Modelling and Management of an Agricultural Watershed of Upper Mahanadi Basin Using HEC-HMS

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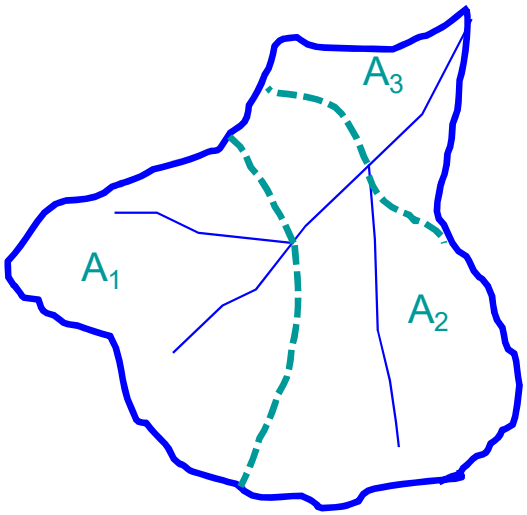
Applications of Watershed Models in India

- **Water Quality and Pollution Control:** Models quantify the impact of pollution from both point and non-point sources to help manage water quality and prevent pollution.
- **Water Quantity and Flood Control:** They are used to assess and manage water resources, including simulating runoff and sediment yield to mitigate floods and droughts.
- **Groundwater Management:** Models help in understanding and improving groundwater recharge through various conservation techniques.
- **Soil and Water Conservation:** They are applied to identify areas vulnerable to soil erosion and to evaluate the effectiveness of conservation measures and land treatments.
- **Integrated Watershed Management:** Models help in creating comprehensive watershed management plans, allowing for a holistic approach to utilizing natural resources and planning developmental initiatives.
- **Evaluating Management Strategies:** They provide a tool to simulate and compare different management scenarios to find the most beneficial and cost-effective solutions for a watershed, such as comparing different tank systems for water storage.

Spatial Scaling of Models

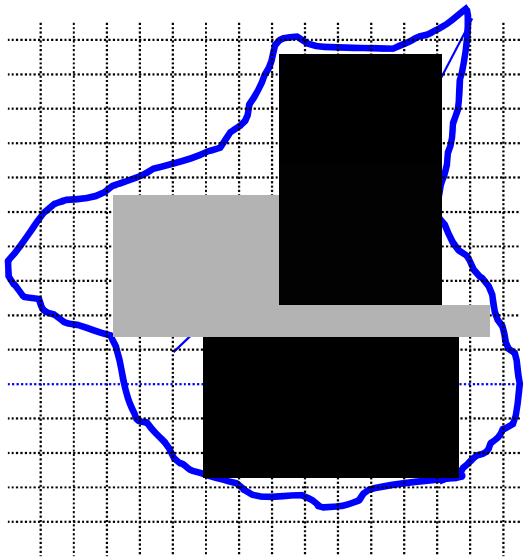
Lumped

Parameters assigned to each sub-basin



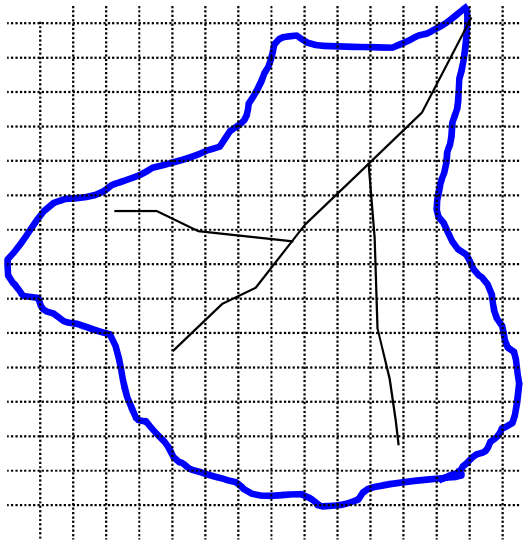
Semi-Distributed

Parameters assigned to each grid cell, but cells with same parameters are grouped



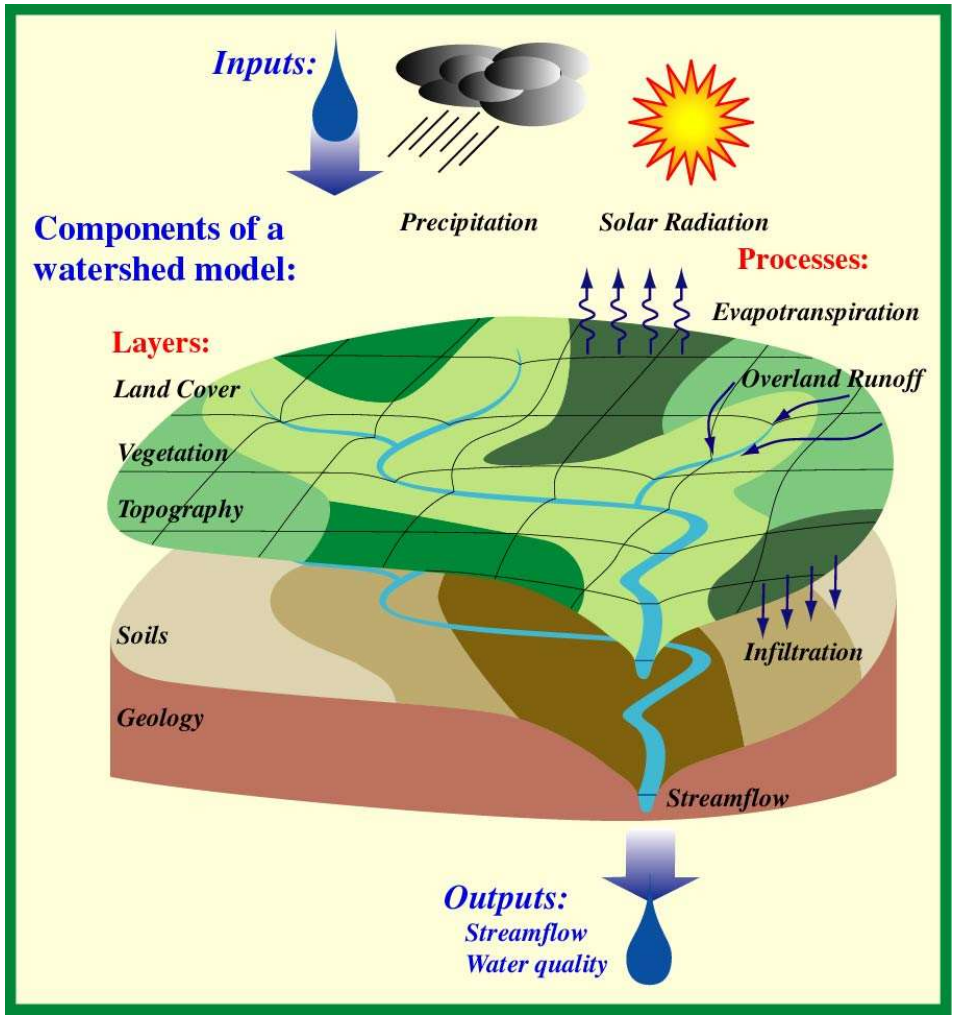
Fully-Distributed

Parameters assigned to each grid cell



HYDROLOGICAL MODELS

Input - Output



= Storage

Based on Hydrologic Cycle and Water Balance

In general, a model can be defined as a deliberately simplified construct of nature erected for the purpose of understanding a phenomenon (Batchelor, 1994).

A watershed hydrology model is an assemblage of component models corresponding to different components of hydrologic cycle (Singh, 1995).

Models used to assess impact of human activities (such as change in land use/land cover, tillage practices and installing soil conservation measures) on water quality are generally referred as water quality models.

- **Several computer models of hydrology are in use to assess various problems related to watershed.**
- **Among these models HEC-HMS is recent one and it has been used most widely for simulating the runoff, sediment yield and water quality of the small, medium and large watersheds or sub-basins.**
- **It is the physically based and conceptual semi-distributed parameter model designed to simulate the rainfall, runoff and soil loss processes in a wide range of geographic areas.**
- **A numerical model that can help to predict runoff volumes, peak flows, and timing of flows by simulating the behaviors of the watersheds, channels and reservoirs.**
- **HEC-HMS is one of the more recently developed semi-distributed parameter continuous time step model Developed by US Army Corps of Engineers, Hydrologic Engineering Center (USACE, 2010).**
- **The Graphical User Interface makes the model user friendly and public domain, Can be downloaded from HEC website at no cost.**

Objectives

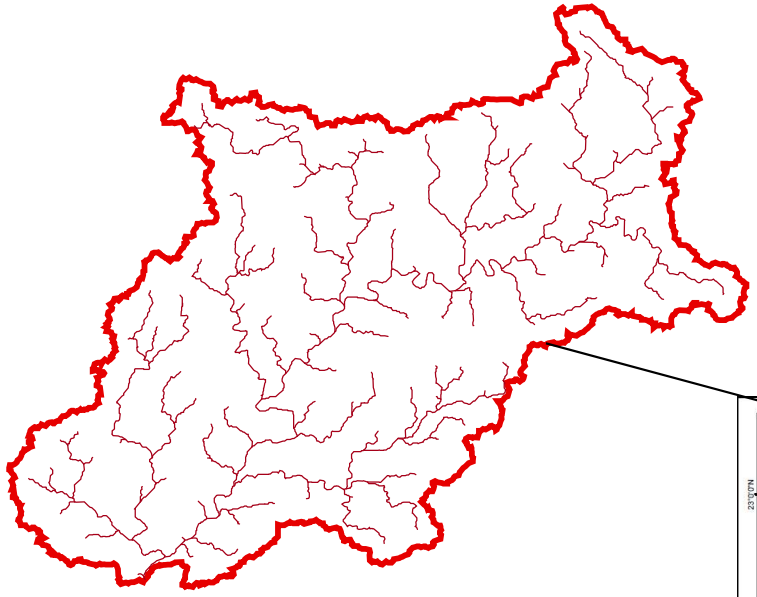
1. To calibrate and validate HEC-HMS model for simulating daily and monthly surface runoff and sediment yield from a watershed.

2. To identify and prioritize critical sub-watersheds on the basis of estimated surface runoff and sediment yield for multiple years.

3. To develop water resources management plan for most critical sub-watershed of the study area.

- **Through the gauging network of rainfall, runoff and sediment yield it is possible to evaluate and assess the impact of watershed management plans on soil, water and nutrient losses.**
- **Hydrological modelling is necessary for design of conservation measure to reduce the ill effects of runoff and sedimentation as well as to identify critical watershed for implanting watershed management programmes with limited financial resources.**
- **A Model should be adequately tested before using for effective management of any watershed.**
- **Adoption of adequate procedure for calibration and validation of a model for a watershed will provide the opportunity to develop the appropriate management plan for critical erosion prone areas.**
- **The implementation of the plan can enhance the productivity of the watershed in a sustainable manner.**

Location of Study Area (Manendragarh Watershed)



Location

Longitude $82^0 13'02''$ E

Latitude $23^0 12'13''$ N

Gauging station Manendragarh (GDSQ)

