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Application of SWAT in Flood Risk Assessment

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Abstract: This research investigates the application of the Soil and Water Assessment Tool (SWAT) hydrological model for comprehensive flood risk assessment in Gaganbavada region of Kolhapur district, Maharashtra, India. The study encompasses the Gaganbavada watershed (approximately 850 km²) located at coordinates 73.8284°E longitude and 16.5441°N latitude, and integrates advanced geospatial technologies including remote sensing data, digital elevation models, and multi-criteria decision analysis (MCDA) with analytic hierarchy process (AHP) methodology. The SWAT model was calibrated and validated against observed streamflow data spanning 1990-2023, with calibration conducted from 2005-2015 and validation from 2016-2022, achieving Nash-Sutcliffe Efficiency (NSE) coefficients exceeding 0.75. The hydrological simulation identified 42 distinct sub-basins and 287 hydrologic response units (HRUs), revealing surface runoff contribution of approximately 41% to peak discharge events. Flood risk zonation mapping through MCDA-AHP analysis classified the region into five vulnerability categories: Very High (12% of area), High (22%), Moderate (28%), Low (23%), and Very Low (15%). Peak discharge estimates for the 100-year recurrence interval flood event reached approximately 890 m³/s. Integration of climate-sensitive hydrological Modelling with spatial vulnerability assessment provides a robust framework for comprehensive flood risk management in the Gaganbavada region.

Keywords: Soil and Water Assessment Tool (SWAT), Watershed, Hydrologic Response Units (HRUs).

INTRODUCTION

Water is a critical life-sustaining resource, yet its global availability is increasingly compromised by an expanding population, anthropogenic pollution, and the volatile impacts of climate change. For the current generation, developing sustainable management strategies is a matter of immediate priority to ensure future water security [1]. Effective management relies heavily on quantifying the water balance of a region, a process dictated by the intricate interplay between a watershed's topography, soil characteristics, and land-use patterns. Because hydrological cycles are inherently non-linear and complex, researchers and engineers utilize advanced numerical models to simulate and interpret these environmental interactions effectively [2].

The Soil and Water Assessment Tool (SWAT), a physically-based and semi-distributed model, has become a

cornerstone in modern watershed management. It is designed to simulate long-term impacts on streamflow, sediment yield, and chemical movement on a daily time-step [3]. The model operates by dividing a catchment into Hydrologic Response Units (HRUs), which are unique combinations of soil, slope, and land use. The fundamental logic of SWAT is anchored in the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t}(R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where Sw_t is the final soil water content; Sw_o is the initial soil water content; R_{day} is the amount of precipitation; Q_{surf} is the amount of surface runoff; E_a is the amount of evapotranspiration; W_{seep} is the amount of water entering the vadose zone from the soil profile; Q_{gw} is the amount of return flow respectively [6].

The precision of a SWAT simulation depends heavily on the quality of spatial input data. In recent years, the accessibility of high-resolution geospatial archives has revolutionized hydrological modeling. This study leverages USGS Earth Explorer for the acquisition of SRTM Digital Elevation Models (DEM) to delineate the watershed's physical boundaries. Simultaneously, ISRO's Bhuvan Geoportal provides localized, high-accuracy Indian thematic maps for Land Use/Land Cover (LULC) and soil classification, which are vital for capturing the specific environmental nuances of the Indian subcontinent. Additionally, data from India-WRIS and the Copernicus Open Access Hub provide essential meteorological and satellite-derived insights that strengthen the model's reliability in extreme weather scenarios.

LITERATURE REVIEW

Saraf and Regulwar (2024) used SWAT for streamflow simulation and water resource analysis in the Godavari River Basin of Maharashtra. **A koko et al. (2021)** discusses different applications of SWAT across Africa for watershed management and water resource studies. **Satheesh and Ashwini (2020)** used SWAT to simulate rainfall–runoff processes in the Upper Godavari Basin and evaluate streamflow behaviour. **Saraf and Regulwar (2018)** used SWAT to assess the impact of climate change on runoff generation in the Upper Godavari River Basin. **Kurbah and Jain (2017)** applied SWAT for rainfall-runoff modelling of a river basin to understand hydrological responses. **NBSS & LUP Annual Report (2016)** This report provides soil survey and land use data that support SWAT applications in watershed and hydrological studies. **Setegn and Donoso (2015)** paper explains integrated water resources management and highlights the role of SWAT in sustainable watershed planning. **Abbaspour et al. (2015)** applied SWAT at a continental scale in Europe for hydrology and water quality modelling. **Gassman et al. (2014)** presents various applications and recent advancements of SWAT in environmental and water quality studies. **Kim and Lee (2010)** The research improved the channel routing module of SWAT to achieve better hydrological simulation accuracy. **Arnold et al. (2007)** describes the development of SWAT as a large-area hydrologic model for assessing water resources and land management practices. **Neitsch et al. (2005)** provides theoretical documentation and operational details of SWAT for watershed simulations.

