 m) occupy a relatively small portion of the total watershed area, indicating limited development of extensive, low-gradient floodplains and suggesting constrained natural floodwater storage capacity. This geomorphic configuration increases the susceptibility of downstream reaches to rapid water-level rise during high-flow events.

A dominant proportion of the basin's area is concentrated within the 300–600 m elevation band, which represents the core geomorphic surface of the Upper Narmada. Several subbasins, such as #4, #6, and #9, exhibit moderate standard deviations (60–73 m) within this zone, reflecting rolling to moderately dissected terrain that functions as major runoff generation and synchronization areas. The hypsometric curves for these subbasins show steady increases in cumulative area, indicating extensive slopes and plateaus that significantly modulate the timing and magnitude of downstream flow delivery.

Higher elevation zones extending from 700 m up to 1,333 m, though covering a smaller areal percentage, are hydrologically critical. These upland areas, particularly evident in Subbasin #10 (max 1,206 m) and Subbasin #13 (max 896 m), provide substantial gravitational potential energy. Subbasins with high standard deviations (e.g., #10: 153.25 m, #3: 84.63 m) are characterized by steep slopes and incised channels that facilitate rapid runoff transmission and high sediment transport capacity. Despite their limited spatial extent, these high-relief zones exert a disproportionate influence on peak discharge generation and sediment supply during extreme rainfall.

From a hydrological perspective, the Upper Narmada Basin demonstrates a dual-response character: energy-dominated processes in its steep upland headwaters and more moderated, storage-influenced responses across its extensive mid-elevation slopes. The convergence of rapid, high-energy flows from elevated subbasins with the delayed runoff from broader mid-elevation areas governs flood wave formation and propagation, creating a compound flood risk scenario during basin-wide storm events.

Overall, the geomorphic and hypsometric profile of the Upper Narmada Basin depicts a landscape in an active phase of geomorphic development, marked by significant relief, well-defined elevation zonation, and a clear dominance of sloping terrain over flat plains. This structure supports efficient basin-wide drainage but limits inherent attenuation, amplifying flood peaks. For watershed management, priority should be given to erosion control and landslide mitigation in high-relief zones above 700 m. The extensive mid-elevation terrain (300–600 m) is suitable for distributed water conservation structures like contour trenches and small reservoirs to intercept runoff and enhance infiltration. Even the limited low-elevation zones require focused floodplain management and channel capacity improvements. This integrated DEM-based assessment provides a foundational scientific framework for strategic planning aimed at flood risk reduction, sediment control, and sustainable water resource management in the Upper Narmada Basin.

HRU Formation

This assessment presents a detailed evaluation of the Upper Narmada Basin based on HRU (Hydrologic Response Unit) distributions derived from land use, soil, and slope classifications. The watershed covers a total area of approximately 4,484,687 hectares (11,081,886 acres), subdivided into 31 subbasins and 228 HRUs, reflecting a complex mosaic of land cover, soil types, and topographic settings. This configuration highlights the basin's transitional geomorphic character—bridging rugged uplands with moderate to gently sloping mid-elevation zones—which strongly influences hydrological processes, erosion susceptibility, and land–water interactions.

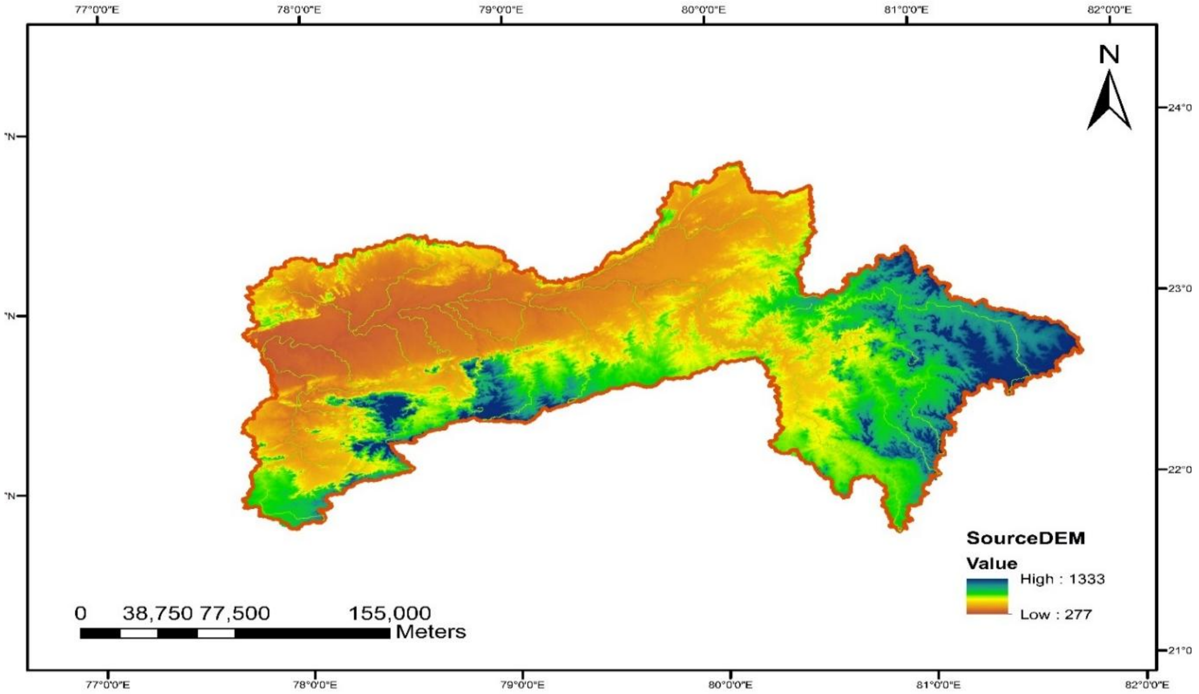


Figure 13 : DEM upper Narmada Basin map

The land use distribution reveals a watershed dominated by agricultural land (AGRL), which occupies 60.31% of the total area, underscoring the basin's significance for food production and rural livelihoods. This is followed by mixed forest (FRST, 23.51%) and range grasses (RNGE, 16.13%), with minor contributions from water bodies and arid range systems. The dominance of agriculture indicates extensive human modification of natural landscapes, which can enhance surface runoff, reduce infiltration, and increase nutrient and sediment loading—particularly in areas with erodible soils and moderate to steep slopes.

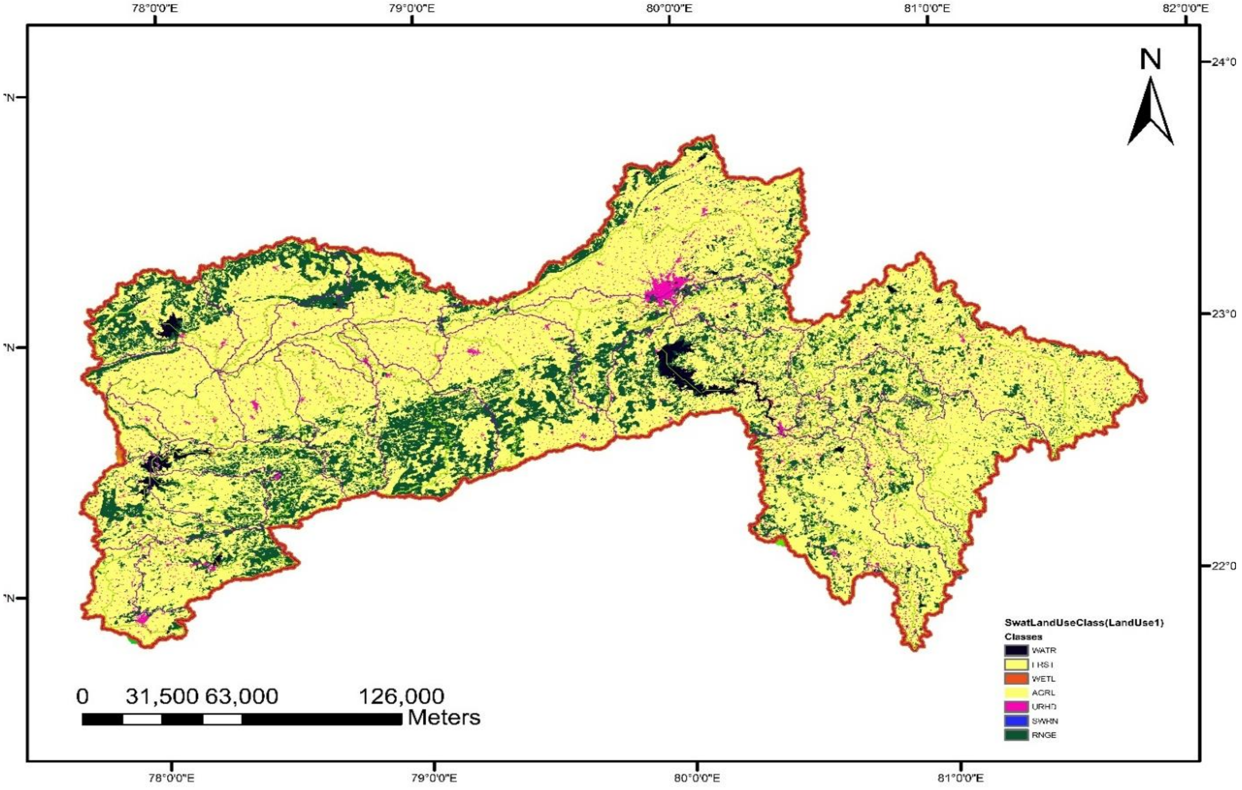


Figure 14: Upper Narmada basin land use map

Soil within the basin are predominantly classified as Vc43-3ab-3861 (47.95% of area) and Vp20-3a-3866 (22.26%), with significant contributions from Bv12-3b-3696 (12.08%) and I-bc-3735 (11.66%). The prevalence of Vc43-3ab-3861—a moderately permeable soil—across large agricultural and forested areas suggests generally favorable conditions for infiltration, though its extensive cultivation may compromise natural hydrologic functions. The co-occurrence of Vp20-3a-3866 in many agricultural subbasins (e.g., Subbasins 1, 7, 8, 14, 15) indicates zones of potential runoff generation due to lower permeability, especially where slope gradients exceed 15%.

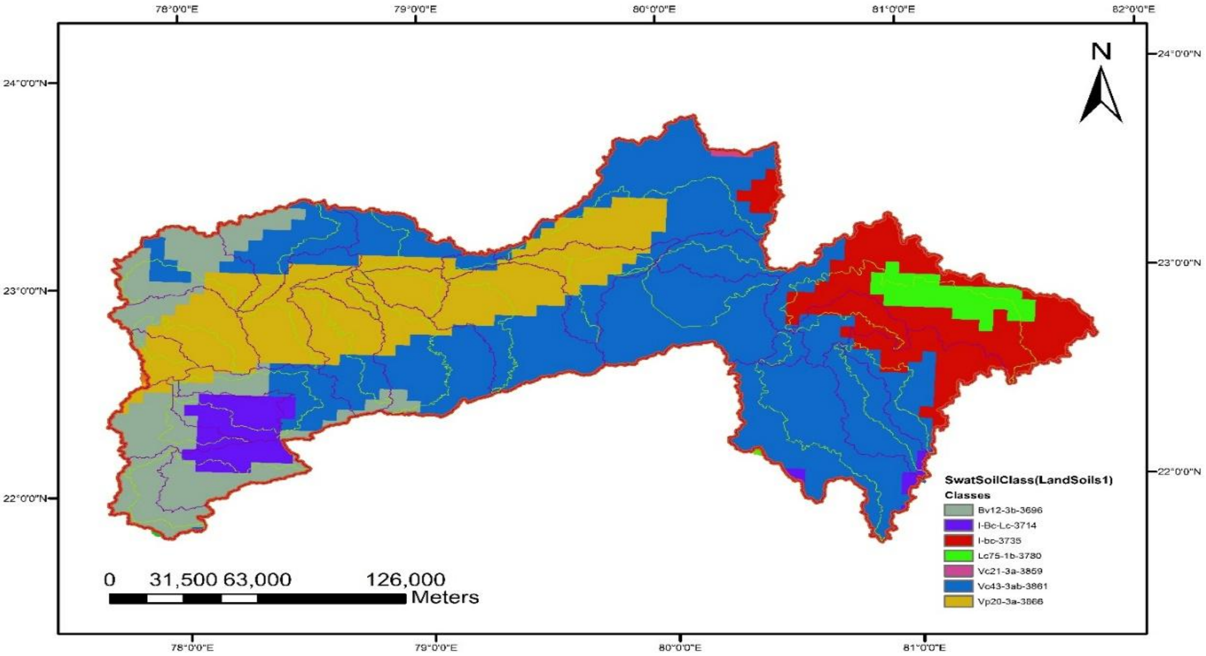


Figure 15: Upper Narmada basin lulc map

Slope analysis shows that the majority of the watershed (85.38%) falls within the 0–15% slope class, reflecting a landscape dominated by gentle to moderate terrain conducive to agriculture and reducing overland flow velocities. However, 10.63% of the area lies in the 15–30% slope range, and nearly 4% exceeds 30% slopes, indicating the presence of dissected uplands and steep valley sides, particularly in forested and range-dominated subbasins (e.g., Subbasins 9, 16, 18, 24). These steeper zones are critical for runoff acceleration, soil erosion, and sediment delivery, especially when coupled with sparse vegetation or intensive land use.

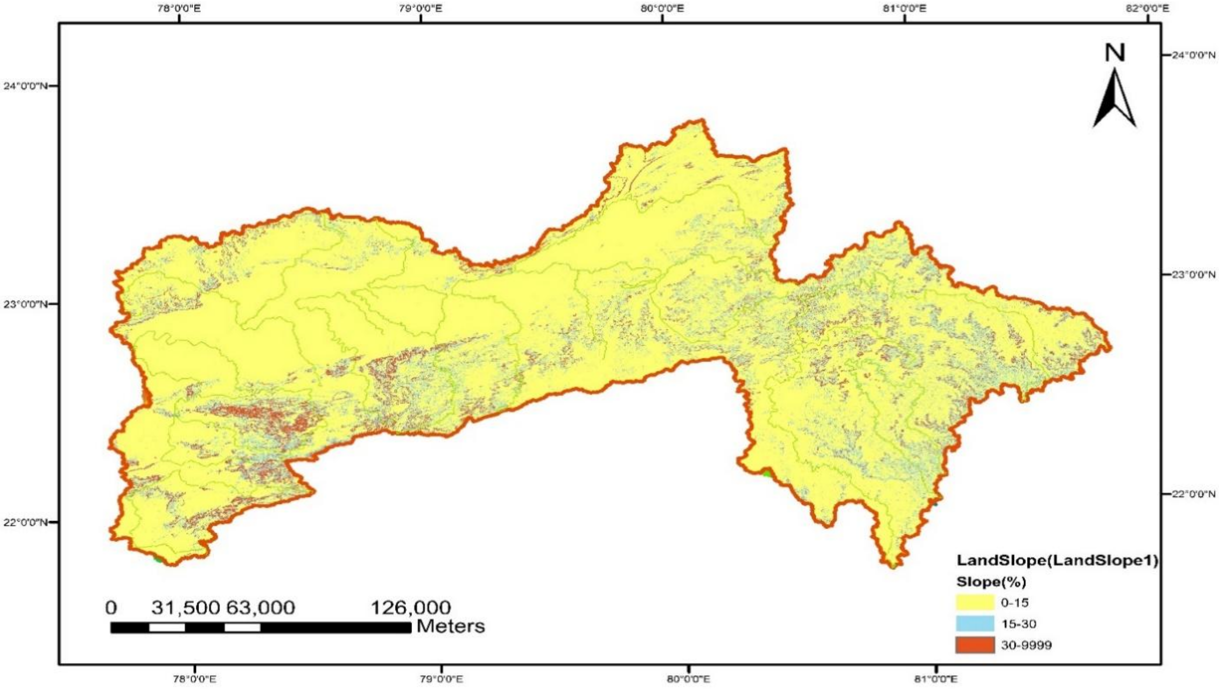


Figure 16: Upper Narmada slope map

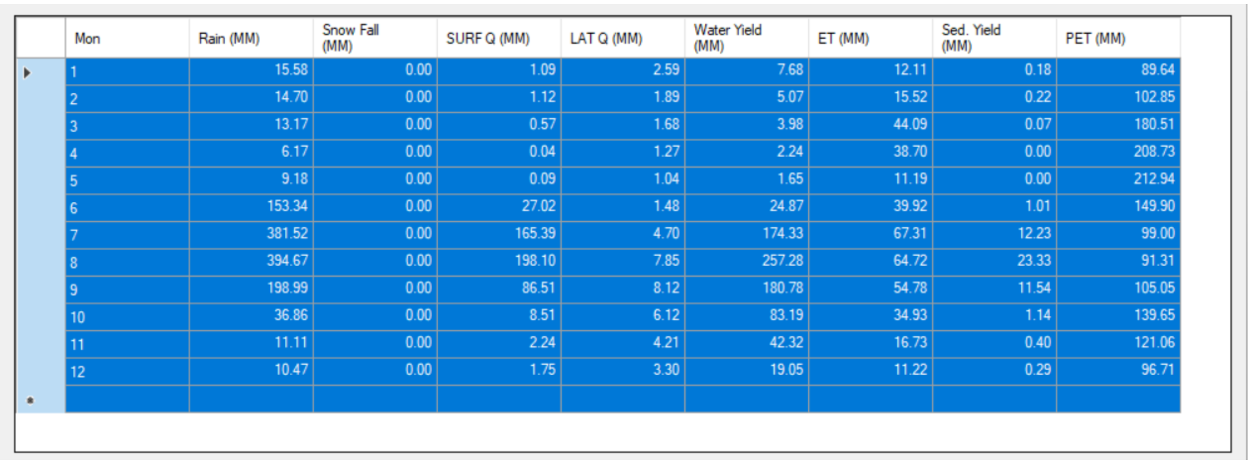
HRU-level analysis reveals distinct spatial patterns of land use–soil–slope interactions. For instance, Subbasin 18—the largest subbasin covering 11.02% of the watershed—is characterized by a mix of forest (35.46%) and agriculture (64.54%) on I-bc-3735 and Lc75-1b-3780 soils, with nearly 25% of its area on slopes >15%. This configuration suggests moderate to high erosion risk in agricultural zones, particularly where steep slopes coincide with erodible soils. Conversely, Subbasin 1 (10.36% of watershed) is almost entirely agricultural on Vc43-3ab-3861 and Vp20-3a-3866 soils with exclusively 0–15% slopes, indicating lower erosion hazard but potential for runoff accumulation and nutrient leaching.

The forest-dominated subbasins (e.g., 22, 24, 27, 29) generally exhibit steeper slopes and more complex soil associations, including I-Bc-Lc-3714 and Bv12-3b-3696. These areas function as critical source zones for baseflow maintenance and sediment retention, but their steep terrain (>30% slopes in parts of Subbasins 24, 27, 31) makes them vulnerable to landslides and gully erosion under extreme rainfall or deforestation.

From a hydrological perspective, the Upper Narmada Basin exhibits a dual-response behavior: gentle-sloped agricultural plains moderate peak flows through extended time of concentration, while steep forested and range uplands generate rapid runoff and sediment during high-intensity events. The widespread distribution of agricultural land on moderate slopes may also lead to diffuse non-point source pollution, requiring integrated soil and water conservation measures.

The implications for watershed management derived from this HRU-based assessment are multifaceted and spatially explicit. Priority must be given to erosion control in steep Hydrologic Response Units where agriculture and range land use intersect, particularly within Subbasins 9, 16, 19, and 24, to mitigate high sediment yields. Concurrently, the promotion of conservation agriculture and contour farming across the extensive, gently sloping agricultural zones is essential to enhance infiltration, reduce surface runoff, and improve soil health. The protection and restoration of forested steep slopes are critical for maintaining slope stability, reducing sediment delivery, and ensuring sustainable streamflow regulation. Furthermore, targeted soil management practices are needed in areas dominated by Vp20-3a-3866 and I-bc-3735 soil types to improve their permeability and effectively lower runoff coefficients. Complementing these measures, the strategic development of distributed water harvesting structures in mid-slope and foothill zones will serve to capture runoff and enhance groundwater recharge. In summary, the HRU-based assessment of the Upper Narmada Basin reveals a landscape fundamentally shaped by the interplay of extensive agriculture on gentle slopes, forest cover on steeper uplands, and a diverse soil matrix that modulates hydrologic response. This integrated understanding provides a robust foundation for designing spatially targeted interventions aimed at holistic flood mitigation, soil conservation, and sustainablewater resource management across the entire basin.

Simulation upper narmada basin



Mon	Rain (MM)	Snow Fall (MM)	SURF Q (MM)	LAT Q (MM)	Water Yield (MM)	ET (MM)	Sed. Yield (MM)	PET (MM)
1	15.58	0.00	1.09	2.59	7.68	12.11	0.18	89.64
2	14.70	0.00	1.12	1.89	5.07	15.52	0.22	102.85
3	13.17	0.00	0.57	1.68	3.98	44.09	0.07	180.51
4	6.17	0.00	0.04	1.27	2.24	38.70	0.00	208.73
5	9.18	0.00	0.09	1.04	1.65	11.19	0.00	212.94
6	153.34	0.00	27.02	1.48	24.87	39.92	1.01	149.90
7	381.52	0.00	165.39	4.70	174.33	67.31	12.23	99.00
8	394.67	0.00	198.10	7.85	257.28	64.72	23.33	91.31
9	198.99	0.00	86.51	8.12	180.78	54.78	11.54	105.05
10	36.86	0.00	8.51	6.12	83.19	34.93	1.14	139.65
11	11.11	0.00	2.24	4.21	42.32	16.73	0.40	121.06
12	10.47	0.00	1.75	3.30	19.05	11.22	0.29	96.71

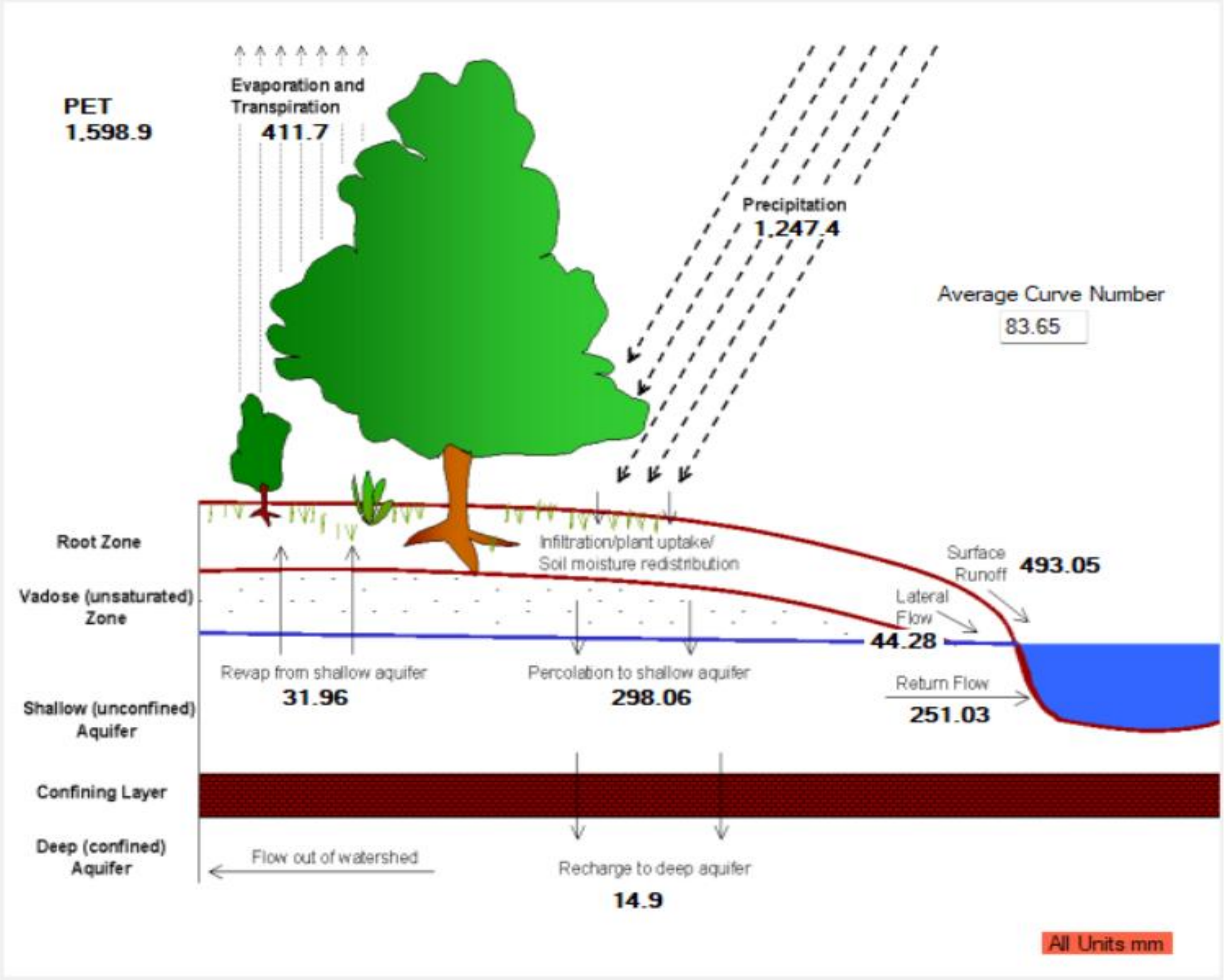


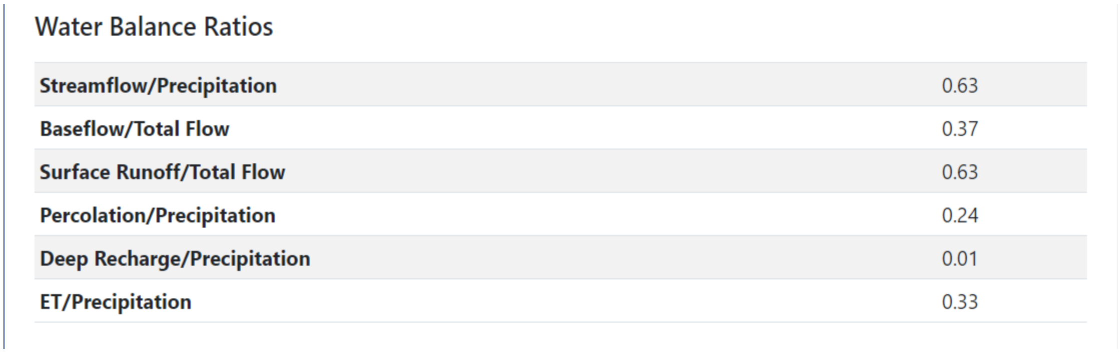
Figure 17:simulation result upper Narmada

Based on the SWAT simulation results for the Upper Narmada Basin, the watershed exhibits a hydrological regime characterized by moderate precipitation input and relatively high atmospheric demand. The annual precipitation is estimated at 1247.4 mm, while the potential evapotranspiration (PET) reaches 1598.9 mm, indicating a clear atmospheric water deficit. This imbalance suggests that evapotranspiration is a dominant process controlling water availability within the basin.

The actual evapotranspiration (ET) is calculated as 411.7 mm, representing a significant proportion of incoming precipitation. Despite high PET, the actual ET remains lower, indicating limitations due to soil moisture availability and seasonal variability. The watershed shows a relatively high average curve number (CN = 83.65), suggesting moderate to high runoff potential influenced by land use, soil type, and antecedent moisture conditions.

Surface runoff is estimated at 493.05 mm, which constitutes a considerable portion of precipitation, indicating that rainfall intensity and watershed characteristics promote overland flow generation during storm events. In addition, lateral flow (44.28 mm) contributes to subsurface movement within the soil profile, although it is relatively smaller compared to surface runoff.

The groundwater system plays a crucial role in the basin hydrology. Recharge to the shallow aquifer is significant, with percolation estimated at 298.06 mm, indicating strong infiltration capacity in parts of the watershed. The return flow (baseflow) from the shallow aquifer is 251.03 mm, highlighting that groundwater contribution to streamflow is substantial and supports sustained river discharge, particularly during non-rainfall periods.



Water Balance Ratios

Streamflow/Precipitation	0.63
Baseflow/Total Flow	0.37
Surface Runoff/Total Flow	0.63
Percolation/Precipitation	0.24
Deep Recharge/Precipitation	0.01
ET/Precipitation	0.33

Table 2:water balance ratio

A smaller fraction of water (14.9 mm) percolates further to recharge the deep aquifer, indicating limited but continuous vertical connectivity between shallow and deep groundwater systems. Additionally, revap from the shallow aquifer (31.96 mm) reflects upward movement of water due to evapotranspiration demand.

Overall, the basin demonstrates a mixed hydrological response, where both surface runoff and groundwater processes are significant. While surface runoff dominates during rainfall events, the strong contribution of baseflow indicates that the watershed maintains streamflow through groundwater support. The system is influenced by high PET, moderate infiltration, and active groundwater recharge, making it sensitive to land use changes and climate variability.

Table 3: Average monthly basin values

Mon	**Rain (MM)**	**Snow Fall (MM)**	**SURF Q (MM)**	**LAT Q (MM)**	**Water Yield (MM)**	**ET (MM)**	**Sed. Yield (T/HA)**	**PET (MM)**
1	15.58	0.00	1.09	2.59	7.68	12.11	0.18	89.64
2	14.70	0.00	1.12	1.89	5.07	15.52	0.22	102.85
3	13.17	0.00	0.57	1.68	3.98	44.09	0.07	180.51
4	6.17	0.00	0.04	1.27	2.24	38.70	0.00	208.73
5	9.18	0.00	0.09	1.04	1.65	11.19	0.00	212.94
6	153.34	0.00	27.02	1.48	24.87	39.92	1.01	149.90
7	381.52	0.00	165.39	4.70	174.33	67.31	12.23	99.00
8	394.67	0.00	198.10	7.85	257.28	64.72	23.33	91.31
9	198.99	0.00	86.51	8.12	180.78	54.78	11.54	105.05
10	36.86	0.00	8.51	6.12	83.19	34.93	1.14	139.65
11	11.11	0.00	2.24	4.21	42.32	16.73	0.40	121.06
12	10.47	0.00	1.75	3.30	19.05	11.22	0.29	96.71

Middle Narmada

Watershed Delineation middle Narmada basin

Geomorphological and Hypsometric Assessment of the Middle Narmada Watershed

This study presents a geomorphological and hypsometric assessment of the Middle Narmada watershed based on Digital Elevation Model (DEM)–derived statistics. The watershed exhibits pronounced but comparatively moderated topographic variability, with elevations ranging from a minimum of approximately 12 m to a maximum of about 1,300 m, resulting in a total vertical relief of nearly 1,288 m. This substantial elevation range reflects the transitional geomorphic setting of the Middle Narmada Basin, which connects the rugged uplands of the upper basin with the relatively subdued downstream reaches, thereby exerting a strong control on spatial patterns of runoff generation and sediment transport

Statistical analysis of elevation data characterizes the Middle Narmada watershed as a moderate-relief basin with a distinctly skewed elevation distribution. The mean elevation of approximately 345.64 m lies well below the mid-point of the elevation range (~656 m), indicating that a large proportion of the watershed area is concentrated within lower to mid-elevation zones. This distribution is indicative of an advanced geomorphic stage, where prolonged erosional processes have reduced extensive high-altitude surfaces and promoted the expansion of gently undulating to moderately sloping terrain. The relatively high standard deviation of about 130.41 m confirms appreciable vertical variability and localized ruggedness, which enhances drainage density and promotes efficient runoff routing during high-intensity rainfall events

Hypsometric analysis reveals well-defined elevation zones that regulate surface area distribution and hydrological behavior across the Middle Narmada watershed. The lowest elevation ranges (<100 m) occupy only a marginal fraction of the total watershed area, suggesting limited development of broad alluvial plains and relatively constrained valley bottoms. This geomorphic configuration implies reduced natural flood storage capacity in localized low-lying zones and heightened sensitivity to rapid water level rise during peak flow conditions.

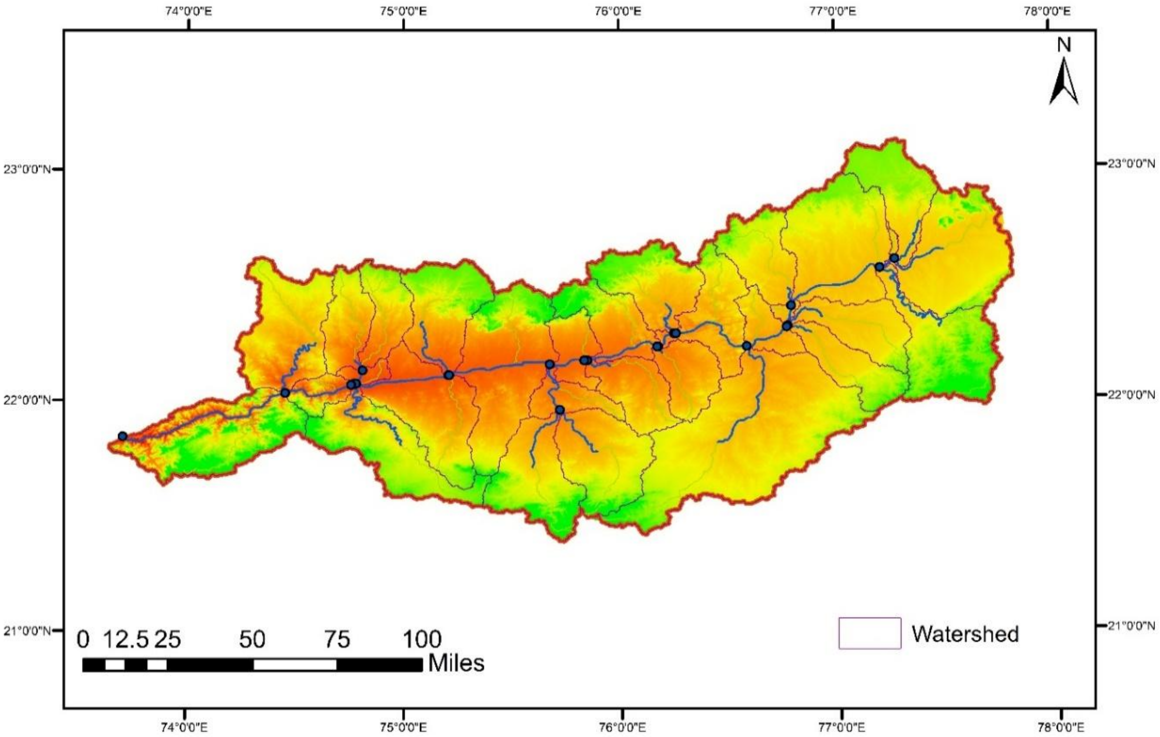


Figure 18:Middle Narmada basin watershed map

A pronounced increase in areal coverage is observed within the 200–400 m elevation band, which represents the dominant geomorphic surface of the Middle Narmada Basin. Several sub-basins within this elevation range exhibit low to moderate standard deviation values (generally below 80 m), reflecting gently sloping to near-planar terrain conditions. Incremental area contribution peaks within narrow elevation intervals, particularly between 250 and 320 m in multiple sub-basins, indicating the presence of extensive mid-elevation terraces or plateau-like surfaces. These geomorphic units function as major runoff accumulation and synchronization zones, significantly influencing flow timing and downstream hydrograph shape .

Higher elevation zones extending beyond 600 m and reaching up to approximately 1,300 m occupy a comparatively smaller proportion of the watershed area but are hydrologically critical. These upland regions provide substantial hydraulic head relative to the basin mean elevation, thereby enhancing gravitational potential energy and promoting rapid runoff along steep slopes and incised channel segments. Despite their limited spatial extent, these high-relief areas exert a disproportionate influence on peak discharge generation and sediment mobilization during extreme precipitation events, particularly in sub-basins exhibiting standard deviation values exceeding 120 m .

From a hydrological perspective, the Middle Narmada watershed exhibits a mixed response characterized by energy-dominated upland zones and storage-influenced mid-elevation surfaces. The extensive mid-elevation belt contributes to delayed runoff response and increased time of concentration, while episodic convergence of high-energy flows from elevated sub-basins can lead to rapid transmission of discharge toward downstream reaches. This interaction between storage-dominated and energy-dominated zones governs flood wave propagation and enhances hydrological sensitivity during extreme rainfall conditions.

Overall, the geomorphic profile of the Middle Narmada watershed reflects an advanced stage of erosional adjustment marked by extensive mid-elevation surfaces, localized high-relief uplands, and relatively constrained low-elevation zones. This configuration supports efficient runoff conveyance while limiting natural attenuation capacity under extreme hydrometeorological forcing. From a watershed management perspective, high-relief zones above approximately 500 m should be prioritized for erosion control and slope stabilization measures to reduce sediment yield. The dominant mid-elevation terrain (200–400 m) provides favorable conditions for distributed water-harvesting interventions such as check dams, percolation tanks, and contour bunding to attenuate peak flows and enhance groundwater recharge. Low-elevation zones, though limited in extent, require strengthened flood management and land-use regulation to mitigate localized flood risk. Collectively, the DEM-based geomorphological and hypsometric assessment of the Middle Narmada watershed provides a robust scientific foundation for flood mitigation, sediment management, and sustainable water resources planning.

HRU Formation

Hydrologic Response Units (HRUs) for the Middle Narmada Basin were delineated using the Soil and Water Assessment Tool (SWAT) through the integration of a digital elevation model (DEM), land use/land cover, soil, and slope datasets. HRUs represent unique combinations of land use, soil type, and slope class within each sub-basin and constitute the basic computational units of the SWAT model. This HRU-based framework enables realistic simulation of spatial heterogeneity in hydrological processes such as surface runoff, evapotranspiration, infiltration, groundwater recharge, and sediment transport across the basin.

