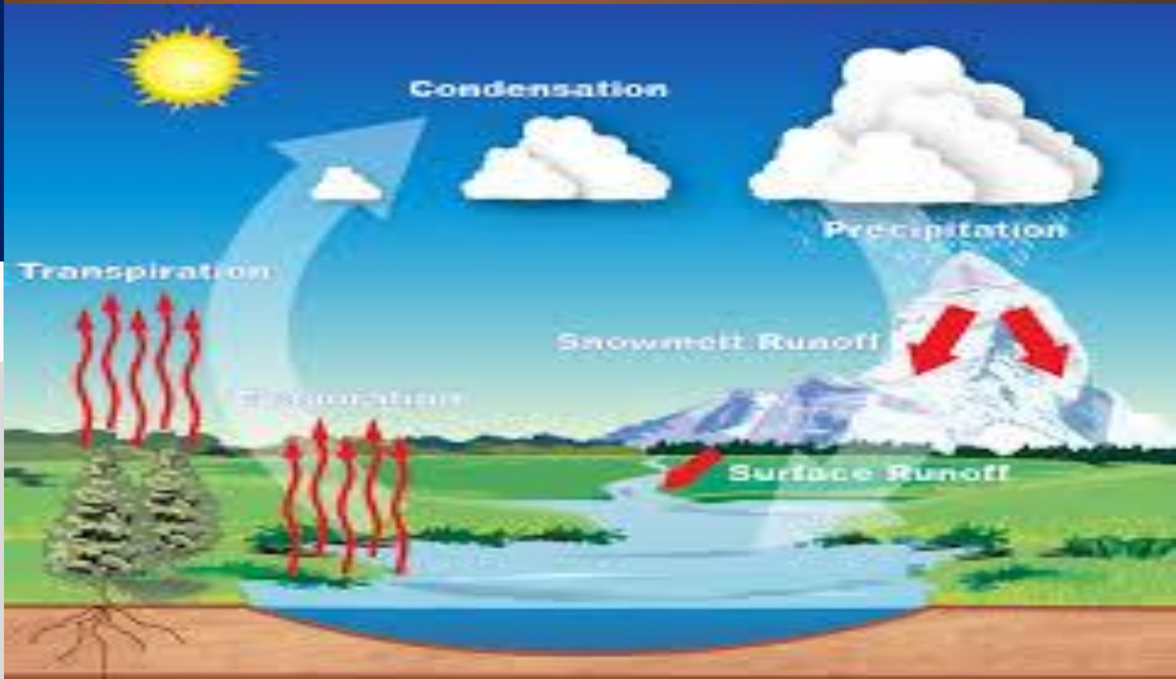
Surface Water and Groundwater Interactions in Kosi River Basin using Surface and Subsurface Hydrological Modelling



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OUTLINES

- **Introduction**
- **Objectives**
- **Surface Water Hydrological Modelling**
- **Sub-surface hydrological Modelling with LULC changes**
- **Landuse/Landcover change Analysis using Evapotranspiration Datasets**
- **Conclusions**
- **Acknowledgement & References**

Introduction

Surface water-Groundwater Interaction

- **Surface water and Groundwater interaction is a natural process and is a complex phenomenon**

- **It is classified as connected and disconnected systems**

- **It can take place in three types**

  A) Water flux entering from aquifer to river (Gaining)

  B) Water flux leaving river (Loosing)