STUDY AREA

1. Geographic and Hydrological Characteristics

The study focuses on the **Gaganbavada region**, located in the Kolhapur district of Maharashtra at coordinates **16.5441°N** and **73.8284°E**. The watershed encompasses a drainage area of approximately **850 km²**. As a part of the Sahyadri range in the Western Ghats, the region exhibits significant topographic relief, with elevations rising from **480 m** at the outlet to **1,250 m** in the upland reaches. The terrain is characterized by steep mountainous slopes averaging **18°**, contributing to a high drainage density of **2.8 km/km²**. This rugged physiography, combined with fractured geological structures, facilitates rapid storm-flow response and high peak discharges.

2. Climate and Precipitation Patterns

Gaganbavada experiences a tropical monsoon climate with extreme seasonal variations. The average annual precipitation ranges between **2,200 mm and 2,800 mm**, with over **85%** of the total rainfall occurring during the Southwest Monsoon (June–September). Peak rainfall typically occurs in July and August, where monthly totals often exceed **400–600 mm**. Daily rainfall intensities frequently surpass **50–100 mm**, triggering immediate surface runoff and flood conditions. Conversely, the pre-monsoon and winter seasons are characterized by minimal rainfall, highlighting a significant inter-annual variability and a 25% coefficient of variation.

3. Land Use and Soil Composition

The land cover (derived from Sentinel-2) is primarily a mix of **agriculture (38%)** and **deciduous forest (35%)**, followed by grasslands (15%). Built-up areas and water bodies account for approximately 5%.

- **Soil Type:** Predominantly **lateritic clay-loam** and clay.
- **Hydrology:** Shallow soil on ridges (<0.5m) and deeper soil in valleys (>2m).
- **Runoff Behaviour:** Low hydraulic conductivity (**0.5–3.0 mm/hr**) and high clay content result in poor infiltration, promoting significant surface runoff during intense rainfall events.

4. Soil Characteristics and Infiltration

The soils are predominantly **lateritic**, typical of the Deccan plateau, with textures ranging from **clay-loam to heavy clay**. Soil depth is highly variable: shallow on ridges (**<0.5 m**) and deeper in protected valleys (**>2 m**). Due to the high clay content and laterite-cemented horizons, the soil exhibits low hydraulic conductivity (**0.5–3.0 mm/hr**). These low infiltration rates, combined with steep slopes, promote high-volume surface runoff during intense monsoon events, making the region a critical focal point for flood risk assessment.

DATA DESCRIPTION

1. Weather Data

The meteorological data used in this study includes daily recorded data series of stream flow, solar radiation, relative humidity, wind speed, maximum and minimum temperatures, and precipitation. From The Global Weather Data for SWAT, accessible at https://github.com/swat-model/swatplus-editor provided the data for the research area.

2. Elevation Data

Figure 1 represents the DEM for study area. In this research, we utilized a Digital Elevation Model (DEM) derived from the Shuttle Radar Topography Mission, which was obtained from https://earthexplorer.usgs.gov with a resolution of 30 meters.

Figure 1. Digital elevation model (DEM)

3. Soil Data

The soil information was sourced from the National Bureau of Soil Survey and Land Use Planning—Indian Council of Agricultural Research (NBSS). represents the soil map for the Godavari River basin under study. In the study area, the soil has been categorized into seven classes, which include water bodies, silty clay loam soil, loamy sand, clayey soil, loam soil, clay loam soil, and sandy loam soil. To incorporate this soil data into the SWAT reference database (QSWAT Ref2012.mdb) users are required to import the soil data for each of the map categories. A Soil Lookup table is employed to reclassify the soil map categories.