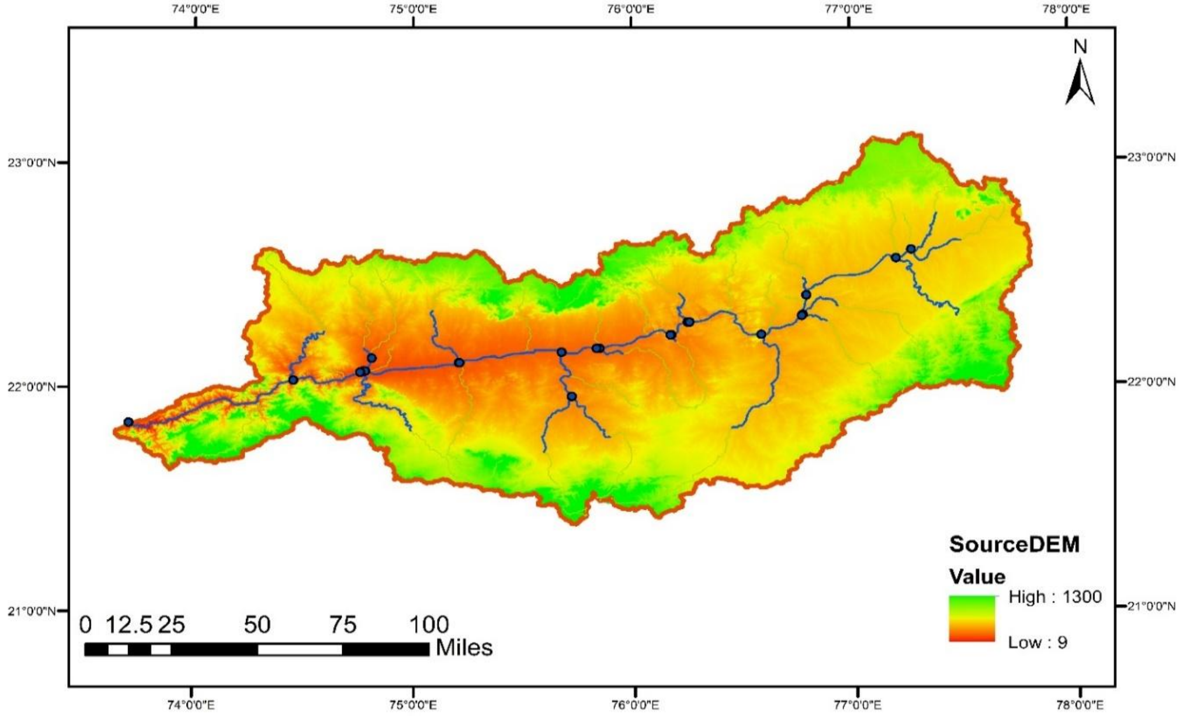


Figure 19: Middle Narmada basin DEM map

In the present study, the Middle Narmada Basin was delineated into 33 sub-basins using DEM-derived drainage characteristics. HRUs were generated using the multiple HRU option in SWAT by applying threshold limits of 15% for land use, 10% for soil, and 10% for slope classes. This threshold-based approach helped preserve dominant hydrological features while minimizing excessive spatial fragmentation, thereby achieving an optimal balance between model detail and computational efficiency. As a result, a total of 155 HRUs were generated across the basin, representing the spatial variability of land use, soil properties, and topographic conditions. The total watershed area included in the HRU analysis is approximately 4.20 million hectares, highlighting the large spatial scale and hydrological complexity of the Middle Narmada Basin.

Analysis of land use distribution within the HRUs reveals that agricultural land is the overwhelmingly dominant land use class, covering approximately 72–73% of the basin area. This extensive agricultural coverage indicates that basin-scale hydrological responses are strongly controlled by cultivation practices, irrigation demand, and soil management, particularly during the monsoon season. Range-grasses constitute nearly 25–26% of the basin area and contribute moderate runoff and sediment yield depending on slope and soil conditions. Forested areas occupy a relatively smaller proportion of the basin, approximately 1–2%,but play an important role in localized runoff moderation and soil conservation. Water bodies account for less than 1% of the basin area and contribute to short-term flow regulation and surface storage.

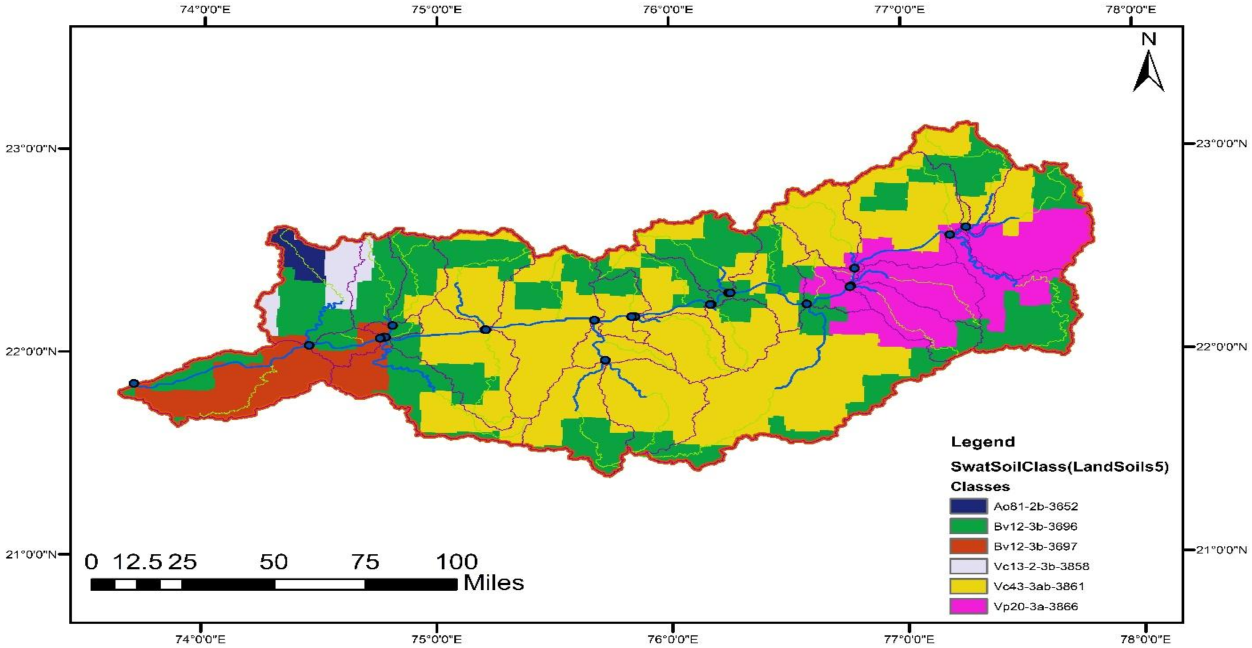


Figure 20: Middle Narmada basin soil map

The soil distribution within the HRUs is dominated by a few major soil series. The Vc43-3ab-3861 soil series is the most extensive, covering nearly 48% of the basin area and is characterized by moderate infiltration capacity and medium erosion susceptibility. The Bv12-3b-3696 soil series accounts for about 29–30% of the basin and contributes significantly to spatial variability in runoff generation and soil moisture dynamics. The Vp20-3a-3866 soil series covers approximately 12–13% of the basin and is associated with relatively higher runoff potential, particularly under intensive agricultural land use. Other soil units such as Bv12-3b-3697, Vc13-2-3b-3858, and Ao81-2b-3652 collectively contribute to heterogeneity in infiltration behavior, subsurface flow, and sediment detachment processes.

Topographic slope is explicitly incorporated into the HRU framework to represent its influence on runoff velocity and erosion potential. The Middle Narmada Basin is predominantly characterized by gentle terrain, with approximately 92% of the basin area falling within the 0–20% slope class. These gently sloping areas are favorable for agriculture but are prone to surface runoff generation during high-intensity rainfall events. Moderately sloping areas (20–40%) constitute about 6% of the basin area and exhibit increased runoff energy and erosion risk. Steep slopes exceeding 40% are very limited in spatial extent, covering less than 2% of the basin, yet they contribute disproportionately to peak runoff and sediment yield during extreme precipitation events.

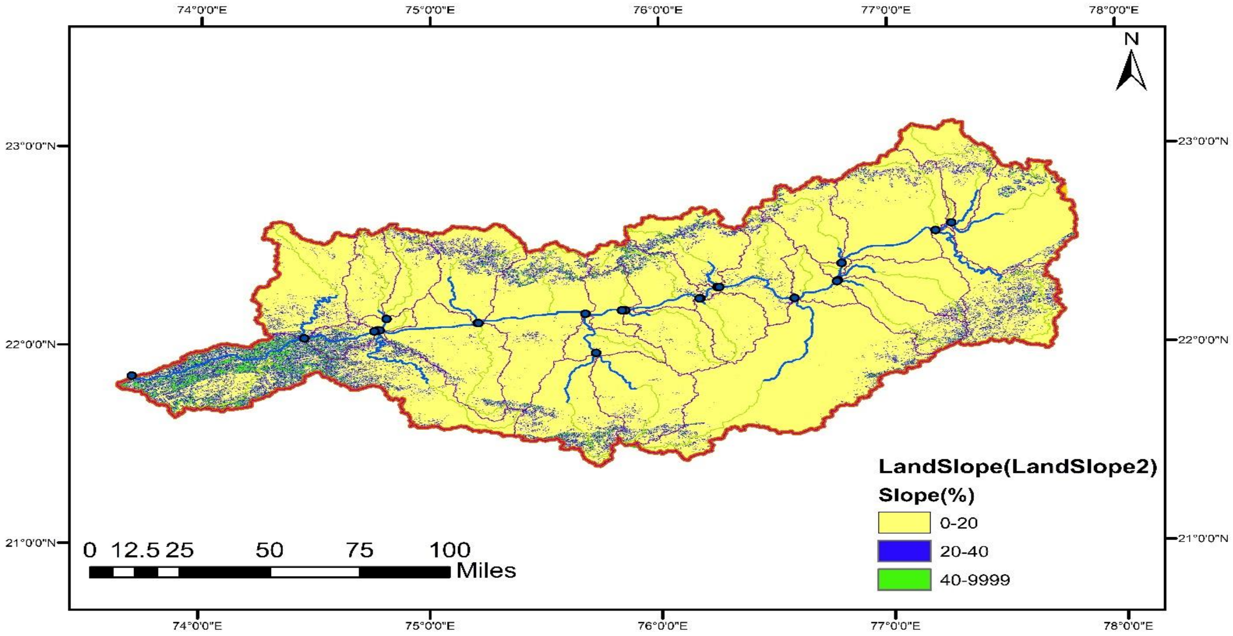


Figure 21: Middle Narmada basin slope map

At the sub-basin scale, HRU characteristics indicate a consistent dominance of agriculture-based HRUs associated with gentle slopes and medium-textured soils. Several sub-basins exhibit agricultural land cover exceeding 80%, suggesting relatively uniform land management practices and a strong influence of cultivation on hydrological response. Range-grass dominated HRUs are more prominent in selected sub-basins and contribute to spatial variation in runoff and sediment yield. Soil distribution within sub-basins is largely governed by the dominance of Vc43-3ab-3861 and Bv12-3b-3696 soil types, while slope distribution remains strongly skewed toward the lower slope categories.

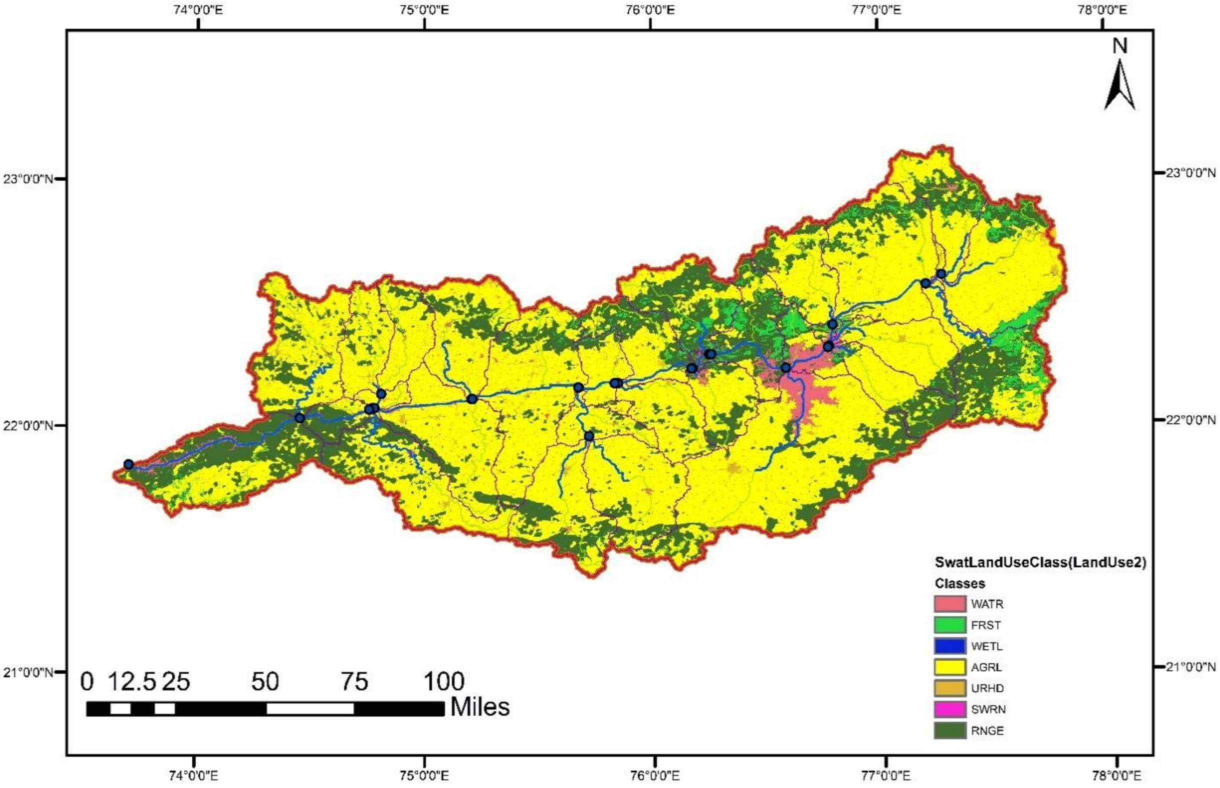
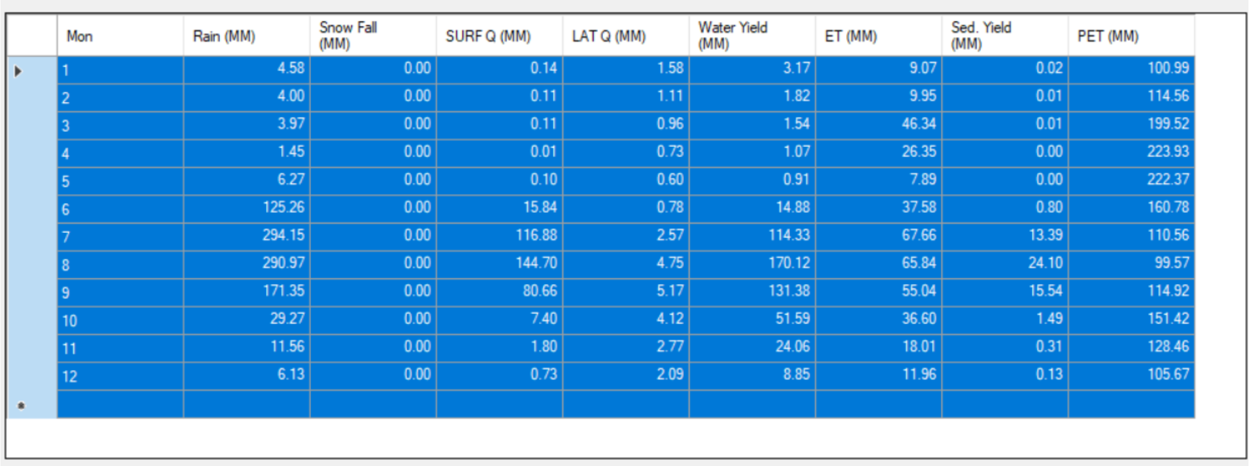


Figure 22: Middle Narmada basin lulc

Overall, the HRU-based analysis indicates that the hydrological behavior of the Middle Narmada Basin is primarily controlled by agriculture-dominated HRUs situated on gentle slopes with moderate infiltration capacity. These HRUs are likely to generate substantial surface runoff during monsoon periods while also supporting high evapotranspiration losses due to extensive crop cover. Although forest-based HRUs occupy a limited area, they contribute to localized enhancement of infiltration and reduction of sediment transport. The developed HRU framework provides a robust foundation for hydrological simulation, sediment yield estimation, and scenario-based water resources assessment using the SWAT model. From a watershed management perspective, the dominance of agricultural HRUs underscores the importance of soil and water conservation measures such as contour farming, improved irrigation practices, and vegetative buffers to enhance hydrological sustainability in the Middle Narmada Basin.

Simulation Middle Narmada basin



Mon	Rain (MM)	Snow Fall (MM)	SURF Q (MM)	LAT Q (MM)	Water Yield (MM)	ET (MM)	Sed. Yield (MM)	PET (MM)
1	4.58	0.00	0.14	1.58	3.17	9.07	0.02	100.99
2	4.00	0.00	0.11	1.11	1.82	9.95	0.01	114.56
3	3.97	0.00	0.11	0.96	1.54	46.34	0.01	199.52
4	1.45	0.00	0.01	0.73	1.07	26.35	0.00	223.93
5	6.27	0.00	0.10	0.60	0.91	7.89	0.00	222.37
6	125.26	0.00	15.84	0.78	14.88	37.58	0.80	160.78
7	294.15	0.00	116.88	2.57	114.33	67.66	13.39	110.56
8	290.97	0.00	144.70	4.75	170.12	65.84	24.10	99.57
9	171.35	0.00	80.66	5.17	131.38	55.04	15.54	114.92
10	29.27	0.00	7.40	4.12	51.59	36.60	1.49	151.42
11	11.56	0.00	1.80	2.77	24.06	18.01	0.31	128.46
12	6.13	0.00	0.73	2.09	8.85	11.96	0.13	105.67

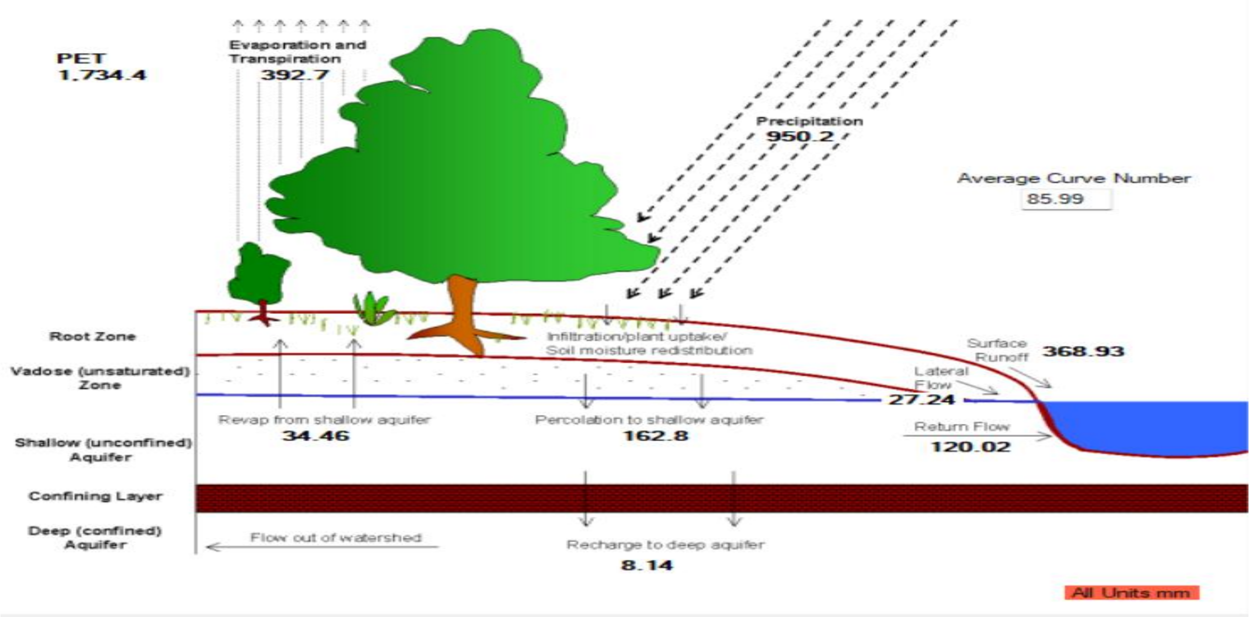


Figure 23:Middle Narmada basin simulation result

Based on the SWAT simulation results, the Middle Narmada Basin exhibits a hydrological system influenced by comparatively lower precipitation and high atmospheric demand. The annual precipitation is estimated at 950.2 mm, while potential evapotranspiration (PET) is significantly higher at 1734.4 mm, indicating a strong and persistent atmospheric water deficit.

The actual evapotranspiration (ET) is 392.7 mm, which accounts for a substantial proportion of the available water, highlighting evapotranspiration as a dominant water loss mechanism. The average curve number (CN = 85.99) indicates relatively high runoff potential, suggesting that land surface conditions, soil properties, and land use promote quick runoff generation during rainfall events.

Surface runoff is estimated at 368.93 mm, representing a major portion of precipitation, particularly during monsoon months (June–September), where rainfall and runoff peaks are clearly observed in the dataset. In contrast, lateral flow (27.24 mm) is relatively low, indicating limited subsurface lateral movement compared to surface runoff.

The groundwater system shows moderate activity. Percolation to the shallow aquifer is 162.8 mm, indicating some degree of infiltration and recharge, though lower than the upper basin. The return flow (baseflow) from the shallow aquifer is 120.02 mm, confirming that groundwater contributes to streamflow, but its role is less dominant compared to surface runoff.

Additionally, revap from the shallow aquifer is 34.46 mm, indicating upward movement of water driven by atmospheric demand. Recharge to the deep aquifer is minimal, with only 8.14 mm, suggesting weak connectivity between shallow and deep groundwater systems.

Table 4:water balance ratio middle narmada

Water Balance Ratios

Streamflow/Precipitation	0.54
Baseflow/Total Flow	0.29
Surface Runoff/Total Flow	0.71
Percolation/Precipitation	0.17
Deep Recharge/Precipitation	0.01
ET/Precipitation	0.41

Overall, the Middle Narmada Basin demonstrates a surface runoff-dominated hydrological response, unlike the upper basin where groundwater plays a stronger role. The high runoff contribution, combined with limited groundwater recharge, indicates a system that responds quickly to rainfall but has relatively lower capacity for sustained baseflow during dry periods. The strong atmospheric water deficit further emphasizes the need for efficient water management practices, particularly focusing on enhancing infiltration and reducing runoff losses.

Table 5:Average monthly basin values

Mon	Rain (MM)	Snow Fall (MM)	SURF Q (MM)	LAT Q (MM)	Water Yield (MM)	ET (MM)	Sed. Yield (T/HA)	PET (MM)
1	4.58	0.00	0.14	1.58	3.17	9.07	0.02	100.99
2	4.00	0.00	0.11	1.11	1.82	9.95	0.01	114.56
3	3.97	0.00	0.11	0.96	1.54	46.34	0.01	199.52
4	1.45	0.00	0.01	0.73	1.07	26.35	0.00	223.93
5	6.27	0.00	0.10	0.60	0.91	7.89	0.00	222.37
6	125.26	0.00	15.84	0.78	14.88	37.58	0.80	160.78
7	294.15	0.00	116.88	2.57	114.33	67.66	13.39	110.56
8	290.97	0.00	144.70	4.75	170.12	65.84	24.10	99.57
9	171.35	0.00	80.66	5.17	131.38	55.04	15.54	114.92
10	29.27	0.00	7.40	4.12	51.59	36.60	1.49	151.42
11	11.56	0.00	1.80	2.77	24.06	18.01	0.31	128.46
12	6.13	0.00	0.73	2.09	8.85	11.96	0.13	105.67

Lower Narmada

Watershed Delineation lower Narmada basin

This study presents a geomorphological and hypsometric assessment of the Lower Narmada watershed based on Digital Elevation Model (DEM)–derived statistics. The watershed exhibits substantial topographic variability, with elevations ranging from a minimum of 277 m to a maximum of 1,333 m, resulting in a total vertical relief of approximately 1,056 m. This considerable elevation difference indicates a heterogeneous terrain and highlights the continued presence of high-relief zones even in the downstream part of the Narmada basin, contributing significantly to spatial variability in hydrological response across the watershed

Statistical analysis of elevation data classifies the Lower Narmada watershed as a moderate- to high-relief basin with a distinctly skewed elevation distribution. The mean elevation of 526.69 m lies notably below the midpoint of the elevation range (805 m), suggesting that a large proportion of the watershed area is concentrated within the lower to mid-elevation zones. This pattern reflects a geomorphologically mature landscape, where long-term erosional processes have reduced extensive highland surfaces while promoting the expansion of intermediate elevation terrains. The relatively high standard deviation of 166.49 m further confirms pronounced vertical variability and rugged topography, which supports the development of a complex drainage network capable of generating high-velocity runoff, particularly during intense rainfall events

Hypsometric analysis reveals distinct elevation zones that govern surface area distribution and hydrological behavior within the Lower Narmada watershed. The lowest elevation range (277–300 m) contributes only a minor fraction of the total watershed area, indicating the absence of broad alluvial plains and suggesting a spatially confined downstream valley. This geomorphic configuration implies limited natural flood storage capacity and increased susceptibility to flooding in localized low-lying regions.

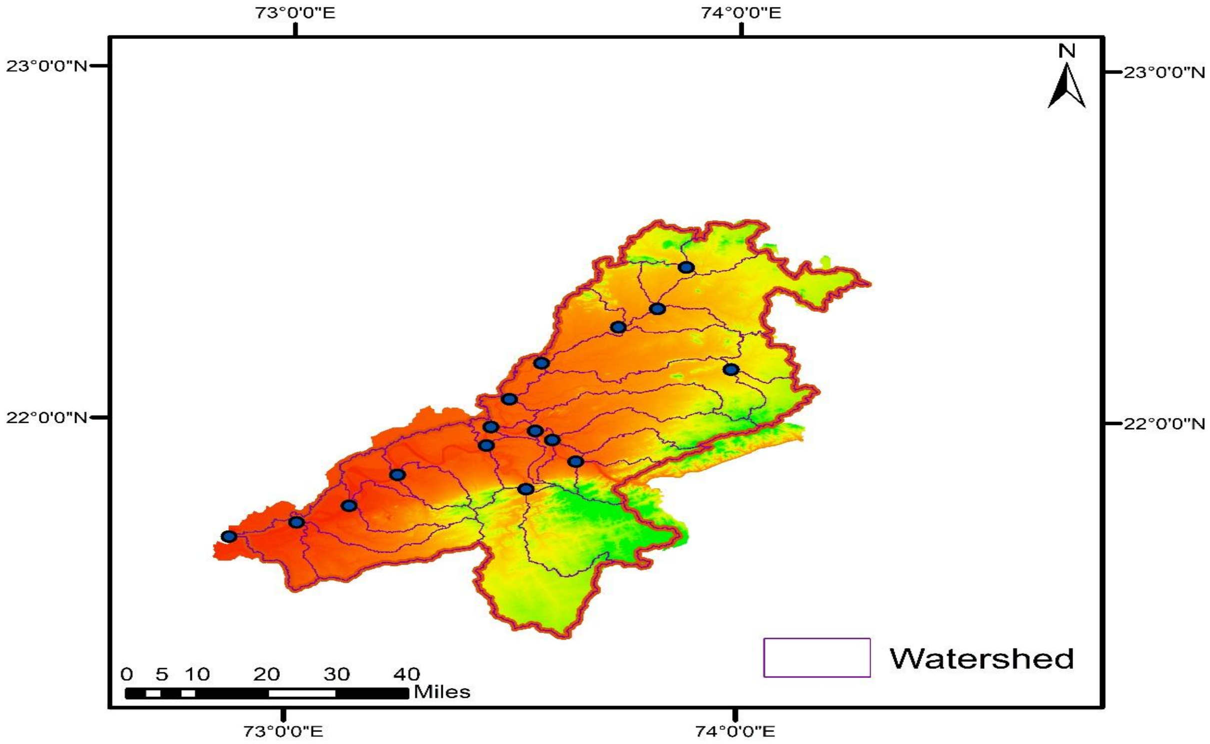


Figure 24: Lower Narmada basin watershed Map

A substantial increase in areal coverage is observed within the 300–400 m elevation band, which represents the dominant geomorphic surface of the watershed. Several sub-basins within this range exhibit relatively low standard deviation values, indicating gently sloping to near-planar terrain. Incremental area contribution peaks within narrow elevation intervals (notably around 310–325 m in certain sub-basins), suggesting the presence of broad mid-elevation terraces or plateau-like surfaces. These zones act as major runoff accumulation and synchronization areas, playing a critical role in regulating downstream flow response

Higher elevation zones extending beyond 600 m and reaching up to 1,333 m occupy a smaller proportion of the watershed area but are hydrologically significant. These upland regions generate a substantial hydraulic head relative to the watershed's mean elevation, enhancing gravitational potential energy and promoting rapid flow velocities along steep channel segments. As a result, these high-elevation areas, despite their limited spatial extent, exert a disproportionate influence on peak discharge generation and sediment transport during extreme precipitation events.

From a hydrological perspective, the Lower Narmada watershed exhibits a mixed response characterized by energy-dominated upland zones and storage-influenced mid-elevation surfaces. While the extensive mid-elevation belt contributes to delayed runoff and increased time of concentration, the convergence of high-energy flows from elevated sub-basins can lead to rapid transmission of discharge toward the downstream outlet. This flow synchronization mechanism, combined with the narrow low-elevation valley, significantly increases flood risk during high-intensity rainfall episodes.

Overall, the geomorphic profile of the Lower Narmada watershed reflects an advanced stage of erosional adjustment marked by extensive mid-elevation surfaces, localized high-relief uplands, and a constrained downstream discharge zone. This configuration promotes efficient runoff conveyance while limiting natural attenuation, thereby enhancing vulnerability to flash flooding under extreme hydrometeorological conditions.

From a watershed management perspective, these findings highlight the need for elevation-sensitive intervention strategies. High-relief zones above approximately 500 m should be prioritized for erosion control and slope stabilization measures to reduce sediment yield. The dominant mid-elevation terrain (300–400 m) offers favorable conditions for distributed water-harvesting structures such as check dams and percolation tanks, which can attenuate peak flows and enhance groundwater recharge. In contrast, the low-elevation discharge zones require strengthened flood protection measures and regulated land-use planning to minimize flood-related damages. Collectively, the DEM-based analysis of the Lower Narmada watershed provides a robust scientific basis for informed watershed management, flood mitigation, and sustainable water resources planning.

HRU Formation

Hydrologic Response Units (HRUs) for the Lower Narmada Basin were delineated using the Soil and Water Assessment Tool (SWAT) through the integration of digital elevation model (DEM), land use/land cover, soil type, and slope datasets. HRUs represent unique combinations of land use, soil, and slope within each sub-basin and form the fundamental computational units of the SWAT model. This HRU-based representation enables the realistic simulation of spatial variability in key hydrological processes such as surface runoff generation, evapotranspiration, infiltration, groundwater recharge, and sediment transport. Given the physiographic diversity and extensive spatial scale of the Lower Narmada Basin, HRU delineation is essential for accurately capturing basin-scale hydrological responses.

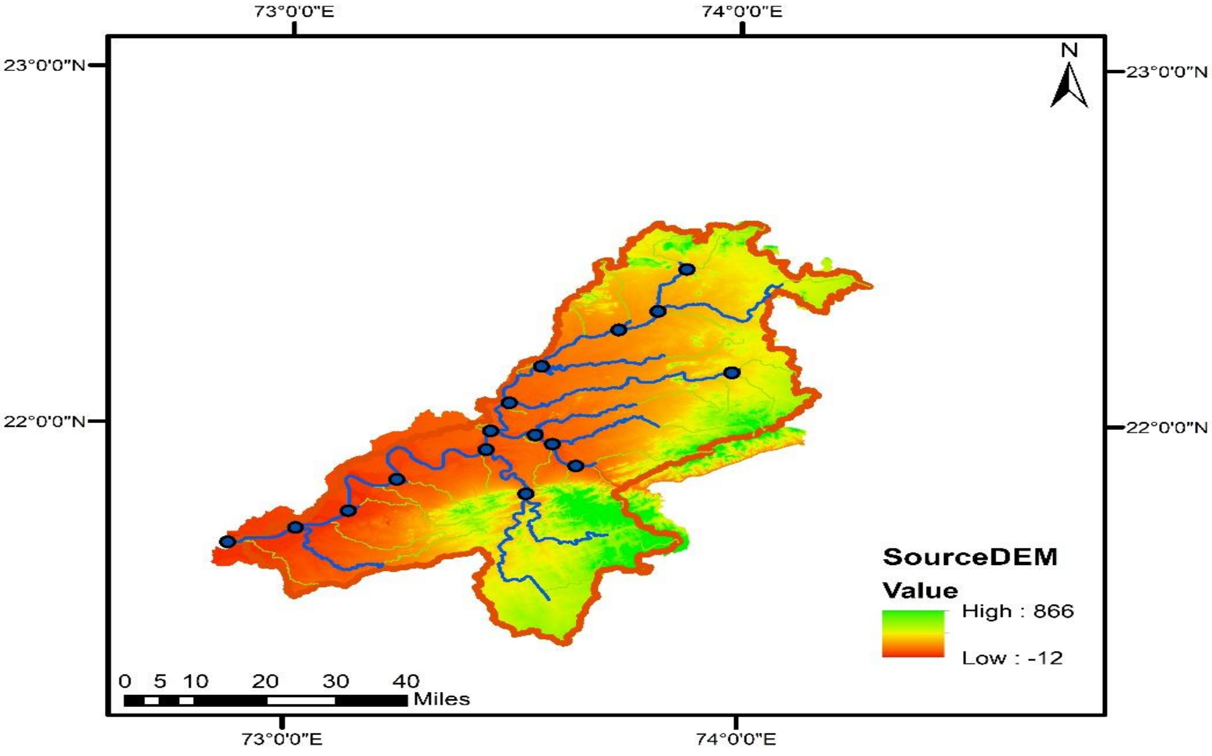


Figure 25: Lower Narmada basin DEM Map

In the present study, the Lower Narmada Basin was delineated into 31 sub-basins using DEM-derived drainage characteristics. HRUs were generated using the multiple HRU option in SWAT by applying threshold limits to land use, soil, and slope classes in order to retain dominant hydrological features while avoiding excessive fragmentation. This approach ensured an optimal balance between spatial detail and computational efficiency. As a result, a total of 228 HRUs were generated across the basin, collectively representing the heterogeneity of land use patterns, soil properties, and topographic conditions. The total watershed area included in the HRU analysis is approximately 4.48 million hectares, reflecting the hydrological complexity of the Lower Narmada Basin.

Analysis of land use distribution within the HRUs indicates that agricultural land is the dominant land use class, covering approximately 50–55% of the total basin area. This extensive agricultural coverage highlights the strong influence of farming practices on hydrological processes, particularly surface runoff, evapotranspiration, and soil erosion. Mixed forest areas account for nearly 25% of the basin and play a critical role in regulating runoff, reducing erosion, and enhancing infiltration. Range-grasses constitute around 19–20% of the basin area and contribute moderate runoff and sediment yield depending on slope conditions. Urban and residential areas occupy a relatively small proportion of the basin, approximately 3%, but exert a disproportionate hydrological impact due to increased impervious surfaces and localized runoff generation. Water bodies and wetlands form a minor component of the basin but contribute to flow regulation and temporary water storage during high-flow periods.

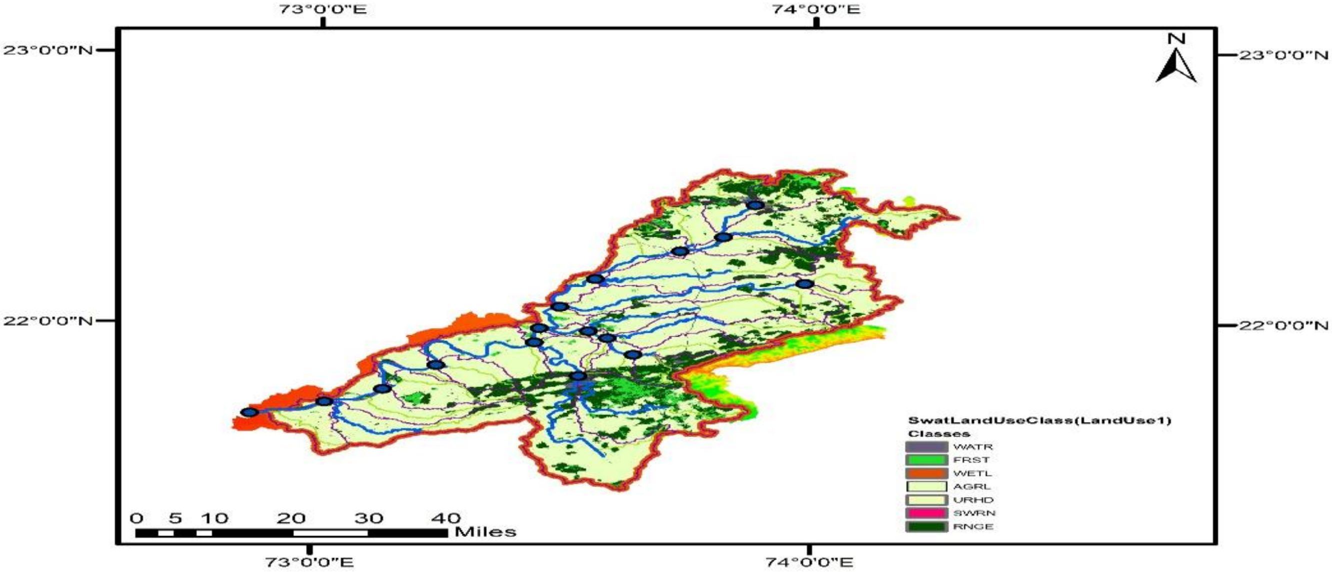


Figure 26: Lower Narmada Basin LULC map

The HRU formation process incorporated multiple soil types, with a few dominant soil units occupying large portions of the basin. The Vc43-3ab-3861 soil series is the most extensive, covering nearly 48% of the basin area and characterized by moderate infiltration capacity and susceptibility to erosion. The Vp20-3a-3866 soil series accounts for about 21% of the basin and is typically associated with moderate to high runoff potential, particularly under intensive agricultural land use. Other soil units such as Bv12-3b-3696 and I-bc-3735 collectively contribute to spatial variability in soil moisture dynamics, infiltration rates, and sediment detachment. The representation of diverse soil classes within HRUs allows the SWAT model to realistically simulate variations in subsurface flow and sediment transport across the basin.