  C) Combination of both

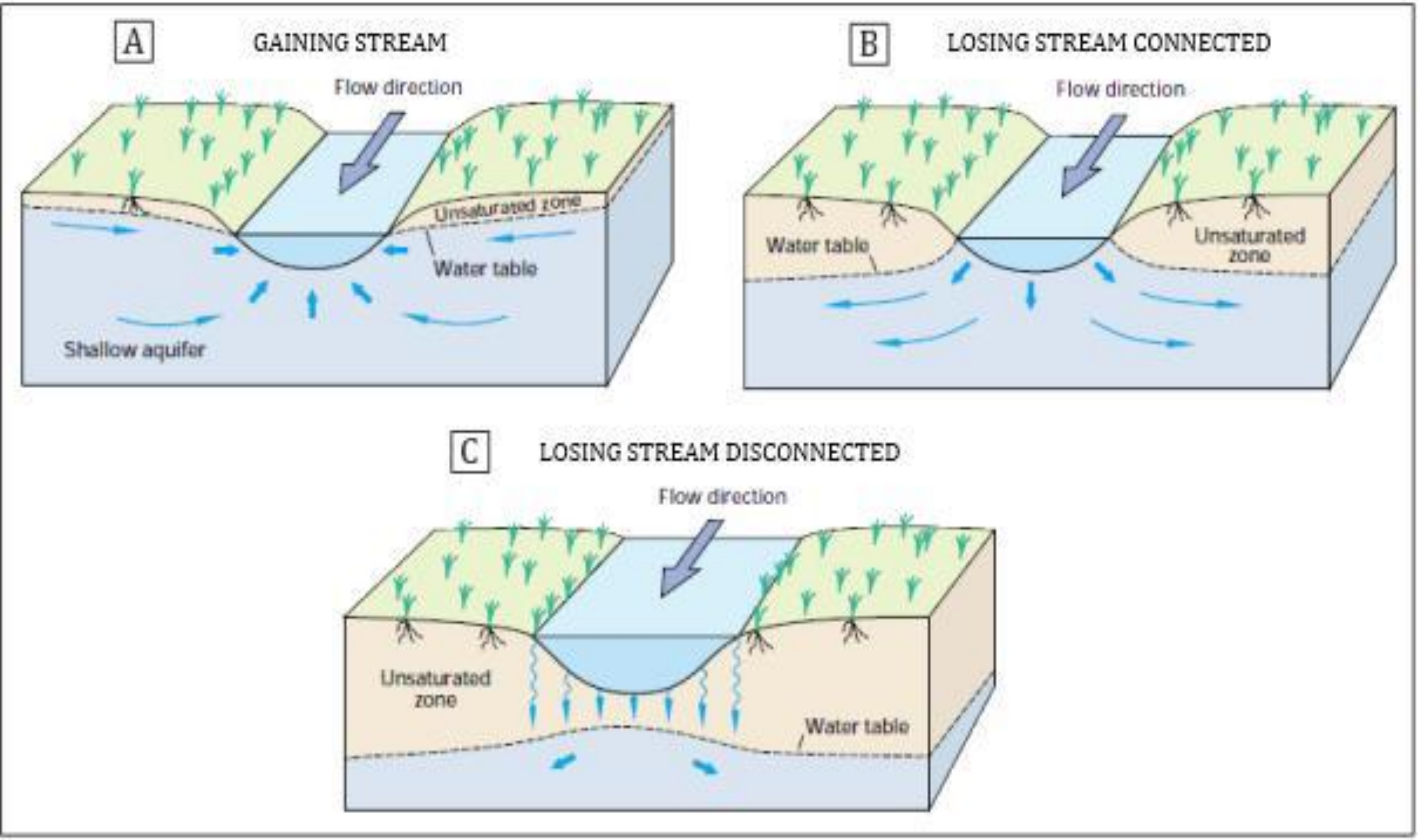
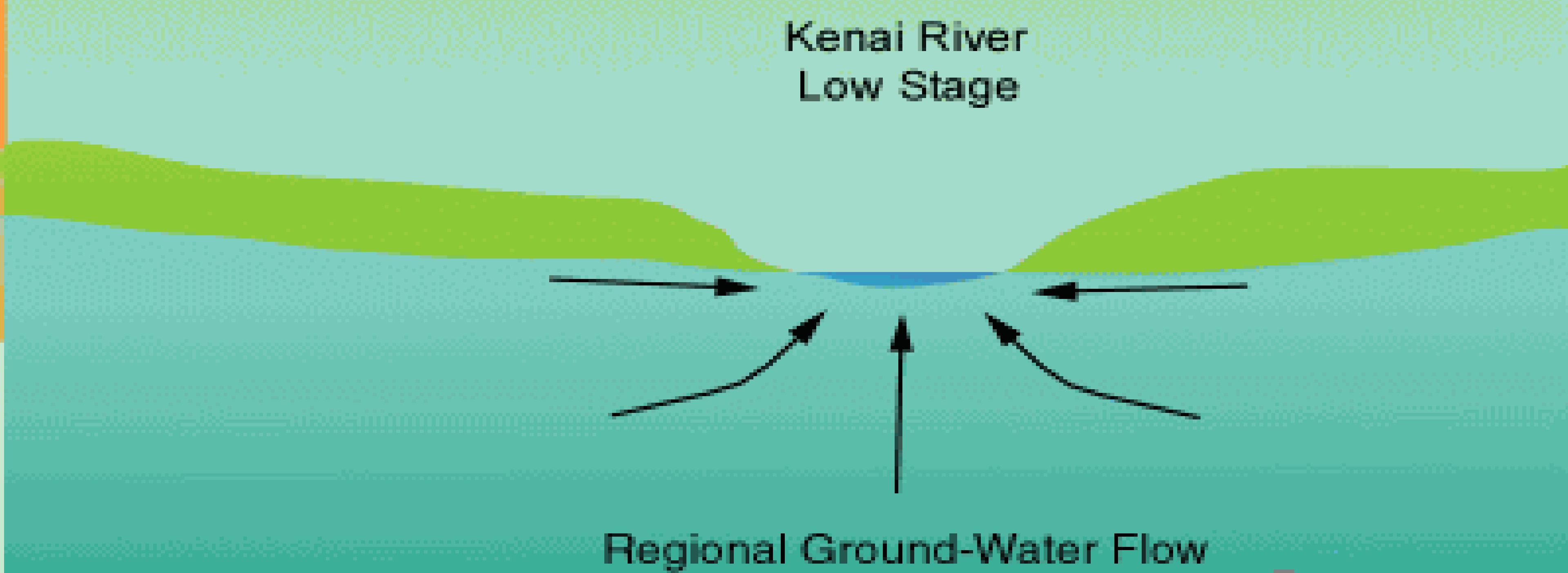