Catchment area 1025 km^2

Elevation

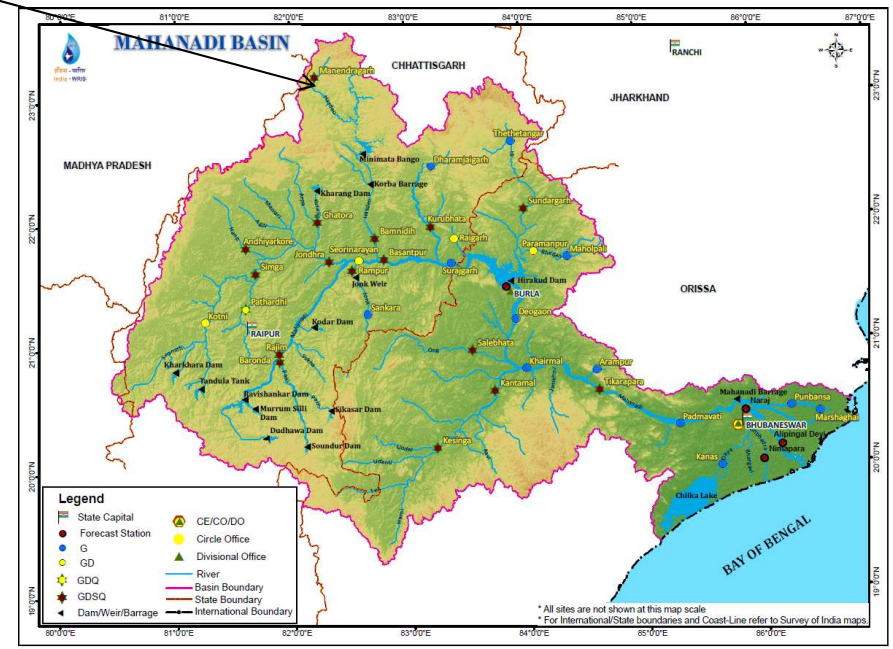
351 to 989 (m) MSL

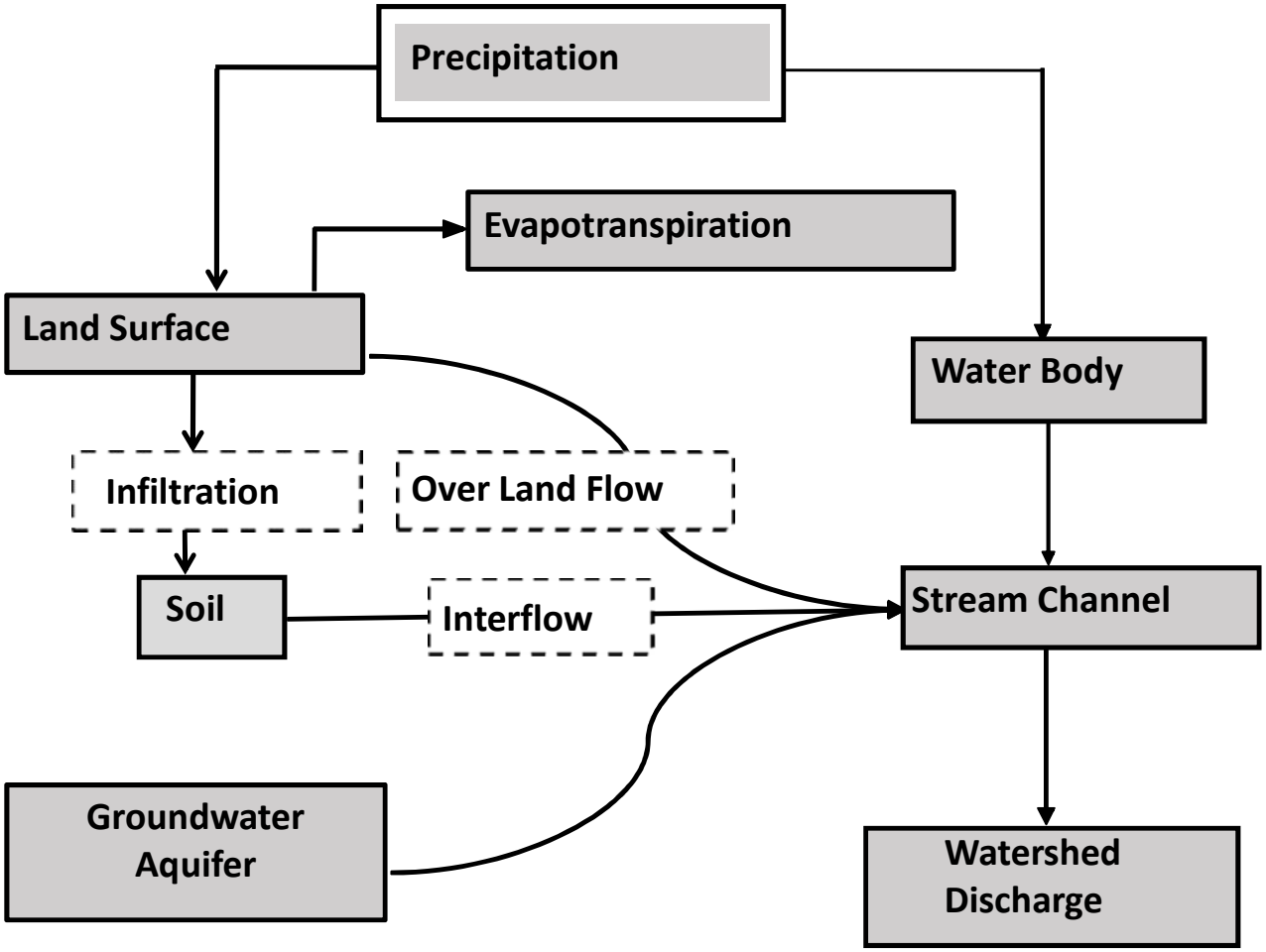
Soil

Clay loam, Coarse sandy clay, Loam, Sandy loam

Topography

Gently undulating and hilly terrain





Typical HEC-HMS Hydrological Representation of Watershed Runoff

Input data for HEC-HMS Model

- Digital Elevation Model (DEM)
- Rainfall data
- Stream flow gauge data
- Sediment yield data
- Soil types
- Land use/cover data
- Drainage network and outlet point

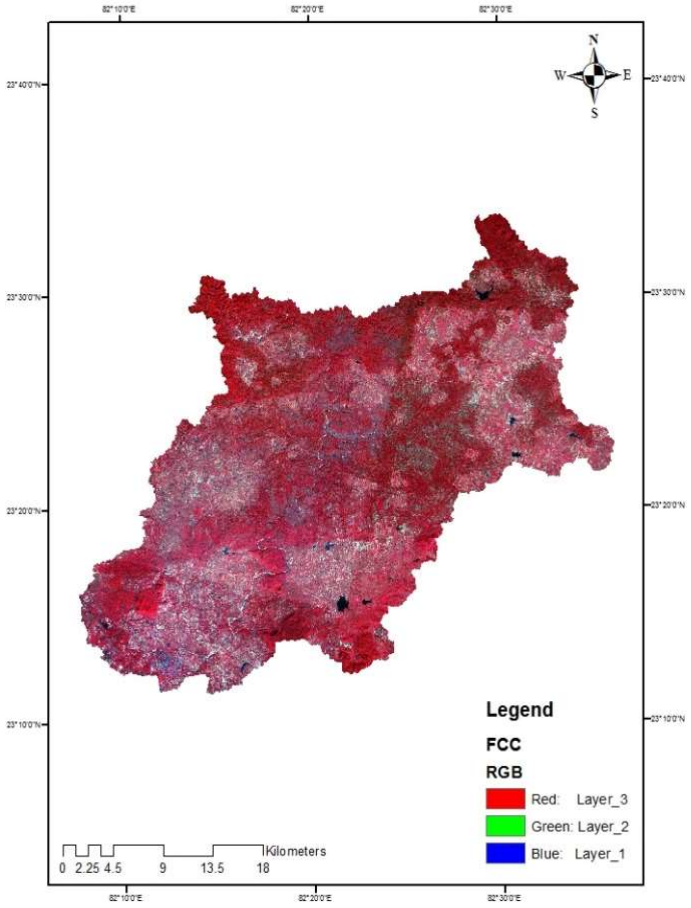
Satellite Data: LISS IV Image *(IRS-P6)*

ISRO Bhoonidhi Portal

Resolution (m)	Spectral Bands	Swath	Revisit
5.8	G-B2 0.52 - 0.59 R-B3 0.62 - 0.68 NIB4 0.77 - 0.86	23.9 km (Mx)* 70 km (Mono mode)	5 Days

* Multispectral mode

SAT	PATH	ROW	DOP
IRSR-2	102	56	23 Oct 2009
IRSR-2	102	56	16 Nov 2009
IRSR-2	102	55	16 Nov 2009
IRSR-2	102	56	23 Nov 2009



Indian Remote Sensing Resourcesat-2 satellite

Web Source: http://www.nrsa.gov.in

Rainfall Data
CWC Stations: from 2000 to 2018
Monsoon and Non- Monsoon both

Discharge Data
CWC Stations: from 2000 to 2018
Monsoon and Non- Monsoon both

Silt Data
CWC Stations: from 2000 to 2018
Total No. of Stations: 01

Toposheets
Office Survey of India, Chhattisgarh
Total no. of toposheest: 2

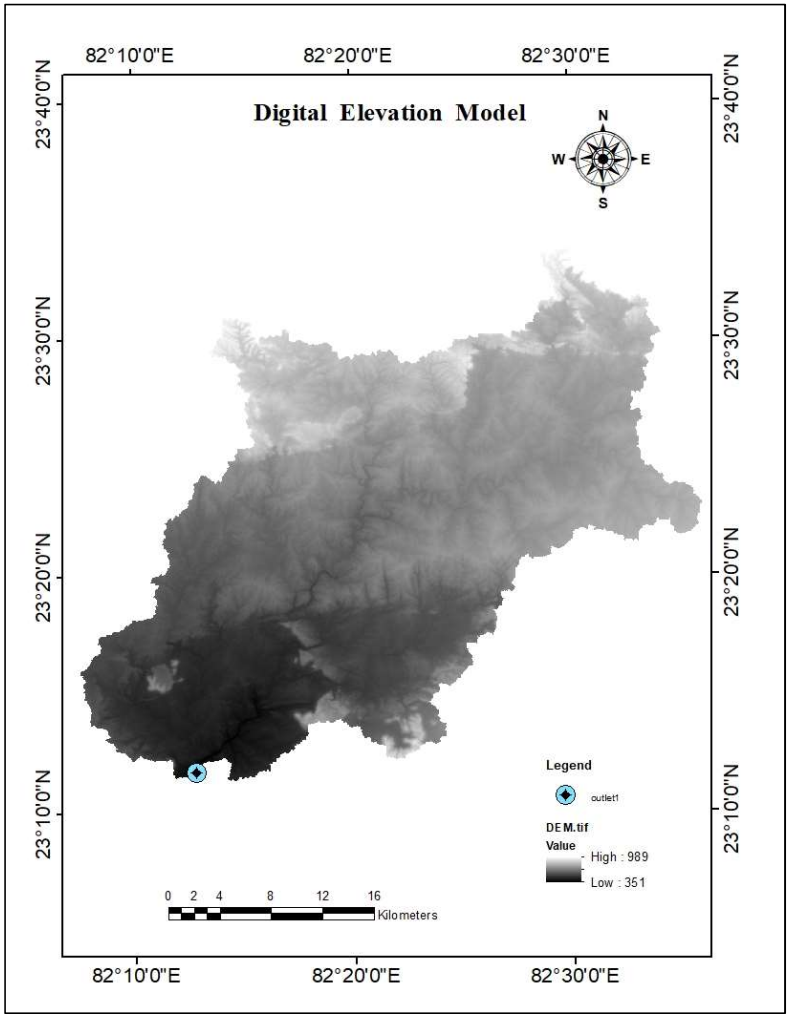
Geological Data
Chhattisgarh State Watershed Management Agency, Govt. of C.G., Raipur

Lineament Data
Chhattisgarh State Watershed Management Agency, Govt. of C.G., Raipur

Soil Texture Map
ICAR-NBSS, Nagpur

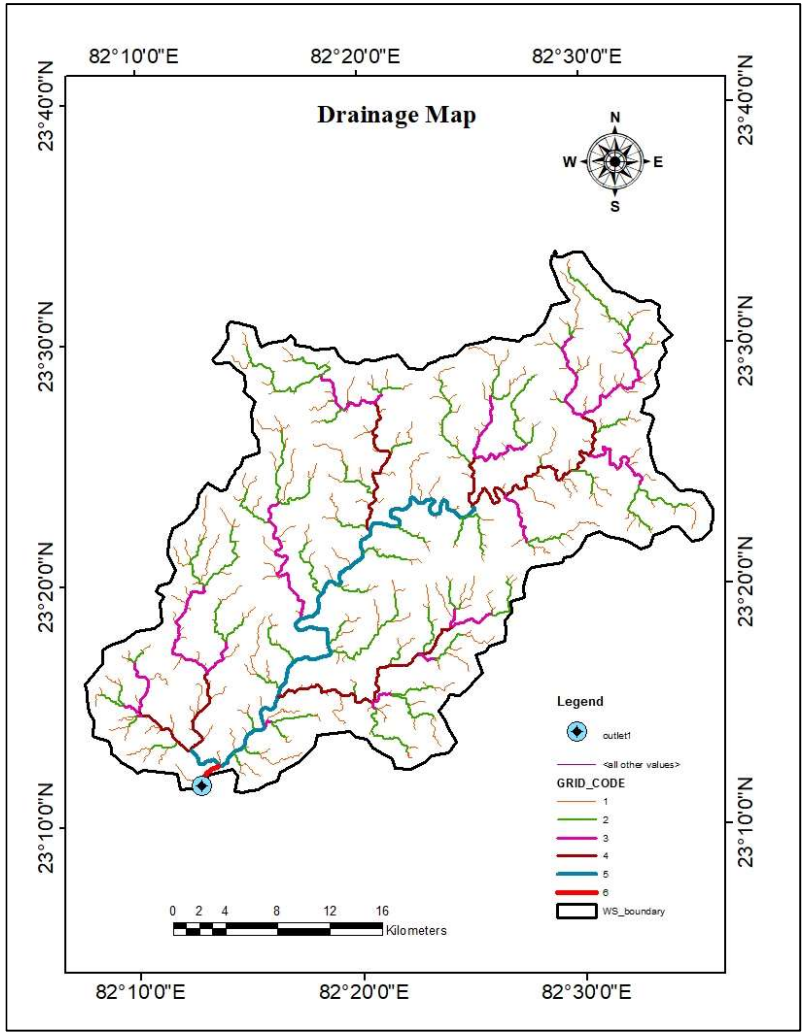
Digital Eelevation Model (12.5m)
Web Source:
(www.vertex.daac.asf.alaska.edu)