Topographic slope, a critical determinant of runoff velocity and erosion potential, is explicitly represented in the HRU framework. The Lower Narmada Basin is predominantly characterized by gentle terrain, with approximately 83% of the basin area falling within the 0–15% slope class. These gently sloping areas are generally favorable for agriculture but are sensitive to surface runoff generation during high-intensity rainfall events. Moderately sloping areas (15–30%) account for about 12% of the basin and exhibit increased runoff energy and erosion risk. Steep slopes exceeding 30% are limited in extent, covering less than 5% of the basin area, yet they contribute disproportionately to peak runoff and sediment yield during extreme precipitation events.

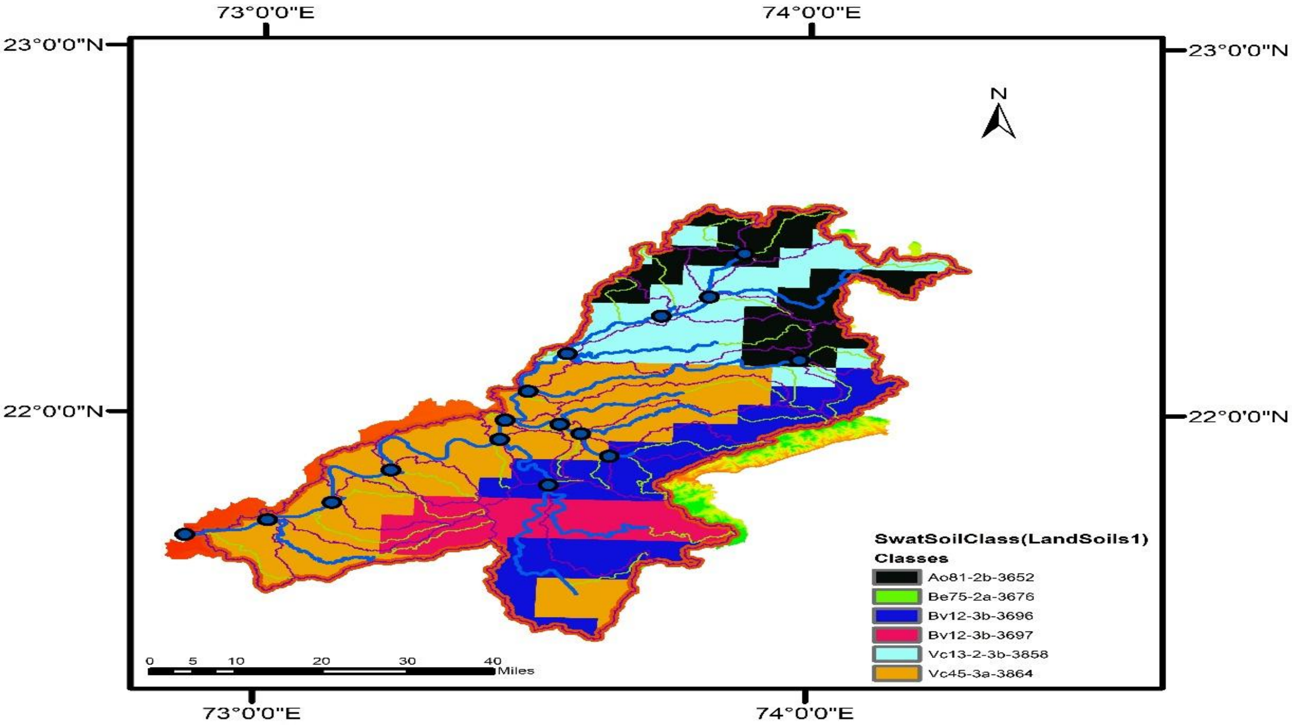


Figure 27: Lower Narmada soil Map

At the sub-basin level, HRU characteristics show a consistent dominance of agricultural land combined with gentle slopes and medium to deep soils. Several sub-basins exhibit agricultural land cover exceeding 70–80%, indicating uniform land management practices and a strong influence of cultivation on hydrological response. Forest-dominated HRUs are more prominent in selected sub-basins and contribute to localized moderation of runoff and sediment transport. Soil distribution within sub-basins is largely governed by the dominance of Vc43-3ab-3861 and Vp20-3a-3866 soil types, while slope distribution remains strongly skewed toward the lower slope classes.

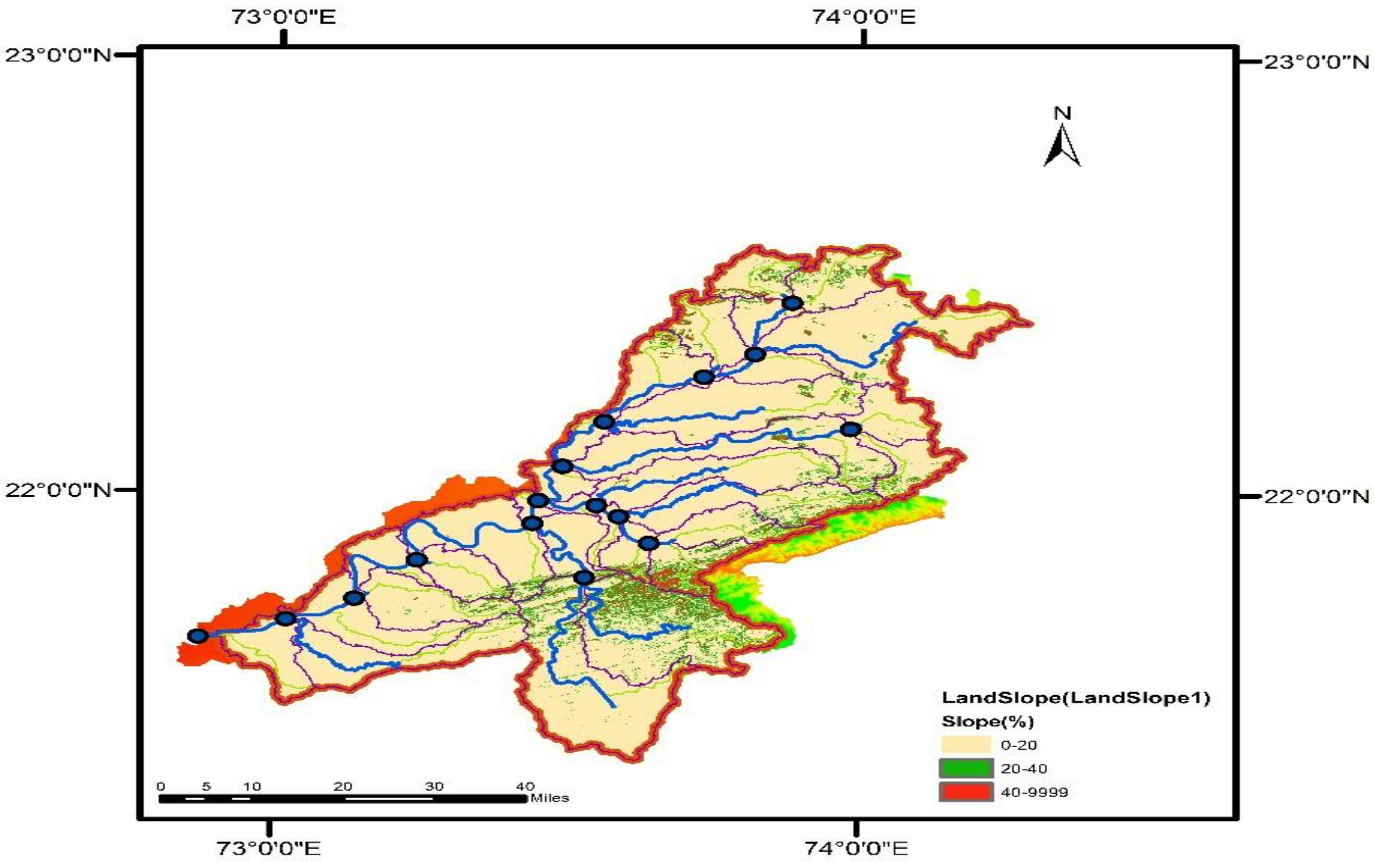


Figure 28: Lower Narmada slope map

The HRU-based analysis indicates that the hydrological behavior of the Lower Narmada Basin is primarily controlled by agriculture-dominated HRUs situated on gentle slopes with moderate infiltration capacity. These HRUs are likely to generate significant surface runoff during monsoon periods, while also supporting high evapotranspiration losses due to extensive crop cover. Forest-based HRUs, though limited in spatial extent, contribute to enhanced infiltration, reduced runoff velocity, and improved baseflow conditions. Urban HRUs, despite their small areal coverage, represent localized hotspots of runoff generation and require careful consideration in future land use planning.

Overall, the HRU framework developed for the Lower Narmada Basin provides a robust scientific basis for hydrological simulation, sediment yield estimation, and scenario-based water resources assessment using the SWAT model. From a watershed management perspective, the dominance of agricultural HRUs on gentle slopes underscores the need for improved soil and water conservation practices, including contour farming, vegetative buffer strips, and improved irrigation management. HRUs located on moderately steep slopes should be prioritized for erosion control and afforestation measures to reduce sediment transport and enhance watershed sustainability.

Simulaton lower narmada basin

The actual evapotranspiration (ET) is 354.8 mm, which accounts for approximately 35% of total precipitation (ET/P = 0.35), confirming that evapotranspiration is a major pathway of water loss. The average curve number (CN = 86.36) suggests high runoff potential due to land surface characteristics, soil properties, and land use conditions.

Surface runoff is the dominant hydrological component, estimated at 454.9 mm, contributing nearly 73% of total streamflow (Surface Runoff/Total Flow = 0.73). This indicates that the basin responds rapidly to rainfall events, particularly during the monsoon months (June–September), as reflected in the monthly dataset where peak rainfall corresponds to high runoff generation.

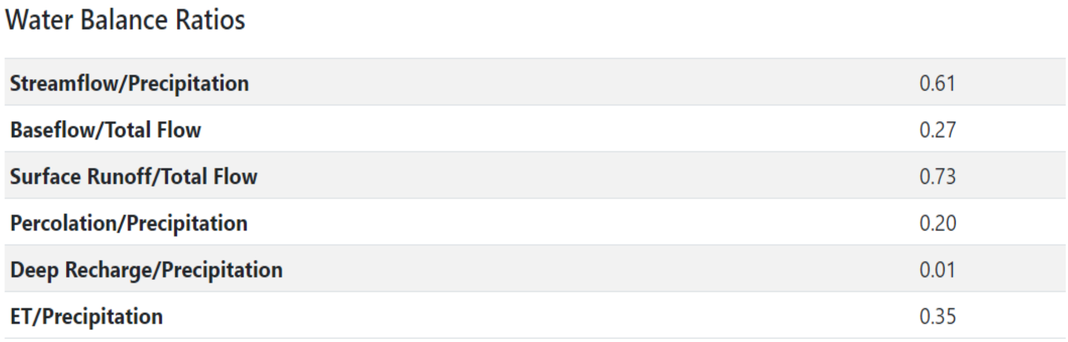
In contrast, lateral flow is minimal (9.83 mm), suggesting that subsurface lateral movement plays a very limited role in this basin. However, percolation to the shallow aquifer is relatively significant (200.8 mm), representing about 20% of precipitation (Percolation/P = 0.20), which indicates moderate infiltration capacity.

The groundwater contribution (return flow) is 154.72 mm, accounting for only 27% of total flow (Baseflow/Total Flow = 0.27). This confirms that, unlike the upper basin, the lower basin is less dependent on groundwater for sustaining streamflow and is primarily driven by surface runoff processes.

Recharge to the deep aquifer is minimal (10.04 mm, ~1% of precipitation), indicating weak vertical connectivity and limited long-term groundwater storage contribution. Additionally, revap from the shallow aquifer (35.87 mm) reflects upward movement of water driven by high evaporative demand.

The streamflow-to-precipitation ratio (0.61) indicates that a significant portion of rainfall is converted into streamflow, primarily through rapid runoff pathways rather than delayed subsurface contributions.

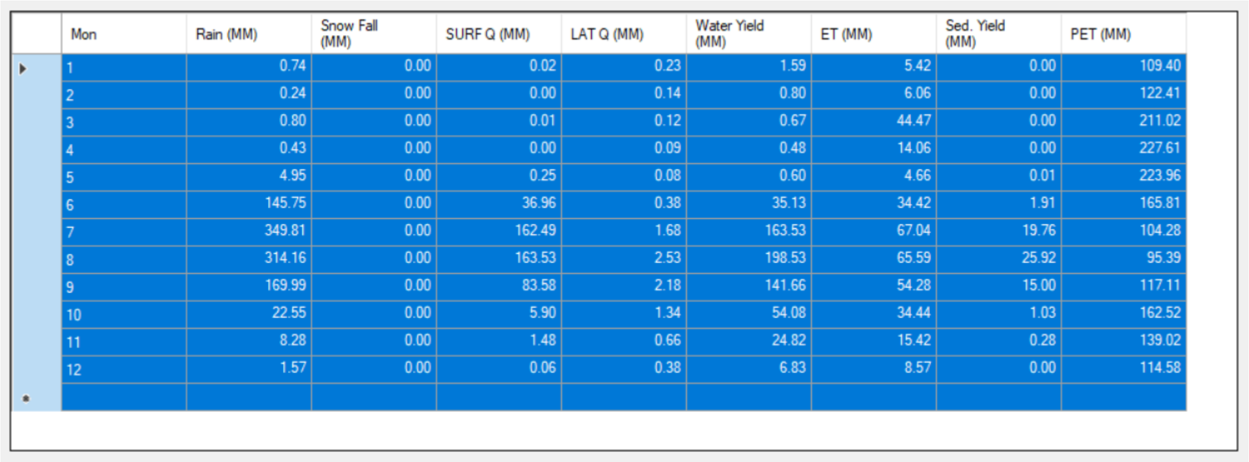
Table 6:water balance ratio for lower narmada basin



Water Balance Ratios

Streamflow/Precipitation	0.61
Baseflow/Total Flow	0.27
Surface Runoff/Total Flow	0.73
Percolation/Precipitation	0.20
Deep Recharge/Precipitation	0.01
ET/Precipitation	0.35

Overall, the Lower Narmada Basin can be characterized as a surface runoff-dominated hydrological system with limited subsurface contribution and moderate groundwater recharge potential. The high runoff response, combined with strong atmospheric demand and relatively lower baseflow contribution, suggests a system that is prone to quick hydrological responses during rainfall events but has reduced capacity for sustaining flows during dry periods. Effective water management in this basin should focus on enhancing infiltration, reducing runoff losses, and improving groundwater recharge to balance the strong surface-dominated hydrological behavior.



Mon	Rain (MM)	Snow Fall (MM)	SURF Q (MM)	LAT Q (MM)	Water Yield (MM)	ET (MM)	Sed. Yield (MM)	PET (MM)
1	0.74	0.00	0.02	0.23	1.59	5.42	0.00	109.40
2	0.24	0.00	0.00	0.14	0.80	6.06	0.00	122.41
3	0.80	0.00	0.01	0.12	0.67	44.47	0.00	211.02
4	0.43	0.00	0.00	0.09	0.48	14.06	0.00	227.61
5	4.95	0.00	0.25	0.08	0.60	4.66	0.01	223.96
6	145.75	0.00	36.96	0.38	35.13	34.42	1.91	165.81
7	349.81	0.00	162.49	1.68	163.53	67.04	19.76	104.28
8	314.16	0.00	163.53	2.53	198.53	65.59	25.92	95.39
9	169.99	0.00	83.58	2.18	141.66	54.28	15.00	117.11
10	22.55	0.00	5.90	1.34	54.08	34.44	1.03	162.52
11	8.28	0.00	1.48	0.66	24.82	15.42	0.28	139.02
12	1.57	0.00	0.06	0.38	6.83	8.57	0.00	114.58

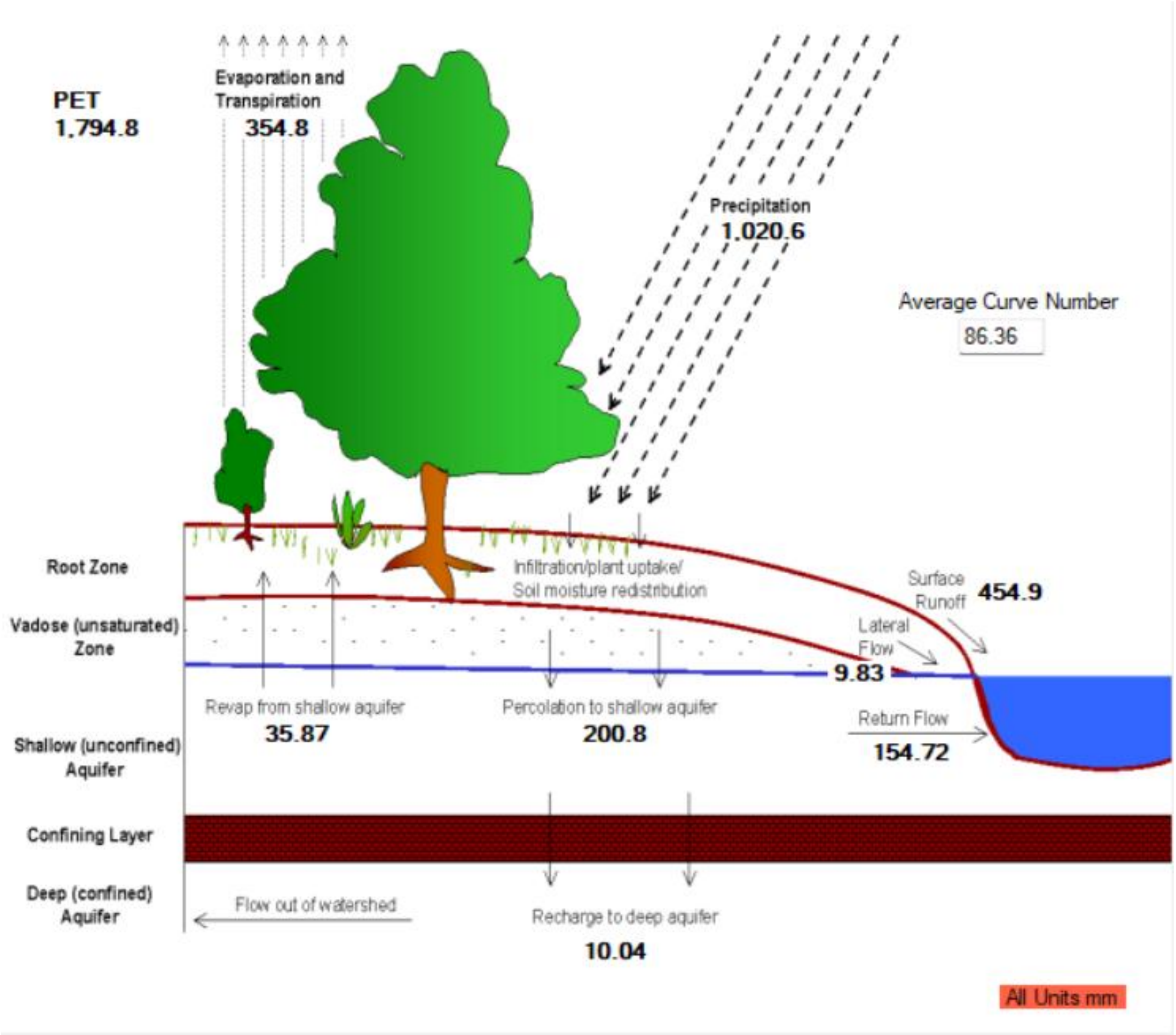


Figure 29: Lower Narmada basin simulation result

Table 7:Average monthly basin values

Mon	Rain (MM)	Snow Fall (MM)	SURF Q (MM)	LAT Q (MM)	Water Yield (MM)	ET (MM)	Sed. Yield (T/HA)	PET (MM)
1	0.74	0.00	0.02	0.23	1.59	5.42	0.00	109.40
2	0.24	0.00	0.00	0.14	0.80	6.06	0.00	122.41
3	0.80	0.00	0.01	0.12	0.67	44.47	0.00	211.02
4	0.43	0.00	0.00	0.09	0.48	14.06	0.00	227.61
5	4.95	0.00	0.25	0.08	0.60	4.66	0.01	223.96
6	145.75	0.00	36.96	0.38	35.13	34.42	1.91	165.81
7	349.81	0.00	162.49	1.68	163.53	67.04	19.76	104.28
8	314.16	0.00	163.53	2.53	198.53	65.59	25.92	95.39
9	169.99	0.00	83.58	2.18	141.66	54.28	15.00	117.11
10	22.55	0.00	5.90	1.34	54.08	34.44	1.03	162.52
11	8.28	0.00	1.48	0.66	24.82	15.42	0.28	139.02
12	1.57	0.00	0.06	0.38	6.83	8.57	0.00	114.58

Spatial Variation of Water Budget Components: Narmada River Basin

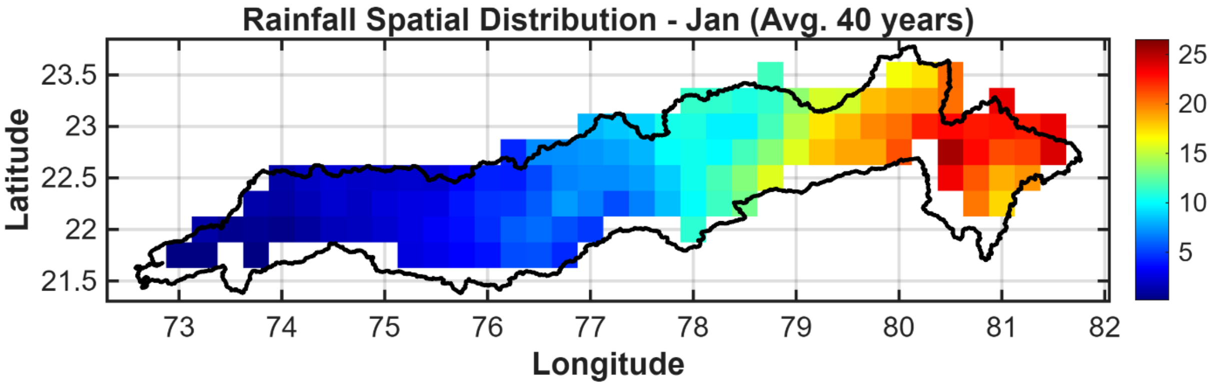
Based on the analysis of the water budget data (1981–2020) across the districts of the Narmada River Basin, the following report details the temporal variation of the three primary hydrologic parameters: Rainfall, Runoff, and Evapotranspiration (ET).

Spatial Variation of Rainfall

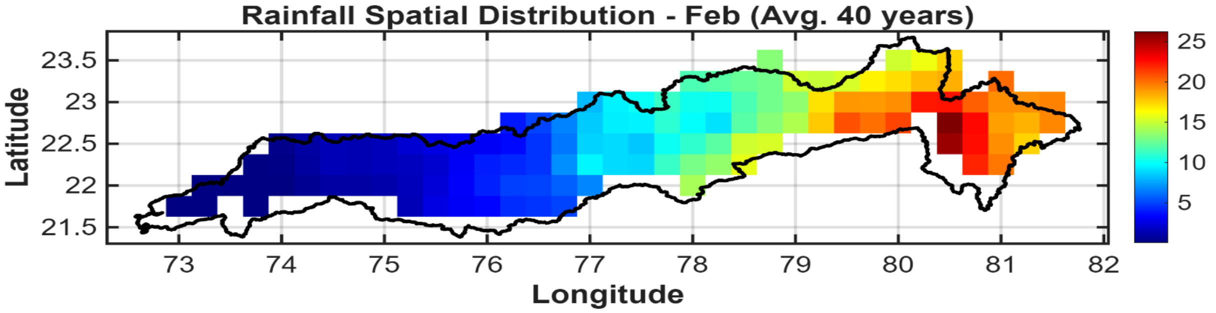
The rainfall profile of the Narmada River Basin is characterized by extreme seasonality, almost entirely dictated by the Indian Summer Monsoon. During the pre-monsoon period (January to May), the basin remains significantly dry, with monthly rainfall typically recording below 40 mm and many western districts seeing near-zero values. The hydrologic cycle begins with a sharp onset in June, where rainfall surges to between 120 mm and 300 mm. The peak intensity occurs during July and August, where rainfall volumes consistently range from 400 mm to 800 mm, with exceptional high-intensity years in the upper and middle reaches (like Hoshangabad and Balaghat) approaching or exceeding 900–1000 mm. Rainfall begins to recede in September, averaging 200–450 mm, before dropping sharply in October, marking the end of the humid season.

Figure 30:Rainfall Spatial Distribution Figures :

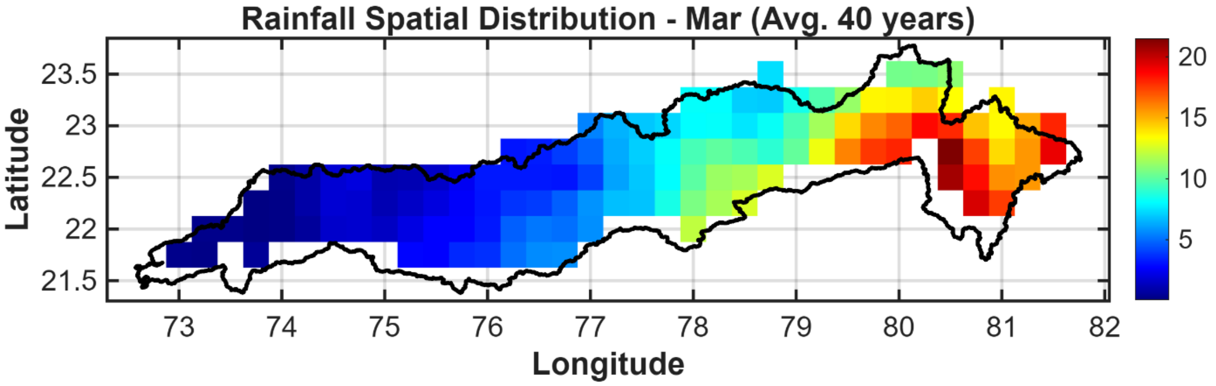
a)



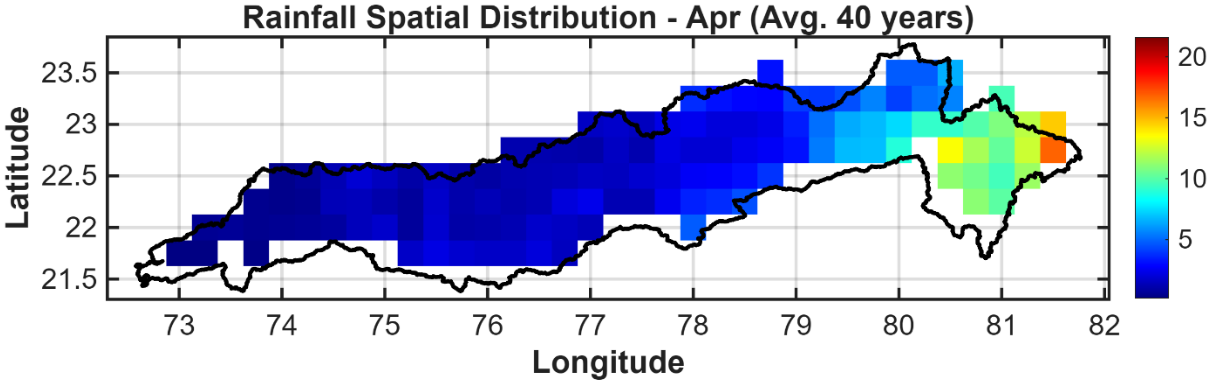
b)


Rainfall Spatial Distribution - Feb (Avg. 40 years)

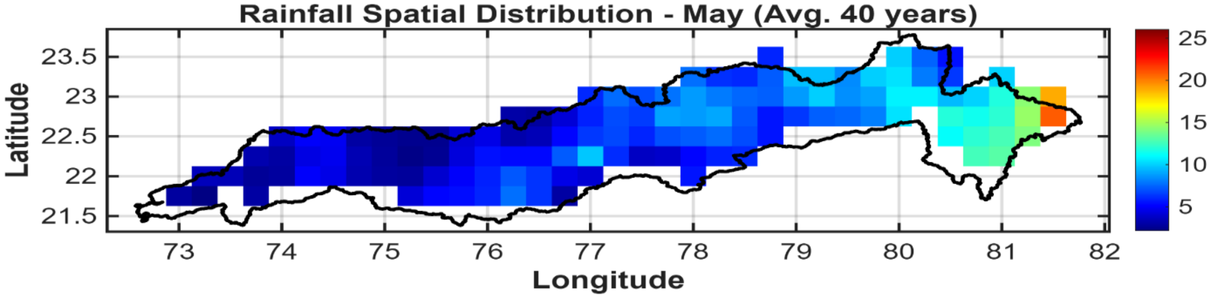
c)


Rainfall Spatial Distribution - Mar (Avg. 40 years)

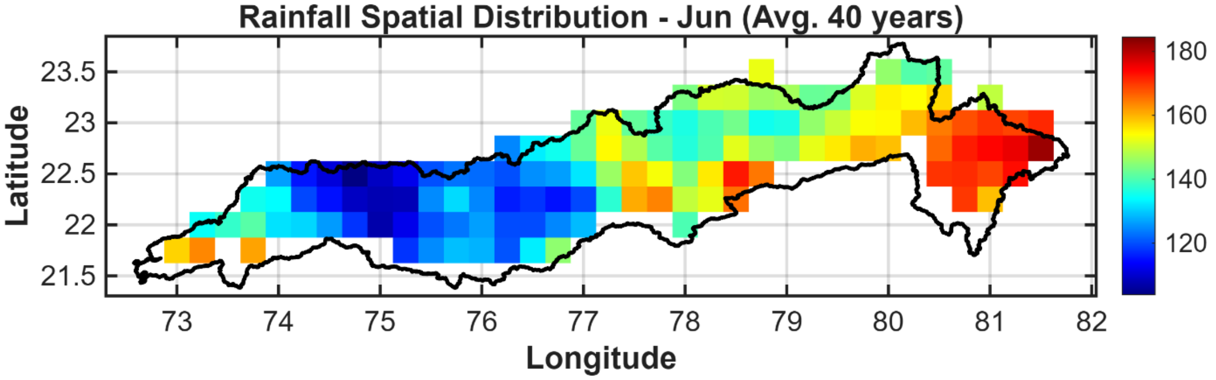
d)


Rainfall Spatial Distribution - Apr (Avg. 40 years)

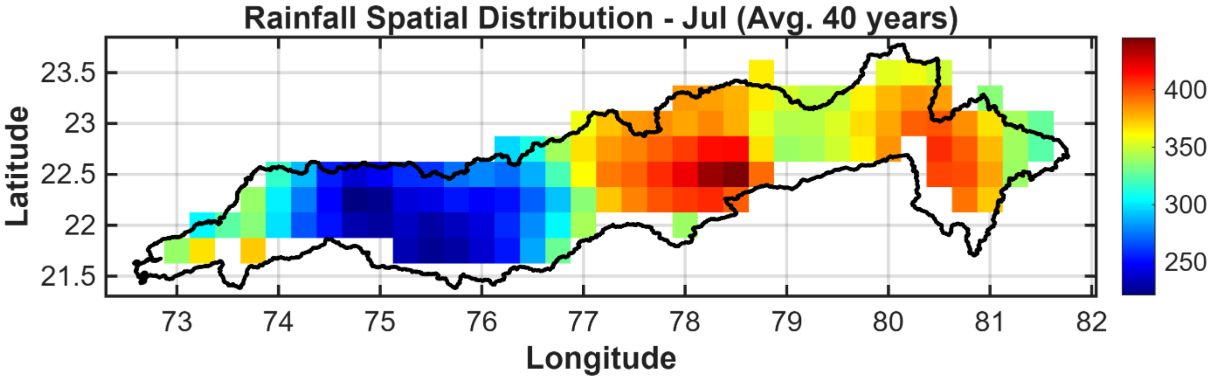
e)


Rainfall Spatial Distribution - May (Avg. 40 years)

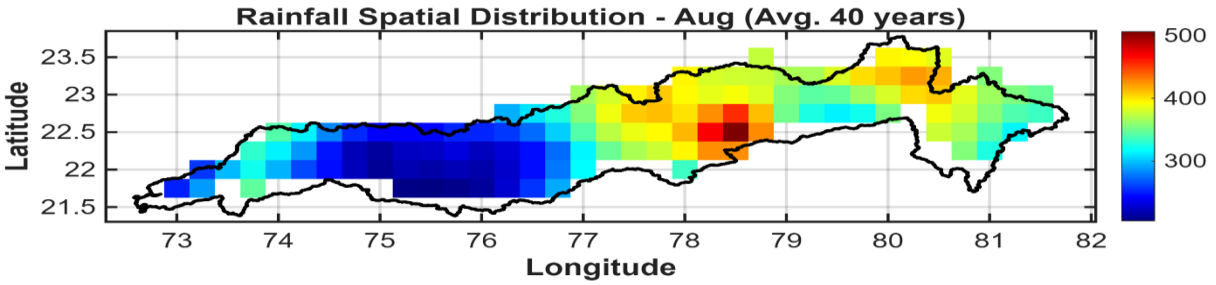
f)


Rainfall Spatial Distribution - Jun (Avg. 40 years)

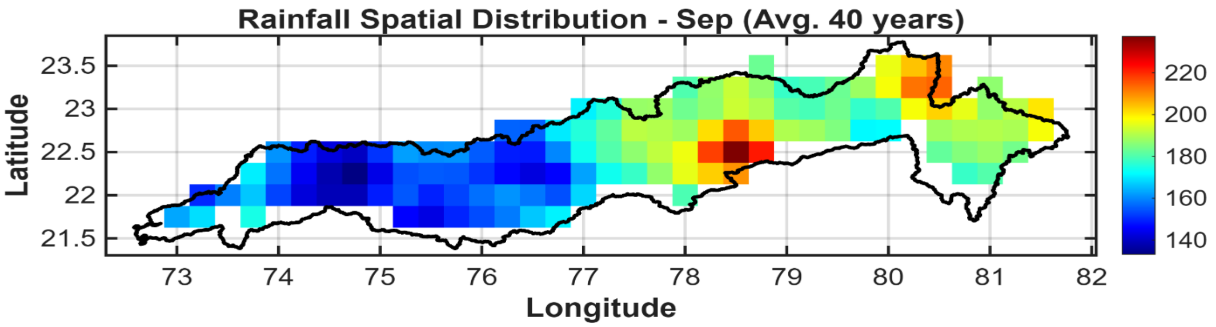
g)


Rainfall Spatial Distribution - Jul (Avg. 40 years)

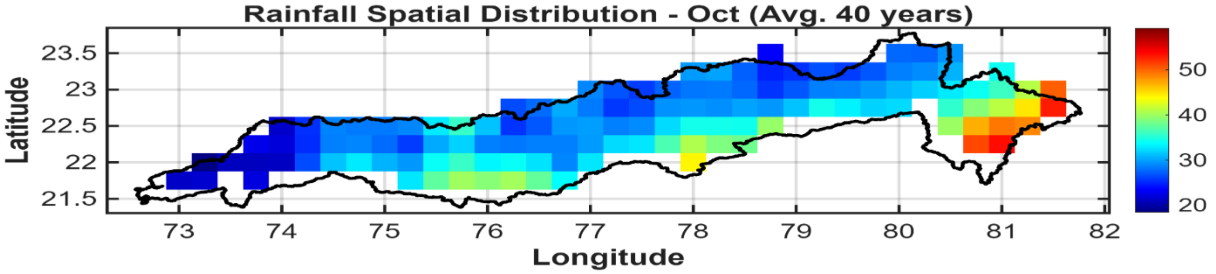
h)


Rainfall Spatial Distribution - Aug (Avg. 40 years)

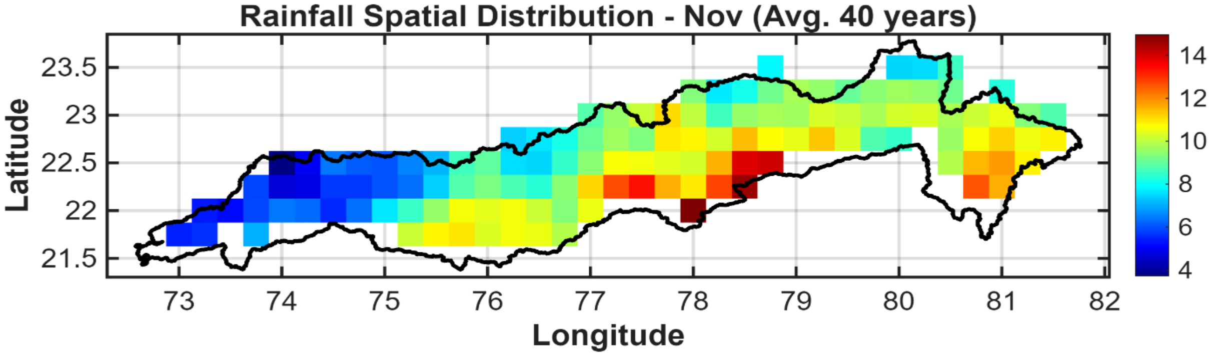
i)


Rainfall Spatial Distribution - Sep (Avg. 40 years)

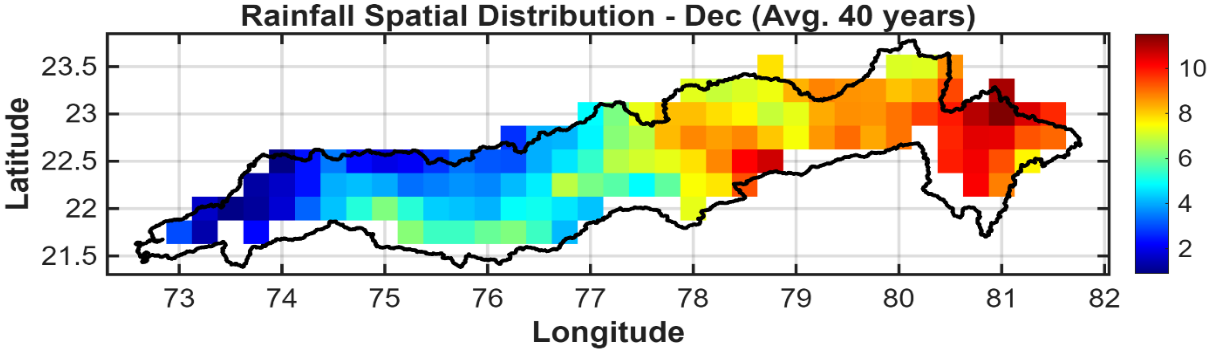
j)


Rainfall Spatial Distribution - Oct (Avg. 40 years)

k)


Rainfall Spatial Distribution - Nov (Avg. 40 years)

l)

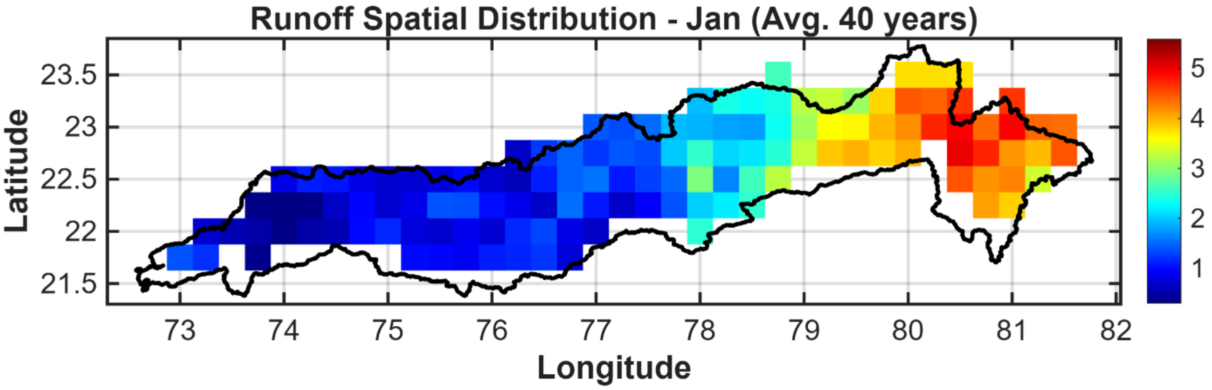

Rainfall Spatial Distribution - Dec (Avg. 40 years)

Spatial Variation of Runoff

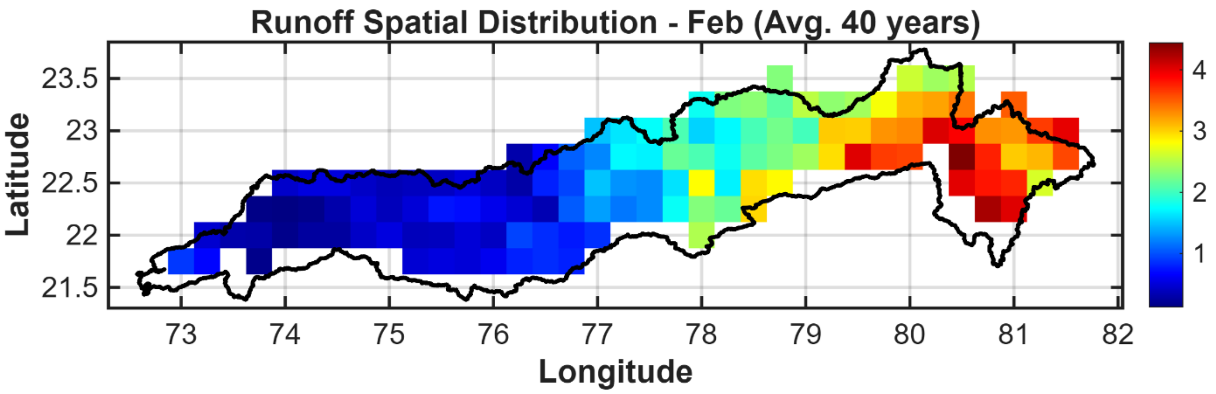
Runoff in the Narmada River Basin exhibits a lagged response to rainfall, dependent on soil moisture saturation. In the dry months from January to May, runoff is virtually non-existent due to high soil moisture deficits and low precipitation. The onset of monsoon in June initiates measurable runoff as the ground begins to saturate. However, the most significant runoff occurs during the peak monsoon months of July and August, ranging from 150 mm to over 500 mm. In high-rainfall districts, the runoff-to-rainfall ratio increases significantly during this period, indicating that the basin's drainage capacity is fully utilized. This substantial surplus results in high river discharge levels, which gradually moderate in September. By October and November, as rainfall ceases, runoff becomes minimal, emphasizing the basin's heavy reliance on peak-monsoon surges for reservoir filling and surface water availability.