Figure: General Conditions for Gaining and Losing Streams in an Aquifer, reproduced from Winter et al. (1998).



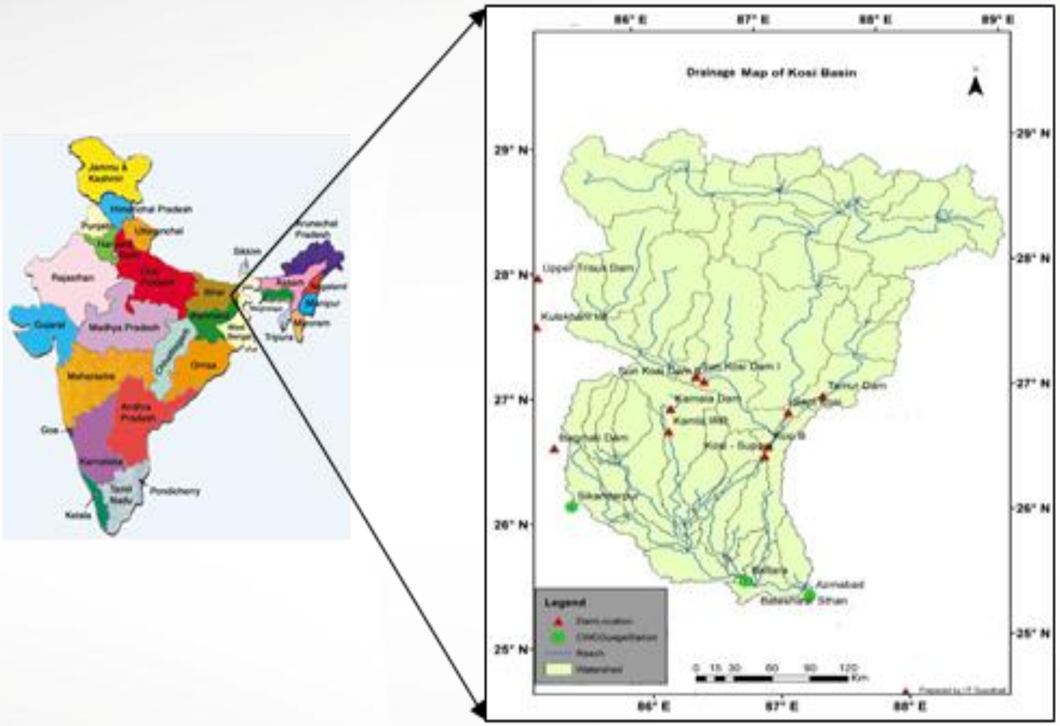
Source: http://www.kenai-watershed.org/spawning/spawning.shtml

Objectives

- **Quantification of water availability using surface hydrological Modelling (SWAT)**
- **To carry out simple water balance study to understand the surface and groundwater interaction exchange pattern.**
- **Comparison of water balance study with sub-surface hydrological model (MODFLOW)**

Surface Water Hydrological Modelling

Study Area



Kosi river sub-basin, Ganges system, India.

- **Latitude - 29°08'18"N to 25°18'51"N**
- **Longitudes - 85°19'50"E to 88°56'57"E**
- **Catchment Area - 86,000 Km^2**

Surface Water Modelling Using SWAT

- ArcSWAT is an ArcGIS -Arc View extension and a graphical user input interface for the SWAT model .

- SWAT is a river based or watershed, scale model to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds with varying soils, land use , and management conditions over a long period of time.