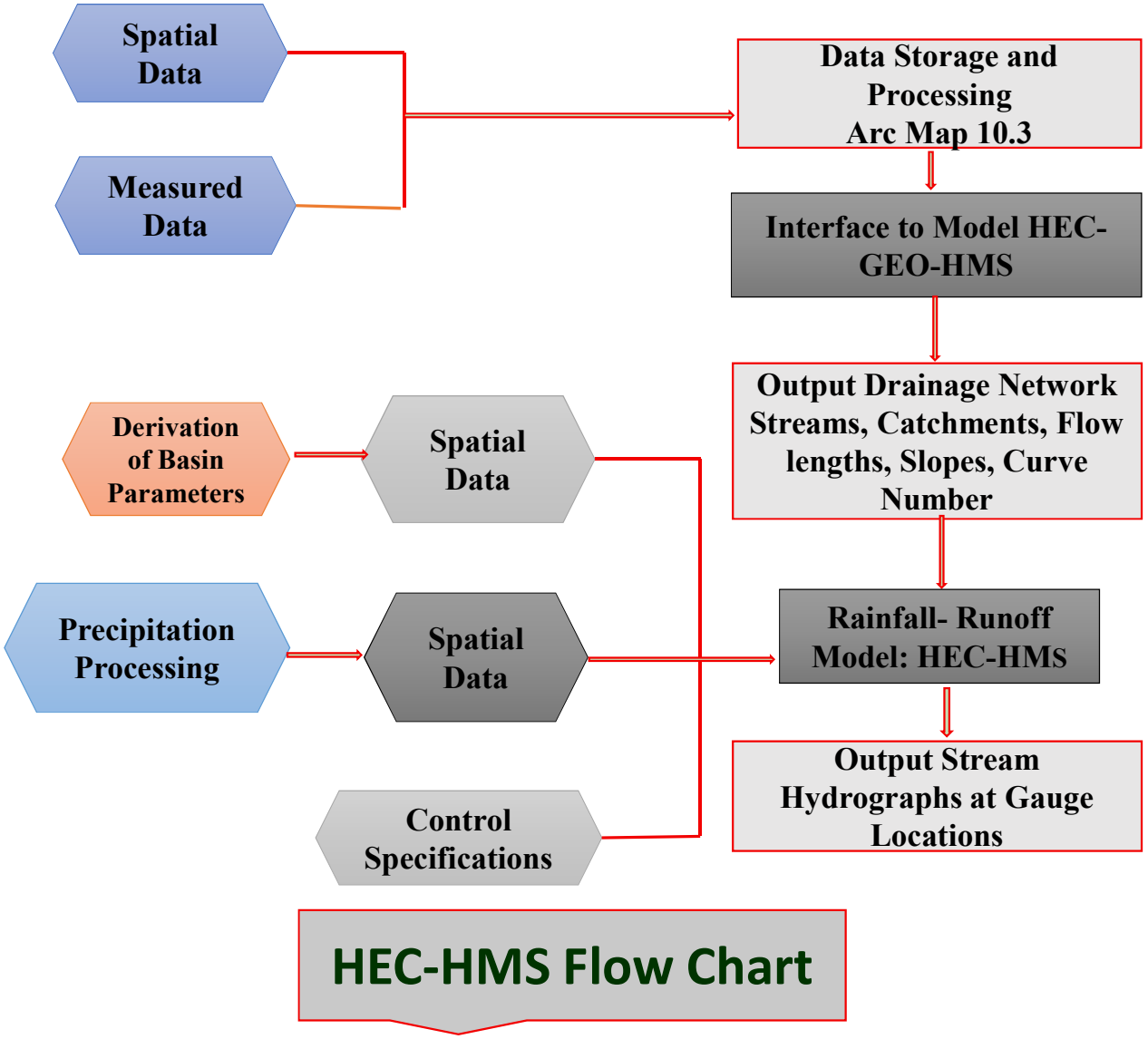
DIGITAL ELEVATION MODEL (DEM)



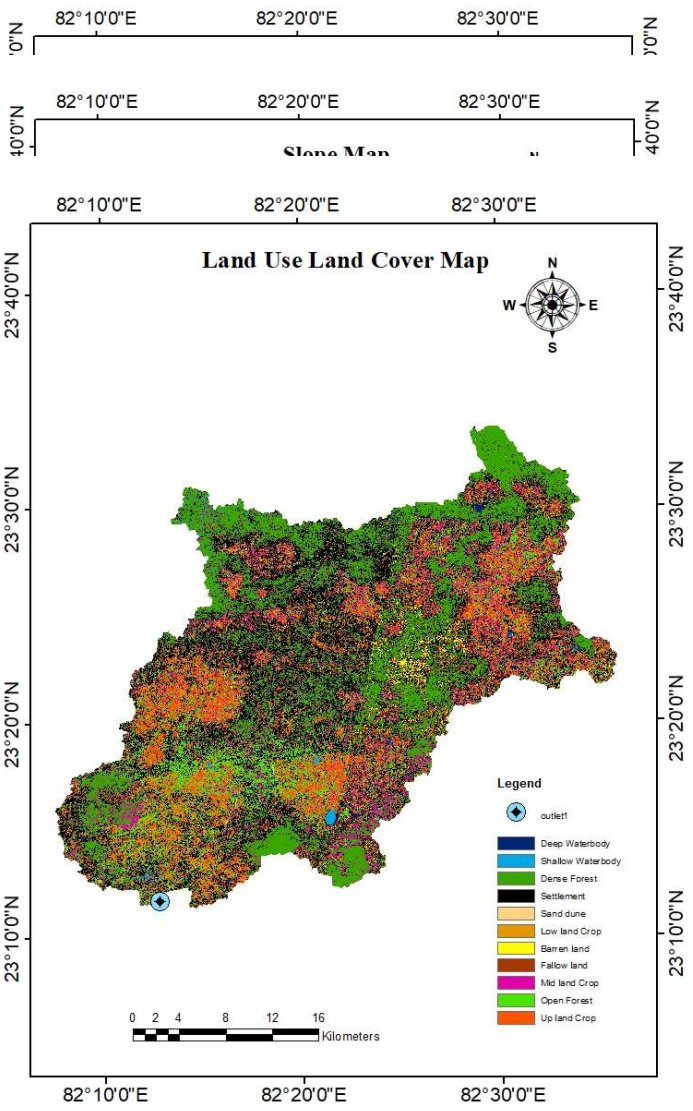
DRAINAGE NETWORK

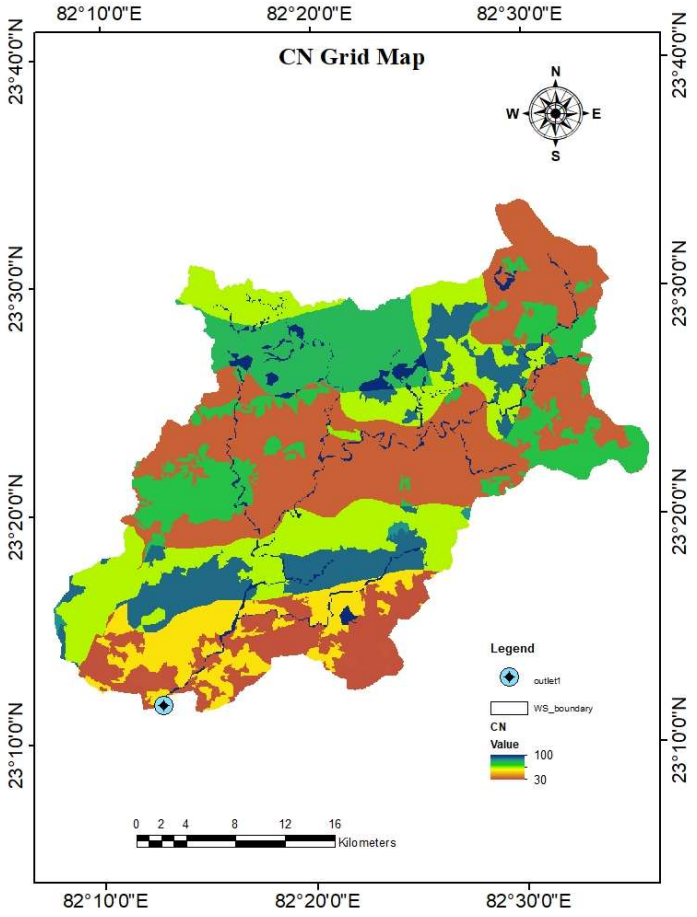
S.No.	Stream Order	Stream Number
1	N1	337
2	N2	163
3	N3	138
4	N4	40
5	N5	1
Total		679

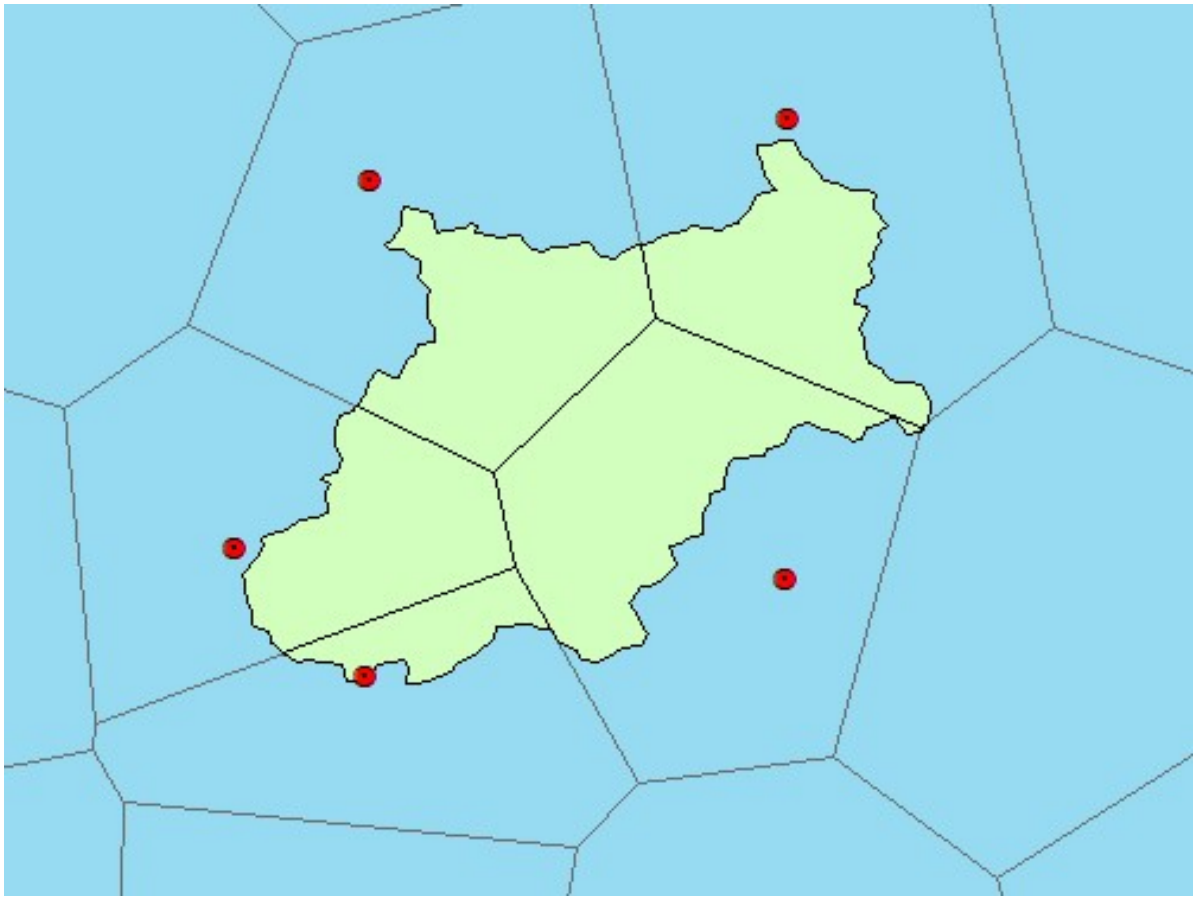



Spatial Data
Measured Data
Data Storage and Processing Arc Map 10.3
Interface to Model HEC-GEO-HMS
Output Drainage Network Streams, Catchments, Flow lengths, Slopes, Curve Number
Derivation of Basin Parameters
Spatial Data
Precipitation Processing
Spatial Data
Rainfall- Runoff Model: HEC-HMS
Output Stream Hydrographs at Gauge Locations
Control Specifications
HEC-HMS Flow Chart