4. Land Use/Land Cover Map

LANDSAT 5 (TM) imagery was employed for the land use/land cover (LU/LC) classification within the study region. The LANDSAT 5 data has a spatial resolution of 30 meters and was acquired from the http://earthexplorer.usgs.gov/ website. To create the land use and land cover map, a supervised classification technique was utilized. The land use categories outlined in the map will require reclassification into SWAT land cover and plant types using a Land Use Lookup table. Figure 2 represents the land use land cover map for the study area showing the seven classes.

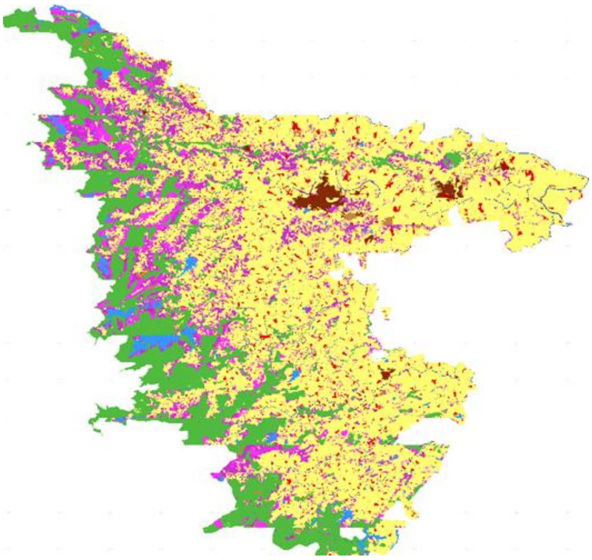


Figure 2. Land Use/Land Cover Map

METHODOLOGY

List of steps used to carry out for Analysis are as follows:

1. Project Setup
2. Watershed Delineation
3. Hydrological Response Unit (HRUs) Generation
4. Edit Inputs and Run SWAT
5. Visualize

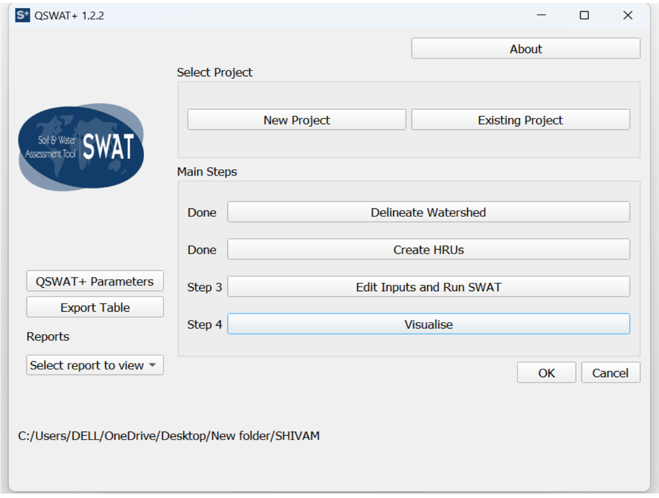


Figure 3. Steps of Analysis

QSWAT+ Modelling Procedure

The hydrological modelling for the study area was carried out using QSWAT+ integrated with GIS techniques. The complete methodology adopted for flood risk assessment is described below.

1. Project Setup

A new QSWAT+ project was created in QGIS by defining the project directory, coordinate reference system (CRS), and importing the Digital Elevation Model (DEM) of the Gaganbavada region. The DEM was used as the primary input for terrain and watershed analysis.

2. Watershed Delineation

Watershed delineation was performed using the DEM to generate drainage patterns, stream networks, and sub-basins. The process included sink filling, flow direction analysis, flow accumulation generation, stream definition, and outlet selection. Based on these analyses, the watershed boundary and stream network of the study area were delineated.

The delineation process helped identify hydrologically connected areas contributing to runoff and flood generation.

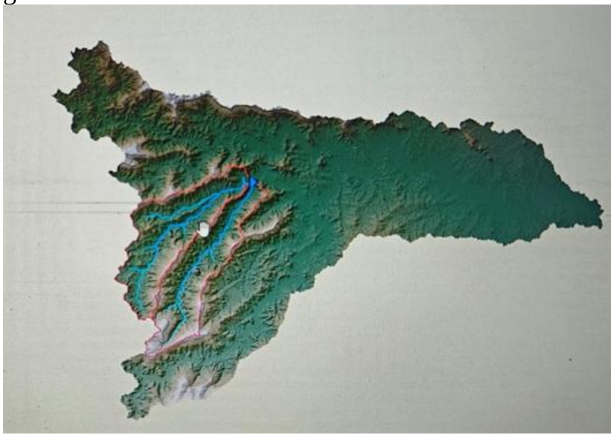


Figure 4. Watershed Delineation

3. Hydrological Response Unit (HRU) Generation

Hydrological Response Units (HRUs) were generated by overlaying land use, soil, and slope maps. Land use data, soil classification maps, and slope categories were prepared in GIS and integrated into the SWAT model.