- SWAT was developed based on SCS Curve number technique

SCS Curve Number Equation is (SCS 1972)

$$Q_{surf} = \frac{(R_{day} - I_a)^2}{(R_{day} - I_a + S)}$$

Where, Q_{surf} = Runoff depth (mm)

R_{day} = Rainfall (mm)

I_a = Initial abstraction = 0.2 S

S = Maximum retention after runoff begins = 28.4 $\left(\frac{1000}{CN} - 10\right)$

SWAT Model Input

- **Digital Elevation Model: USGS, SRTM (shuttle radar topography mission) (90m)**

- **Landuse/landcover (LULC) data: MODIS Landcover type product (MCD12Q1) at 500_m resolution for the year 2000 and 2006 have been used**

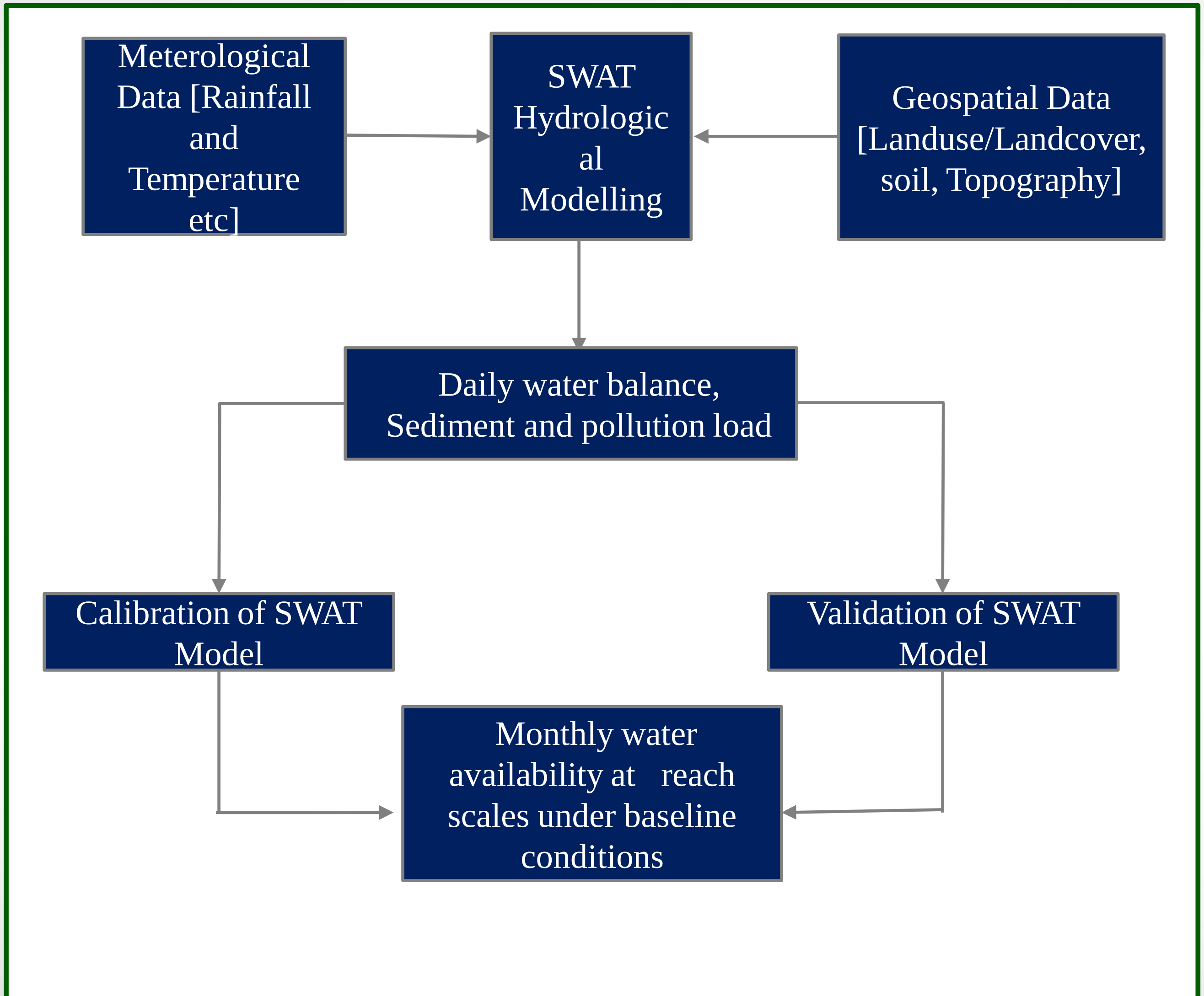
- **Soil data: To start with, data at a resolution of 1: 10,000,000 has been obtained from FAO. However, all efforts are being made to use 1:500,000 digital soil atlas from National Bureau of Soil survey and Land Use Planning (NBSS&LUP), India.**