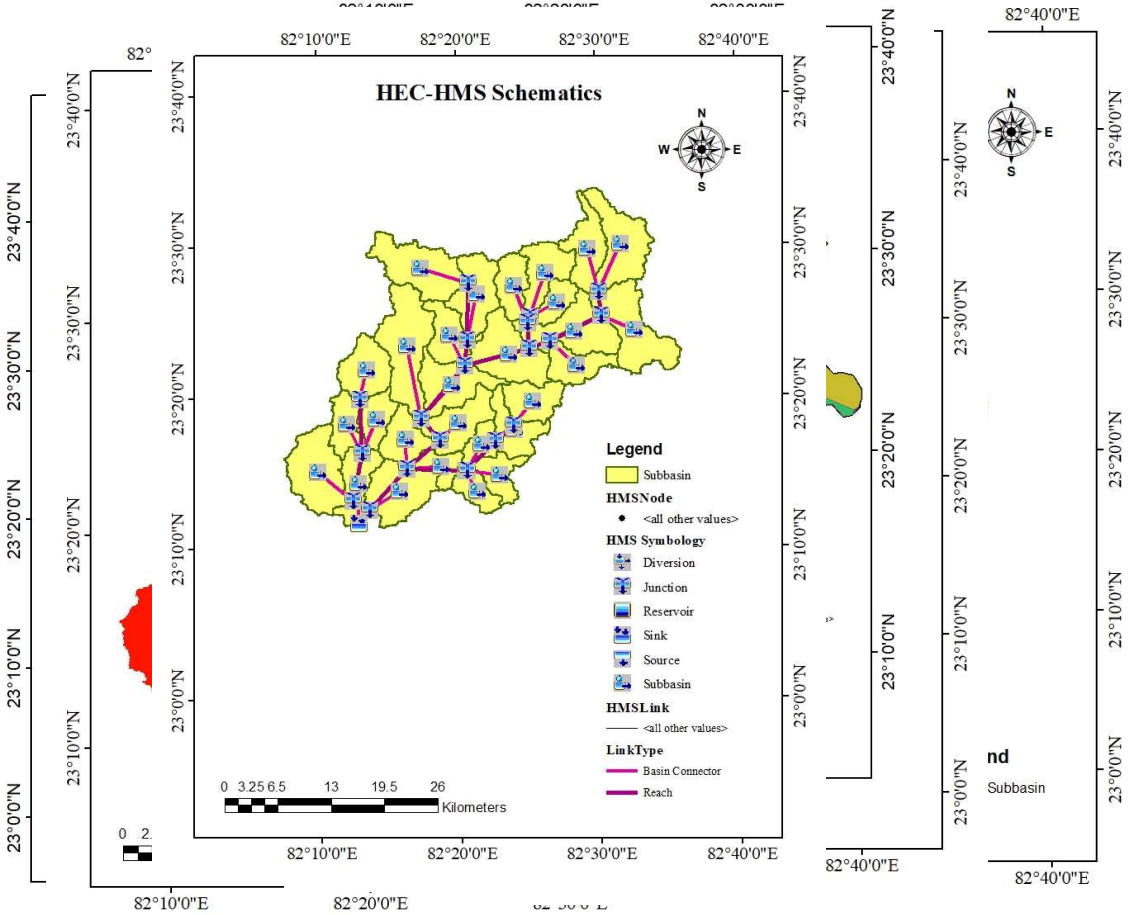
Curve **Number** (CN) Calculation





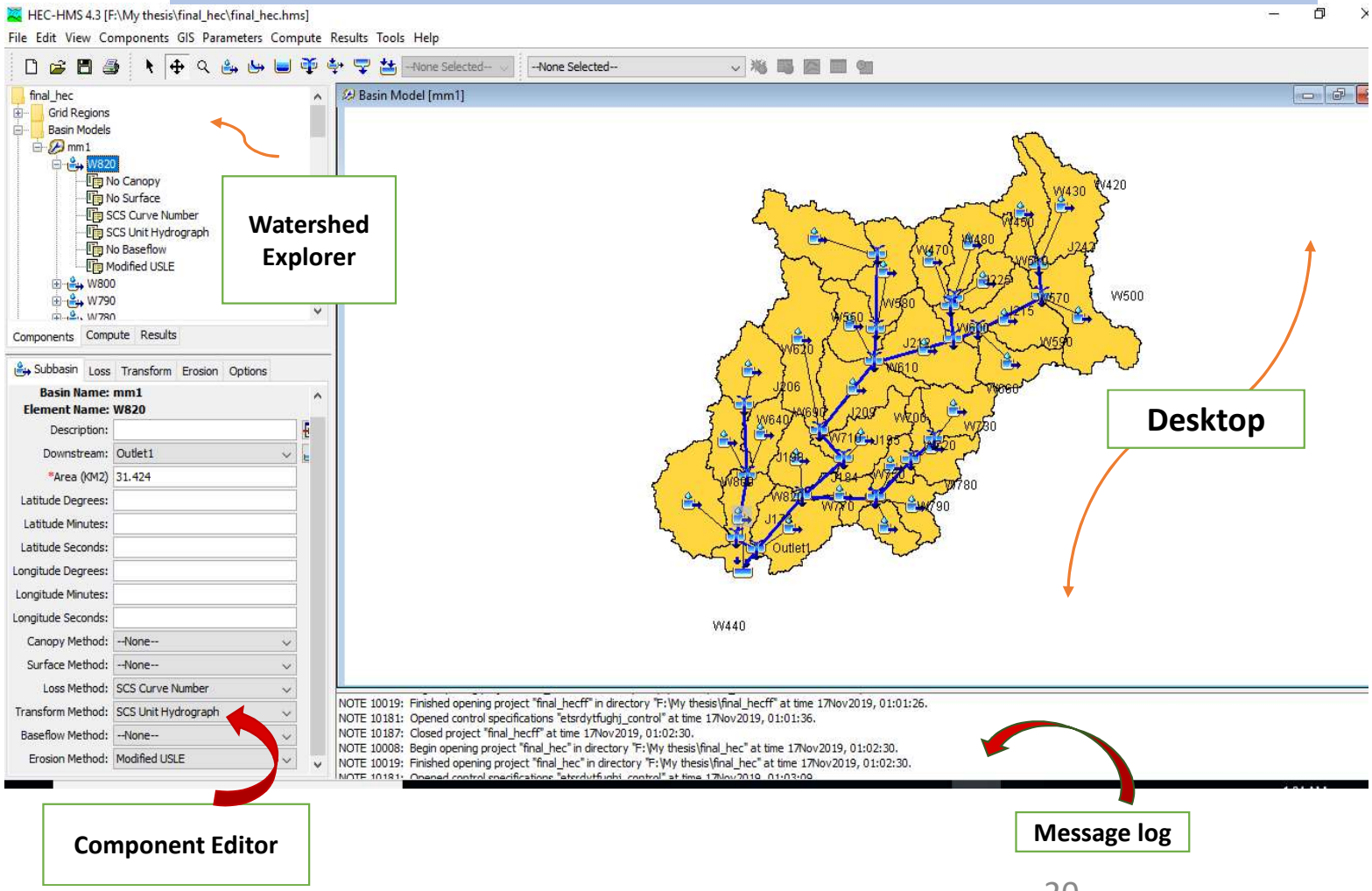


Location of Rain Gauge Stations in the Study Area



HEC-HMS Model Setup

Version used- HEC- HMS 4.3, September 2018



Watershed Explorer

Desktop

Component Editor

Message log

S. No	Process	HMS Model	Method used	Input data	Equation used
1	Computing Runoff Volume	Loss method	SCS CN method	Initial Abstraction, Curve Number, Percent Impervious.	$Q = \frac{(P-\lambda)^2}{P+(1-\lambda)S}$
2	Modelling Direct Runoff	Transform method	SCS Unit Hydrograph model	Basin Lag.	Lag time $= \frac{I^{0.8} \times (S+1)^{0.7}}{1900 \times Y^{0.5}}$
3	Computing Sediment	Erosion method	Modified USLE	Volume of runoff(m3) Peak flow (m3 s-1) Soil erodibility(Mg MJ-1 mm-1) Slope Length Slope steepness, Crop factor, Soil erosion control practice factors	$Y = 11.8 (Q.q_p)^{0.56}$ K.L.S.C.P
4	Modelling Channel flow	Routing method	Muskingum	Muskingum (K), hr Muskingum (X)	Based on water balance Eq.

Model Calibration

The manual calibration procedure as described by Sorooshian and Gupta (1995) was adopted.

Before calibration, trial run (pre-calibration) of models with default values of different parameters were done. After that some of the parameters were calibrated for the study watershed.

Calibration was done on monthly basis for simulating the discharge and sediment yield for monsoon season (June-October) of six years from 2000 through 2005. The simulation output was compared with the observed counterparts.

Criteria for Model Evaluation Performance

1. The Coefficient of Determination (r^2)

$$r^2 = \left\{ \frac{\sum_{i=1}^{N}\left(Y_i^{obs} - Y_{mean}^{obs}\right)\left(Y_i^{sim} - Y_{mean}^{sim}\right)^2}{\sum_{i=1}^{N}\left(Y_i^{obs} - Y_{mean}^{obs}\right)^2 \sum_{i=1}^{N}\left(Y_i^{sim} - Y_{mean}^{sim}\right)^2} \right\}$$

2. Nash-Sutcliffe Efficiency (E_{NS})

$$E_{NS} = 1 - \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right)^2}{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_{mean}^{obs}\right)^2} \right]$$

3. Percent Bias

$$PBIAS = \left[\frac{\sum_{i=1}^{n}\left(Y_i^{obs} - Y_i^{sim}\right) \times 100}{\sum_{i=1}^{n}\left(Y_i^{obs}\right)} \right]$$

Where,
Y_i^{obs} is observed hydrological variable,

Y_i^{sim} is simulated hydrological variable,

Y_{mean}^{obs} is average of observed hydrological variable,

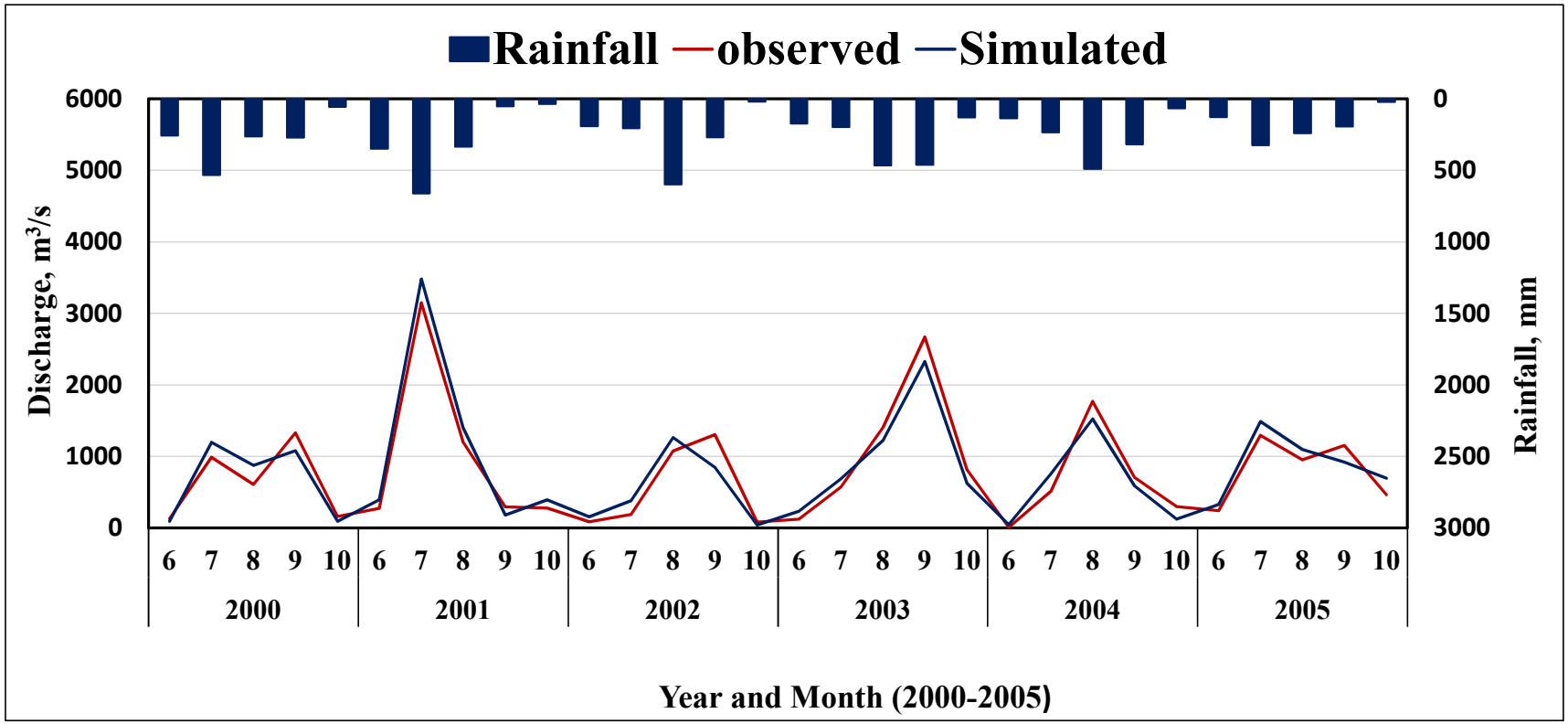
Y_{mean}^{sim} is average simulated hydrological variable and

N is the total number of events.