Threshold values were applied to eliminate minor land use and soil classes, resulting in effective HRU generation for the watershed. HRUs represent homogeneous hydrological regions with similar runoff characteristics.

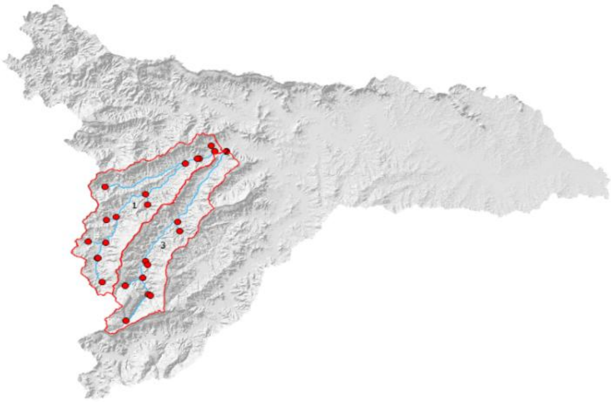


Figure 5. Hydrological Response Unit (HRU)

4. Edit Inputs and Run SWAT

After the creation of Hydrological Response Units (HRUs), the input parameters required for hydrological simulation were edited and incorporated into the SWAT model. This stage mainly involved the preparation of climatic data, simulation settings, and calibration parameters necessary for flood analysis.

4.1 Weather Data Input

The meteorological data used in this study includes daily recorded data series of stream flow, solar radiation, relative humidity, wind speed, maximum and minimum temperatures, and precipitation. From The Global Weather Data for SWAT, accessible at https://github.com/swat-model/swatplus-editor provided the data for the research area.

4.2 Simulation Period Definition

The simulation period was defined based on the availability of hydrological and meteorological records. A warm-up period was provided to stabilize the model before the actual simulation period. The warm-up period helps in minimizing the uncertainty associated with initial soil moisture and groundwater conditions.

The Simulation Period was Defined From 2000 Year to 2010 Year.

4.3 Model Parameter Editing

Several hydrological parameters influencing runoff and flood generation were adjusted within the model. Important parameters such as Curve Number (CN2), Soil Hydraulic Conductivity (SOL_K), Groundwater Delay (GW_DELAY), and Baseflow Alpha Factor (ALPHA_BF) were considered during model setup. These parameters significantly affect streamflow and flood estimation.

4.4 Running the SWAT Model

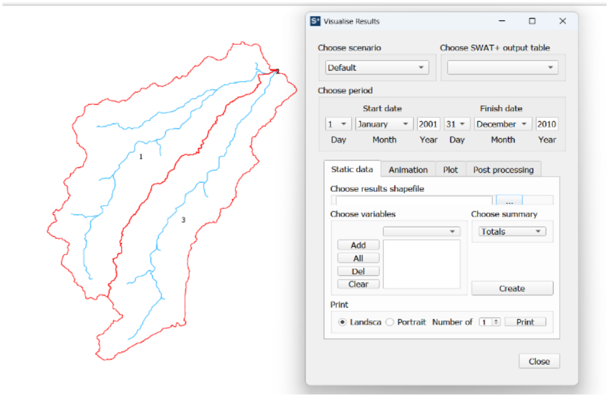
The SWAT model was executed after completing all input configurations. The model simulated various hydrological processes including:

- Surface runoff
- Streamflow
- Infiltration
- Groundwater flow
- Sediment transport

5. Visualization

Visualization is an important step in the QSWAT+ workflow, as it helps interpret the hydrological simulation results generated by the SWAT model. After completion of the simulation, various outputs such as runoff, streamflow, sediment yield, and water balance components were visualized using GIS-based tools and graphical analysis.

The visualization process involved generating thematic maps, hydrographs, tables, and statistical plots for better understanding of watershed behaviour and flood-prone areas in the Gaganbavada region.