- **Weather data: Daily gridded rainfall data at 0.5°×0.5° resolution has been obtained from Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (Aphrodite), developed by the Climate Research Department, Meteorological Research Institute, Japan (http://www.chikyu.ac.jp/precip/index.html).**

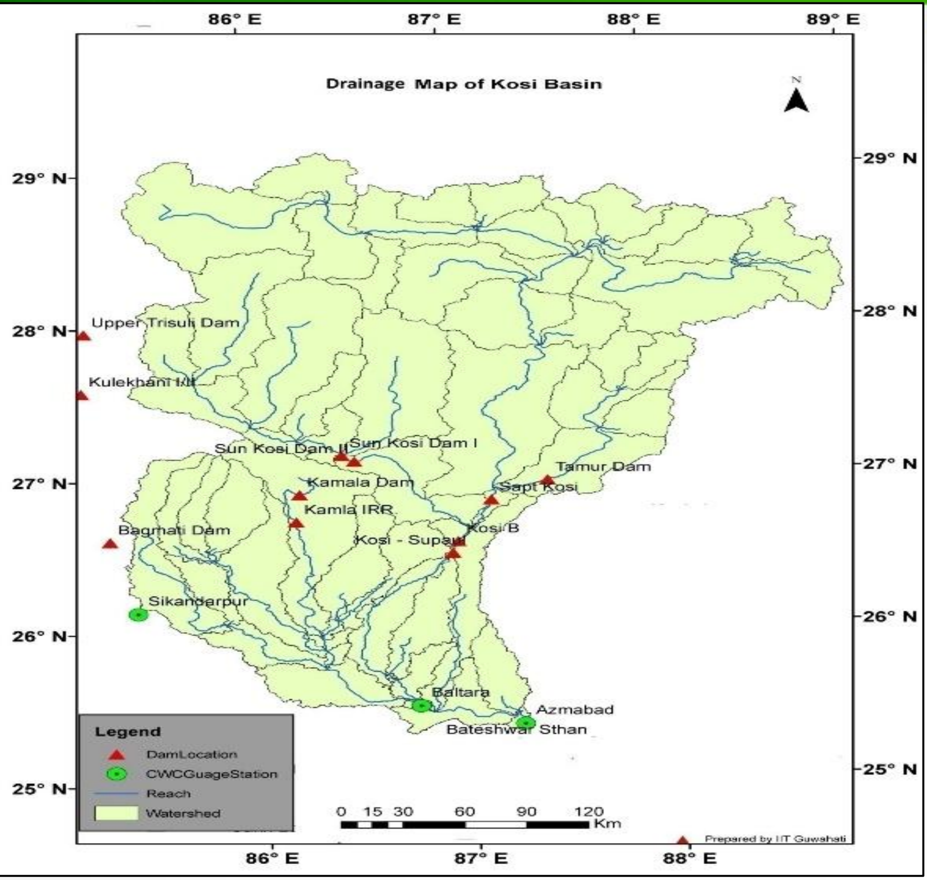
- **Daily gridded temperature (max and min) at 1°×1° resolution has been obtained from Princeton University (http://hydrology.princeton.edu/home.php).**