Initial and Calibrated Values of the Parameters

S. No.	Method	Parameter	Input Value	Calibrated Values
1	Loss Rate Parameter	Initial Abstraction (I_a) mm	23.4	20.0
2		Curve Number (CN)	Varies	2 % decrease for agricultural cover and 5 % decrease for forest and settlements
3	Transform Parameter	Lag Time (T_{lag}) min	110	110
4	Routing Method Constants	Muskingum (K) hr	0.23	0.13
5		Muskingum (X)	0.27	0.03

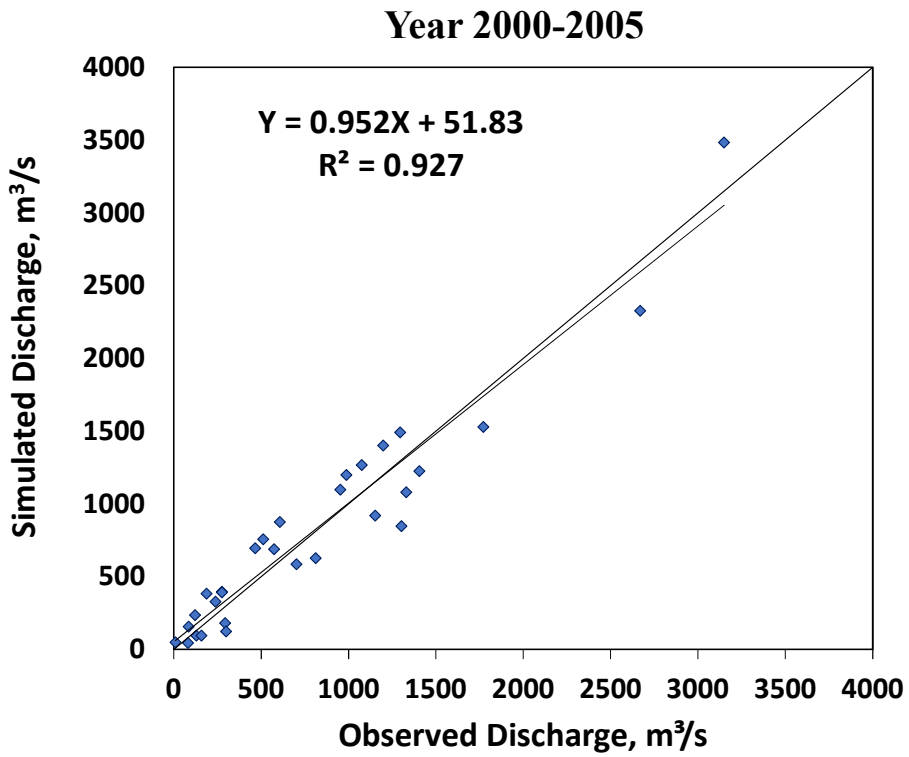
S. No.	Method	Parameter	Input Value	Calibrated Values
6	Sediment Method	K	0.07	0.26
7		LS	1.6	2
8		C	0.45	0.05
		P	1	0.5
9		Threshold (m3/s)	1	1
10		Threshold (m3/s) Exponent	1 0.7	1 0.2

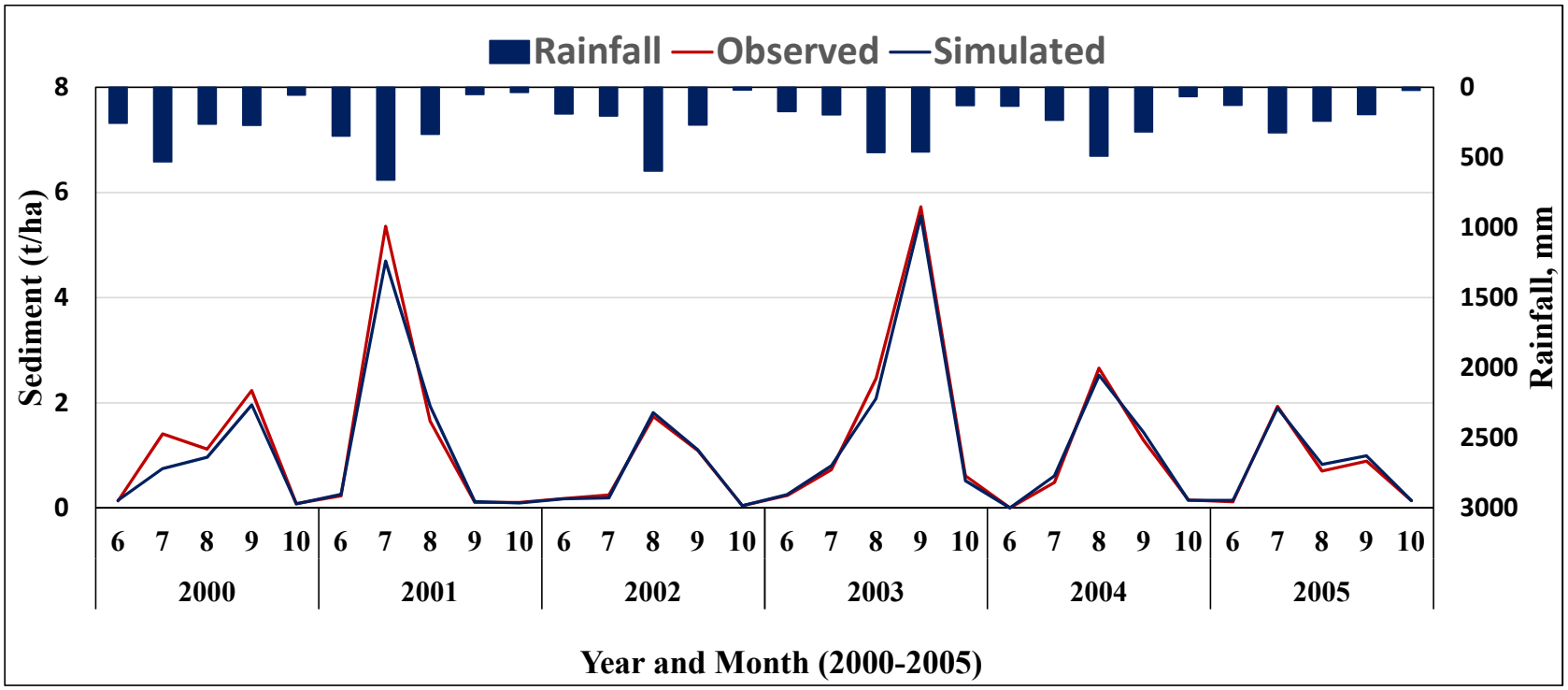


Graphical comparison of simulated and observed monthly discharge of monsoon season of the years 2000-2005 (calibration runs)

Statistical Analysis of Observed and Simulated Monthly Discharge (m^3/s)

Statistical Parameters	2000-2005	
	Observed	Simulated
Mean	803.63	828.57
Maximum	3148.71	3261.54
Std Dev	755.04	731.11
Count	30	30
Coefficient of determination (R^2)	0.94	
Nash-Sutcliffe coefficient (E_{NS})	0.927	
t-critical	2.05	
t-statical	-0.23	
PBIAS	1.702	

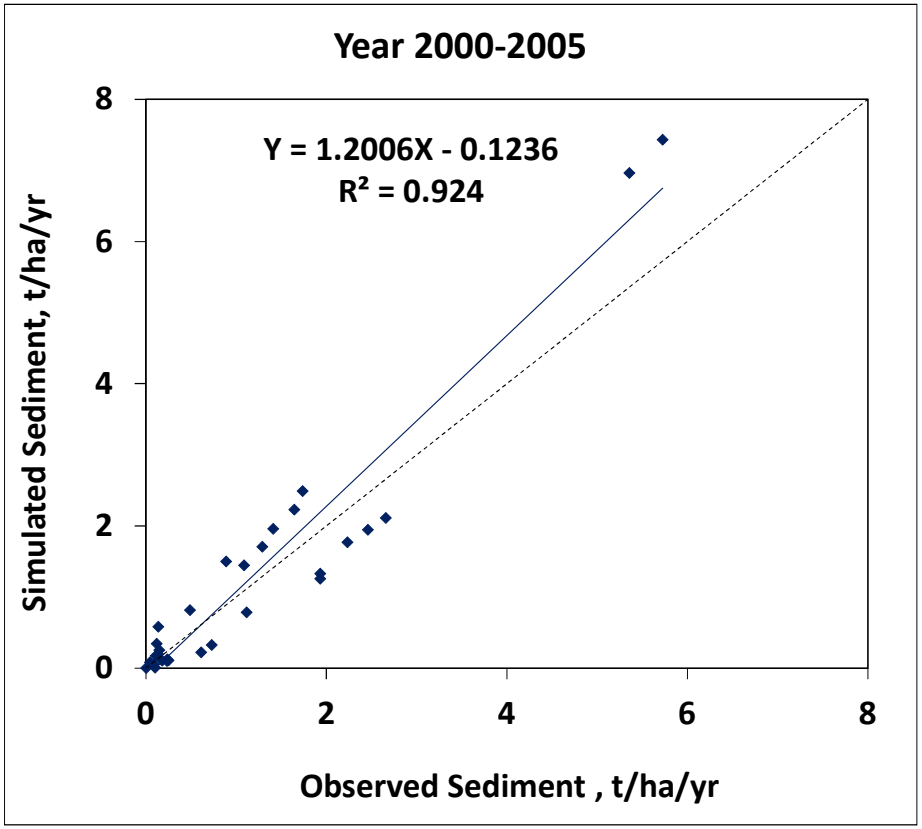




Graphical comparison of simulated and observed monthly sediment yield of monsoon season for the years 2000-2005 (calibration runs)

Statistical Analysis of Observed and Simulated Monthly Sediment Yield (t/ha/yr)

Statistical Parameters	2000-2005	
	Observed	Simulated
Mean	1.129	1.076
Maximum	5.726	5.552
Std Dev	1.434	1.331
Count	30	30
Coefficient of determination (R^2)	0.924	
Nash-Sutcliffe coefficient (E_{NS})	0.84	
t Critical	2.045	
t Stat	1.389	
PBIAS	9.490	