Figure 31:Runoff spatial Distribution figures

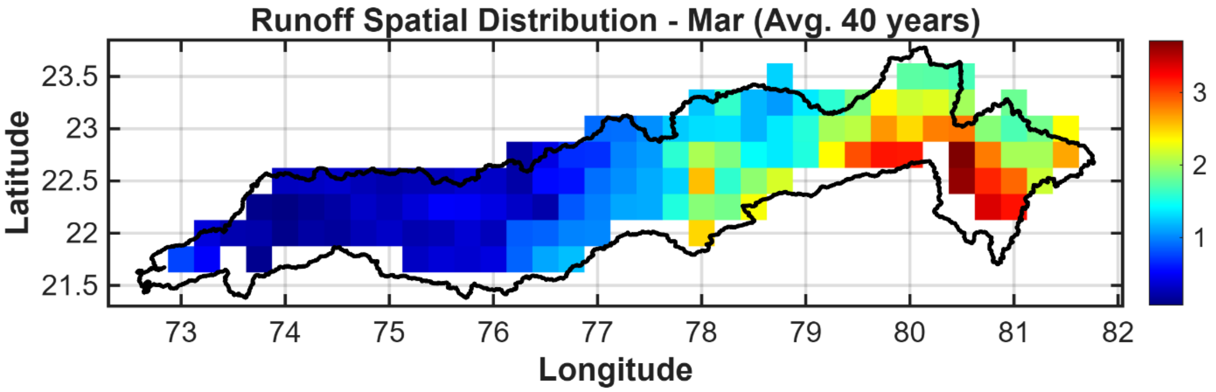
a)



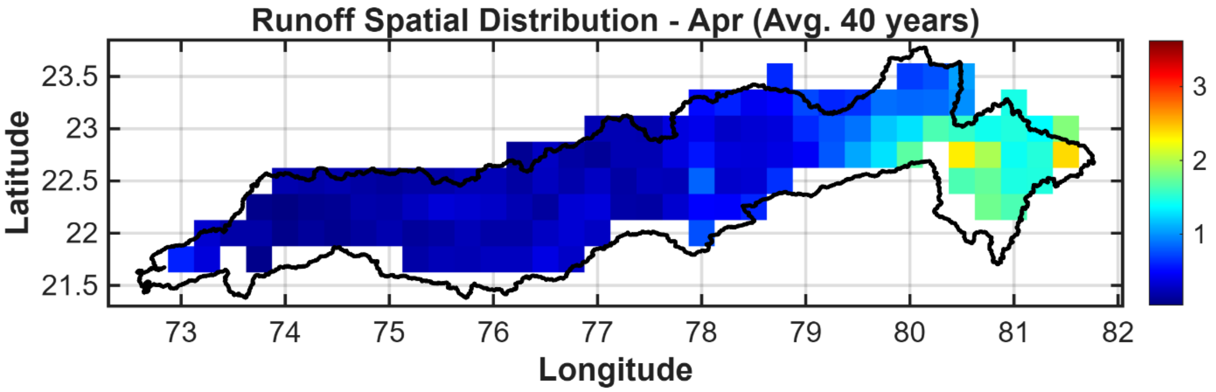
b)


Runoff Spatial Distribution - Feb (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
4
3
2
1

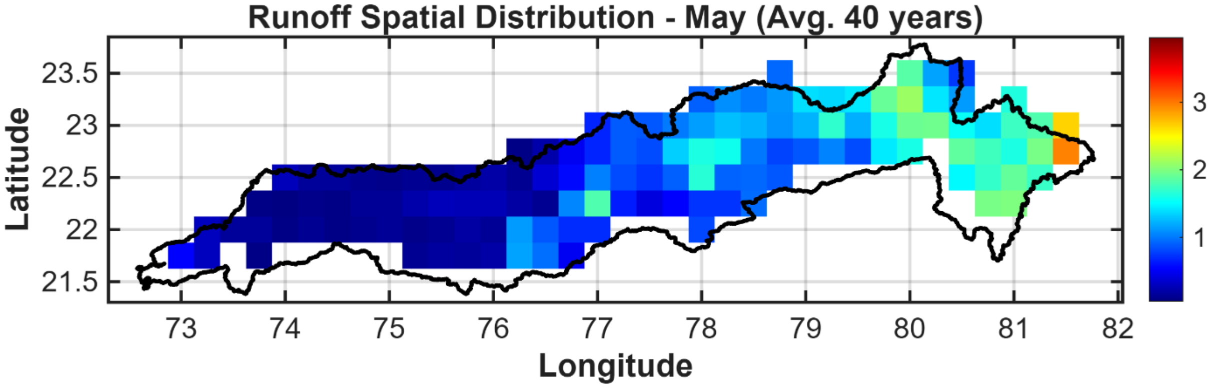
c)


Runoff Spatial Distribution - Mar (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
3
2
1

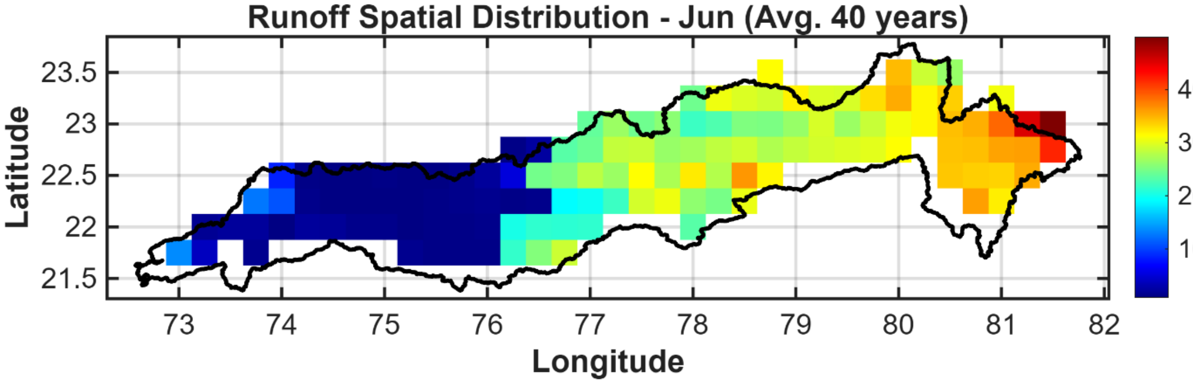
d)


Runoff Spatial Distribution - Apr (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
3
2
1

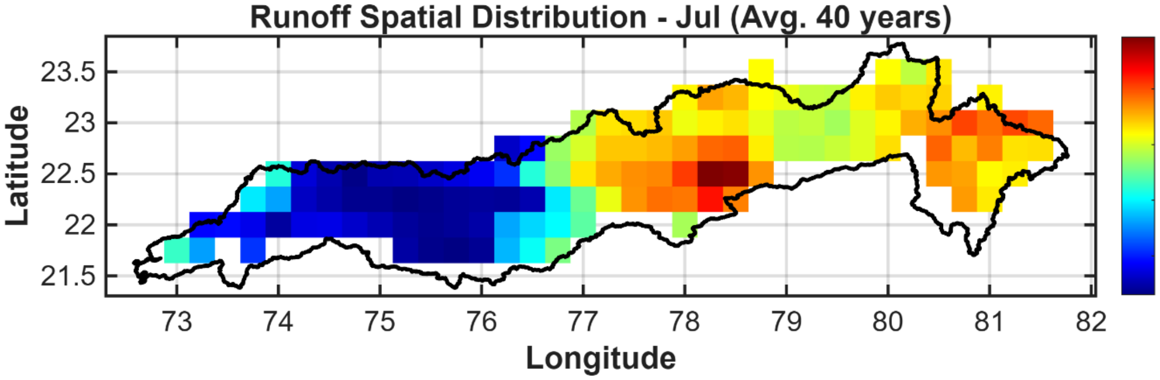
e)


Runoff Spatial Distribution - May (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
3
2
1

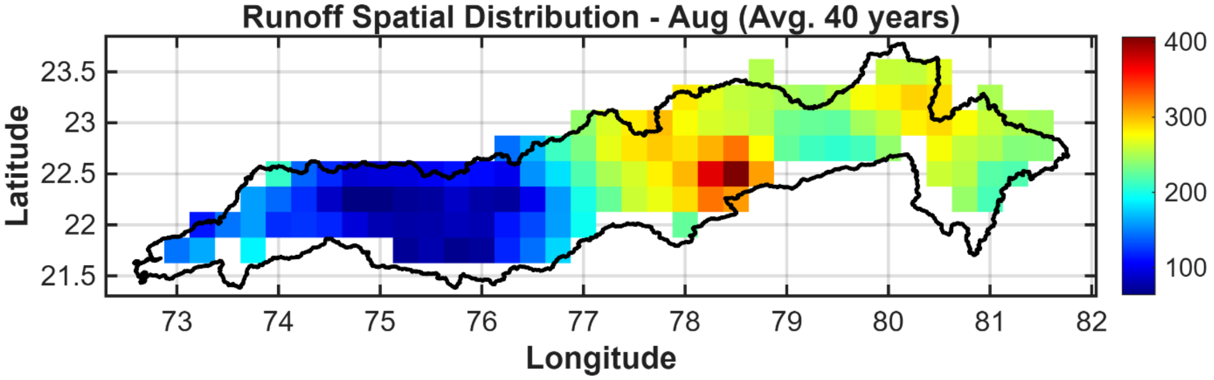
f)


Runoff Spatial Distribution - Jun (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
40
30
20
10

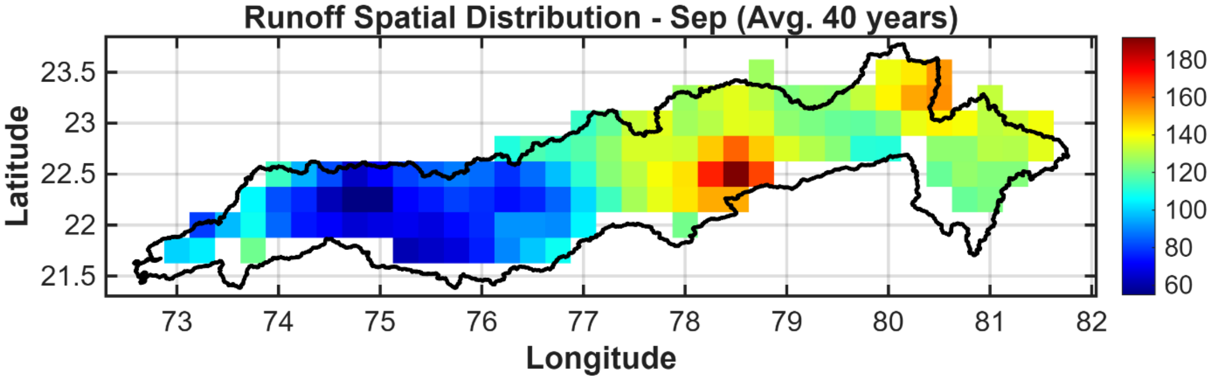
g)


Runoff Spatial Distribution - Jul (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
200
150
100
50

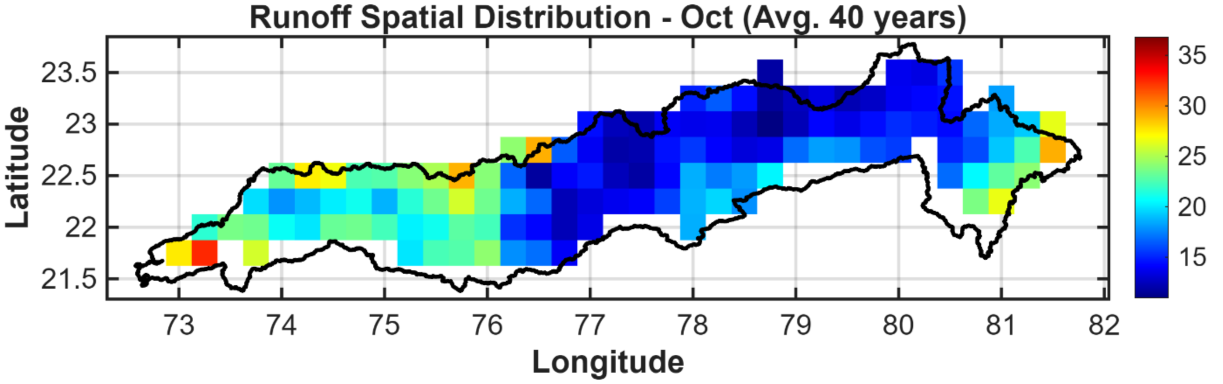
h)


Runoff Spatial Distribution - Aug (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
400
300
200
100

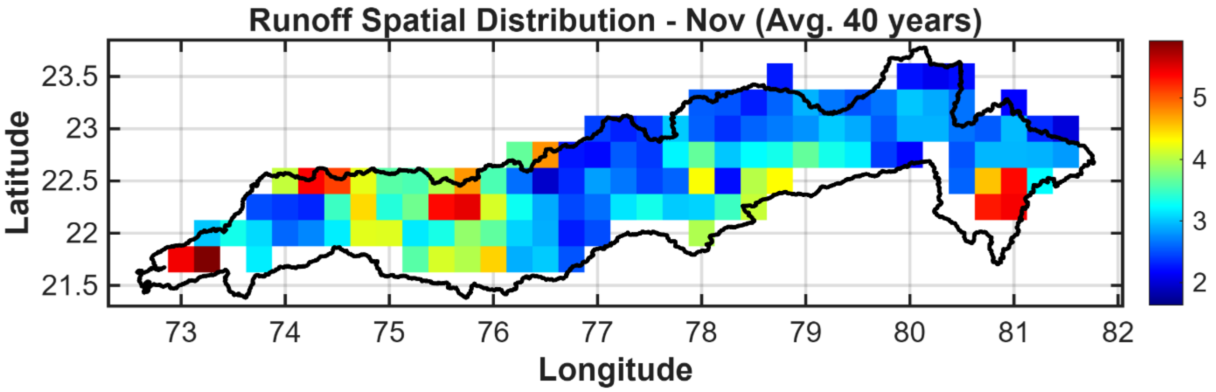
i)


Runoff Spatial Distribution - Sep (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
180
160
140
120
100
80
60

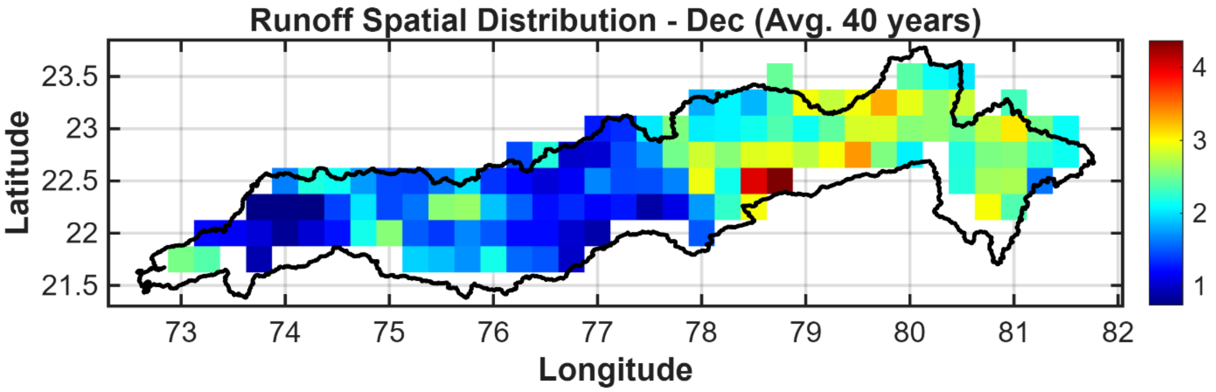
J)


Runoff Spatial Distribution - Oct (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
35
30
25
20
15

K)


Runoff Spatial Distribution - Nov (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
5
4
3
2

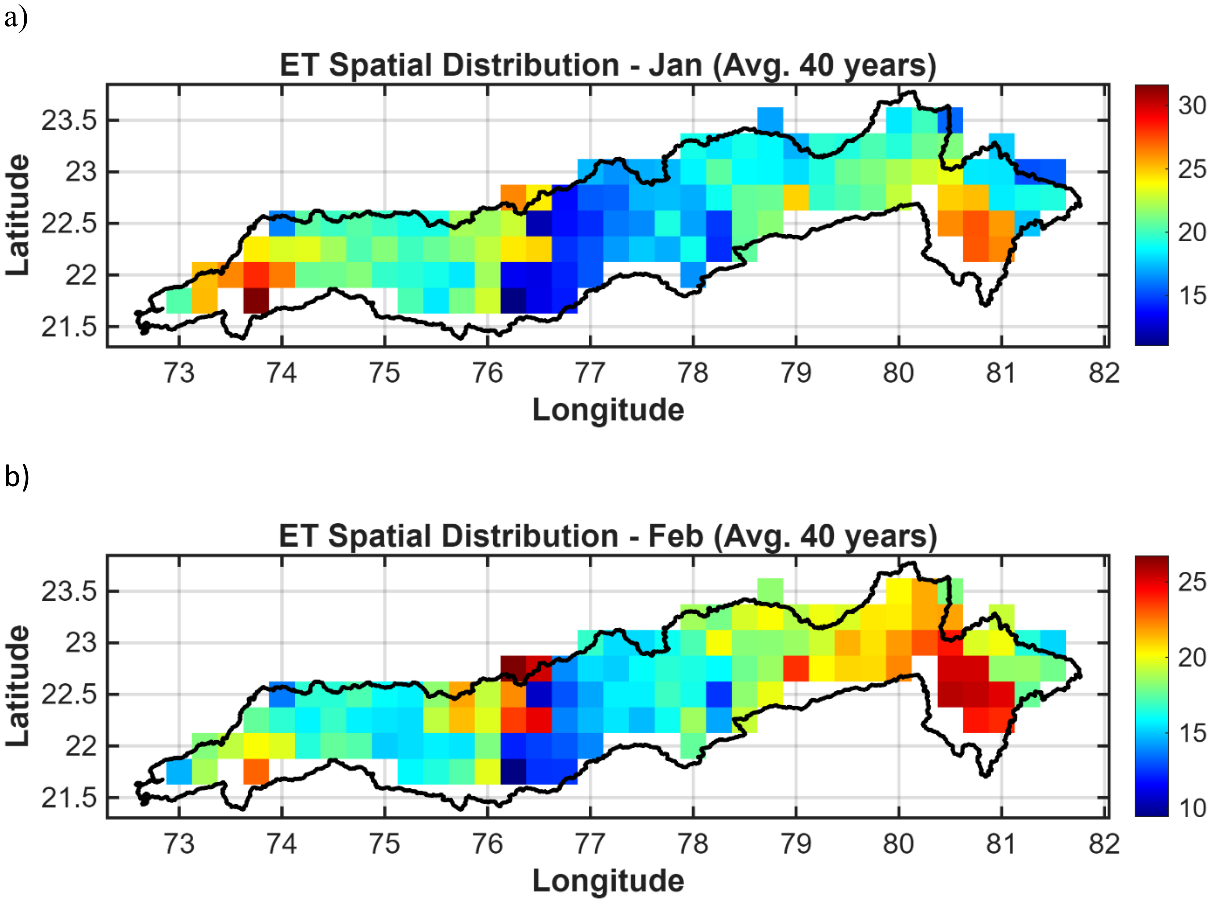
l)


Runoff Spatial Distribution - Dec (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
4
3
2
1

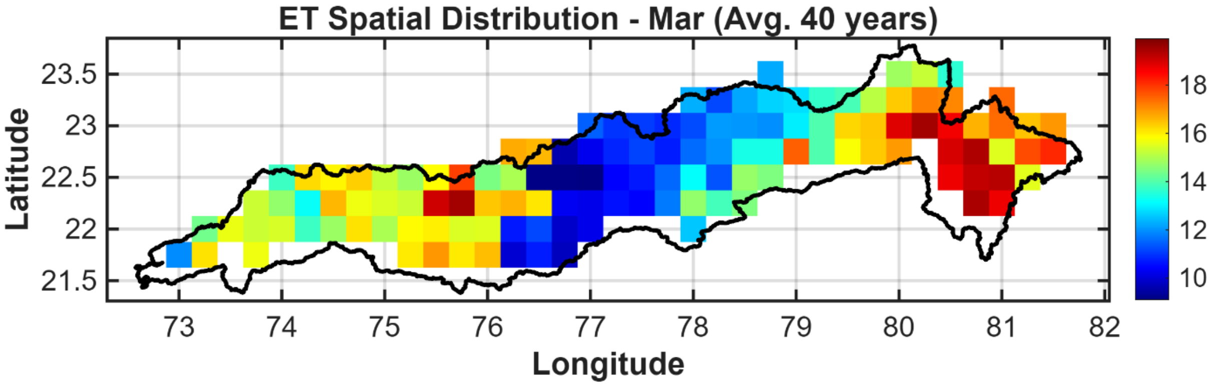
Spatial Variation of ET

The temporal variation of Evapotranspiration (ET) in the basin is closely aligned with moisture availability and solar radiation. During the dry season (January–May), ET levels are at their annual minimum because of limited soil moisture, despite rising temperatures. As the monsoon arrives in June, ET increases sharply, reflecting the abundance of water for plant transpiration and surface evaporation. Throughout the peak monsoon period (July–September), ET remains relatively stable and reaches its maximum levels, typically ranging between 100 mm and 150 mm. This plateau indicates that ET is "energy-limited" rather than "water-limited" during these months. Following the monsoon, ET begins a gradual decline from October through December as soil moisture is depleted and temperatures drop, eventually returning to its lowest levels in the winter months.

Figure 32 : Spatial variation of Evapotrasnpiartion figures

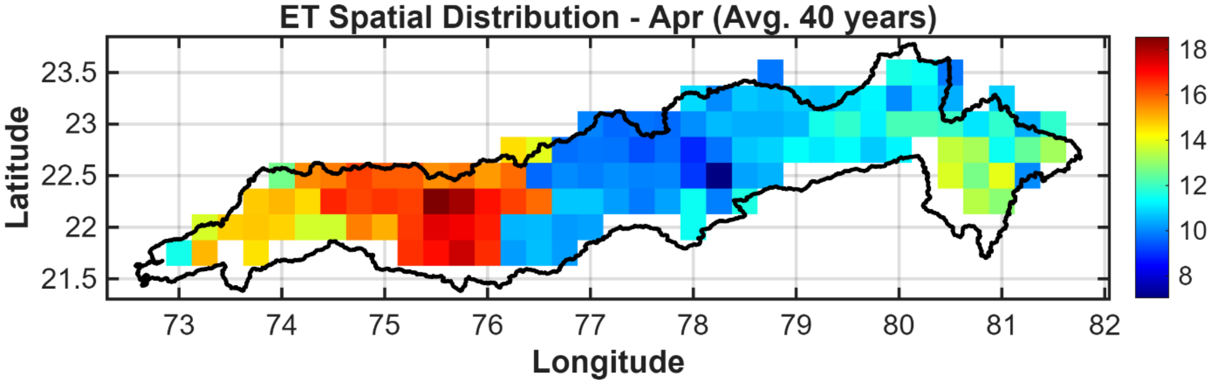


c)



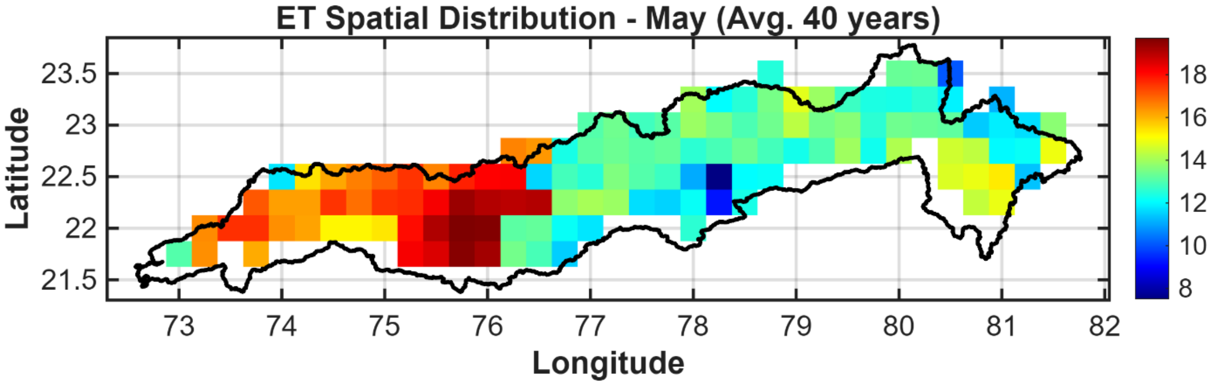
ET Spatial Distribution - Mar (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
18
16
14
12
10

d)



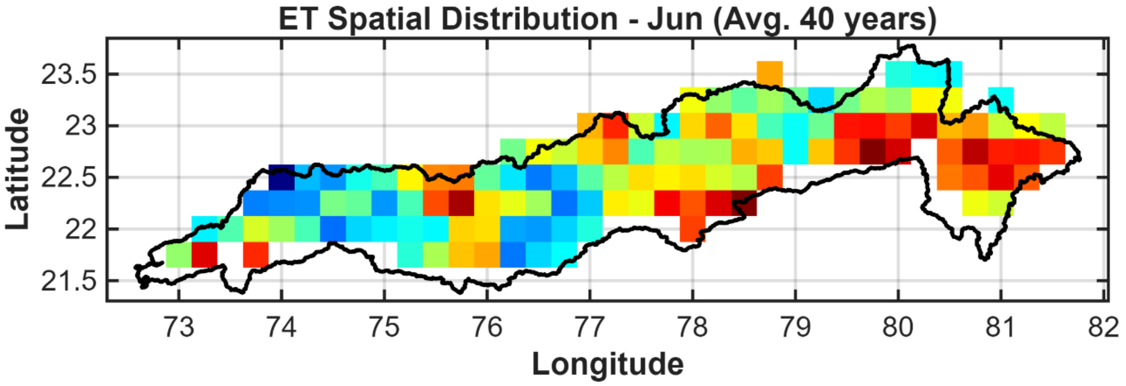
ET Spatial Distribution - Apr (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
18
16
14
12
10
8

e)

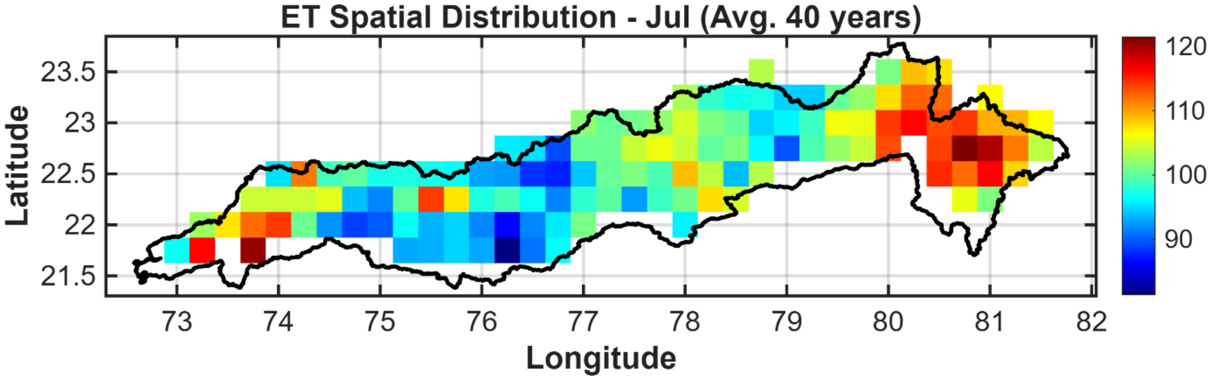


ET Spatial Distribution - May (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
18
16
14
12
10
8

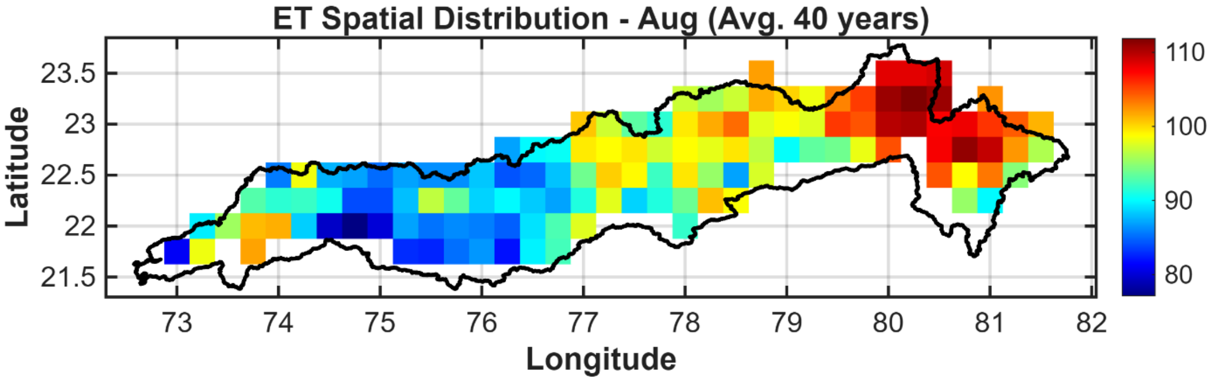
f)


ET Spatial Distribution - Jun (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
65
60
55
50

g)


ET Spatial Distribution - Jul (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
76
77
78
79
80
81
82
120
110
100
90

h)


ET Spatial Distribution - Aug (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
Longitude
73
74
75
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77
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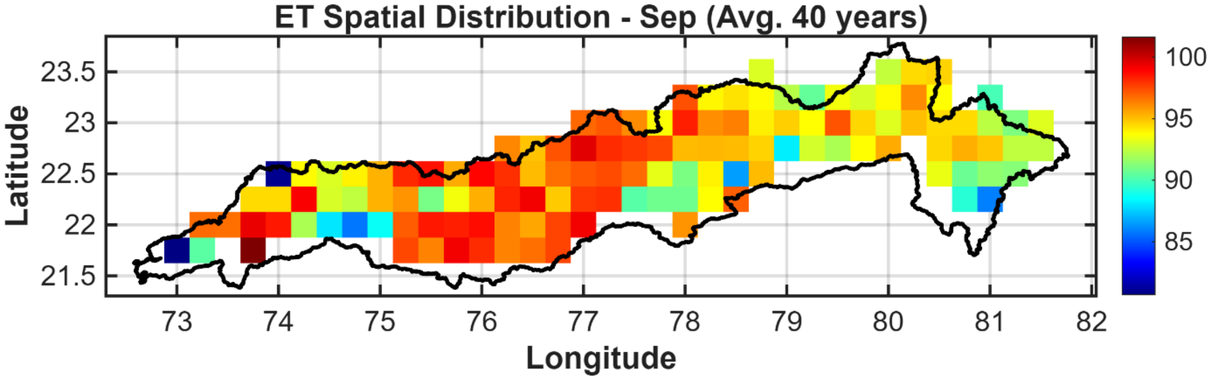
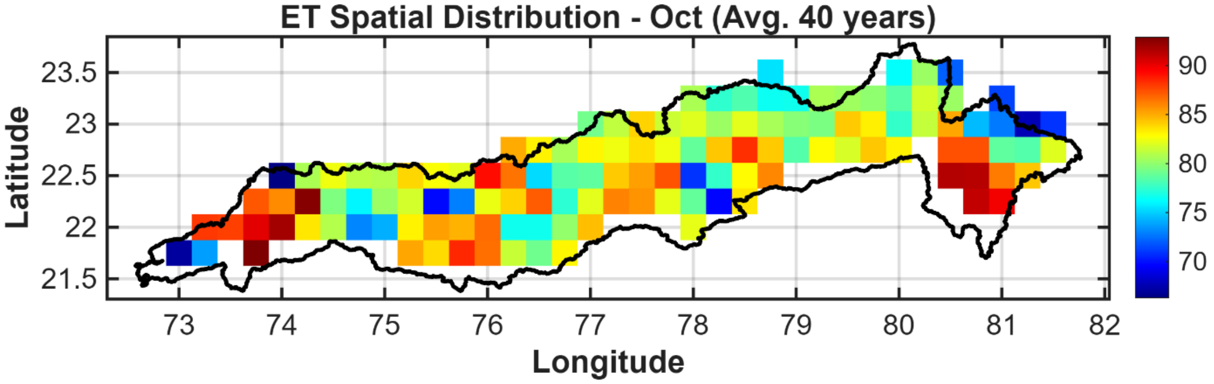
79
80
81
82
110
100
90
80

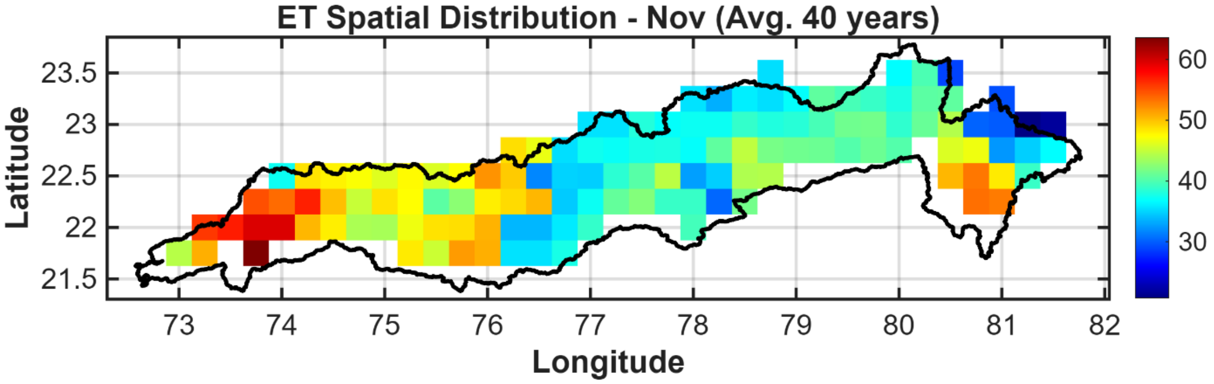
i)


ET Spatial Distribution - Sep (Avg. 40 years)

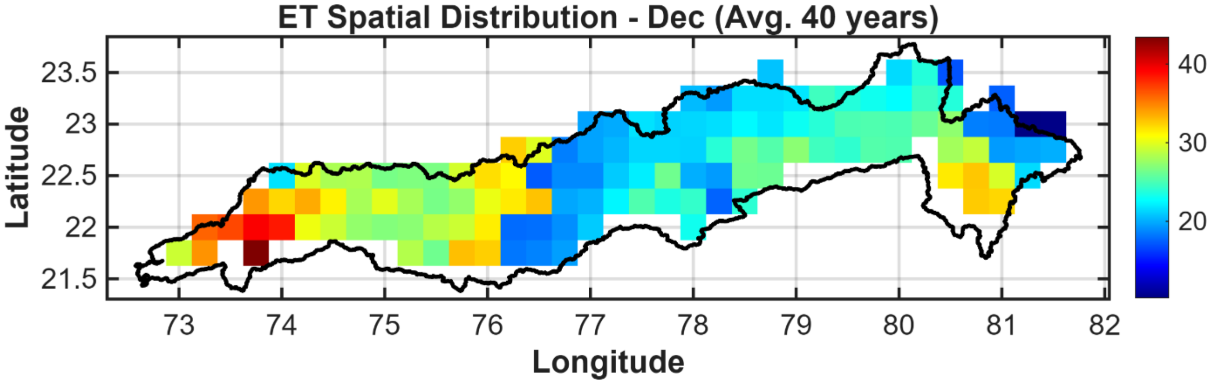
j)


ET Spatial Distribution - Oct (Avg. 40 years)

k)


ET Spatial Distribution - Nov (Avg. 40 years)

l)


ET Spatial Distribution - Dec (Avg. 40 years)
Latitude
23.5
23
22.5
22
21.5
73
74
75
76
77
78
79
80
81
82
Longitude
40
30
20

Temporal Variation of Water Budget Components: Narmada River Basin

The temporal variation graphs of the water budget components for the Narmada River Basin clearly depict a strong seasonal control of hydrological processes, governed primarily by the southwest monsoon. The month-wise trends shown in the figures indicate distinct phases of low-flow, rising flow, peak flow, and recession, which are characteristic of a monsoon-driven watershed system.