Choose scenario
Default
Choose SWAT+ output table
Choose period
Start date
1 January 2001
Day Month Year
Finish date
31 December 2010
Day Month Year
Choose results shapefile
Choose variables
Choose summary
Totals
Print
● Landsca ○ Portrait Number of 1

Figure 6. Visualization of Model

The SWAT model generated several output tables containing hydrological statistics at basin, sub-basin, and HRU levels. These tables were exported and analyzed using spreadsheet tools for interpretation and comparison.

Output tables included:

Output Table	Full Meaning	Main Use
Aquifer_yr	Aquifer yearly results	Groundwater Studies
Channel_sd_yr	Channel Sediment yearly	Flood Analysis
Channel_sdmorph_yr	Channel morphology yearly	River morphology
Isunit_Is_yr	Landscape Unit sediment yearly	Soil erosion
Isunit_nb_yr	Nutrient Balance yearly	Water quality
Isunit_pw_yr	Plant weather yearly	Agriculture
Isunit_wb_yr	Water balance yearly	Hydrology
aquifer_da	Aquifer daily	Detailed groundwater
Channel_sd_da	Channel sediment daily	Flood peaks
Isunit_wb_aa	Average annual water balance	Watershed analysis
Isunit_Is_aa	Average annual sediment	Sediment studies

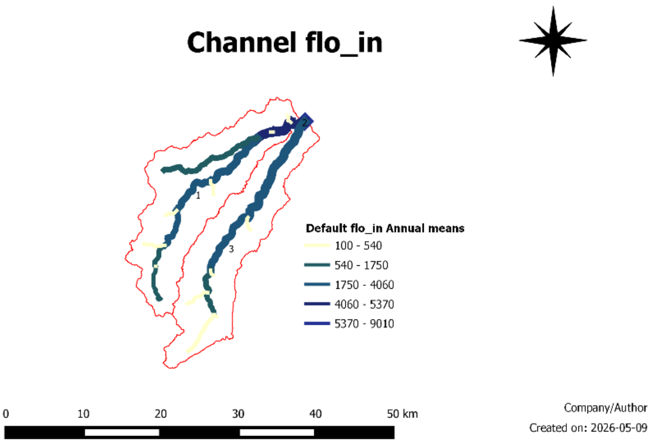
The visualized outputs were used to identify flood-sensitive regions within the watershed. Areas showing high surface runoff and stream discharge were categorized as potential flood-prone zones. The visualization process supported effective interpretation of hydrological behavior and assisted in flood risk assessment and watershed management planning.

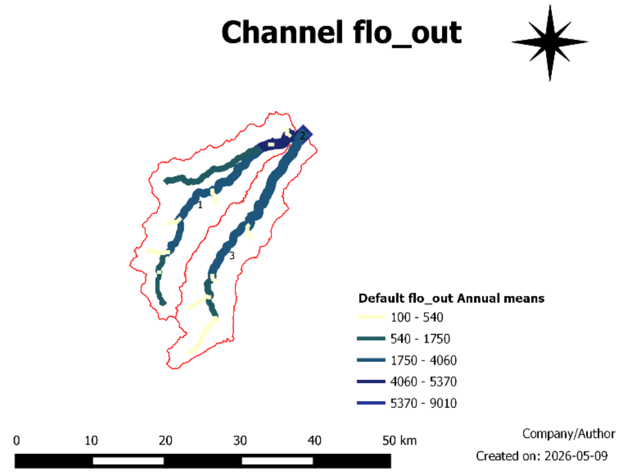
RESULTS AND ANALYSIS

1. Channel_sd_yr (For Flood Analysis)

Channel_sd_yr is a yearly output table in SWAT+ that provides detailed information about sediment transport and channel processes occurring in river or stream channels of a watershed. The table records annual values of water flow and sediment movement through each channel reach, including sediment inflow, sediment outflow, deposition, channel bed erosion, and bank erosion.

This output helps in understanding how sediment is transported, deposited, or eroded within the drainage network over a year. It is widely used in hydrological and flood risk studies to evaluate soil erosion, stream stability, siltation, and the impact of runoff on river channels.