Sensitivity Analysis

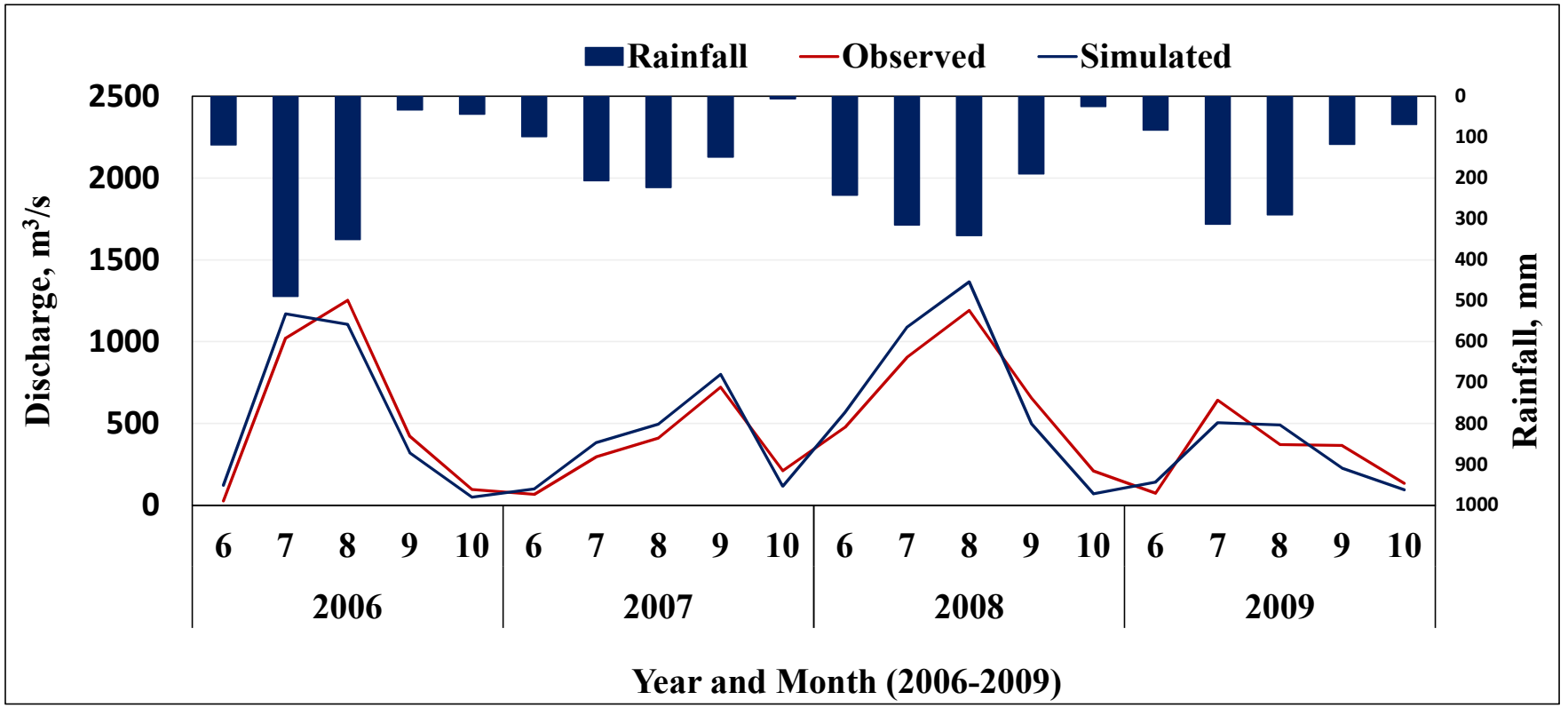
- Distributed models involve too many parameters.
- To determine the relative change in model output with respect to the change in model input variables.
- From the sensitivity analysis it is possible to determine which variables need to be closely estimated to make accurate predictions of the watershed yields.
- So, to ensure efficient calibration, sensitivity analysis was carried out for filtering out less influential parameters.

Results of Sensitivity Analysis of Calibrated HEC-HMS Model

Parameters	Values	Annual runoff (m^3/s)	% deviation	Annual sediment (t/ha/yr)	% deviation
Initial Abst. (mm)	25	519.38	**0.88**	7.42	0
	15	528.63	**-0.89**	7.42	0
Curve Number	25% increased	572.55	**-9.27**	7.42	0
	25% decreased	465.93	**11.08**	7.42	0
Lag time	165	523.99	0.00	7.42	0
	55	523.99	0.00	7.42	0
Erodibility Factor	0.325	523.99	0.00	8.8	**-18.60**
	0.195	523.99	0.00	5.5	**25.88**
Topographic Factor	2.5	523.99	0.00	8.4	**-13.21**
	1.5	523.99	0.00	5.56	**25.07**
Cover Factor	0.625	523.99	0.00	8.6	**-15.90**
	0.375	523.99	0.00	4.5	**39.35**
Practice Factor	0.625	523.99	0.00	8.3	**-11.86**
	0.375	523.99	0.00	5.5	**25.88**
Base variable	**Calibrated**	**523.99**		**7.42**	

Model Validation

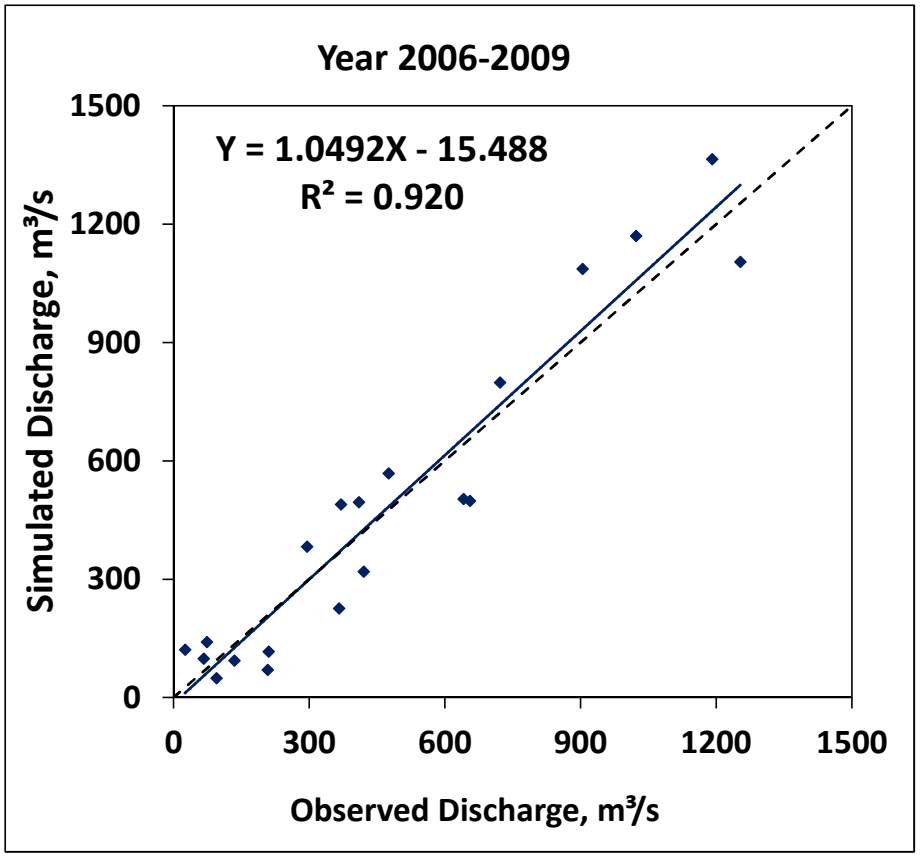
- Validation is the essential part of a model testing after calibration.
- Model should be validated properly to know the model performance without any changes in the input file except climatic parameters.
- Validation was done on monthly basis for simulating the discharge and sediment yield for monsoon season (June-October) of four years from 2006 through 2009.
- The simulation output was compared with the observed counterparts.

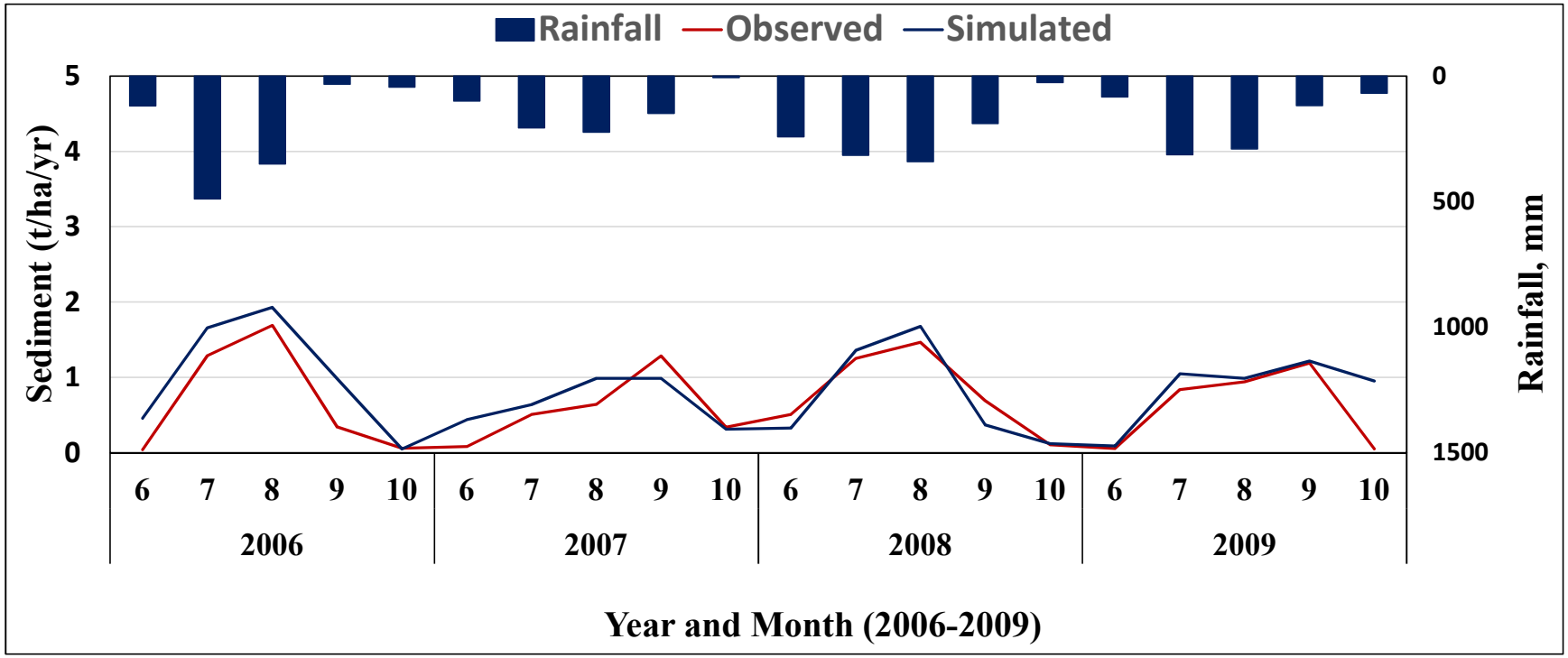


Graphical comparison of simulated and observed monthly discharge of monsoon season for the years 2006-2009 (validation runs)

Statistical Analysis of Observed and Simulated Monthly Discharge (m^3/s)

Statistical Parameters	2006-2009	
	Observed	Simulated
Mean	476.933	480.84
Maximum	1253.05	1244.96
Std Dev	378.15	389.66
Count	20	20
Coefficient of determination (R^2)	0.920	
Nash-Sutcliffe coefficient (E_{NS})	0.94	
t Critical	2.093	
t Stat	0.34	
PBIAS	1.702	

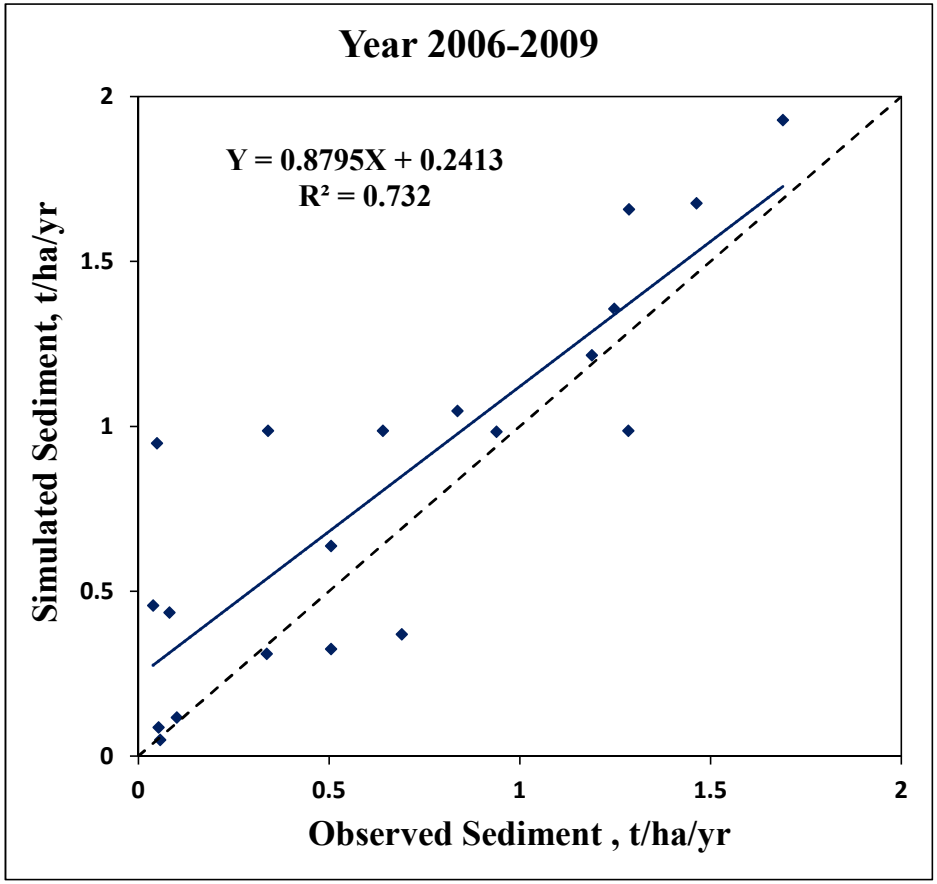




Graphical comparison of simulated and observed monthly sediment yield of monsoon season for the years 2006-2009 (validation runs)