Rainfall Analysis Based on Graphs

As observed in the rainfall graph, precipitation remains very low during January, February, and March, indicating dry winter conditions with minimal hydrological contribution. A marginal increase is visible during April and May, corresponding to occasional pre-monsoon rainfall; however, this increase is not sufficient to generate significant runoff or recharge at the basin scale.

A sharp and prominent rise in rainfall occurs in June, clearly marking the onset of the southwest monsoon. The graphs show maximum rainfall peaks during July and August, which together contribute the largest share of annual precipitation in the Narmada River Basin. These peak months reflect intense and sustained rainfall events. Rainfall starts declining in September, indicating monsoon withdrawal, and drops sharply by October, after which very low rainfall conditions persist during November and December. This skewed rainfall distribution highlights the basin's dependence on a short monsoon period for annual water input.

Runoff Analysis Based on Graphs

The runoff graph shows a pattern closely aligned with rainfall but with a more pronounced threshold behavior. From January to May, runoff values remain nearly negligible, reflecting dry soil conditions, high infiltration capacity, and absence of effective rainfall. Even during pre-monsoon months, despite increasing temperatures, runoff generation is minimal due to insufficient rainfall.

With the onset of monsoon in June, the runoff curve shows a rapid increase, indicating reduced infiltration and increasing surface flow. The highest runoff peaks are observed during July and August, coinciding with peak rainfall months. These peaks represent periods of soil saturation, excess rainfall, and dominant overland flow processes. In September, runoff begins to decline gradually as rainfall intensity decreases, while a sharp reduction is evident in October due to the cessation of monsoon rainfall.

During November and December, runoff values are low and are mainly sustained by groundwater discharge (baseflow) rather than direct rainfall. This behavior emphasizes the basin’s limited natural storage capacity and strong reliance on monsoon rainfall for streamflow generation.

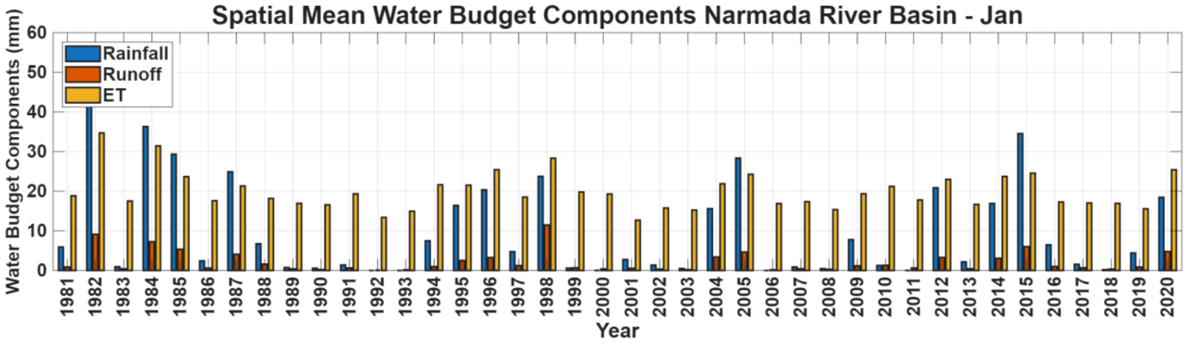
Evapotranspiration (ET) Analysis Based on Graphs

The evapotranspiration graph shows a comparatively smoother and more evenly distributed pattern throughout the year. ET values are moderate during January and February, owing to lower temperatures and reduced solar radiation. A steady rise in ET is evident from March onwards, reaching high values during April and May, driven by increasing temperatures and high atmospheric demand during the summer season.

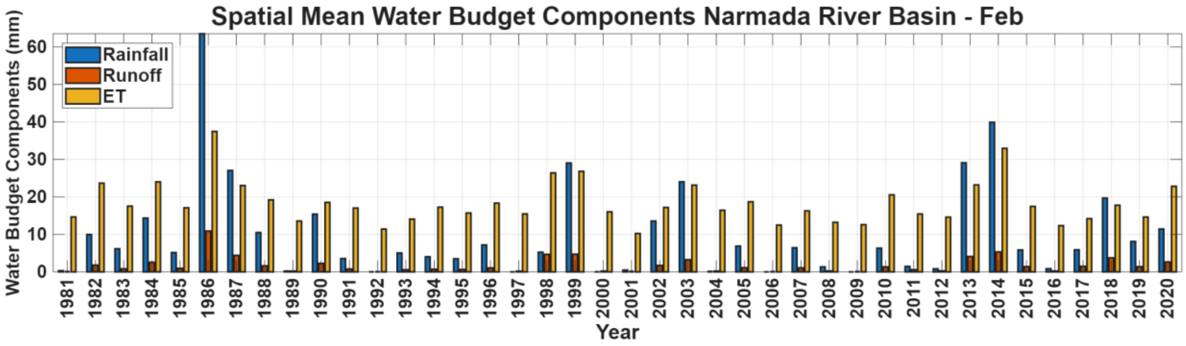
During the monsoon months (June to September), ET remains relatively high but shows less variability compared to rainfall and runoff. This indicates that although soil moisture availability is high during monsoon, increased humidity and cloud cover partially limit evaporative demand. Vegetation growth and agricultural activity during this period enhance transpiration, contributing to sustained ET levels. After the monsoon, ET values decline gradually during October and November, reaching lower levels again in December.

Figure 33: spatial mean water budget componet figure

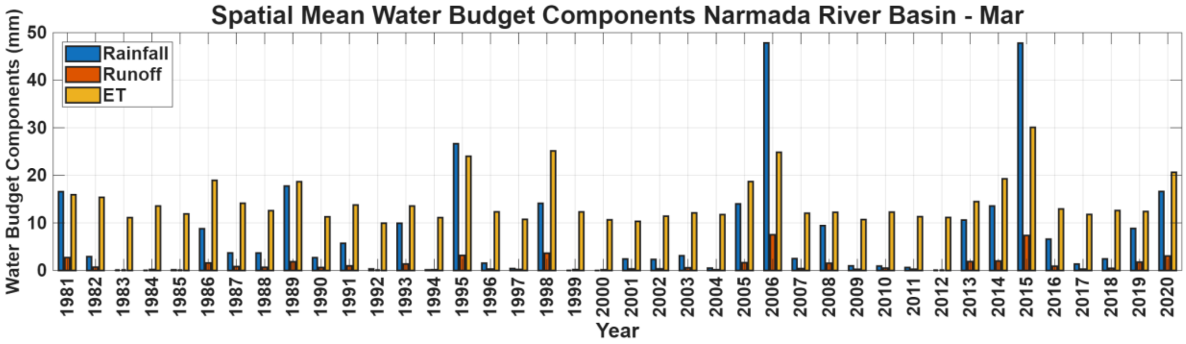
a)



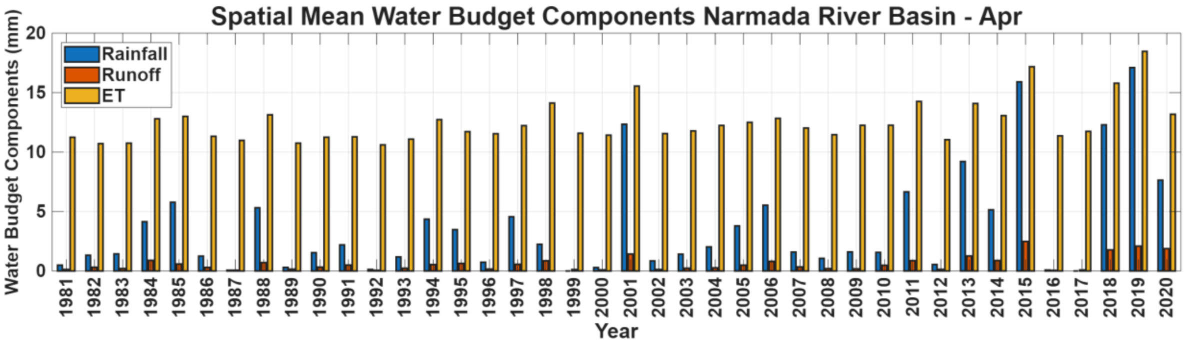
b)



c)



d)


Spatial Mean Water Budget Components Narmada River Basin - Apr
Water Budget Components (mm)
Rainfall
Runoff
ET
0
5
10
15
20
Year
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
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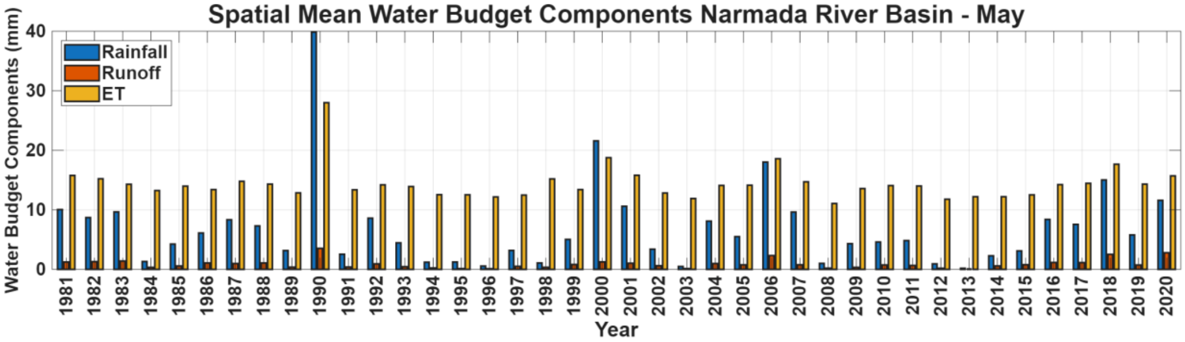
2014
2015
2016
2017
2018
2019
2020

e)


Spatial Mean Water Budget Components Narmada River Basin - May
Water Budget Components (mm)
Rainfall
Runoff
ET
0
10
20
30
40
Year
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
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2000
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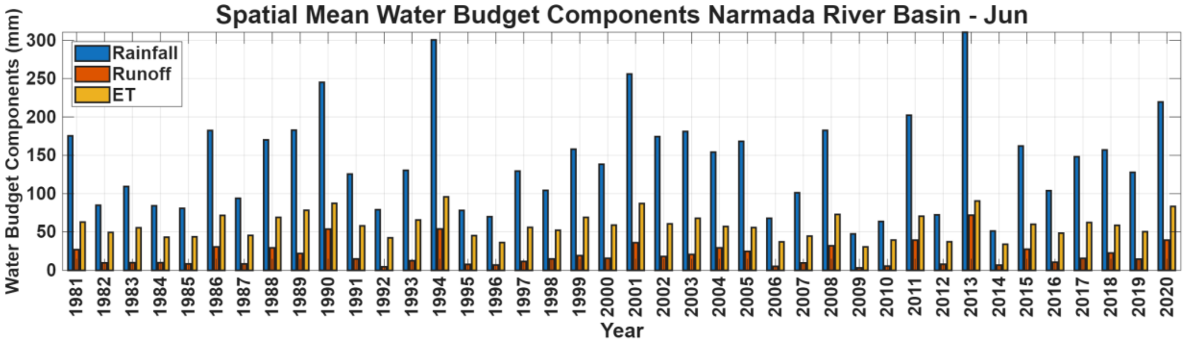
2014
2015
2016
2017
2018
2019
2020

f)


Spatial Mean Water Budget Components Narmada River Basin - Jun
Water Budget Components (mm)
Rainfall
Runoff
ET
0
50
100
150
200
250
300
Year
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
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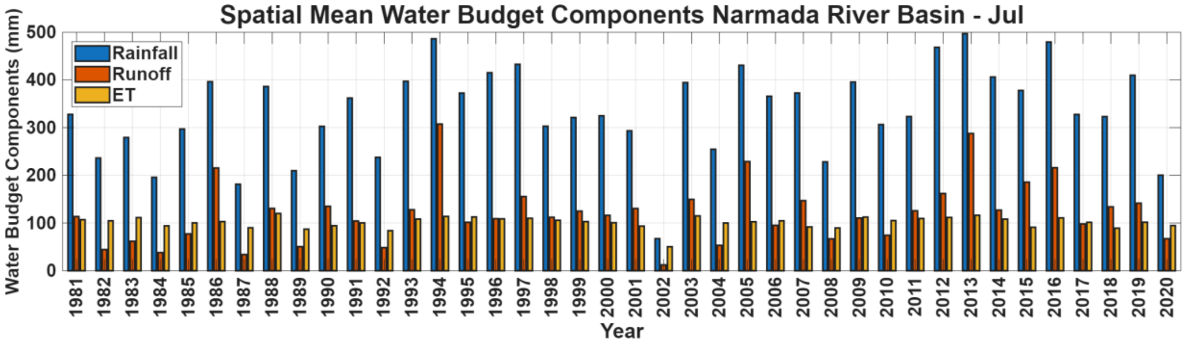
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020

g)


Spatial Mean Water Budget Components Narmada River Basin - Jul
Water Budget Components (mm)
Rainfall
Runoff
ET
0
100
200
300
400
500
Year
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
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2012
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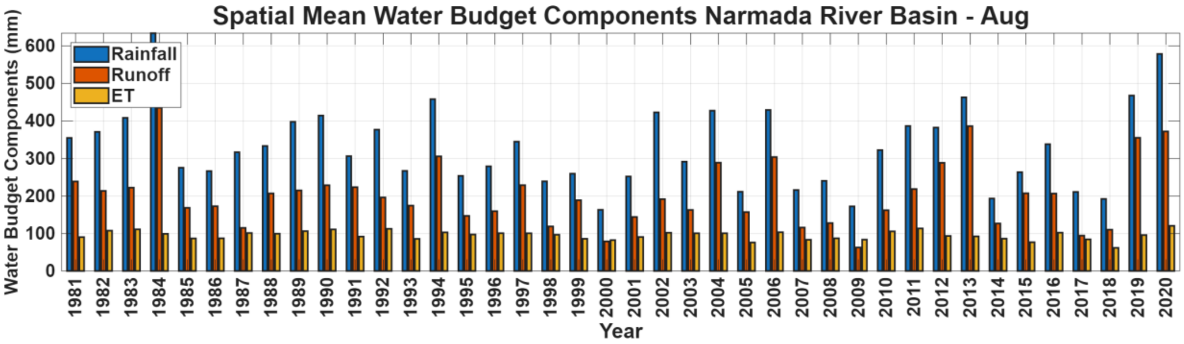
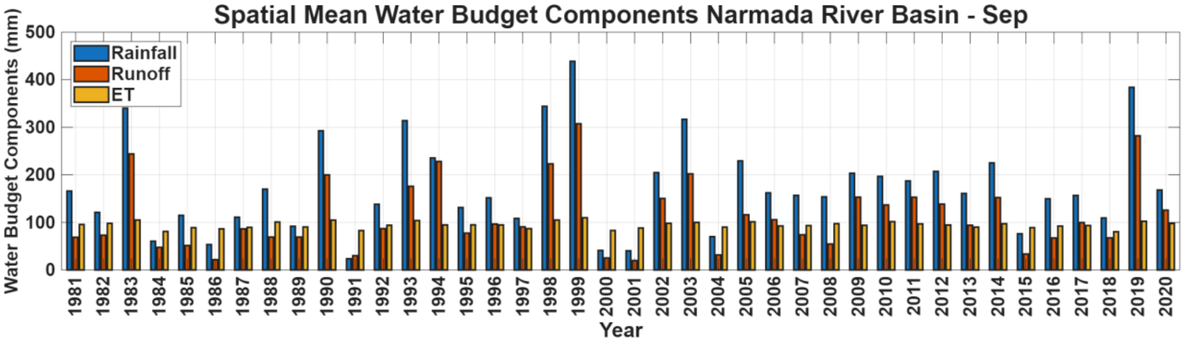
2015
2016
2017
2018
2019
2020

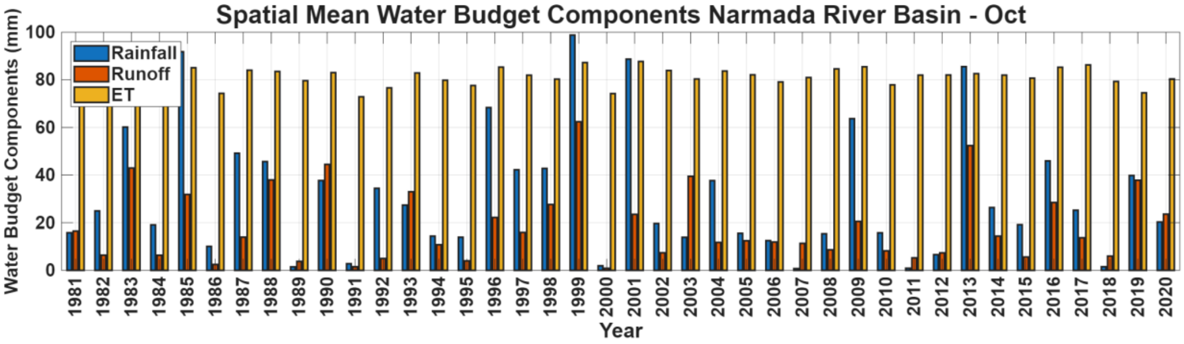
h)


Spatial Mean Water Budget Components Narmada River Basin - Aug
Water Budget Components (mm)
0
100
200
300
400
500
600
Rainfall
Runoff
ET
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

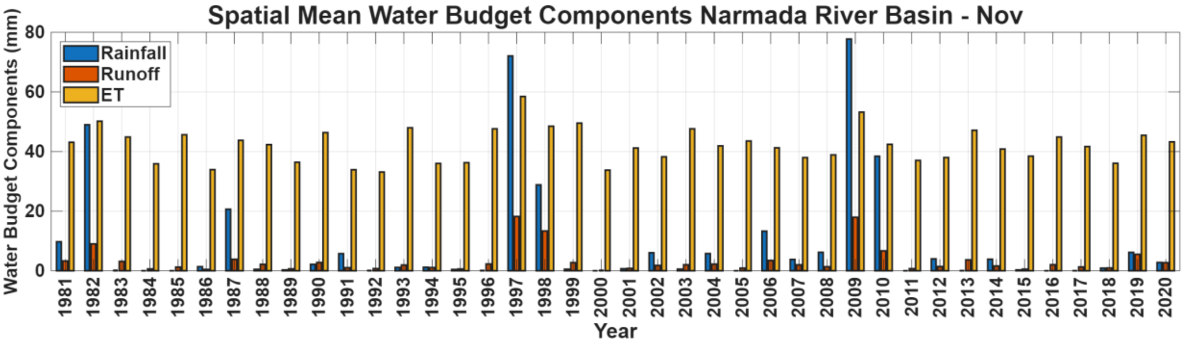
i)


Spatial Mean Water Budget Components Narmada River Basin - Sep
Water Budget Components (mm)
0
100
200
300
400
500
Rainfall
Runoff
ET
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

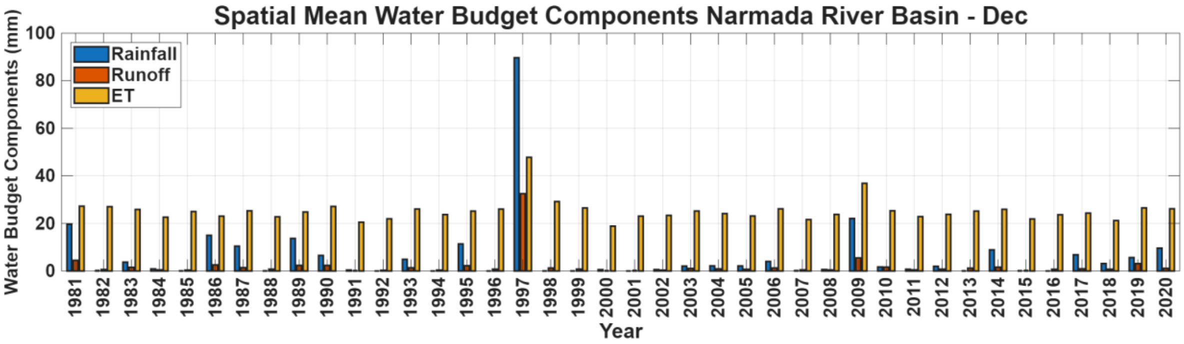
j)


Spatial Mean Water Budget Components Narmada River Basin - Oct
Water Budget Components (mm)
0
20
40
60
80
100
Rainfall
Runoff
ET
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

k)


Spatial Mean Water Budget Components Narmada River Basin - Nov
Water Budget Components (mm)
0
20
40
60
80
Rainfall
Runoff
ET
1981 1982 1983 1984 1985 1986 1987 1988 1989 1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020
Year

l)



Integrated Interpretation of Graph-Based Variations

The combined interpretation of the rainfall, runoff, and ET graphs reveals a clear temporal imbalance between water supply and water demand in the Narmada River Basin. Rainfall and runoff are highly concentrated during a short monsoon window (June–September), whereas evapotranspiration demand peaks earlier during the summer months (March–May), when water availability is limited. This mismatch leads to seasonal water stress, especially in rainfed and semi-arid regions of the basin.

The graphs further indicate that a large portion of monsoon rainfall is rapidly converted into runoff during peak months, increasing flood potential while limiting natural groundwater recharge. Conversely, prolonged dry periods with low runoff highlight the basin's vulnerability to drought conditions in the absence of regulated storage.

Watershed Management Implications from Graph Analysis

From a watershed management perspective, the graph-based analysis strongly supports the need for effective monsoon water harvesting and storage. Structures such as reservoirs, check dams, percolation tanks, and soil conservation measures are essential to capture excess monsoon runoff and enhance groundwater recharge. Proper regulation of monsoon flows can reduce flood risks during peak rainfall months and improve water availability during lean periods.

Overall, the temporal variation graphs provide critical insights into the hydrological functioning of the Narmada River Basin and underline the importance of integrated watershed management strategies aligned with its pronounced seasonal variability.

Administrative Boundary Watershed Modeling

The watershed delineation map of the Narmada River Basin clearly illustrates the spatial distribution of multiple watersheds and sub-basins across different administrative districts, highlighting the basin's complex hydrological structure. The basin extends from the eastern highlands near the Amarkantak region through central Madhya Pradesh and into the western plains before draining into the Arabian Sea, encompassing districts such as Dindori, Mandla, Jabalpur, Narsinghpur, Seoni, Chhindwara, Hoshangabad, Betul, Harda, Khandwa, Khargone, Barwani, Dhar, Dewas, Indore, Sehore, Raisen, Bhopal, Narmadapuram, Nandurbar, Bharuch, Surat, and adjoining areas. Each district is represented by one or more distinct watershed units, differentiated by unique colors, indicating that water budget estimation has been carried out at a watershed scale rather than a uniform basin scale. The upper basin districts such as Dindori, Mandla, and Jabalpur are characterized by relatively smaller but hydrologically significant watersheds, forming the headwater regions with higher rainfall contribution and runoff generation. The central basin districts, including Hoshangabad, Sehore, Raisen, Betul, Harda, and Narsinghpur, show comparatively larger and interconnected watershed units, reflecting mixed land use patterns, moderate slopes, and regulated flows due to major reservoirs. In the lower basin, districts like Khandwa, Khargone, Barwani, Dhar, and Nandurbar display elongated and broader watersheds, indicating increased influence of channel flow, irrigation withdrawals, and storage structures. The clear demarcation of watershed boundaries across districts demonstrates that the water budget components—rainfall, runoff, evapotranspiration, and storage—have been systematically estimated for each watershed unit within its respective district. This spatially distributed watershed framework ensures that district-wise water budget assessment captures local hydrological variability, upstream–downstream interactions, and physiographic controls, thereby providing a scientifically robust basis for integrated watershed and basin-level water resource management in the Narmada River Basin.

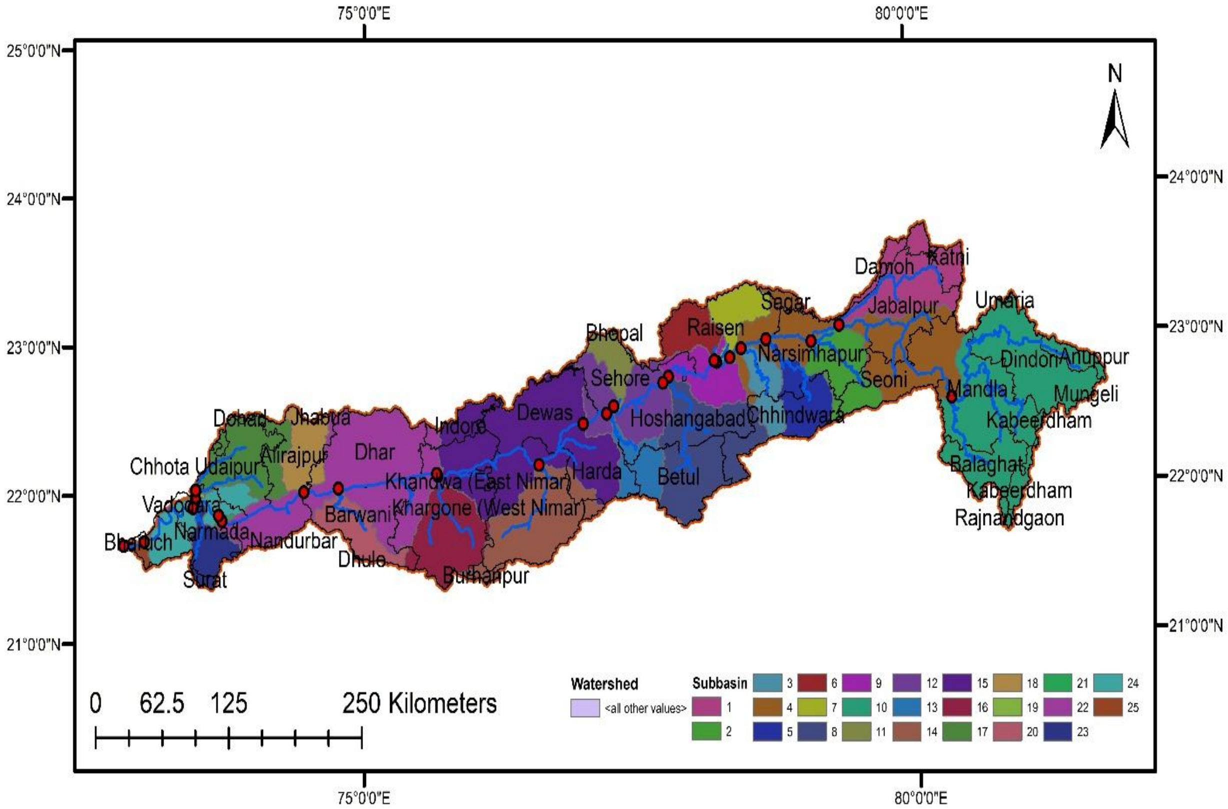


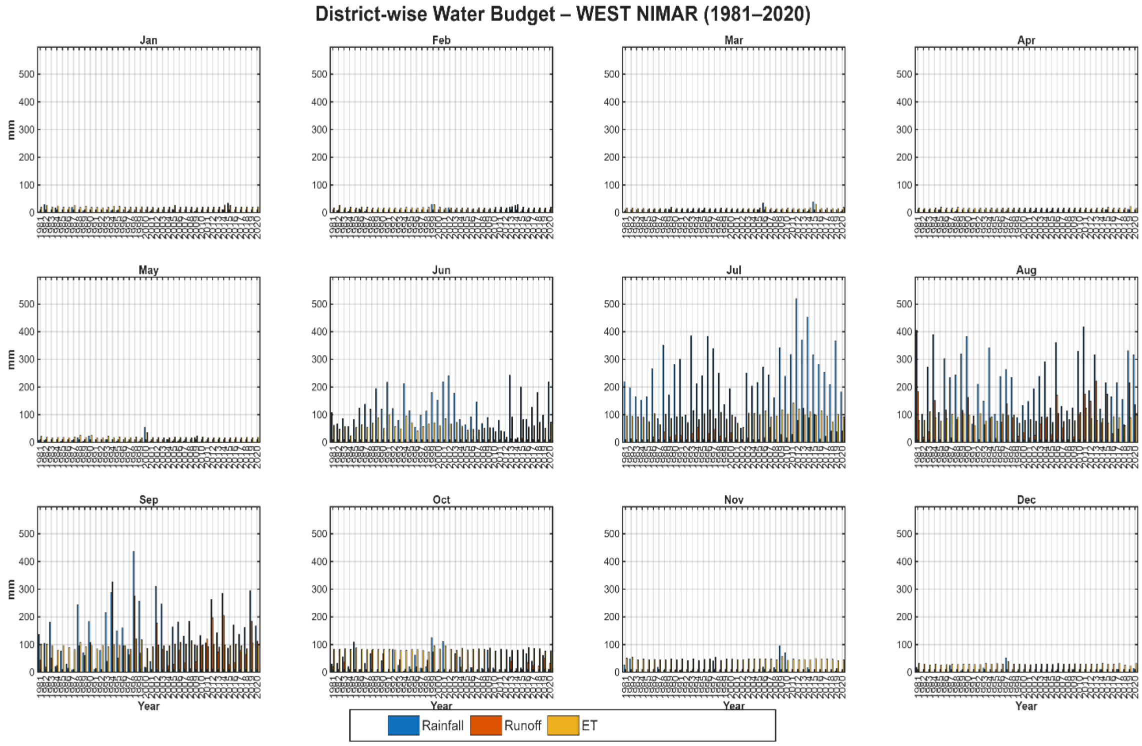
Figure 34: Administrative Boundary Watershed Modeling map

West Nimar

water budget of West Nimar is mainly controlled by the monsoon season. Rainfall is very low from January to May, resulting in minimal runoff and low evapotranspiration. A sharp increase in rainfall begins in June, with peak values during July and August, which also produce the highest runoff and evapotranspiration, indicating surplus water conditions. Rainfall and runoff gradually decrease from September onwards, while evapotranspiration remains moderate in October before declining in winter. Overall, the region experiences a clear contrast between a wet monsoon period and a long dry season, highlighting the importance of monsoon rainfall for water availability in West Nimar.

Figure 35: distrcit wise water budget Graphs

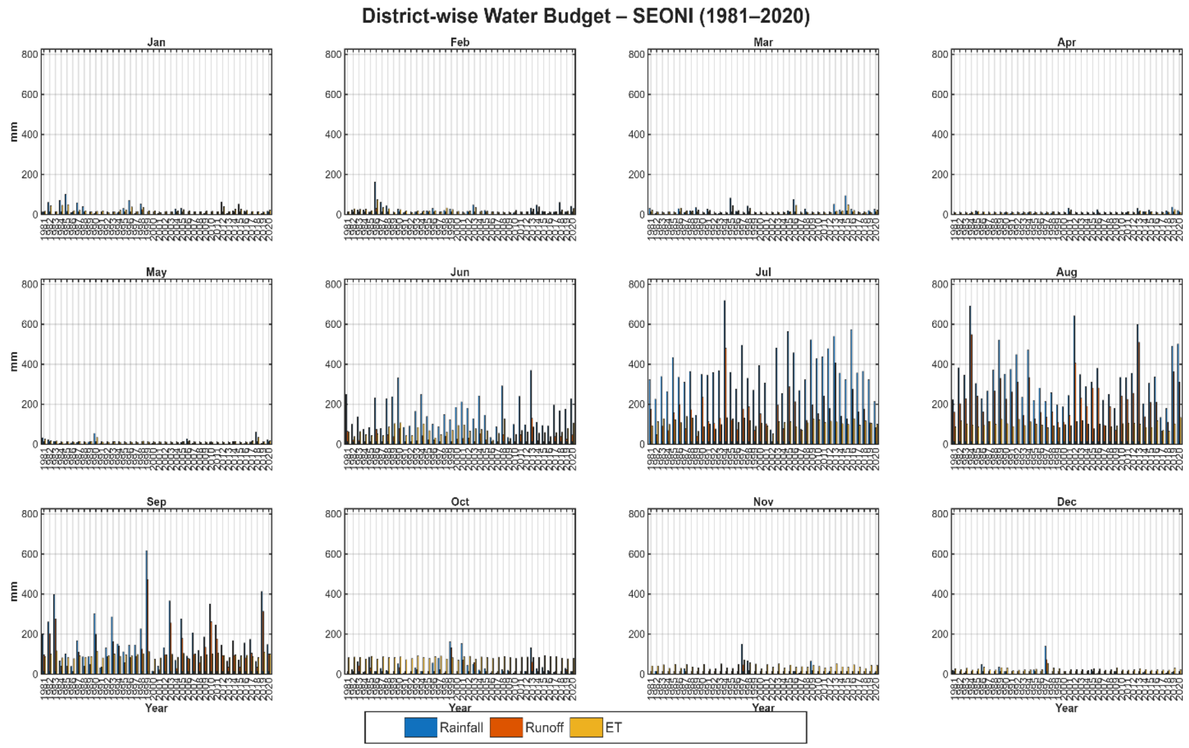
a)



Seoni

The diagram illustrates the monthly district-wise water budget of Seoni (1981–2020), highlighting rainfall, runoff, and evapotranspiration (ET). Rainfall remains very low from January to May, generally below 50–60 mm, with negligible runoff and low ET. The onset of the monsoon in June increases rainfall to around 150–300 mm, accompanied by rising runoff and ET. July and August are the wettest months, with peak rainfall often reaching 600–700 mm, producing the highest runoff (up to 300–400 mm) and maximum ET values of about 120–150 mm, indicating strong water surplus conditions. Rainfall decreases in September but still remains significant (around 200–400 mm), supporting continued runoff and ET. From October onwards, rainfall sharply declines (mostly below 100 mm), runoff becomes minimal, and ET gradually reduces through November and December. Overall, Seoni shows a strong dependence on intense monsoon rainfall, with July–August being critical months for water availability, groundwater recharge, and surface flow.

b)



Sehore

District-wise Water Budget Summary: Sehore (1981–2020)

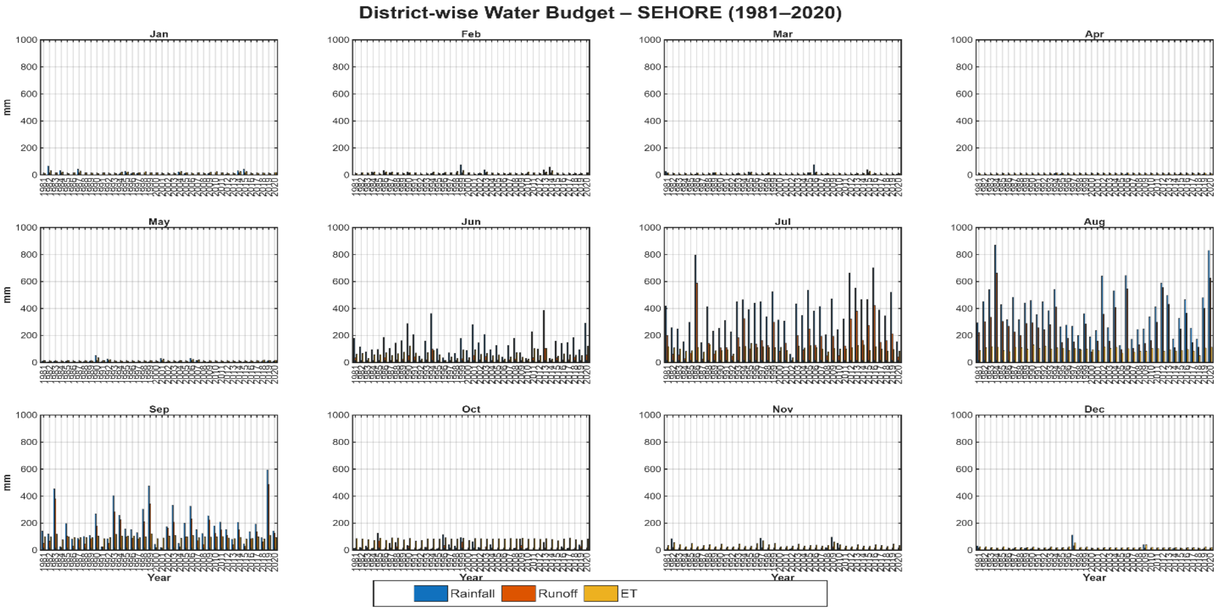
The monthly water budget of Sehore district shows a strong seasonal variation dominated by the southwest monsoon. During the dry season (January–May), rainfall remains very low, generally below 40–50 mm, resulting in negligible runoff and low evapotranspiration (ET). With the onset of monsoon in June, rainfall increases to about 150–300 mm, leading to a corresponding rise in runoff and ET.