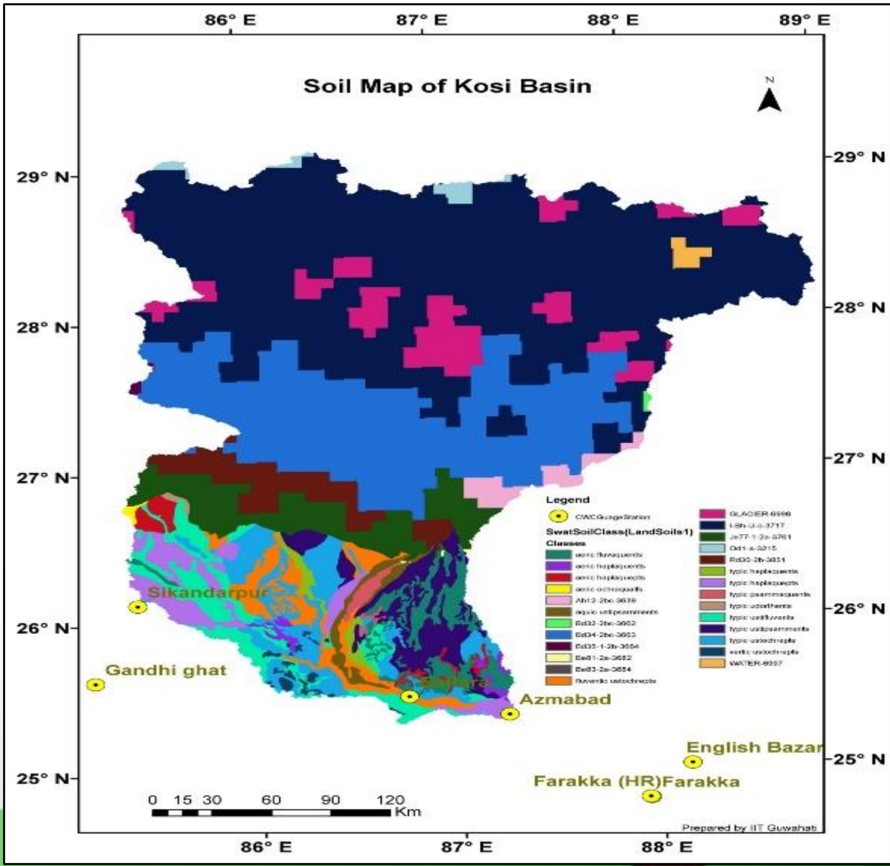
- **Stream-flow discharges: Measured stream-flow discharges (available at Baltara gauging station from 1970-2006) are used for model calibration and validation. This data, in hard copy form, has been obtained from the Central Water Commission.**