Statistical Analysis of Observed and Simulated Monthly Sediment Yield (t/ha/yr)

Statistical Parameters	2006-2009	
	Observed	Simulated
Mean	0.67	0.83
Maximum	1.69	1.93
Std Dev	0.54	0.56
Count	20	20
Coefficient of determination (R^2)	0.732	
Nash-Sutcliffe coefficient (E_{NS})	0.92	
t Critical	2.43	
t Stat	2.09	
PBIAS	7.442	



Identification and Prioritisation of Critical Sub-watersheds

1. **On the basis of average annual runoff and sediment yield.**
2. **Identified critical sub-watersheds are arranged in descending order and then priorities were fixed for their management.**

Soil Erosion Classes	Slight	Moderate	High	Very High	Severe	Very Severe
Soil Erosion Range (t/ha/yr)	0-5	5-10	10-20	20-40	40-80	>80

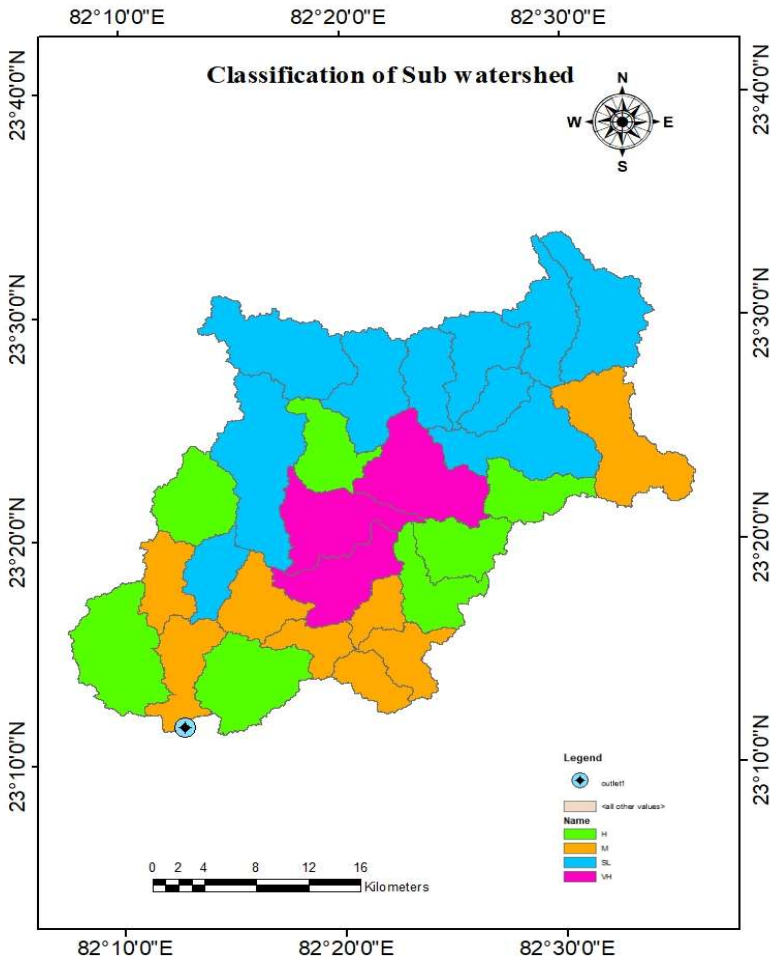
Singh *et al.*, 1992

Model output for identification of the critical watersheds (2010-2027)

S. No	WS Code	Area (km^2)	Slope (%)	CN	Runoff (mm)	Contribution per unit area to the total runoff	Sediment (t/ha/yr)	Soil erosion class	Priority
1	W480	26.472	10.76	80	566.204	0.014	1.671	SL	28
2	W510	18.199	5.86	75	589.15	0.010	1.990	SL	27
3	W470	41.453	9.94	80	702.16	0.028	2.101	SL	26
4	W690	22.882	9.04	62	605.16	0.013	2.284	SL	25
5	W450	34.744	10.57	80	638.17	0.021	2.942	SL	24
6	W570	53.757	6.05	70	630.163	0.033	3.599	SL	23
7	W440	56.125	11.04	78	647.642	0.035	3.872	SL	22
8	W420	52.005	11.15	65	730.29	0.037	4.454	SL	21
9	W430	36.045	12.13	65	637.296	0.022	4.639	SL	20
10	W550	69.23	9.35	64	716.16	0.048	4.796	SL	19
11	W790	17.479	16.97	43	630.277	0.011	6.205	M	18
12	W500	58.933	5.71	70	773.942	0.044	6.262	M	17
13	W720	15.192	5.65	74	634.85	0.009	6.594	M	16
14	W640	24.84	8.56	74	703.965	0.017	7.452	M	15
15	W750	18.232	12.72	64	645.27	0.011	8.643	M	14
16	W820	31.424	7.59	63	711.821	0.022	8.734	M	13
17	W710	28.707	8.92	70	685.261	0.019	9.364	M	12
18	W780	23.035	12.91	50	643.27	0.014	9.501	M	11

S. No	WS Code	Area (km^2)	Slope (%)	CN	Runoff (mm)	Contribution per unit area to the total runoff	Sediment (t/ha/yr)	Soil erosion class	Priority
19	W620	36.639	7.1558	63	690.25	0.024	10.986	H	10
20	W730	29.137	9.599	72	680.174	0.019	12.588	H	9
21	W580	30.494	8.54196	66	780.225	0.023	12.966	H	8
22	W800	56.037	8.669	42	805.262	0.044	13.320	H	7
23	W590	27.316	6.0648	66	741.397	0.020	13.996	H	6
24	W770	48.29	9.8807	40	760.326	0.035	14.996	H	5
25	W660	30.077	10.117	73	722.161	0.021	17.678	H	4
26	W700	39.662	9.475	64	840.183	0.032	20.358	VH	3
27	W600	54.667	7.745	65	810.244	0.043	22.527	VH	2
28	W610	44.045	9.21444	64	925.168	0.039	27.648	VH	1

Classification of Sub-watersheds



Development plan of land and water based on Farming Situation

- **The development plan of land and water based on farming situation study area was carried out by the Multi Criteria Evaluation (MCE) approach and Weighted Overlay Function.**

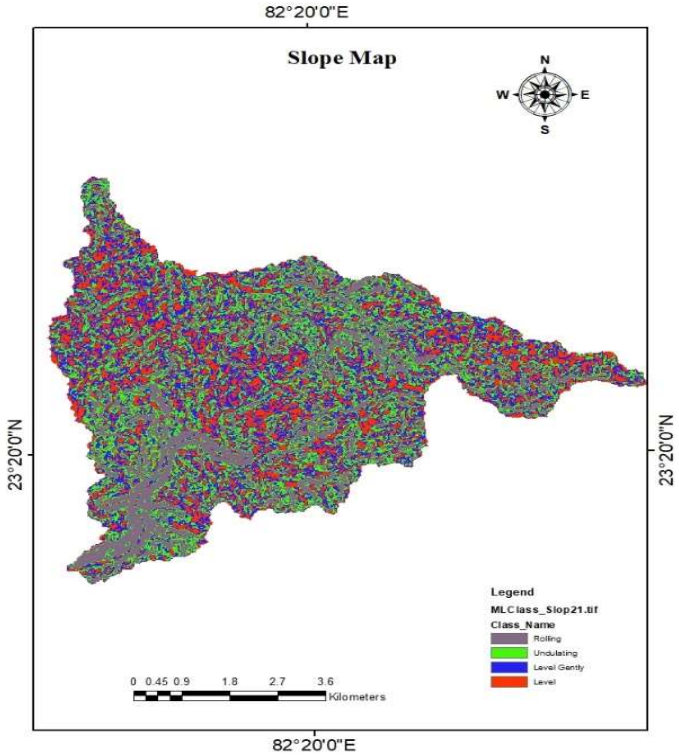
- **Weighted Overlay Analysis used the Five type of map**
  - **LULC map**
  - **Slope map**
  - **Farming Situation map**
  - **Stream Order map**
  - **Lineament map**

Weightage Criteria for Suitability of Water Storage Structures Prospect

Parameter	Influence(%)	Feature Classes	Feature Weight
LULC	20	Barren land	4
		Current Fallow	4
		Water Body	3
		Forest	3
		Agricultural land	5
		Settlement	1
Slope	20	Nearly level	6
		Very gently sloping	5
		Gently sloping	4
		Moderately sloping	3
		Strongly sloping	2
Soil	20	Matasi / Tikara	3
		Dorsa / Mal	5
		Bhata /Marhan	2
		Kanhar / Gabhar	5
		Forest	5
Stream Order	20	1st Order	2
		2nd Order	3
		3rd Order	3
		4th Order	5
		5th Order	3
		6th Order	4
Lineament	20	Fault	1

Characterization of Slope

Slope Map

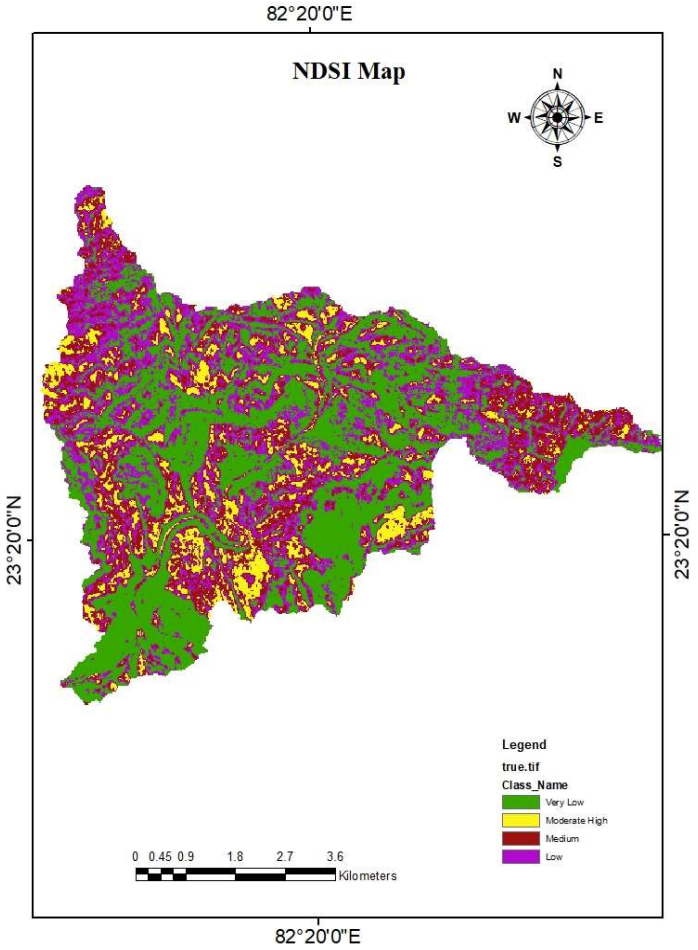


Slope Map of critical sub-watershed (SW610)

Slope Categories

Class	Percentage	Slope Category
1	<2%	Nearly Level
2	2-3%	Very gently sloping
3	3- 5%	Undulating
4	>5	Rolling

(Source: Ahmad *et al.* (2016))

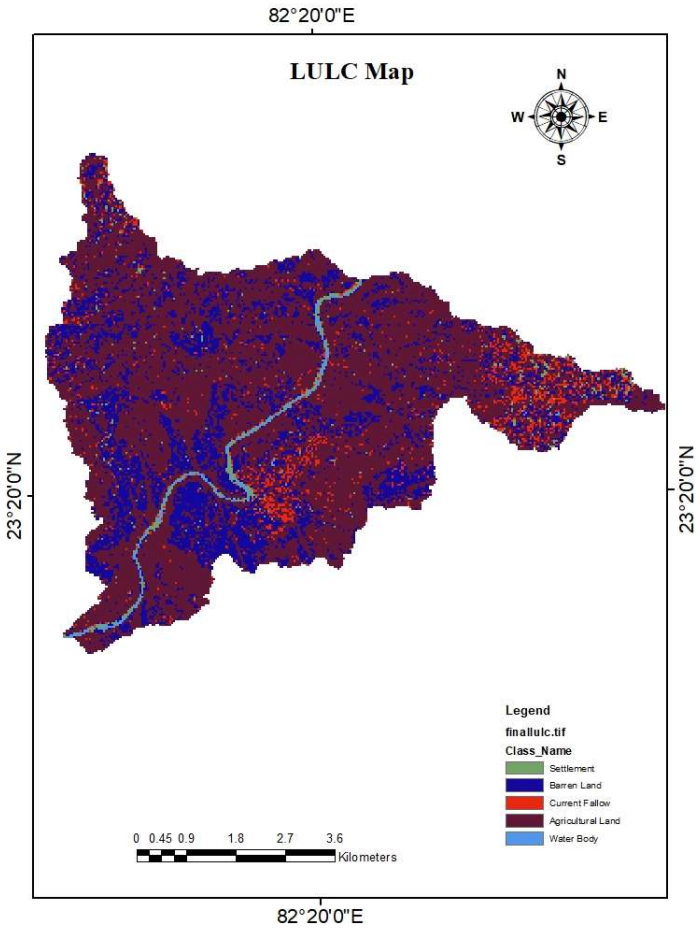


NDSI Map of Critical Sub-watershed (SW610)