The peak monsoon months of July and August record the highest rainfall, frequently ranging between 400 and 800 mm, and in some years approaching 900 mm. These months also exhibit maximum runoff values of approximately 200–400 mm, while ET reaches its highest levels of around 120–160 mm, indicating significant water surplus and favorable conditions for surface flow and groundwater recharge.

In September, rainfall declines to about 200–400 mm, yet runoff and ET remain moderate, reflecting continued availability of soil moisture. The post-monsoon period (October–November) experiences a sharp reduction in rainfall (mostly below 100 mm), with minimal runoff and gradually decreasing ET. During December, rainfall and runoff are negligible, and ET is at its lowest due to cooler conditions.

Overall, Sehore's water budget is highly monsoon-dependent, with July and August being the most critical months for water availability. The long dry season highlights the need for effective rainwater harvesting, surface storage, and groundwater management to ensure sustainable water use throughout the year.

c)

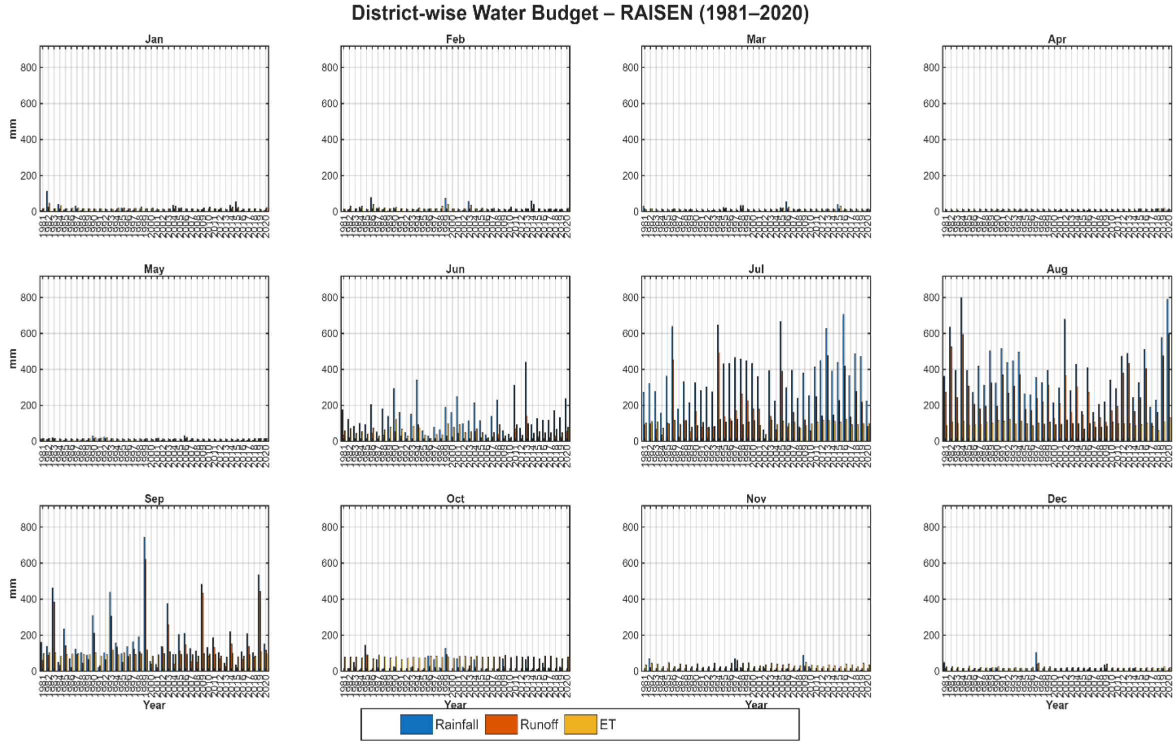


Raisen

The district-wise water budget of Raisen for the period 1981–2020 shows a clear seasonal pattern governed by monsoon rainfall. During the pre-monsoon and winter months (January–May), rainfall remains very low, generally below 40–50 mm, resulting in negligible runoff and low evapotranspiration (ET). With the onset of the southwest monsoon in June, rainfall increases to about 150–300 mm, leading to a noticeable rise in runoff and ET.

The peak monsoon period (July–August) records the highest rainfall in Raisen, commonly ranging between 400 and 700 mm, with some years exceeding 800 mm. These months also generate the highest runoff values, approximately 200–350 mm, while ET reaches its maximum at around 110–150 mm, indicating strong water surplus conditions and enhanced groundwater recharge. Rainfall decreases in September but remains significant (about 200–400 mm), supporting moderate runoff and sustained ET. During the post-monsoon months (October–November), rainfall sharply declines to mostly below 100 mm, with minimal runoff and gradually reducing ET. In December, rainfall and runoff are negligible, and ET reaches its lowest levels due to cooler temperatures. Overall, the 1981–2020 water budget for Raisen highlights a strong dependence on monsoon rainfall, with July and August being the most critical months for water availability, emphasizing the importance of effective water storage and conservation measures to manage the long dry season.

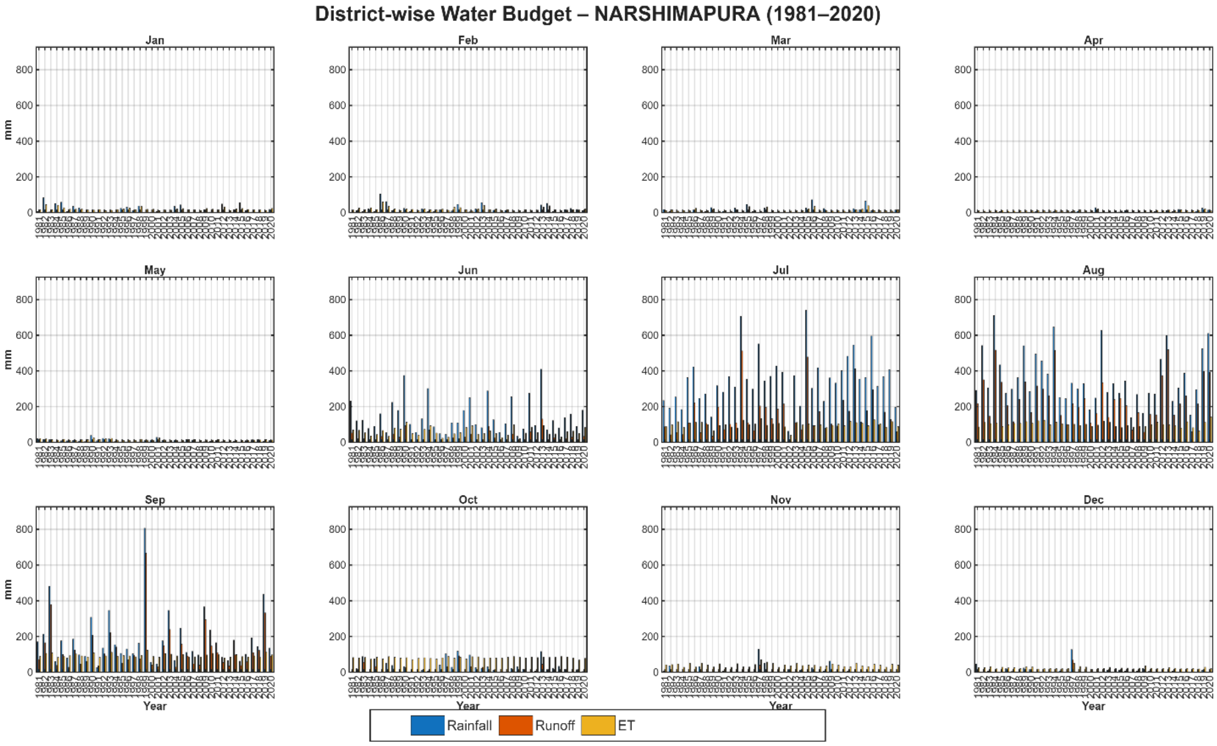
d)



Narsinghpur

The Narsinghpur district water budget (1981–2020) exhibits a robust monsoon-driven cycle characterized by high peak intensity and significant seasonal variability. During the dry months from January to May, rainfall remains minimal—mostly below 40 mm—resulting in negligible surface runoff and very low Evapotranspiration (ET) as soil moisture becomes depleted. The transition begins with the monsoon onset in June, where rainfall sharply increases to between 150 mm and 300 mm, triggering the year's first significant surface runoff and a rise in ET. This progression culminates in the peak monsoon period of July and August, which records the highest water surplus; rainfall during these months is intense, generally ranging from 400 mm to 800 mm, with extreme years approaching 900 mm. Consequently, these months generate substantial runoff, often between 200 mm and 550 mm, while ET peaks at 120–150 mm due to saturated soils and abundant surface water. While rainfall begins to recede in September to approximately 200–450 mm, runoff and ET levels remain moderate. By the post-monsoon period (October–December), rainfall drops sharply below 100 mm and eventually becomes negligible, causing runoff to cease and ET to decline to its annual low. Overall, Narsinghpur's water availability is heavily concentrated in this brief monsoon window, underscoring the vital importance of runoff harvesting and groundwater recharge structures to sustain the district through the prolonged dry season.

e)

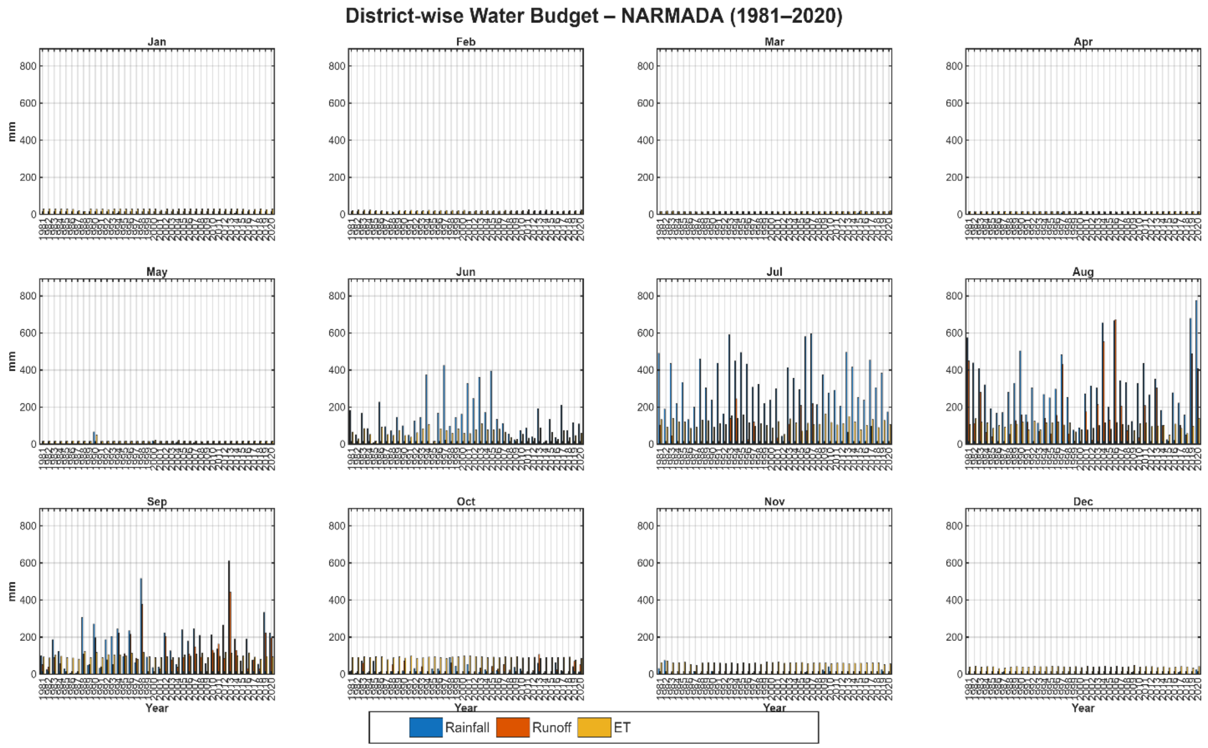


Narmada

The district-wise water budget of Narmada for the period 1981–2020 shows a distinct monsoon-dominated hydrological regime. During the winter and pre-monsoon months (January–May), rainfall remains very low (generally below 40–50 mm), resulting in negligible runoff and low evapotranspiration (ET). With the onset of the southwest monsoon in June, rainfall increases to approximately 150–300 mm, accompanied by a noticeable rise in runoff and ET.

The peak monsoon months (July and August) receive the highest rainfall, typically ranging between 400 and 700 mm, with some years exceeding 800 mm. Runoff during these months reaches about 200–350 mm, while ET attains maximum values of around 110–150 mm, indicating strong water surplus conditions and favorable groundwater recharge. Rainfall declines in September (about 200–400 mm), but runoff and ET remain moderate. During the post-monsoon period (October–November), rainfall drops sharply below 100 mm, with minimal runoff and declining ET, followed by very low values in December. Overall, the water budget highlights the strong dependence of Narmada district on monsoon rainfall and the need for efficient water conservation during the prolonged dry season.

f)

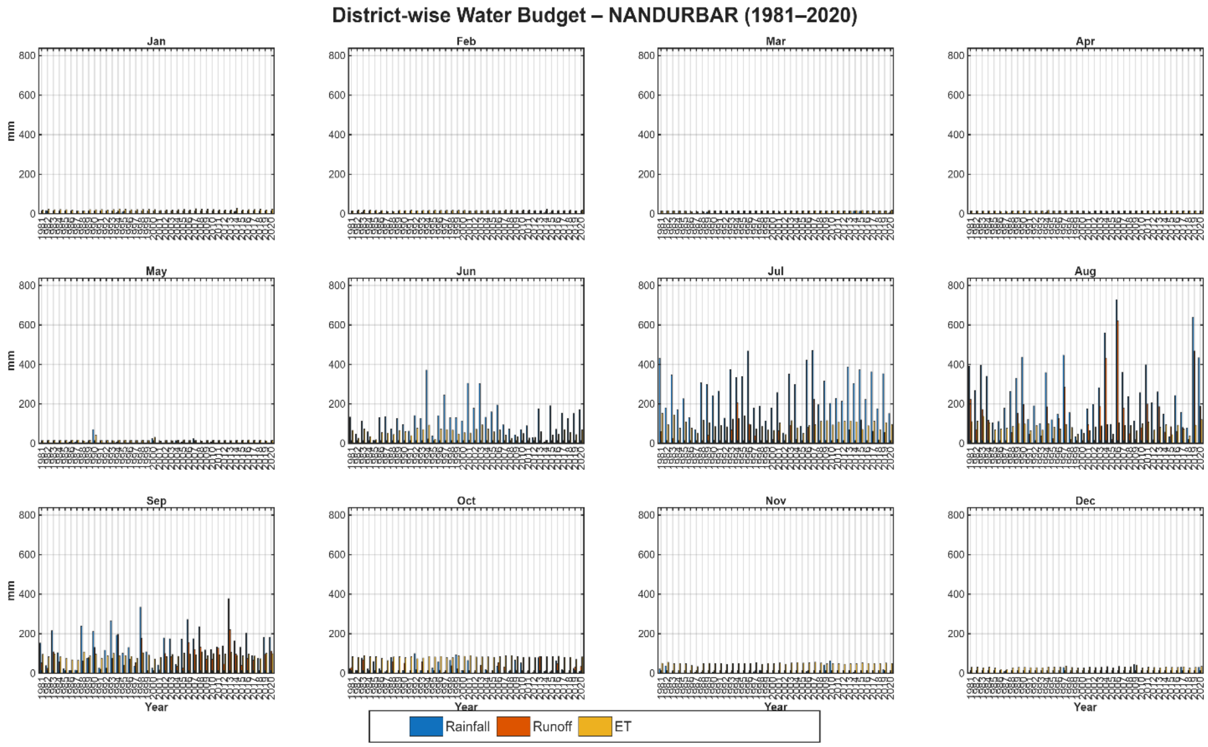


Nandurbar

The Nandurbar district water budget (1981–2020) exhibits strong seasonal variability controlled by monsoon rainfall. Rainfall during the dry months (January–May) is minimal, mostly below 40 mm, resulting in negligible runoff and low ET. The monsoon onset in June increases rainfall to around 120–250 mm, initiating surface runoff and higher ET.

The peak monsoon period (July–August) records high rainfall ranging from 350 to 650 mm, with occasional years approaching 700–800 mm. These months generate substantial runoff of approximately 180–320 mm, while ET peaks at around 100–140 mm, reflecting surplus water availability. Rainfall decreases in September to about 200–350 mm, but runoff and ET remain moderate. During the post-monsoon months (October–November), rainfall drops below 100 mm, runoff becomes minimal, and ET gradually declines, reaching its lowest levels in December. The analysis indicates that Nandurbar's water availability is highly dependent on monsoon rainfall, emphasizing the importance of runoff harvesting and groundwater recharge structures.

g)

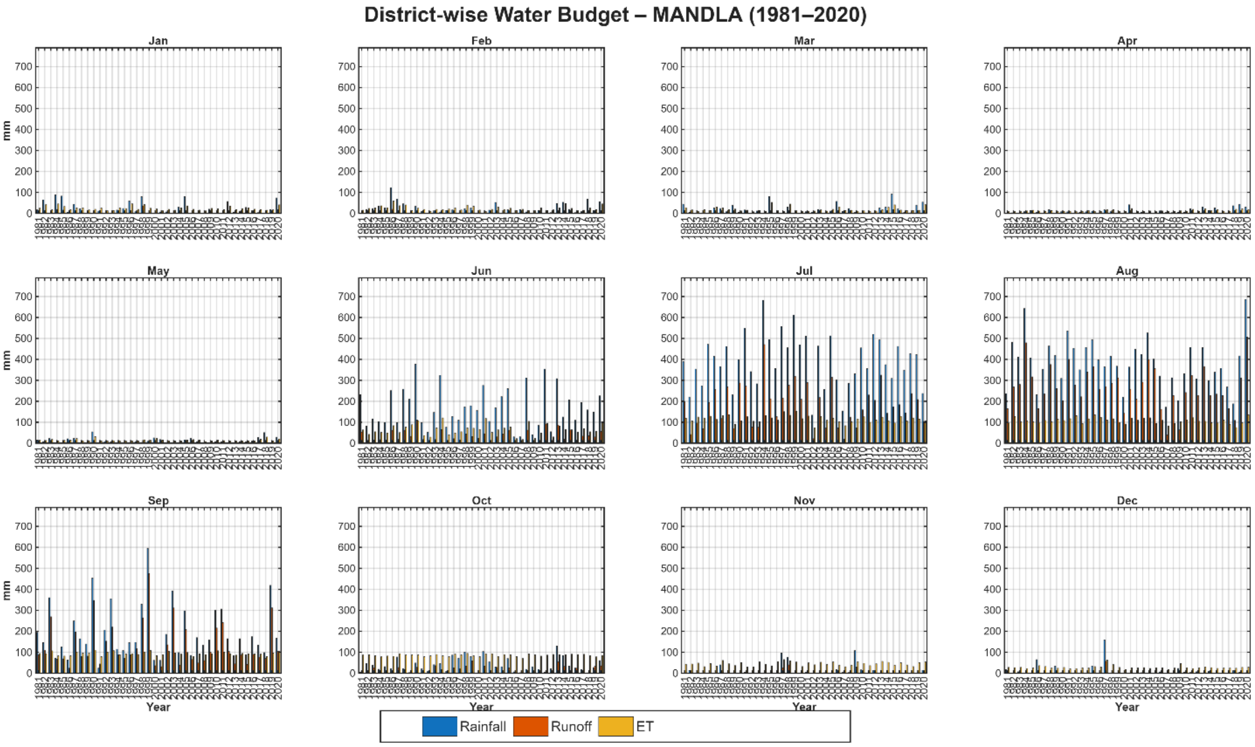


Mandla

The water budget of Mandla district for 1981–2020 shows a pronounced monsoon influence with relatively higher rainfall compared to surrounding districts. During the winter and pre-monsoon months (January–May), rainfall remains low (generally below 50 mm), resulting in limited runoff and low ET. The onset of monsoon in June increases rainfall to approximately 180–320 mm, leading to increased runoff and ET.

The peak monsoon months (July and August) receive the highest rainfall, commonly between 400 and 650 mm, with some years exceeding 700 mm. Runoff during this period reaches about 220–380 mm, while ET peaks around 120–160 mm, indicating significant water surplus and strong recharge potential. In September, rainfall reduces to 200–400 mm, yet runoff and ET remain moderate. The post-monsoon period (October–November) shows a sharp decline in rainfall (mostly below 100 mm), minimal runoff, and decreasing ET, followed by very low values in December. Overall, Mandla's water budget underscores its strong reliance on monsoon rainfall and highlights the importance of managing surplus monsoon water to sustain dry-season demands.

h)



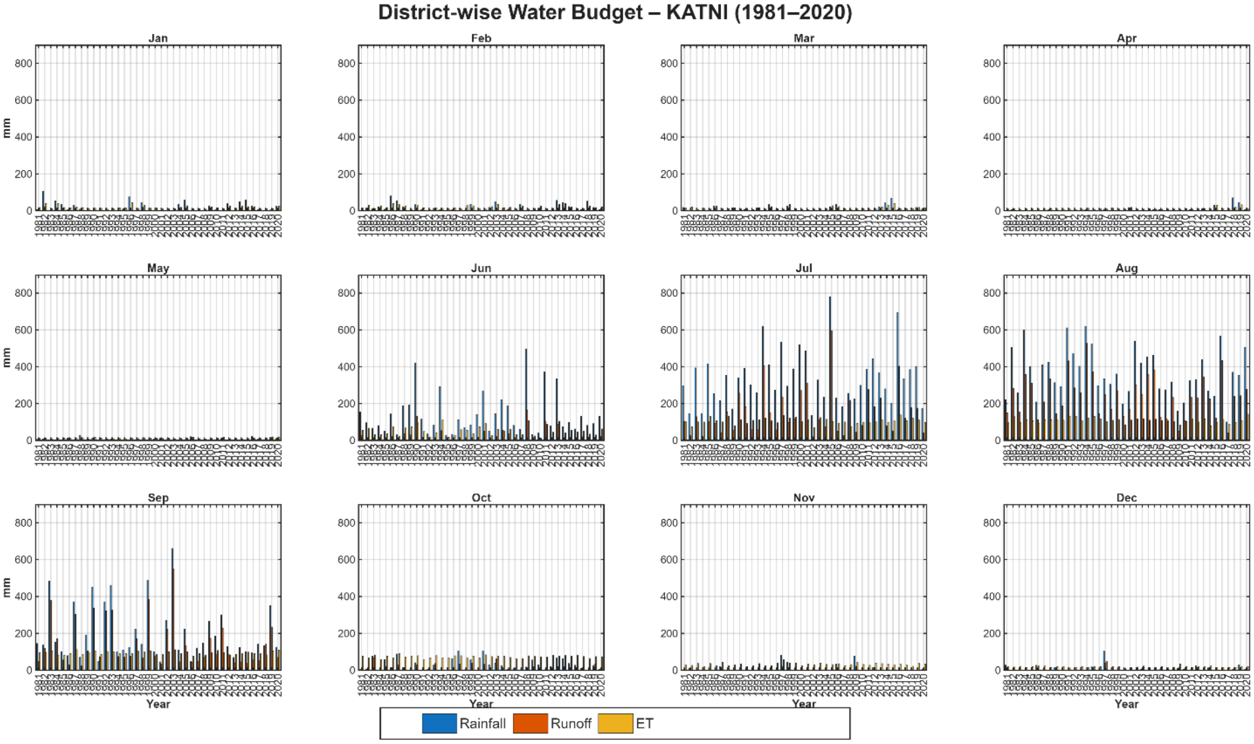
Katni

District-wise water budget from (1981–2020),

Katni shows a strong, concentrated monsoon. Pre-monsoon rainfall is negligible. June rainfall averages 150–250 mm, which swells in July and August to 350–650 mm. A significant July spike in the historical record reaches near 800 mm.

Peak runoff is substantial, ranging from 200 mm to 400 mm, while ET remains at 110–130 mm. September rainfall is moderate to high (200–350 mm). The water budget indicates a surplus in the mid-monsoon that can be harvested in tanks and farm ponds to provide life-saving irrigation for the Rabi season.

i)



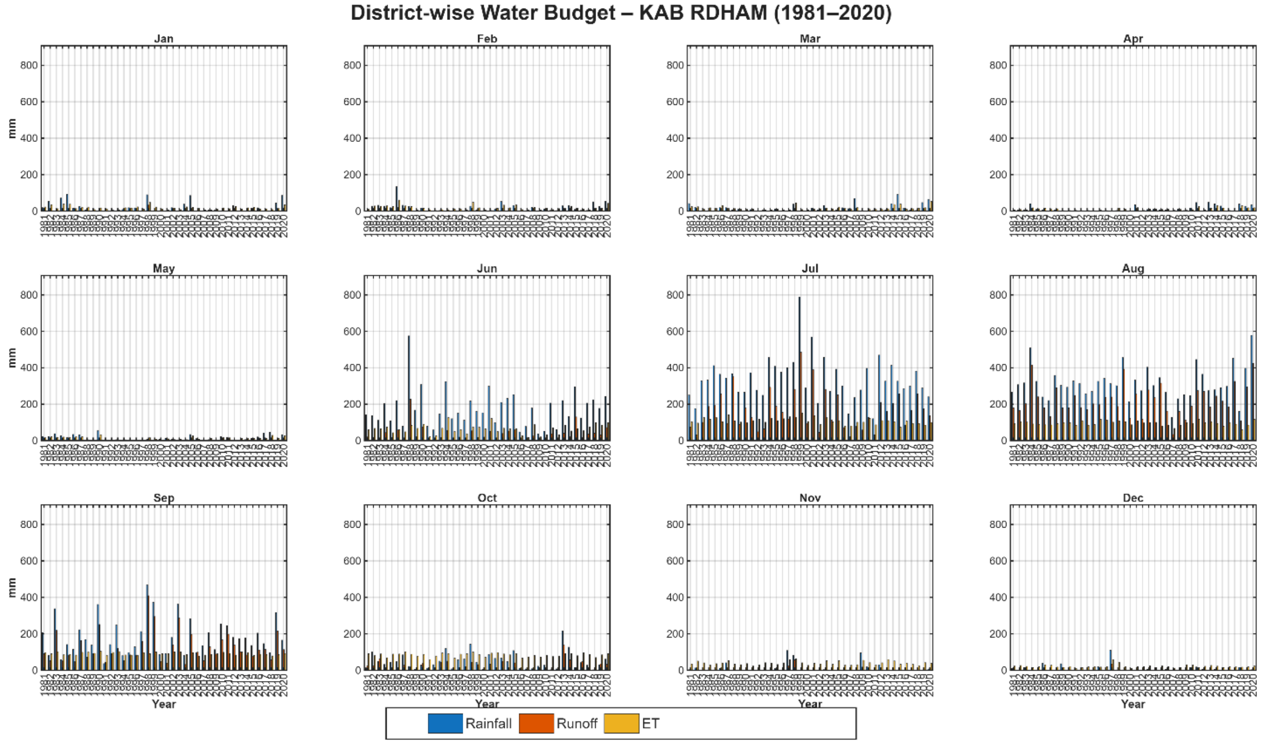
Kabirdham

District-wise water budget from (1981–2020),

Kabirdham shows a consistent monsoon pattern with a relatively late peak. Rainfall is minimal from January to May. June sees an increase to 150–200 mm. The peak months of July and August record rainfall between 300 mm and 500 mm, with a notable spike in July reaching nearly 800 mm in specific historical years.

Runoff is well-defined in July and August, typically ranging from 150 mm to 300 mm. ET remains stable at roughly 100–120 mm. The post-monsoon recession is gradual in October but hits negligible levels by December. The district's water security depends heavily on the high-intensity July bursts, necessitating robust drainage and recharge planning.

j)



District-wise Water Budget – KAB RDHAM (1981–2020)

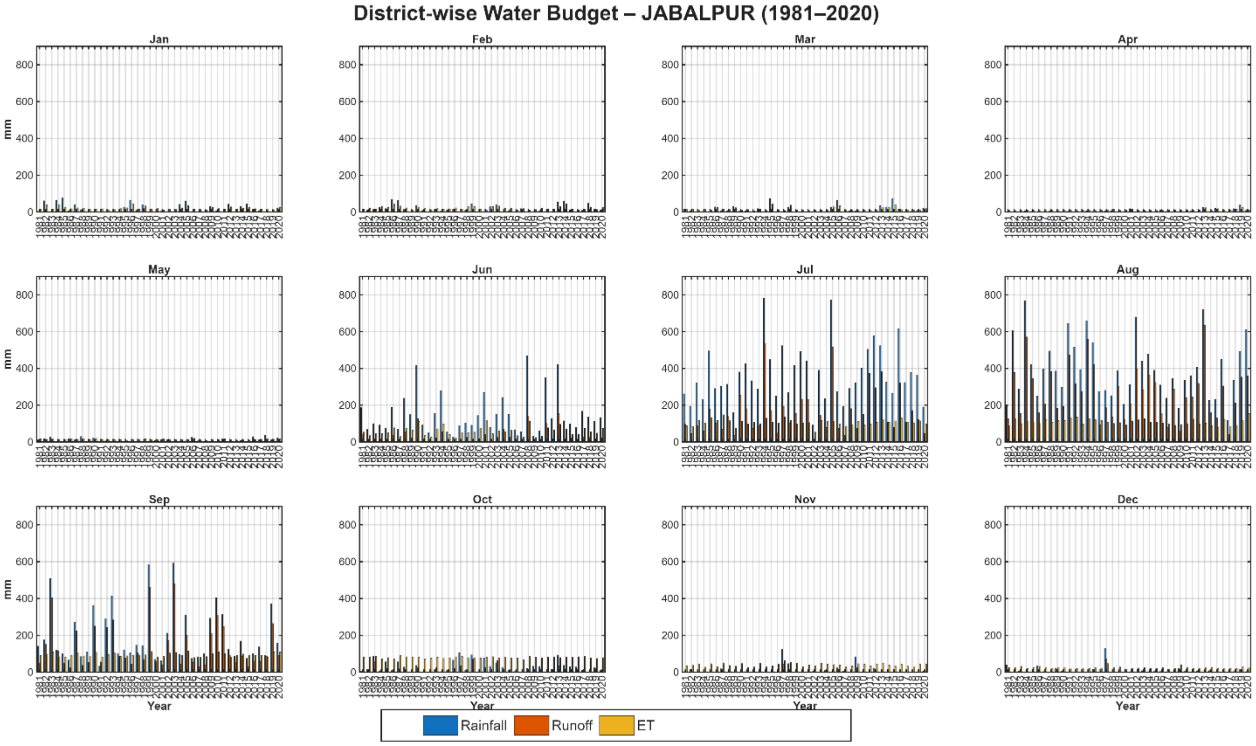
Jabalpur

District-wise water budget from (1981–2020),

Jabalpur displays a robust and reliable monsoon profile. Rainfall is low (under 40 mm) until May. June initiates the cycle with 150–300 mm. During July and August, rainfall is heavy, ranging from 400 mm to 700 mm.

Runoff is very pronounced in these months, often between 250 mm and 450 mm, indicating high saturation levels in the watershed. ET remains steady at 110–130 mm. Rainfall in September is often still high (250–400 mm). The district's hydrologic profile suggests excellent opportunities for groundwater recharge, as the sustained rainfall keeps the soil moisture high for extended periods.

k)



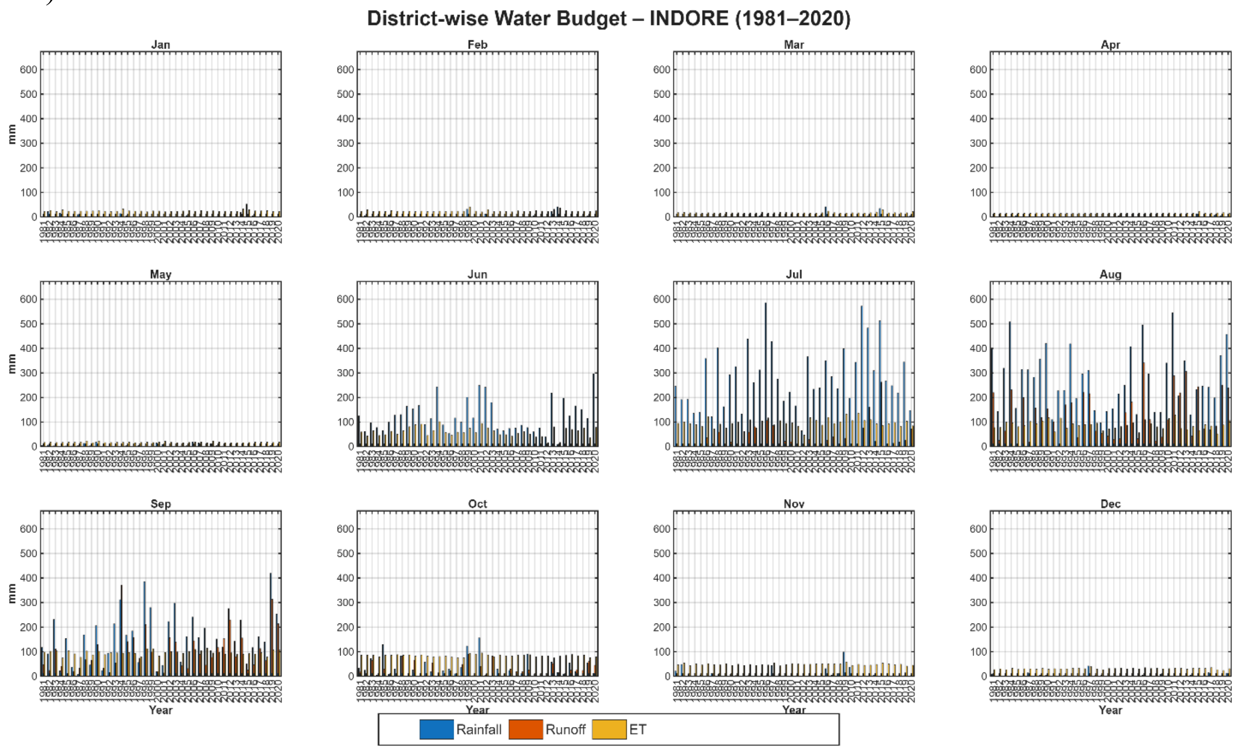
Indore

District-wise water budget from (1981–2020),

The Indore district water budget shows moderate but highly variable rainfall. Pre-monsoon months are dry (under 20 mm). June rainfall fluctuates between 100 mm and 250 mm. The peak monsoon period of July–August sees rainfall ranging from 250 mm to 500 mm, with rare spikes touching 600 mm.