Methodology

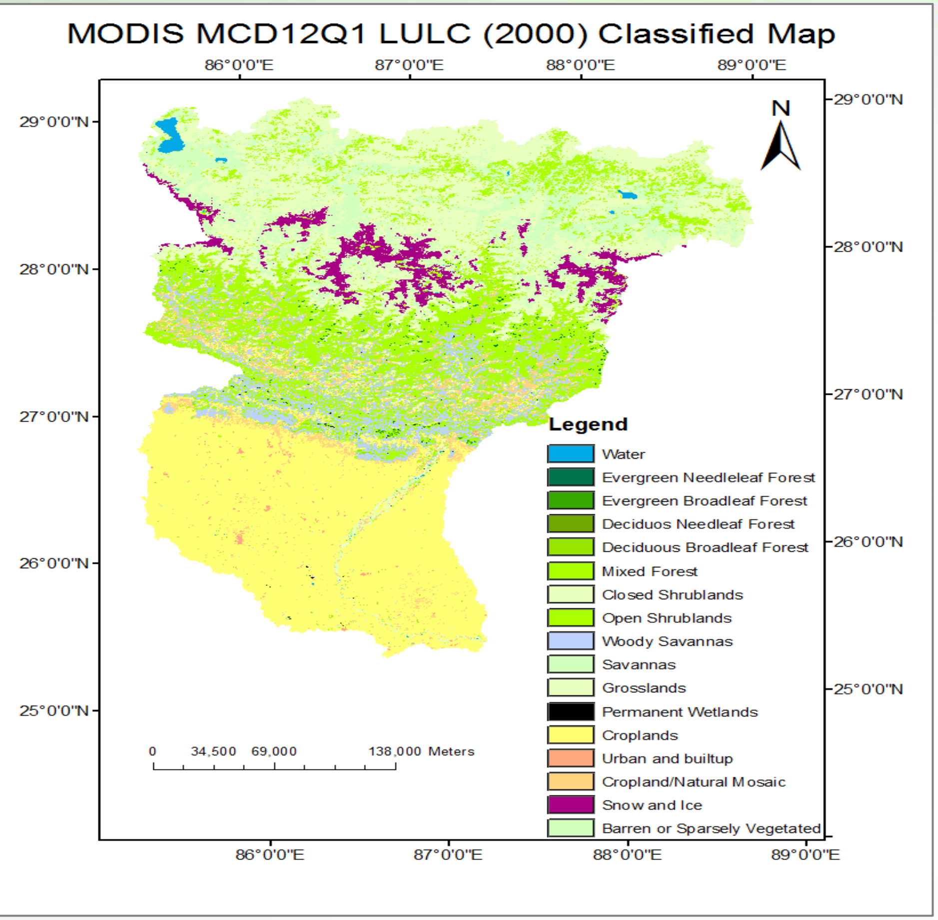


Geospatial Data Sets





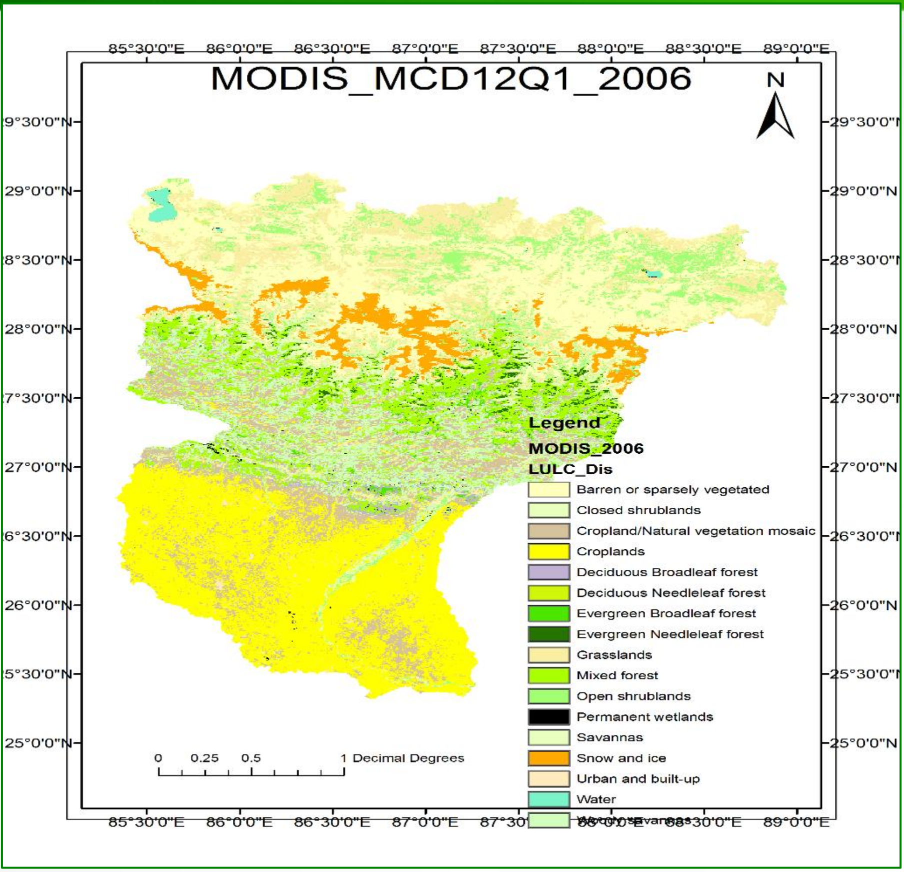
Geospatial Data Sets



2000

S.No	Class	Class Name	Area in Percentage
1	WATR	Water	0.44
2	FRSE	Evergreen Needleleaf forest	3.12
3	FREB	Evergreen Broadleaf forest	2.04
4	FRSD	Deciduous Needleleaf forest	3.04
5	FRDB	Deciduous Broadleaf forest	4.18
6	FRST	Mixed forest	13.36
7	RNGC	Closed shrublands	4.13
8	RNGO	Open shrublands	10.81
9	RNGW	Woody savannas	12.02
10	RNGE	Savannas	1.08
11	RNGG	Grasslands	15.06
12	WETF	Permanent wetlands	0.02
13	AGRR	Croplands	16.9
14	URMD	Urban and built-up	0.14
15	AGRL	Cropland/Natural vegetation mosaic	2.34
16	SNOW	Snow and ice	5.04
17	PAST	Barren or sparsely vegetated	6.28