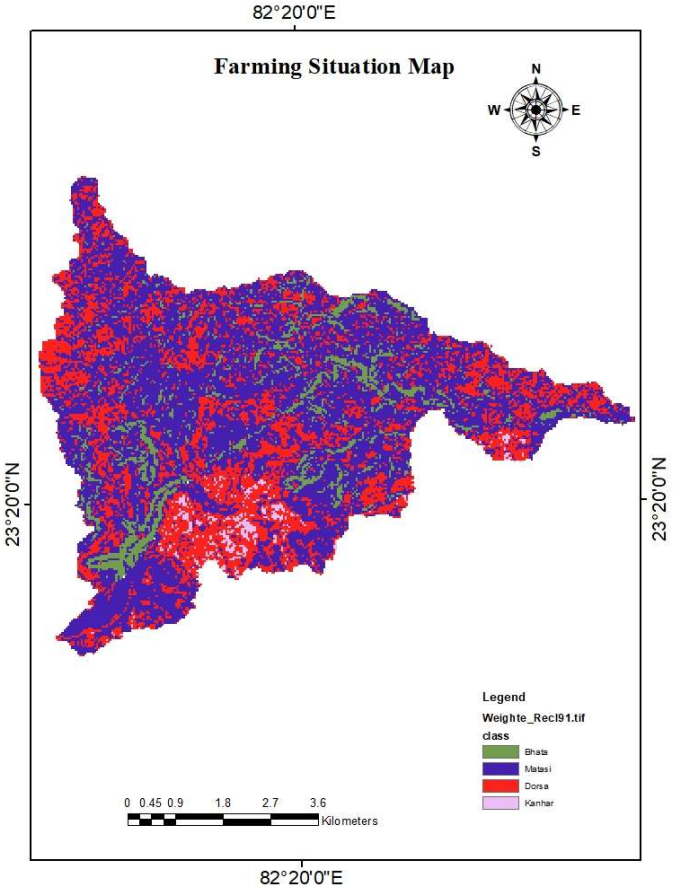
S. No.	Classes	Range of NDSI Value	Area (km^2)
1	Very Low	-1 - 0.007	18.55
2	Low	0.007 - 0.051	4.06
3	Moderately Low	0.051 - 0.125	8.13
4	Medium	0.125 - 0.143	8.98
5	Moderately High	>0.143	4.31

Land Use/Land Cover Map

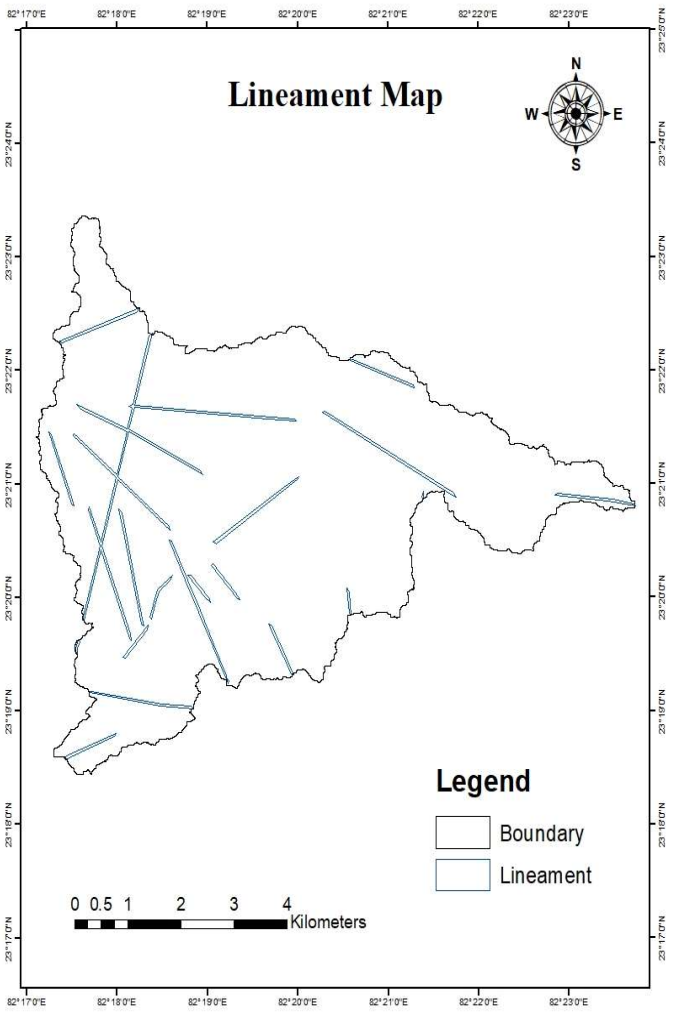
Class Name	Area (sq km)	Area (%)
Forest	10.67	24.23
Water body	0.38	0.86
Barren land	10.22	23.21
Settlement	0.84	1.91
Agriculture	20.00	45.41
Current fallow	1.87	4.25

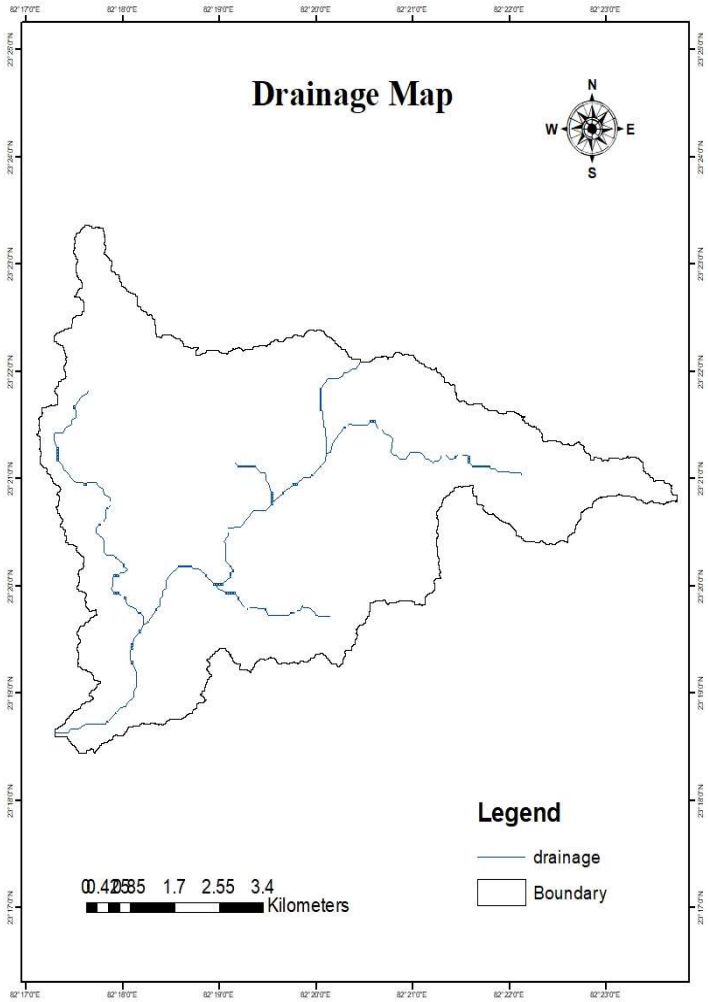


Farming Situations Map

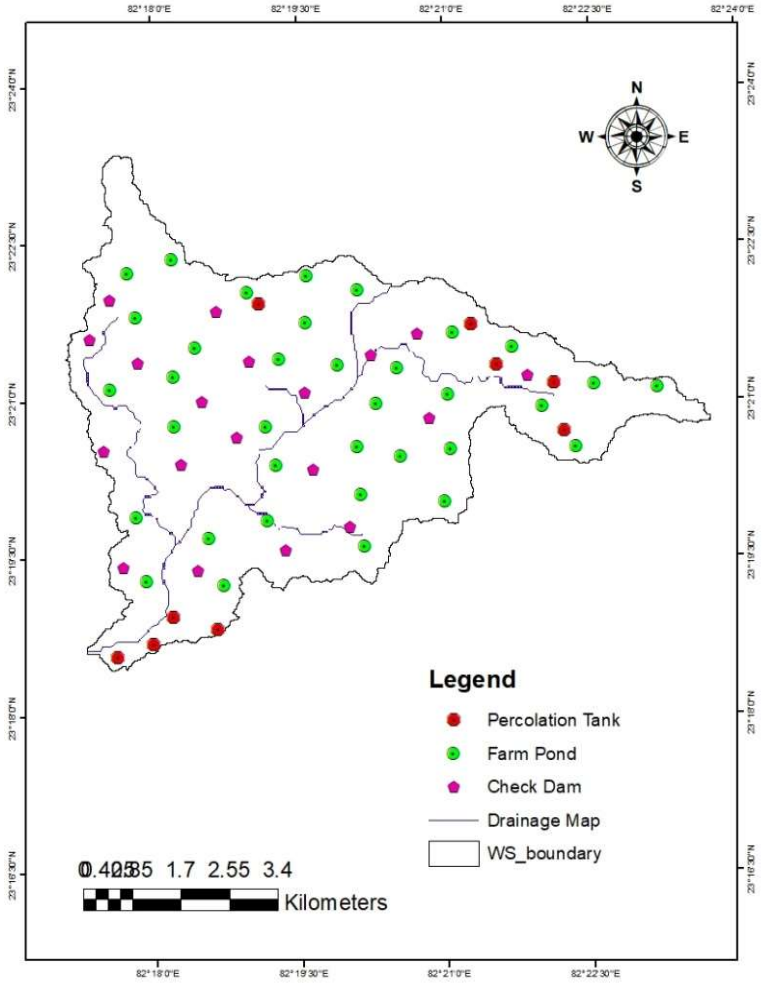


Farming Situation	Soil Order	Soil Texture	Slope	Area (Km^2)	% Area
Dand	Entisol	S to SCL	>5	0.65	1.48
Goda chawar	Inceptisols	SCL to SL	3-5	12.97	29.45
Chawar	Alfisols	C Loam	2-3	26.86	60.99
Gadar chawar	Vertisols	Clay	<2	3.37	7.65
Total				44.04	





Lineament and Drainage maps of critical sub-watershed (SW610)



S. No.	Type of Structures (Numbers)	Farming situations			
		Dand	Goda chawar	Chawar	Gadar chawar
1	Check Dam	0	8	8	3
2	Farm Pond	4	16	12	2
3	Percolation Tank	1	5	3	0
Total		5	29	23	5

Check Dams (19)

Farm Ponds (34)

Percolation Tank (9)

Total Structures (62)

Conclusions

1. **Based on the Results obtain by adequately varified HEC-HMS model runs the sub-watershed SW610 was found to be yielding highest annual runoff and sediment yield, can be considered for developing the best water management plan for reducing the runoff and soil loss well within the permissible limit.**

2. **Appropriate sites for 4 farm ponds and1 percolation tank are proposed in the *Dand* farming situation; 8 check dams, 16 farm ponds and 5 percolation tanks, are proposed in the *Goda chawar* farming situations.**

3. **Similarly, 8 sites for check dams, 12 for farm ponds and 3 for percolation tanks are proposed in the *Chawar* farming situations, also for *Gadar chawar* farming situation 3 sites for check dams and 2 sites for farm pond are proposed for better soil and water conservation and management of the critical sub-watershed SW610 of Manendragarh watershed of upper Mahanadi basin.**

Use of this study in following key watershed programmes

Integrated Watershed Management Programme (IWMP): A key program launched in 2009, aimed at addressing watershed management through a unified approach.

•National Watershed Development Programme for Rainfed Areas: Launched in 1990, this is another major government initiative that has been integrated into newer programs.

•Prime Minister Krishi Sinchayee Yojana (PMKSY): A program that includes the Watershed Development Component (WDC-PMKSY) with the goal of restoring ecological balance by conserving degraded natural resources.
It has three components:

Har Khet Ko Pani (HKKP), Repair, Renovation & Restoration (RRR) of Water Bodies, and Surface Minor Irrigation (SMI) Scheme.



Thank you!!