Runoff during these peak months is moderate, generally between 100 mm and 200 mm, while ET fluctuates around 90–120 mm. September rainfall remains significant at 150–300 mm before a steep decline in October. The variability in Indore's peaks suggests that urban water management and rainwater harvesting are vital to buffer against years with lower monsoon intensity.

l)



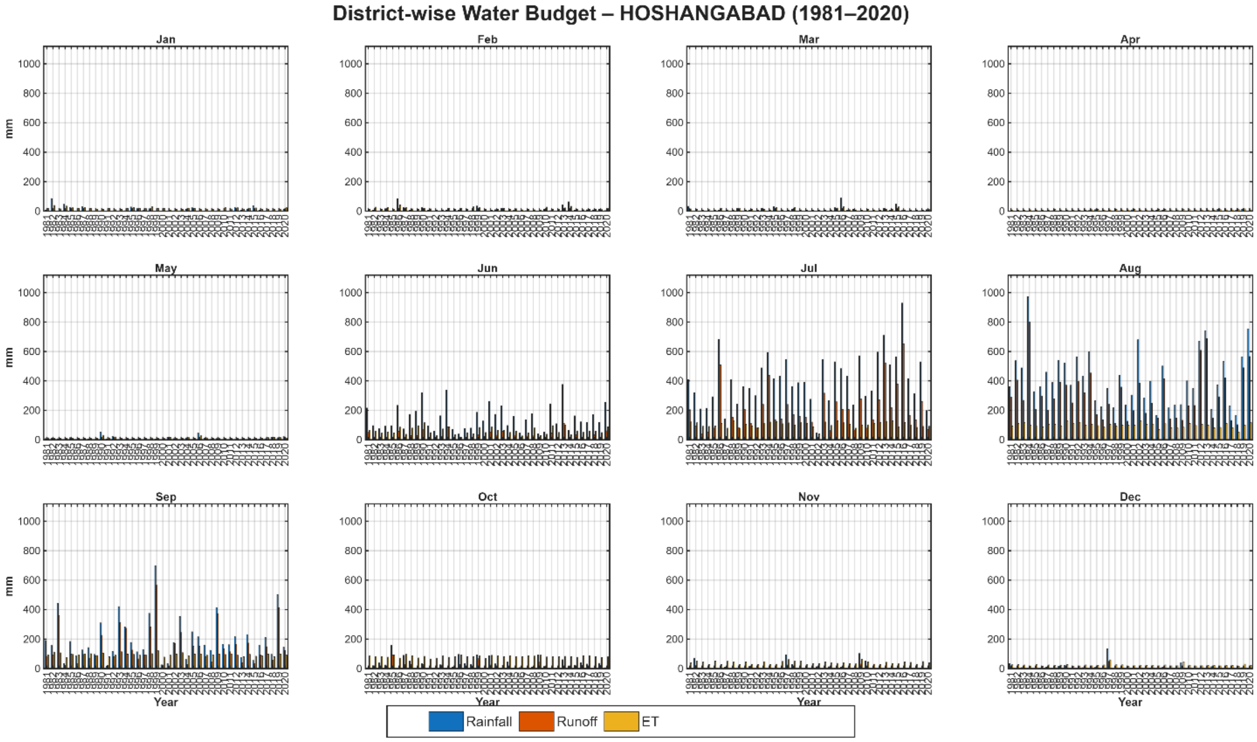
Hoshangabad

District-wise water budget from (1981–2020),

Hoshangabad features one of the highest water budget scales among the districts. While dry months are quiet, the monsoon intensity is extreme. June rainfall reaches 200–350 mm, and the peak months of July–August see massive rainfall ranging from 400 mm to 800 mm, with rare extremes approaching 1000 mm.

Runoff is exceptionally high, frequently exceeding 400 mm during peak spikes, while ET peaks at 130–150 mm. September still holds high volumes (200–500 mm). Because of the extreme runoff and rainfall volumes, this district is highly prone to seasonal flooding, requiring sophisticated reservoir management and flood-control structures.

m)



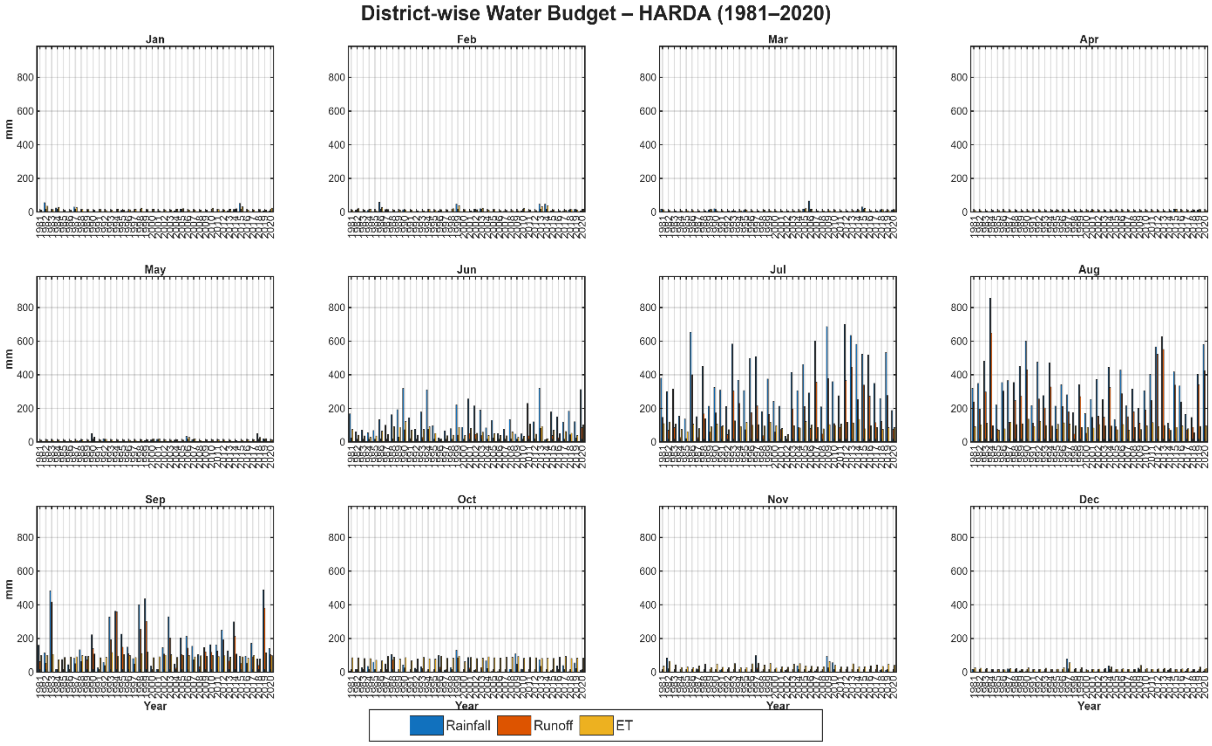
Harda

District-wise water budget from (1981–2020),

The Harda water budget is marked by high-intensity August peaks. Dry months see little to no activity. June rainfall is moderate (150–250 mm), but July and August show a surge, with rainfall typically between 350 mm and 650 mm. One notable August peak in the data exceeds 800 mm.

Runoff tracks closely with these peaks, often reaching 300–400 mm in August. ET remains around 100–120 mm. September rainfall is variable but averages 200–400 mm. The significant gap between rainfall and ET during August highlights a huge surplus that, if not managed, results in high soil erosion and rapid runoff loss.

m)

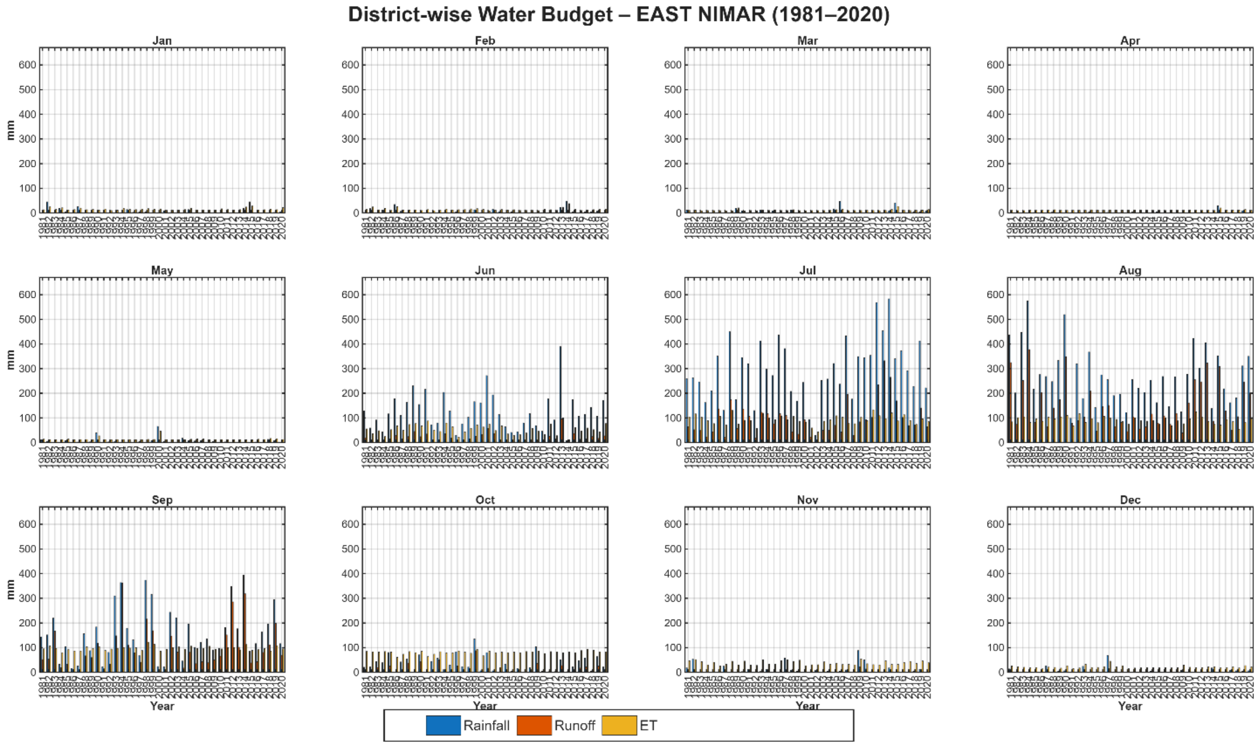


East Nimar

District-wise water budget from (1981–2020),

The East Nimar water budget is characterized by concentrated monsoon activity. Rainfall from January to May is negligible, typically under 30 mm, leading to minimal runoff and low ET. The monsoon arrives in June, with rainfall climbing to 100–200 mm. The peak occurs in July and August, where rainfall frequently ranges between 300 mm and 550 mm, with significant spikes exceeding 600 mm in high-intensity years. During these months, runoff is substantial, often reaching 150–250 mm, while ET stays consistent around 100 mm. Rainfall recedes in September (150–300 mm) and drops sharply by October. The high runoff-to-rainfall ratio in peak months suggests a need for localized check dams to capture surplus water for the dry winter months.

n)



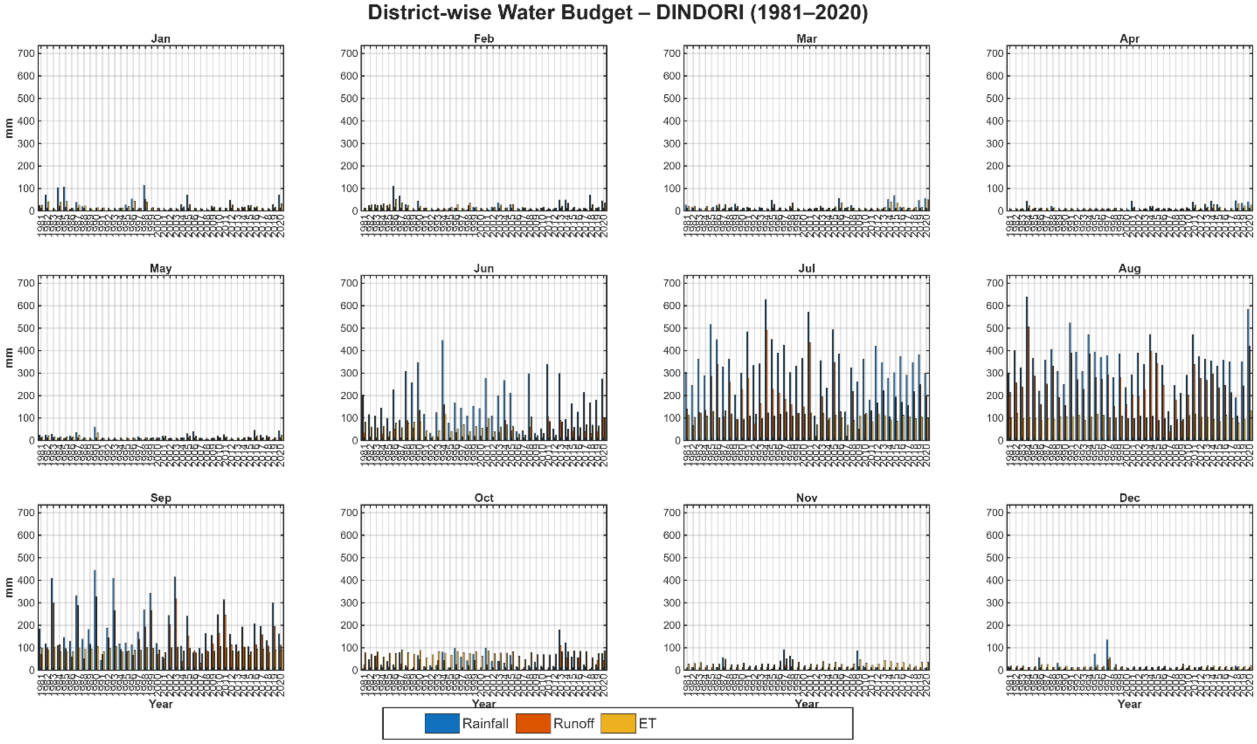
Dindori

District-wise water budget from (1981–2020),

Dindori exhibits a very high-volume water budget. The dry season (Jan–May) remains largely inactive with rainfall below 50 mm. June sees a steady rise, but July and August are the most critical, with rainfall consistently between 350 mm and 600 mm, and exceptional years peaking near 700 mm.

Runoff in Dindori is particularly high, often exceeding 300 mm in August, indicating a landscape with high drainage potential. ET during the peak monsoon is approximately 110–130 mm. September continues to receive healthy rainfall (200–400 mm). Given the high runoff volumes, Dindori has massive potential for large-scale surface water storage and catchment management.

o)



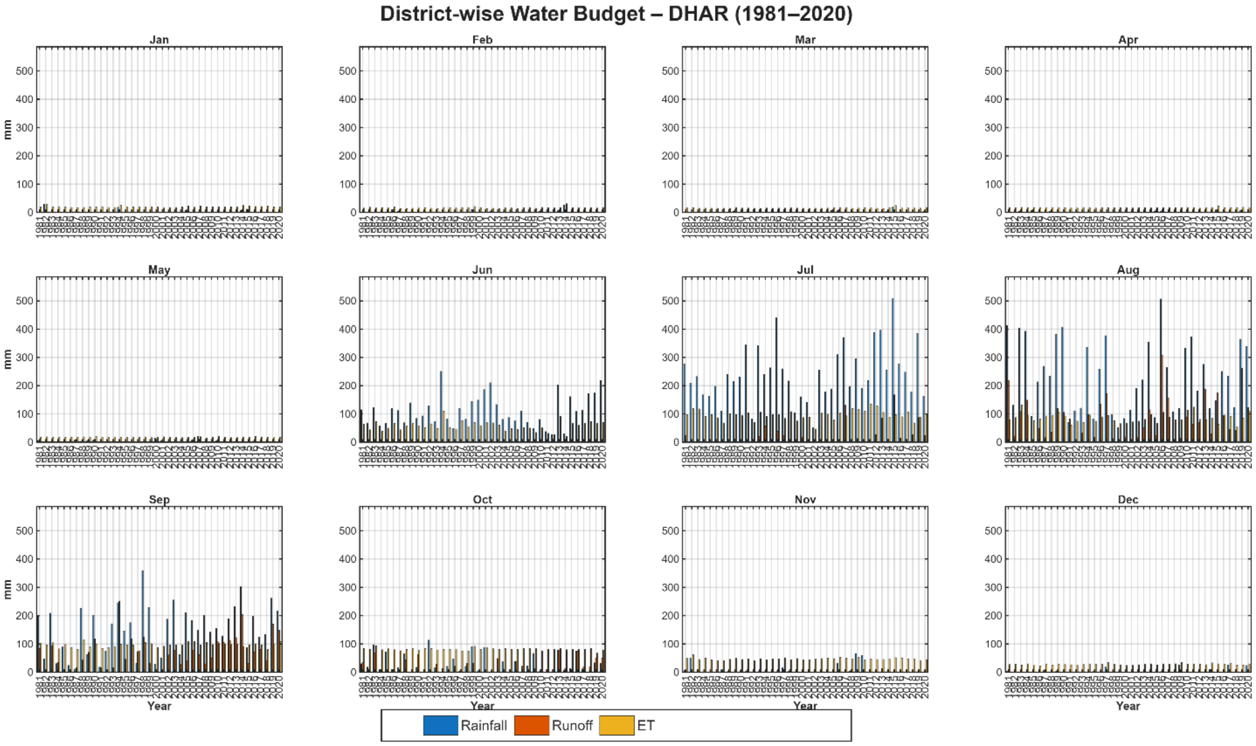
Dhar

District-wise water budget from (1981–2020),

Dhar has a lower overall water budget compared to the eastern districts. Rainfall from January to May is nearly zero. June rainfall stays between 80–180 mm. The peak months of July and August see rainfall ranging from 200 mm to 450 mm, with a maximum recorded near 500 mm.

Runoff is lower here, typically 80–180 mm, and ET is a significant component of the budget at 80–110 mm. Rainfall drops quickly in September (100–250 mm). Due to the lower rainfall totals and high ET relative to runoff, Dhar should focus on "more crop per drop" initiatives and micro-irrigation to manage its tighter water budget.

p)



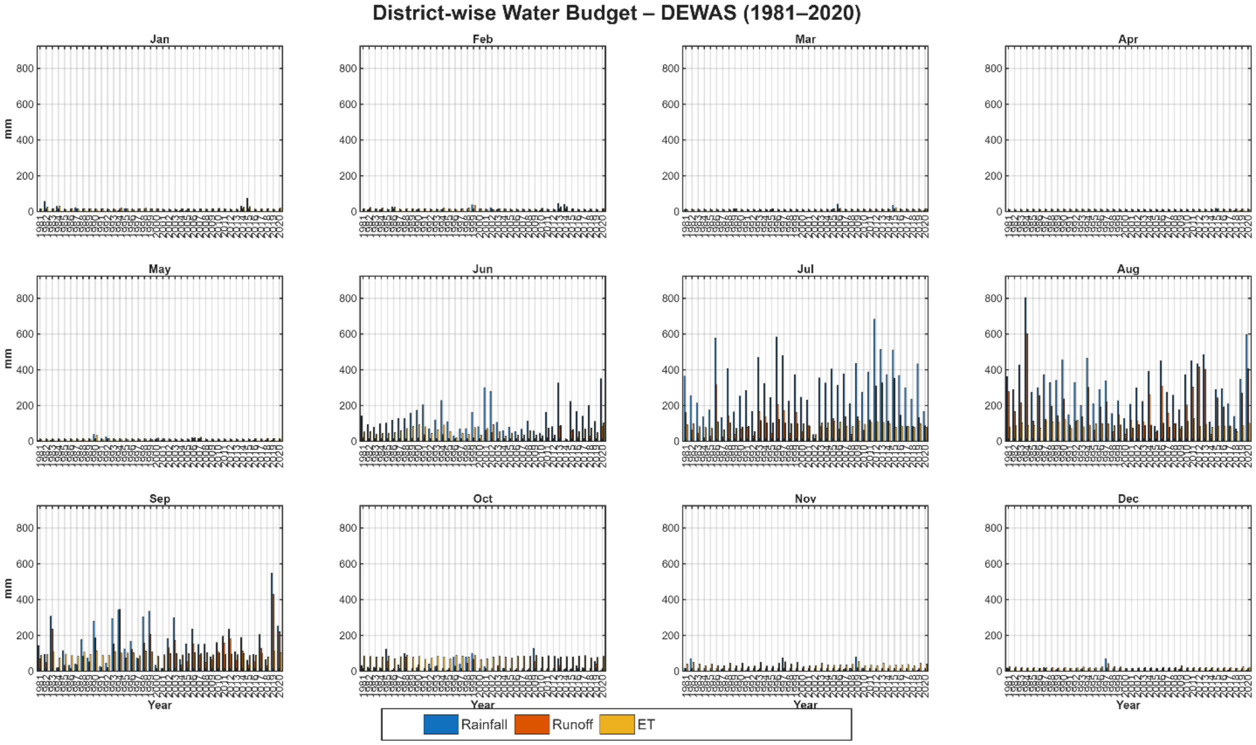
Dewas

District-wise water budget from (1981–2020),

Dewas experiences a moderate monsoon with significant year-to-year variability. Dry months are consistently below 30 mm. June rainfall is typically 100–200 mm. The peak months of July and August show rainfall between 250 mm and 550 mm.

Runoff during the peak is moderate, usually 100–250 mm, while ET averages 100 mm. September rainfall varies widely, often between 150 mm and 350 mm. The analysis suggests that Dewas is sensitive to monsoon fluctuations; therefore, enhancing the efficiency of ET through better crop choices and soil moisture conservation is essential for agricultural stability.

q)



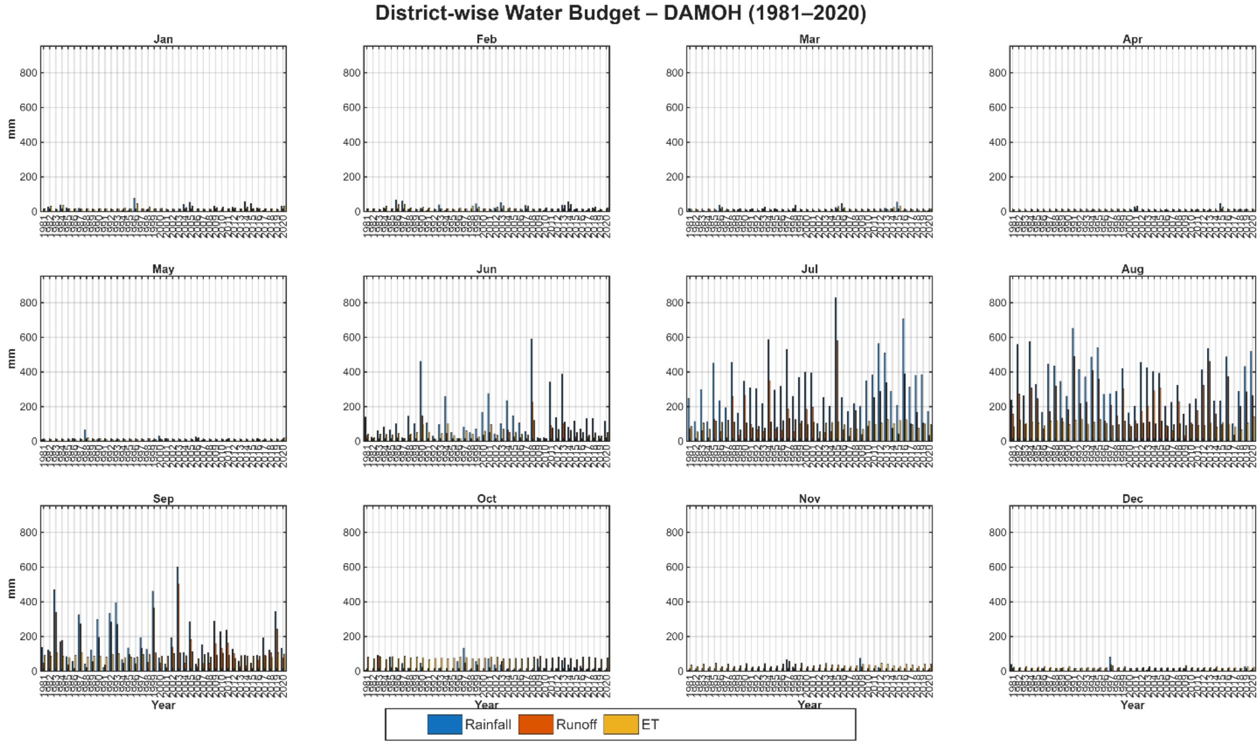
Damoh

District-wise water budget from (1981–2020),

Damoh exhibits a robust monsoon-controlled water budget. Rainfall from January to May is minimal, typically below 40 mm, leading to negligible runoff. June rainfall increases to 100–300 mm, initiating ET and surface runoff.

The peak months of July and August see high rainfall ranging from 400 to 800 mm. These months generate substantial runoff of 200–500 mm, with ET peaking at 100–130 mm, indicating significant water availability. Rainfall remains significant in September (200–600 mm) before dropping below 100 mm in October. The data highlights that Damoh’s water security is entirely dependent on successfully harvesting the July–September surplus.

r)



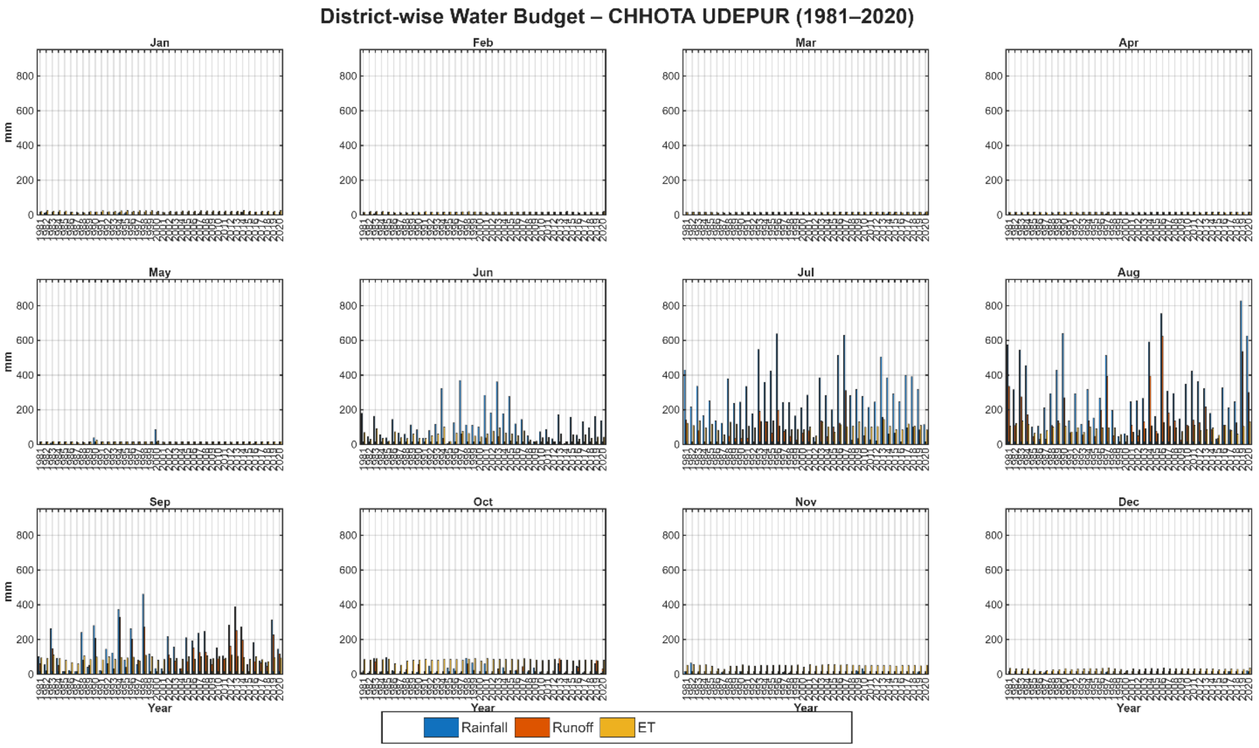
Chhota Udepur

District-wise water budget from (1981–2020),

Chhota Udepur follows a pattern of sharp monsoon onset. Rainfall is negligible from January to May. June records 100–350 mm, initiating surface runoff.

Peak rainfall in July and August ranges from 300 to 800 mm, generating substantial runoff between 150 and 500 mm. ET during this period remains around 100 mm, reflecting a consistent surplus. Rainfall decreases in September to 100–400 mm, and runoff becomes minimal by October as the dry season begins. The high variability in peak rainfall suggests that groundwater recharge is critical for buffering against lean years.

s)

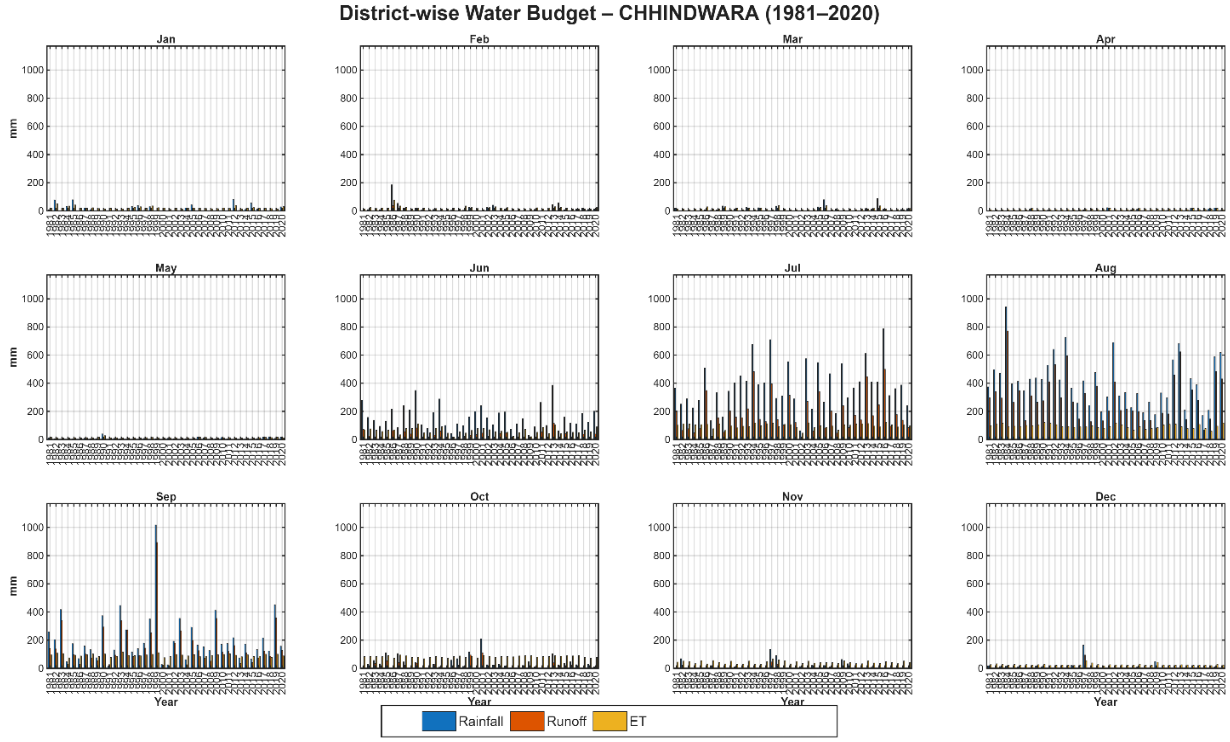


Chhindwara

District-wise water budget from (1981–2020),

The Chhindwara water budget exhibits high seasonal variability driven by the southwest monsoon. Rainfall during the dry months (January–May) is minimal, generally staying below 50 mm, which results in negligible runoff and low ET. The monsoon onset in June raises rainfall to approximately 100–350 mm, initiating measurable surface runoff and increasing ET.

t)



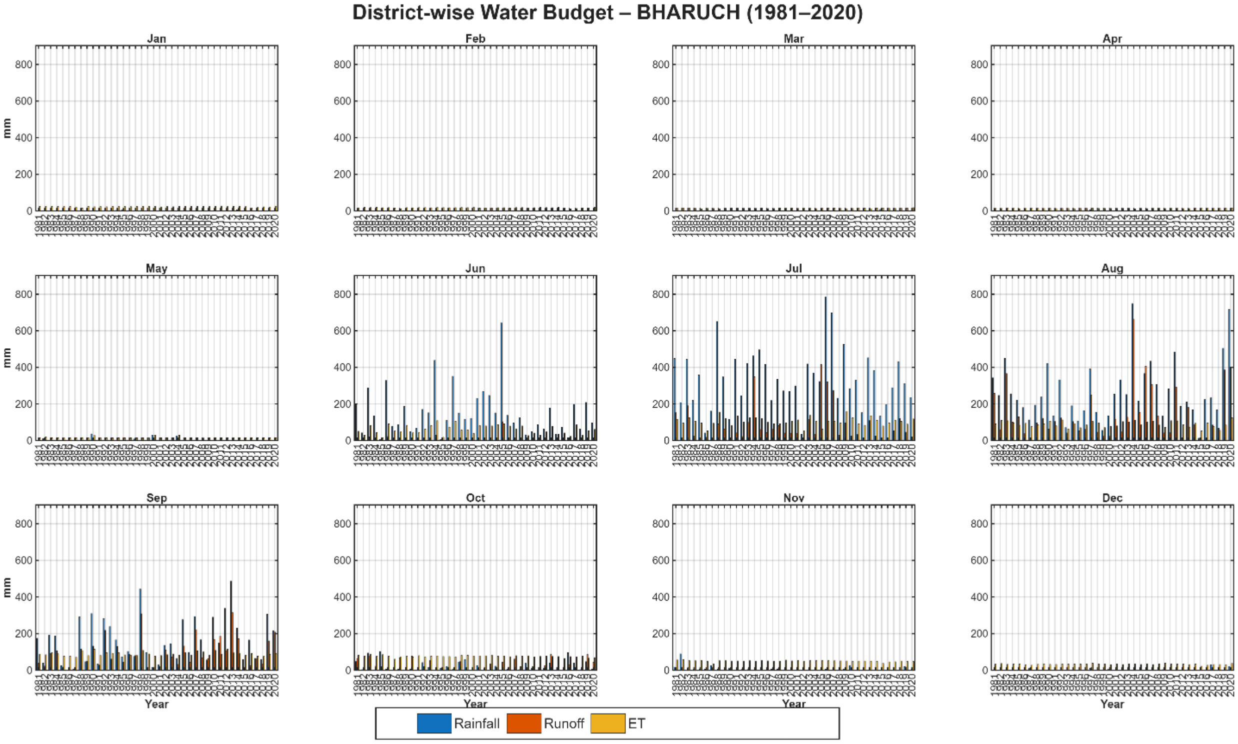
The peak monsoon period (July–August) records substantial rainfall ranging from 400 to 800 mm, with specific years approaching 900 mm. These months generate significant runoff of approximately 200–450 mm, while ET peaks at around 100–140 mm, indicating a large water surplus. Rainfall decreases in September to 200–400 mm, but runoff remains moderate. Post-monsoon, rainfall drops sharply, and ET declines to its lowest levels by December.

Bharuch

District-wise water budget from (1981–2020),

The water budget for Bharuch shows extreme seasonality with a very dry pre-monsoon phase. From January to May, rainfall is almost non-existent (mostly below 20 mm), resulting in zero runoff. The onset in June is variable, with rainfall between 100 and 400 mm, triggering the first runoff events of the year.

u)



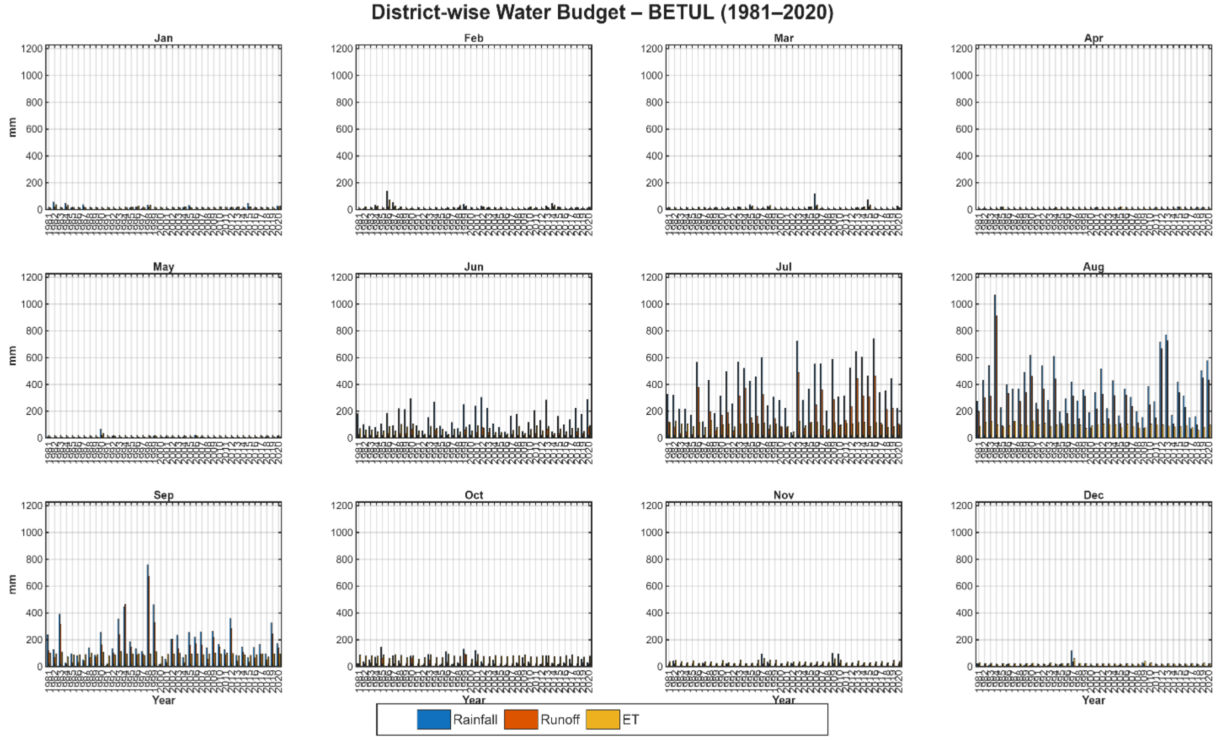
During the peak months of July and August, rainfall ranges between 300 and 750 mm, with occasional high-intensity years spiking above 800 mm. This period generates substantial runoff, often between 150 and 500 mm, while ET remains stable near 100 mm. September maintains moderate rainfall (100–500 mm), but by October, the budget enters a deficit phase as rainfall and runoff drop toward minimal levels.

Betul

District-wise water budget from (1981–2020),

The Betul water budget shows some of the highest peak intensities in the region. Dry months (January–May) are minimal, with rainfall below 50 mm. June rainfall climbs to 100–300 mm, starting the hydrologic response.

v)



The peak period (July–August) is intense, with rainfall ranging from 400 to 800 mm, and rare years exceeding 1000 mm in August. Runoff is exceptionally high, ranging from 200 to 600 mm, while ET peaks at roughly 120 mm. September continues to show high variability with rainfall between 200 and 800 mm. Given these massive runoff volumes, Betul has significant potential for large-scale water harvesting to mitigate the dry post-monsoon months.