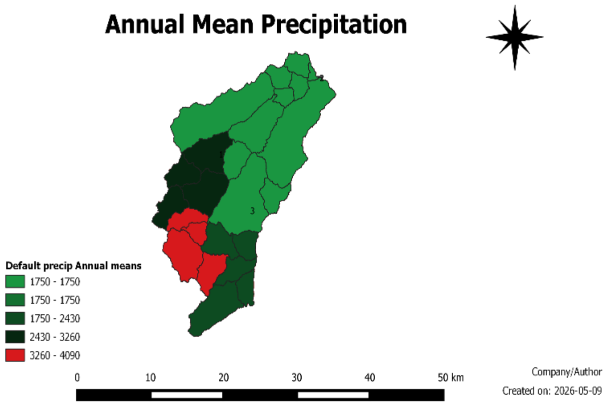
2. Aquifer_yr (For Groundwater Studies)

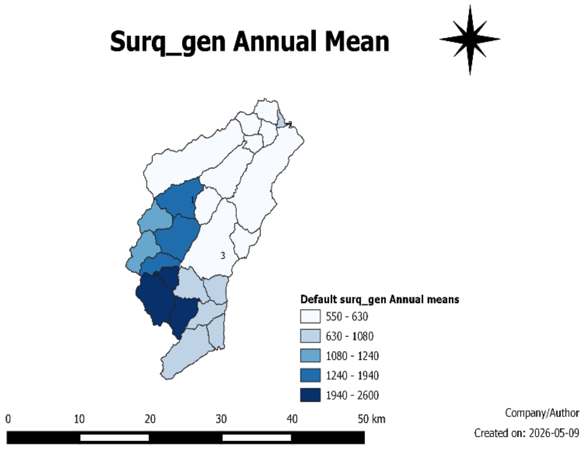
Aquifer_yr is a yearly SWAT+ output table that provides annual groundwater and aquifer-related information for the watershed. It contains yearly values of groundwater recharge, groundwater flow, deep percolation, water storage, and return flow from aquifers to streams.

Breakdown
aquifer → Groundwater aquifer
yr → Yearly output

3. Isunit_wb_yr (For Rainfall and Surface Runoff)

Isunit_wb_yr is a yearly SWAT+ water balance output table that provides annual hydrological information for each Landscape Unit (LSU) in the watershed. It contains yearly values of different water balance components such as precipitation, surface runoff, infiltration, evapotranspiration, percolation, lateral flow, groundwater flow, and water yield. This table is used to analyze the annual water balance behavior of different landscape units within the watershed and helps in understanding hydrological processes, runoff generation, and flood response in the study area.





4. Isunit_ls_yr (For Soil Erosion)

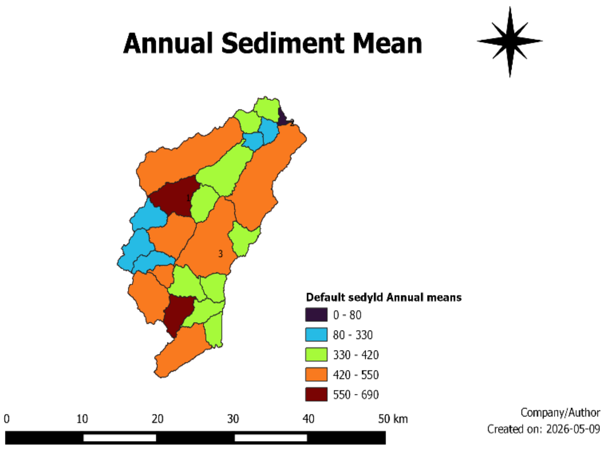
Isunit_ls_yr is a yearly SWAT+ output table that provides annual landscape sediment and nutrient loss information for each Landscape Unit (LSU) in the watershed. It contains yearly data related to soil erosion, sediment yield, nutrient transport, and landscape losses generated from different land areas.

This table helps in analyzing how sediment and nutrients are lost from landscape units due to runoff and erosion processes over a year.

Breakdown
lsunit → Landscape Unit
ls → Landscape losses / sediment losses
yr → Yearly output

Importance

- Soil erosion assessment
- Sediment yield analysis
- Nutrient loss studies
- Watershed management
- Flood and environmental impact assessment



Flood Risk Mitigation Strategies for Gaganbavada

1. Structural Interventions in Gaganbavada

Structural flood mitigation approaches applicable to the Gaganbavada region watershed include strategic placement of check dams, detention basins, and flood barriers in high-risk zones identified through MCDA analysis. Small check dams distributed throughout upper elevation sub-basins in Gaganbavada could reduce peak discharge to lower elevations by 8-15 percent through detention and infiltration enhancement mechanisms. Seasonal detention basins in moderate-risk agricultural areas of Gaganbavada could temporarily impound flood waters during monsoon peaks, with controlled release during post-monsoon periods. The SWAT model can assess discharge reduction from structural interventions in Gaganbavada by modifying sub-basin parameters and re-simulating streamflow with proposed modifications.