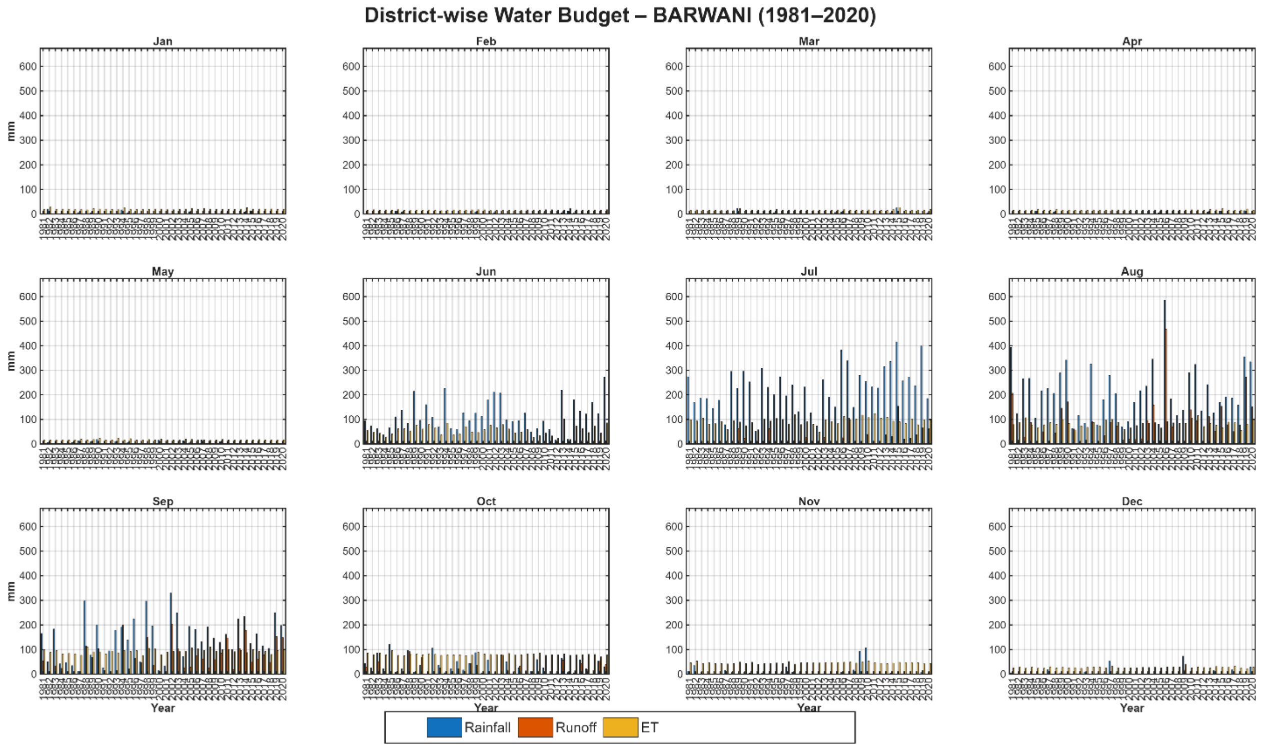
Barwani

District-wise water budget from (1981–2020),

Barwani has a more constrained water budget compared to eastern districts. Rainfall is very low from January to May. June rainfall is relatively low, ranging from 50 to 250 mm, resulting in late-starting runoff.

Peak rainfall in July and August is moderate, ranging from 200 to 450 mm, with occasional August spikes near 600 mm. Runoff is also moderate, typically 50–300 mm, while ET remains around 100 mm. Rainfall in September ranges from 100 to 300 mm. Because the surplus is smaller than in other districts, efficient water management and runoff harvesting are vital for Barwani's agricultural stability.

w)



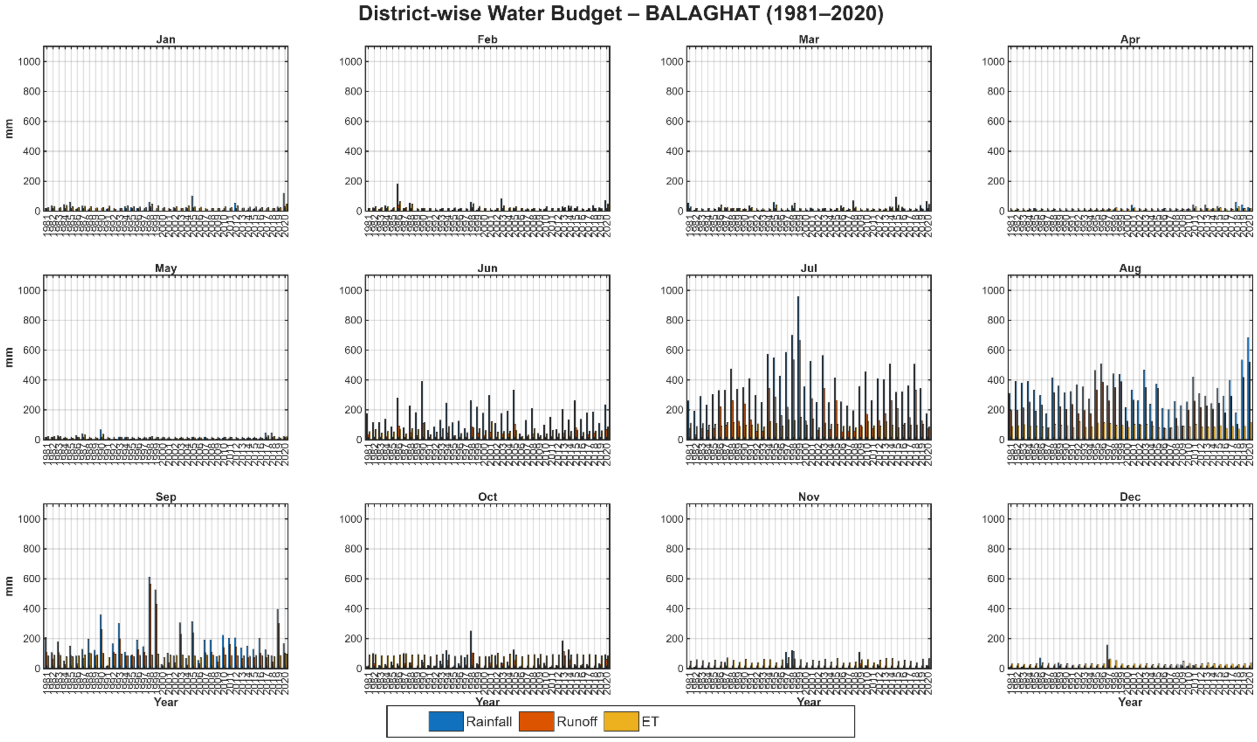
Balaghat

District-wise water budget from (1981–2020),

Balaghat exhibits a very high-volume water budget with massive surpluses. Dry months see rainfall below 50 mm. June rainfall is high, ranging from 100 to 400 mm, quickly initiating runoff.

The peak monsoon (July–August) is extremely wet, with rainfall ranging from 400 to 900 mm, and July often exceeding 900 mm. This results in massive runoff of 300–700 mm, while ET peaks at 120–150 mm. September remains very wet (200–600 mm). The consistent and high runoff volumes in Balaghat emphasize its role as a major water-surplus district, where surface storage is highly effective.

x)



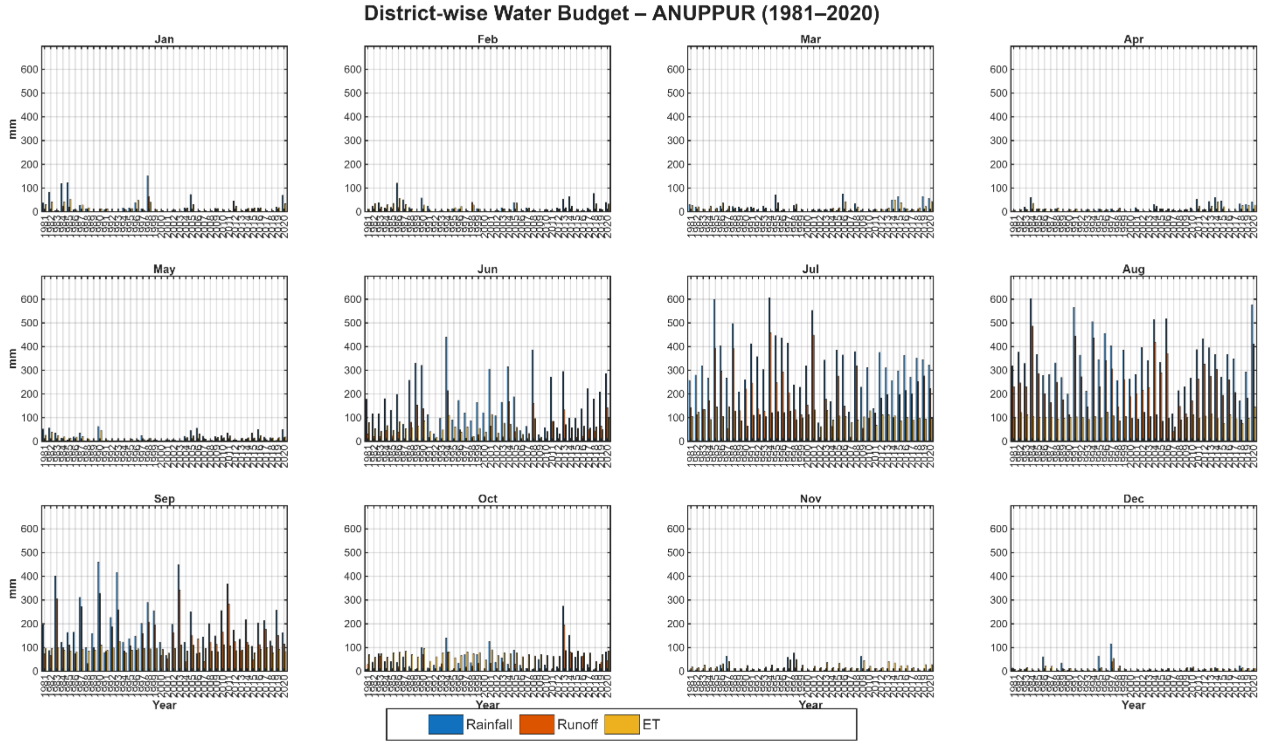
Anuppur

District-wise water budget from (1981–2020),

The Anuppur water budget displays a steady monsoon progression. Rainfall during dry months is minimal, mostly below 50 mm. June rainfall rises to 100–400 mm, initiating higher ET and runoff.

The peak period (July–August) records rainfall between 400 and 600 mm. These months generate runoff of 200–450 mm, while ET remains stable at approximately 120 mm. September rainfall remains moderate to high (200–450 mm), but runoff declines quickly in October as rainfall drops. The analysis indicates that Anuppur's water budget is highly sensitive to the duration of the monsoon.

y)



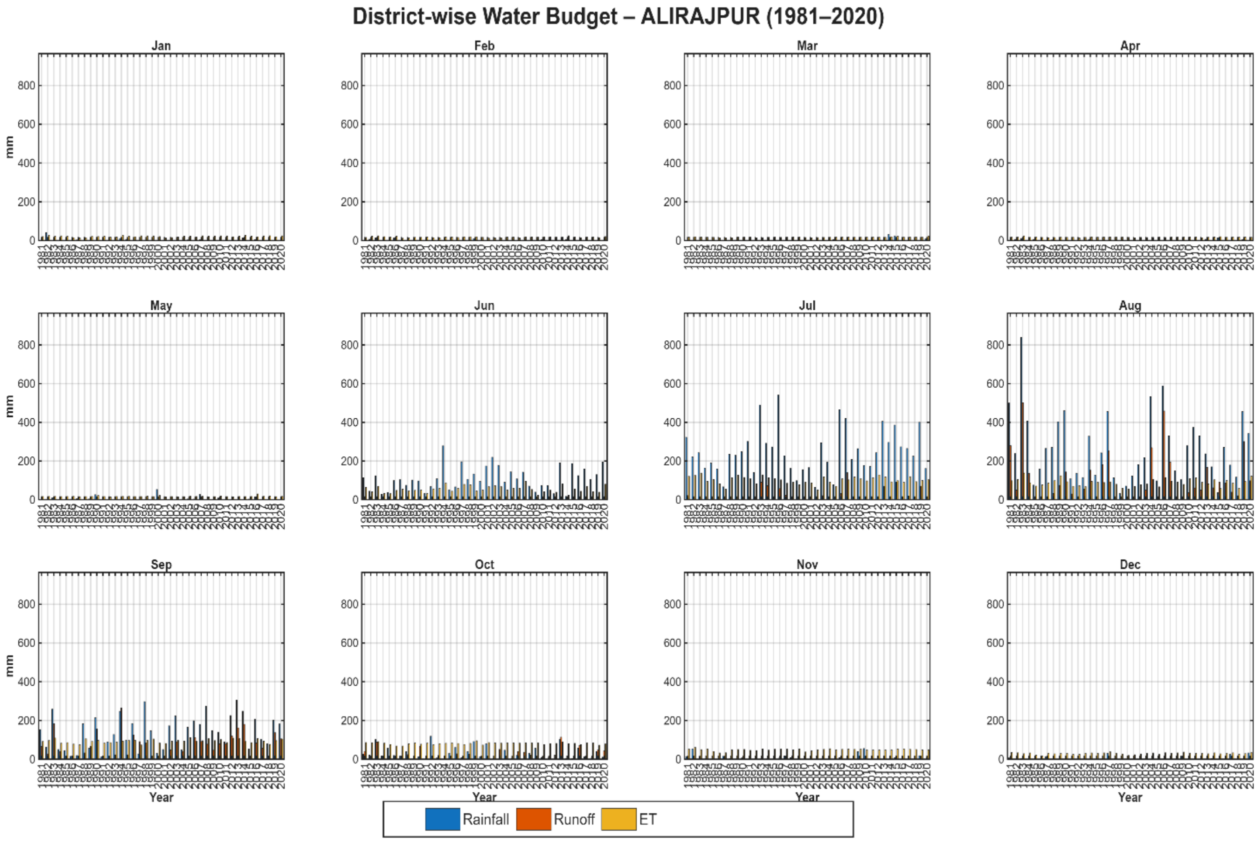
Alirajpur

District-wise water budget from (1981–2020),

Alirajpur’s water budget is characterized by concentrated rainfall in a narrow window. Dry months (January–May) see negligible activity with rainfall under 20 mm. June sees a rise to 100–300 mm, starting the runoff cycle.

The peak monsoon period (July–August) records rainfall between 300 and 600 mm, with August occasionally spiking toward 800 mm. Runoff during these months is approximately 100–400 mm, reflecting a surplus, while ET stays around 100 mm. Rainfall recedes in September to 100–300 mm. The high runoff relative to the total rainfall in peak months emphasizes the need for recharge structures to sustain the district during the long dry season.

z)


District-wise Water Budget – ALIRAJPUR (1981–2020)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
mm
0
200
400
600
800
1981
2020
Year
Rainfall
Runoff
ET

Validation

Model Validation at Garudeshwar Station (Narmada River Basin)

Hydrological model validation was undertaken to assess the performance, reliability, and predictive capability of the ArcSWAT-based watershed model developed for the Narmada River Basin. The validation was conducted at the Garudeshwar gauging station, located at the downstream outlet of the basin, which integrates the cumulative hydrological response of all upstream sub-basins and hydrological response units (HRUs). Owing to its basin-outlet position, Garudeshwar provides an appropriate location for evaluating large-scale runoff generation, channel routing, and overall basin hydrological behavior.

The model was validated using daily observed streamflow data for a common validation period from 2005 to 2018. Simulated discharge (FLOW_OUTcms) generated by the SWAT model was compared with observed streamflow to evaluate the model's ability to reproduce flow magnitude, timing, and seasonal variability. The validation results indicate that the model reasonably captures the temporal dynamics of streamflow, including the monsoon-driven increase in discharge and the gradual recession during post-monsoon and dry seasons, reflecting an appropriate representation of rainfall–runoff processes and watershed storage mechanisms.

Observed streamflow at the Garudeshwar station exhibits substantial variability, characteristic of the monsoon-dominated hydrological regime of the Narmada Basin. Daily discharge ranges from very low baseflow conditions during dry periods to extreme peak flows during intense monsoon rainfall events. The simulated streamflow generated by the ArcSWAT model also shows significant variability and successfully reproduces the seasonal hydrological pattern of the basin. However, the model tends to overestimate discharge, particularly during high-flow conditions, resulting in higher simulated mean flows compared to observations. This overestimation may be attributed to uncertainties in spatial rainfall distribution, parameterization of runoff generation processes, and simplified representation of channel routing and floodplain storage within the model framework.

Visual comparison of observed and simulated hydrographs demonstrates that the model effectively captures the overall trend and timing of streamflow variations at the basin outlet. The simulated peaks generally coincide with observed peak flows, indicating that the model adequately represents the rainfall–runoff response of the basin. Minor discrepancies are observed during extreme flood events, which are common in large river basins and are often associated with limitations in representing localized high-intensity rainfall, transmission losses, and in-channel storage processes.

Statistical evaluation of model performance using the coefficient of determination (R^2) yielded a value of approximately 0.60 at the Garudeshwar station, indicating a moderate to good agreement between observed and simulated streamflow. This level of performance suggests that the ArcSWAT model is capable of capturing the dominant hydrological processes governing basin-scale runoff, including seasonal flow variability and baseflow contributions. The relatively better agreement during low- to moderate-flow conditions indicates a reasonable simulation of groundwater recharge, soil moisture dynamics, and baseflow processes.

Overall, the validation results confirm that the developed ArcSWAT model for the Narmada River Basin performs satisfactorily at the basin outlet and is hydrologically consistent for long-term simulations. Despite some overestimation during peak flow events, the model reliably reproduces seasonal trends, flow timing, and basin-scale hydrological responses. Therefore, the validated model is considered suitable for watershed-scale runoff estimation, basin-wide water balance analysis, assessment of land use and climate variability impacts, and long-term water resources planning and management within the Narmada River Basin.

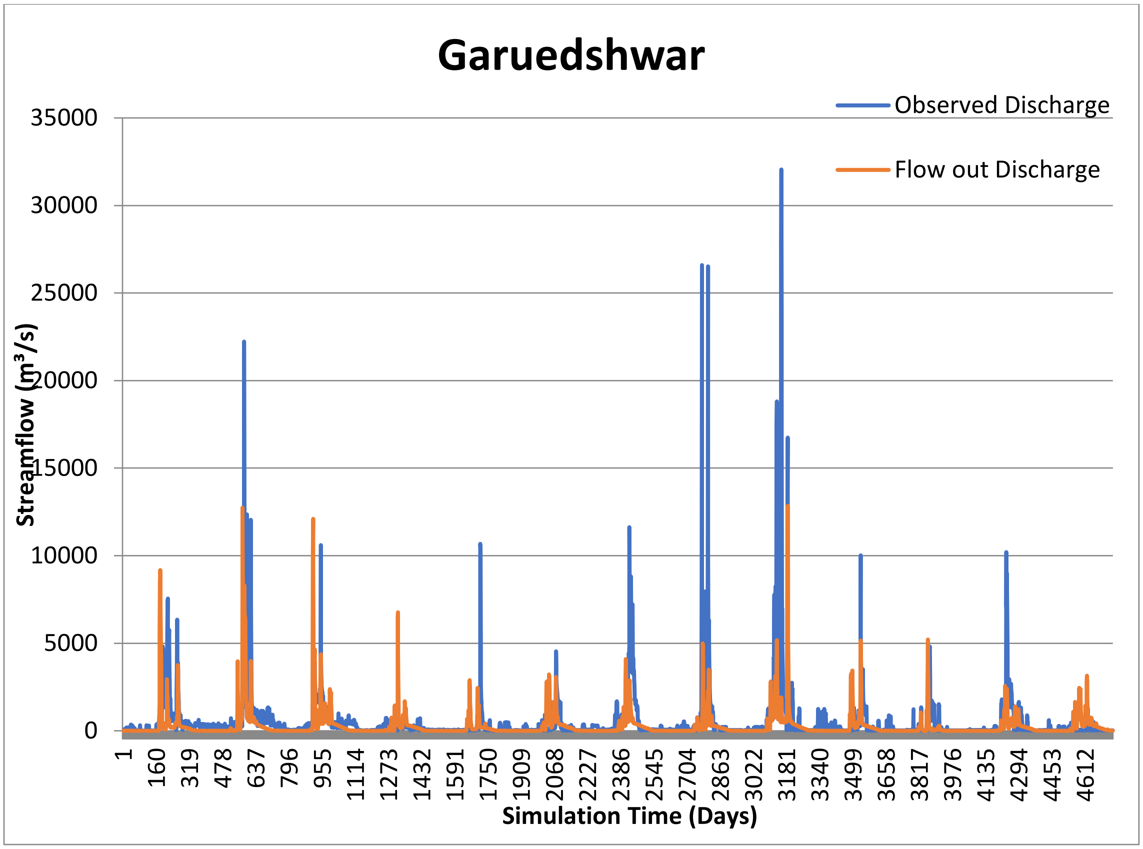


Figure 36: Validation graph Garudeshwar

The observed daily streamflow at the Garudeshwar gauging station exhibits a wide range of hydrological variability, reflecting the monsoon-dominated hydroclimatic regime of the Narmada River Basin. Observed discharge varies from very low baseflow conditions of approximately 2.9 m³/s during dry periods to extreme peak flows reaching about 60,642 m³/s during intense monsoon rainfall events, with a median flow of around 194 m³/s and a mean flow of approximately 529 m³/s. These high peak discharges are associated with concentrated monsoon precipitation, whereas the low-flow conditions represent groundwater-dominated baseflow during non-monsoon months. This wide range of observed streamflow highlights the strong seasonal control on river discharge within the basin.

The simulated streamflow generated by the ArcSWAT watershed model also demonstrates substantial variability and successfully captures the seasonal flow dynamics of the basin. Simulated daily discharge ranges from approximately 152 m³/s to about 45,470 m³/s, with a median flow of nearly 390 m³/s and a mean flow of approximately 1,058 m³/s. While the model effectively reproduces the seasonal pattern of streamflow, it tends to simulate higher average discharges compared to observed values. This indicates a systematic overestimation of streamflow, particularly during high-flow periods, which is a common limitation in large-basin hydrological modeling. Graphical comparison of observed and simulated hydrographs at the Garudeshwar station reveals that the overall trend and temporal variation of streamflow are well represented by the model. The seasonal rise in discharge during the monsoon period and the recession during post-monsoon and dry seasons are clearly captured. Simulated peak flows generally align with the timing of observed peaks, indicating that the model appropriately represents the rainfall–runoff response of the basin. However, some degree of overestimation is evident during extreme flood events, which may be attributed to spatial variability in rainfall, uncertainties in input datasets, and parameterization limitations within the model.

Analysis of climatic inputs further supports the model behavior. The rainfall data indicate a mean daily rainfall of approximately 3.0 mm, with maximum daily rainfall reaching about 89 mm. Periods of high rainfall correspond closely with peak streamflow events, confirming precipitation as the dominant driver of runoff generation in the Narmada Basin. Temperature data exhibit realistic seasonal patterns, with mean maximum and minimum temperatures of approximately 32.3 °C and 18.6 °C, respectively. These temperature variations influence evapotranspiration and soil moisture dynamics, which are adequately represented in the SWAT model structure.

The comparison between observed and simulated streamflow indicates a moderate to good model performance at the basin outlet. The model successfully reproduces the seasonal hydrological behavior of the basin, the timing of peak flows during the monsoon season, and baseflow conditions during dry periods. Although discrepancies are observed during extreme flood events, the overall agreement between observed and simulated discharge demonstrates the model's capability to represent basin-scale hydrological processes.

The tendency of the model to overestimate high flows may be attributed to assumptions of spatially uniform rainfall distribution, simplified channel routing schemes, and limitations in representing floodplain storage processes. In contrast, relatively lower deviations during low-flow periods indicate a reasonable simulation of groundwater contribution and baseflow generation mechanisms. The long-term validation carried out over multiple years enhances confidence in the reliability and robustness of the model.

Overall, the validation results at the Garudeshwar station confirm that the developed ArcSWAT-based hydrological model for the Narmada River Basin performs satisfactorily at the basin outlet. The model captures the temporal variability, seasonal trends, and hydrological response of the basin with acceptable accuracy. Consequently, the validated model is suitable for watershed-scale runoff estimation, water balance analysis, and basin-level water resources planning and management.

Validation of Hydrological Model at Sandia Station (Narmada River Basin)

Validation of the hydrological model was carried out at the Sandia gauging station, which represents an important intermediate control point within the Narmada River Basin. The validation utilized daily observed discharge data and the corresponding simulated streamflow output (FLOW_OUTcms) generated by the ArcSWAT watershed model. The dataset consists of approximately 5,113 daily observations spanning the period from 2005 to 2018, providing a sufficiently long temporal coverage to capture both seasonal and interannual hydrological variability within the basin.

The observed streamflow at the Sandia station exhibits substantial temporal variability, characteristic of the monsoon-driven hydrological regime of the Narmada Basin. Observed daily discharge ranges from zero flow conditions during dry periods to peak flows of approximately 25,288 m^3/s during intense monsoon events, with a median discharge of about 186 m^3/s and a mean discharge of approximately 429 m^3/s. The hydrograph reflects low-flow conditions during non-monsoon months and sharp increases during the monsoon season, indicating a strong rainfall–runoff response and relatively limited baseflow contribution during prolonged dry periods.

The simulated streamflow produced by the ArcSWAT model also demonstrates pronounced seasonal variability. Simulated discharge varies from zero flow to a maximum of approximately 15,020 m^3/s, with a median value of around 111 m^3/s and a mean discharge of approximately 708 m^3/s. Comparison with observed data indicates that the model tends to simulate higher average discharge volumes, suggesting a tendency toward overestimation of flow, particularly during moderate to high flow conditions.

Graphical comparison of observed and simulated hydrographs at the Sandia station shows a reasonable agreement in the timing of streamflow variation. Simulated peaks generally coincide with observed monsoon flow events, indicating that the model adequately captures the temporal dynamics of rainfall–runoff processes. The seasonal rising and recession limbs of the hydrograph are well represented; however, underestimation of some extreme peak flows and overestimation during moderate flow periods are evident. Scatter analysis between observed and simulated discharge indicates a consistent relationship with acceptable dispersion, further supporting the model's ability to represent general discharge patterns.

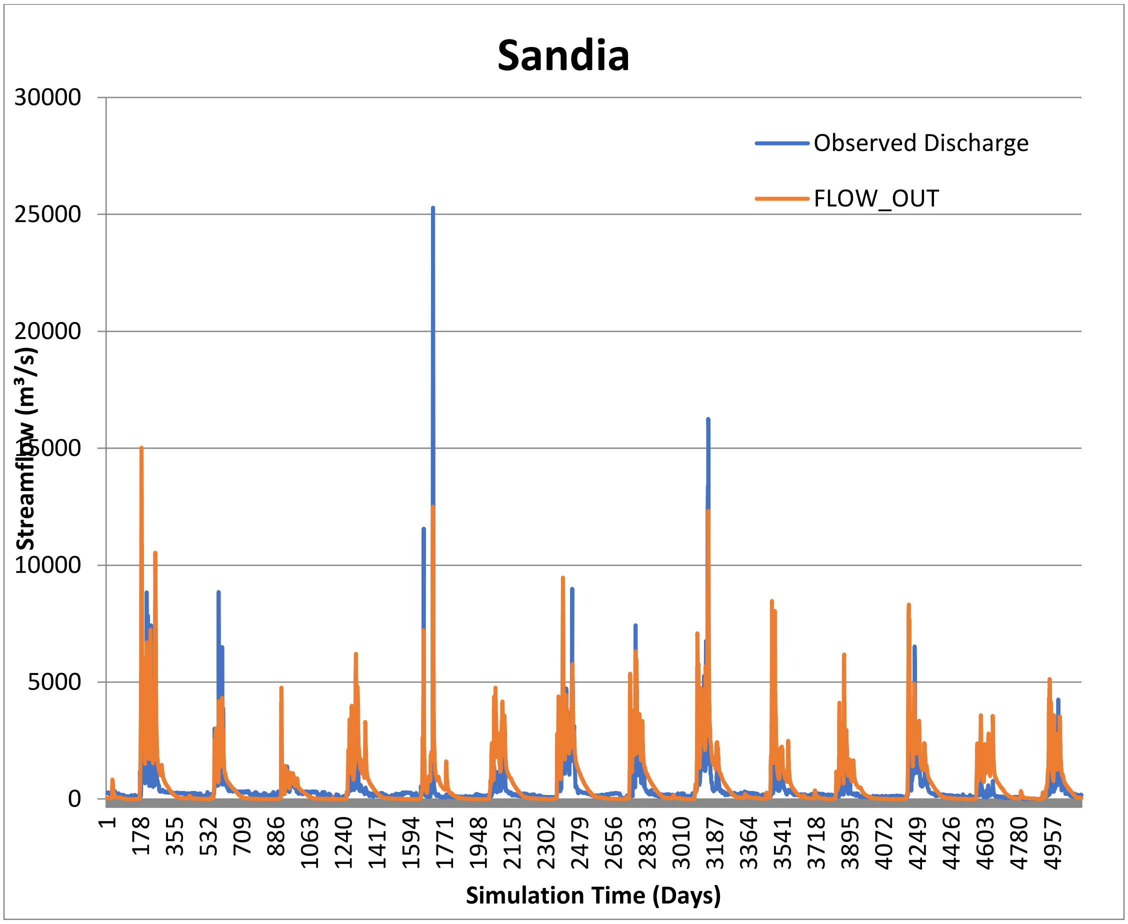


Figure 37:Validation graph sandia

Statistical evaluation of model performance using the coefficient of determination (R^2) yields a value of approximately 0.60, indicating a moderate correlation between observed and simulated streamflow at the Sandia station. This level of agreement suggests that the model satisfactorily captures the dominant hydrological processes governing runoff generation at the sub-basin scale.

From a technical perspective, the model performs well in simulating seasonal flow variability and overall discharge trends. Deviations observed during high-flow events may be attributed to spatial variability in rainfall distribution, uncertainties in watershed and channel parameters, and simplified channel routing representation within the model framework. Reduced accuracy during extreme flood events indicates potential scope for further improvement through refined calibration of surface runoff generation and channel routing parameters. Nevertheless, the model effectively represents basin-scale hydrological behavior at this intermediate control point.

The successful validation at the Sandia station demonstrates the applicability of the model for sub-basin and watershed-scale runoff estimation, comparative hydrological analysis across the Narmada Basin, and water resources planning and management studies. The consistency of validation results at both the Sandia and Garudeshwar stations enhances confidence in the robustness and reliability of the developed hydrological model.

Overall, based on graphical comparison and statistical evaluation, the ArcSWAT-based hydrological model exhibits satisfactory validation performance at the Sandia station. The moderate R^2 value confirms reliable simulation of streamflow dynamics, supporting the suitability of the model for watershed-scale and basin-scale hydrological assessments within the Narmada River Basin.

Use of the Water Budget Report for the Narmada River Basin

1. Basin-Scale Hydrological Understanding and Watershed Planning

The Water Budget Report of the Narmada River Basin provides a comprehensive, process-based quantification of hydrological components using the SWAT (Soil and Water Assessment Tool) model. From the Narmada River basin perspective, this report establishes a scientifically validated understanding of how precipitation is partitioned into surface runoff, evapotranspiration, soil moisture storage, shallow aquifer recharge, baseflow contribution, and deep percolation across the Upper, Middle, and Lower Narmada watersheds.

The primary technical use of this report lies in integrated watershed and river basin planning, as it captures spatial and temporal variability of hydrological processes at sub-basin and HRU levels. By identifying where water is generated (runoff-producing zones), where it is stored (soil and shallow aquifers), and where it is lost (evapotranspiration and rapid drainage), the report enables watershed planners to move beyond generalized assumptions and adopt hydrologically informed, location-specific interventions.

For the Narmada River system, this is critical because the basin functions as a hydrologically heterogeneous watershed, where headwater regions control energy and sediment, middle reaches regulate storage and transformation, and lower reaches experience flow convergence and flood risk. The report therefore provides a basin-wide technical foundation for watershed prioritization, treatment planning, and inter-sectoral water allocation.

2. Application in Watershed-Based Flood Risk Assessment and Runoff Regulation

The water budget analysis clearly demonstrates that the Narmada Basin is runoff-dominated during the monsoon season, with more than 70–80% of annual runoff generated between June and September. Sub-basin-wise runoff estimates, combined with slope and hypsometric analyses, identify specific watersheds in the Upper and Middle Narmada as high-energy runoff source zones, while the Lower Narmada functions as a flow-accumulation and flood-vulnerable zone.

From a watershed management perspective, this report is technically valuable for:

Identification of runoff-generating micro-watersheds

Estimation of peak flow contribution from different elevations

Prioritization of upstream runoff moderation to reduce downstream flood risk

The temporal resolution of the water balance allows identification of critical months (July–August) when peak discharge and sediment transport occur. This enables integration of watershed treatment planning with reservoir operation, flood forecasting systems, and disaster preparedness strategies, ensuring that flood management is addressed at the basin scale rather than through isolated downstream structures.

3. Use in Groundwater Recharge Planning and Baseflow Protection

One of the most critical technical contributions of this report is the quantification of groundwater–surface water interaction across the Narmada Basin. The SWAT-simulated outputs indicate that dry-season flow in the Narmada River and its tributaries is primarily sustained by shallow aquifer return flow, while deep aquifer recharge remains limited across most sub-basins.

From a watershed perspective, this establishes that:

The shallow aquifer system is the hydrological backbone of perennial flow

Any reduction in recharge or excessive abstraction directly impacts river continuity

Watershed interventions must prioritize recharge enhancement over extraction

The report can be directly used to delineate groundwater recharge potential zones, identify watersheds suitable for managed aquifer recharge (MAR), and regulate groundwater abstraction in baseflow-dependent sub-basins. Integration of these findings with administrative boundaries allows district-level agencies to align groundwater policies with actual hydrological behavior rather than normative estimates.

4. Agricultural Watershed Management and Irrigation Planning

HRU-level analysis confirms that agriculture dominates land use across the Narmada Basin (50–75% depending on reach), making it the most influential factor controlling runoff, evapotranspiration, soil erosion, and soil moisture dynamics. The water budget report quantifies crop water use, PET–ET relationships, and seasonal soil moisture stress, providing a robust technical basis for watershed-based agricultural water management.

The report supports:

Optimization of irrigation scheduling based on seasonal water availability

Identification of watersheds vulnerable to moisture stress during high PET periods

Promotion of crop diversification and water-efficient cropping systems

Design of micro-irrigation and on-farm water conservation measures

From the Narmada River perspective, sustainable agriculture within the basin is essential not only for livelihoods but also for reducing runoff peaks, enhancing infiltration, and maintaining baseflow contributions.

5. Soil Conservation, Sediment Control, and Reservoir Sustainability

The integration of land use, soil type, and slope at the HRU level enables identification of critical source areas (CSAs) contributing disproportionately to sediment yield. The report clearly establishes that erosion-prone watersheds in the Upper and Middle Narmada significantly influence sediment inflow into major reservoirs such as Bargi and Sardar Sarovar.

Technically, the report can be used to:

Prioritize ridge-to-valley soil and water conservation measures

Reduce sediment inflow into reservoirs and canal systems

Improve operational life and storage efficiency of hydraulic infrastructure

This watershed-based sediment management approach is essential for sustaining long-term river regulation capacity and minimizing downstream geomorphic instability.

6. Institutional Planning, Policy Support, and Adaptive Watershed Management

By aligning hydrological outputs with administrative boundaries, the report serves as a decision-support tool for state and district-level planning institutions. It bridges the gap between watershed-scale science and implementable programs by enabling:

Evidence-based prioritization of watershed treatments

Integration of water budgeting into river rejuvenation initiatives

Scenario analysis for land-use and climate variability

The report also establishes a baseline hydrological condition against which future changes can be assessed, making it suitable for adaptive watershed management under changing climatic and anthropogenic pressures.

Recommendations for the Narmada River Basin

1. Distributed Runoff Moderation Across Upper and Middle Watersheds

Given the dominance of surface runoff during monsoon months, priority should be given to distributed, non-structural and semi-structural watershed interventions, including:

Check dams, contour bunds, and percolation tanks in mid-slope HRUs

Restoration of natural drainage paths and floodplain connectivity

Synchronization of reservoir operation with upstream runoff moderation

These measures will reduce peak discharge, enhance infiltration, and lower flood risk in downstream watersheds.

2. Protection and Enhancement of Shallow Aquifer Recharge

To sustain baseflow and dry-season river continuity:

Recharge zones identified through SWAT outputs must be protected from over-extraction

Managed aquifer recharge structures should be implemented in suitable HRUs

Groundwater abstraction should be regulated in shallow-aquifer–dependent watersheds

3. Targeted Soil and Water Conservation in Agricultural HRUs

Agricultural watersheds on gentle to moderate slopes should be prioritized for:

Contour farming, terracing, and graded bunding

Mulching, residue management, and conservation tillage

Vegetative buffer strips along streams and drainage lines

4. Land Use Regulation in Hydrologically Sensitive Zones

Steep slope (>15–20%) and erosion-prone watersheds should be subjected to:

Restriction on intensive agriculture

Promotion of afforestation and grassland restoration

Control of unplanned urban expansion in flood-prone lowland

5. Monitoring, Updating, and Adaptive Implementation

The SWAT-based water budget framework should be:

Periodically updated using observed hydro-meteorological data

Integrated with real-time monitoring systems

Used as a continuous planning tool rather than a one-time assessmen

Final Conclusion

From a watershed management perspective, the Narmada River Basin functions as a hydrologically interconnected, spatially heterogeneous system, where monsoon-driven surface runoff governs peak flows while shallow aquifer return flow sustains dry-season river continuity. The long-term sustainability of the Narmada River depends not on increased water extraction, but on retaining rainfall within the basin, enhancing infiltration, protecting groundwater recharge, reducing runoff energy, and aligning land use with hydrological capacity.

The present Water Budget Report provides a scientifically robust foundation for watershed prioritization, ridge-to-valley treatment planning, and adaptive river basin management. Effective implementation of the recommended watershed interventions can significantly reduce flood risk, enhance groundwater sustainability, and strengthen the resilience of the Narmada River system under increasing climatic variability and development pressures.

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