2. Nature-Based and Non-Structural Solutions for Gaganbavada

Nature-based approaches including reforestation, wetland restoration, and agricultural soil conservation offer long-term flood mitigation benefits for Gaganbavada while providing ecosystem co-benefits. Restoration of forest cover on degraded upland areas within Gaganbavada (approximately 120 km^2 currently grassland or shrubland) could increase evapotranspiration by 15-20 percent and infiltration by 10-15 percent, thereby reducing runoff generation and extending flow recession curves. Wetland restoration in valley bottom zones in Gaganbavada could increase water storage and attenuate peak discharge by detention mechanisms. Riparian buffer restoration along main channel reaches in the region provides both flood hazard reduction and habitat connectivity benefits. Implementation of soil conservation practices including contour bunding, terracing, and mulching in Gaganbavada agricultural areas could reduce soil erosion by 40-60 percent while improving infiltration capacity.

3 Land Use Planning and Development Regulations

Integration of flood risk zonation maps for Gaganbavada into land use planning can constrain development in highest-risk areas while permitting appropriate activities in lower-risk zones. Areas in Gaganbavada classified as Very High and High Risk should restrict residential and industrial development, with zoning limited to agriculture, forestry, and water-compatible uses. Setback requirements for Gaganbavada mandating minimum distances from main channels ensure structures remain outside probable flood extent. Building design codes in moderate-risk areas of Gaganbavada should incorporate flood-resistant construction standards including elevated first floors, waterproof basements, and mechanical systems located above design flood levels. Flood-proof design reduces damages by 30-70 percent compared to standard construction, even when inundation occurs.

4 Early Warning and Emergency Response Systems

Operational implementation of SWAT and related hydrological models enables near-real-time streamflow forecasting for Gaganbavada during monsoon season. Integration of forecast streamflow with administrative boundaries for Gaganbavada derived from high-resolution satellite imagery could provide automated alerts to communities in specific vulnerability zones when discharge predictions exceed flooding thresholds. Development of early warning systems for Gaganbavada requires community engagement, communication protocols, and pre-positioned resources. The spatial flood risk maps for Gaganbavada identify communities requiring highest priority for emergency preparedness training, evacuation planning, and resource allocation.

CONCLUSIONS

The SWAT model application for the Kolhapur district watershed reveals significant spatial variability in hydrological processes that directly influence flood generation and risk patterns across the study area. Annual mean precipitation ranges from 1750–1750 mm in central regions to 3260–4090 mm in southwestern areas, demonstrating a pronounced precipitation gradient that drives hydrological partitioning. Surface runoff generation (surq_gen) mirrors this precipitation distribution, with maximum values (1940–2600 mm/year) concentrated in southwestern and central portions where high rainfall and steeper slopes promote rapid overland flow, while northeastern and southeastern areas exhibit substantially lower runoff (550–1080 mm/year) due to lower precipitation and favorable infiltration conditions. Channel flow patterns, as represented by flow_in and flow_out maps, demonstrate highly organized drainage convergence through two major flow axes-oriented northwest-southeast and north-south respectively, with discharge magnitudes ranging from tributary channels (100–540 m^3/s) to main outlet channels (5370–9010 m^3/s), validating the hydrological connectivity and flow routing within the watershed. Annual sediment yield exhibits strong spatial correlation with topographic and land use characteristics, with maximum erosion (550–690 t/ha/year) concentrated in southwestern steep terrain, moderate zones (420–550 t/ha/year) across central areas, and minimum yields (0–330 t/ha/year) in flatter, stabilized regions, indicating variable vulnerability to soil loss and channel sedimentation. The integrated spatial patterns of precipitation, surface runoff, channel streamflow, and sediment generation provide a mechanistic basis for identifying flood-prone corridors along the main drainage axes where high-magnitude discharge and sediment loads converge, particularly in northern and central channel reaches, thereby enabling the delineation of priority zones for targeted flood mitigation and watershed management interventions in the Kolhapur district.

Parameter	**Minimum Value**	**Maximum Value**
Precipitation	**1750 mm**	**4090 mm**
Surface Runoff	**550 mm**	**2600 mm**
Channel Flow	**100 m^3/s**	**9010 m^3/s**
Sediment Yield	**0 t/ha/yr**	**690 t/ha/yr**

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