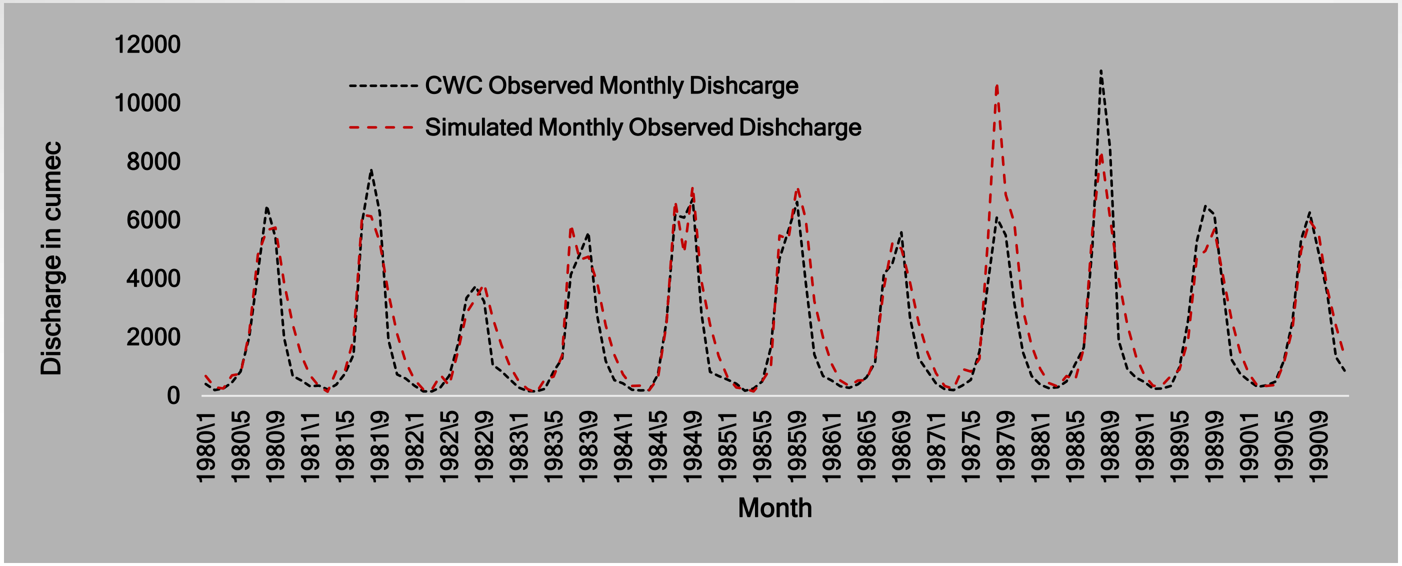
Geospatial Data Sets



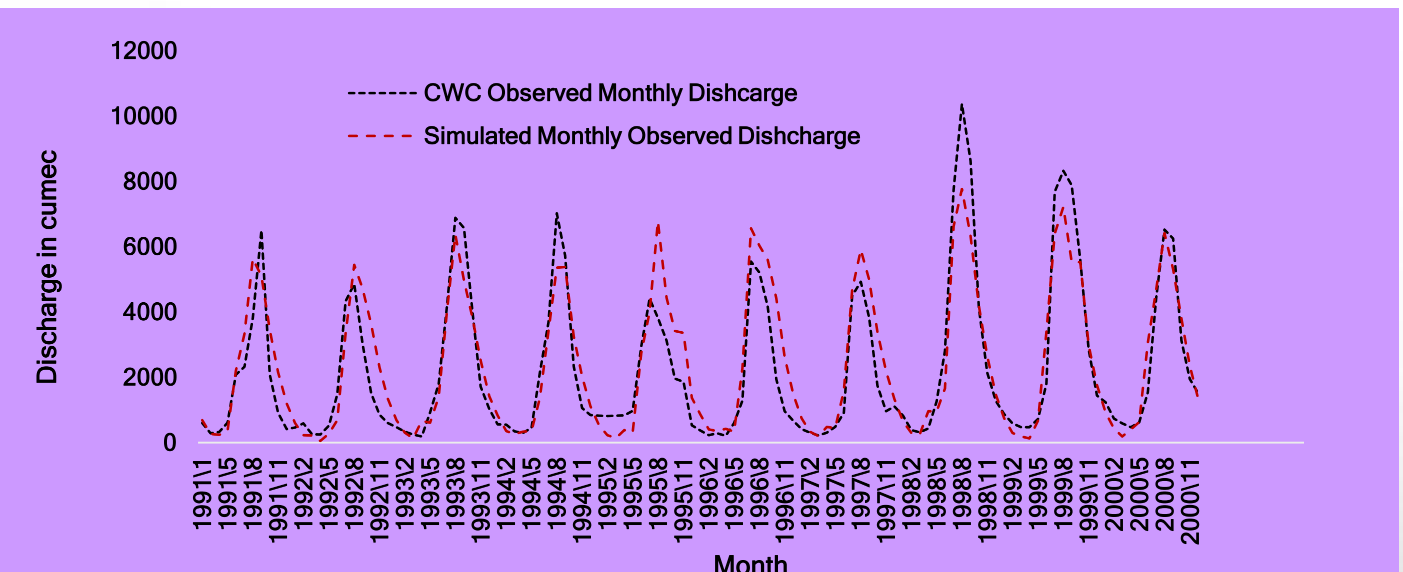
2006

S.No	Class	Class Name	Area in Percentage
1	WATR	Water	0.38
2	FRSE	Evergreen Needleleaf forest	0.91
3	FREB	Evergreen Broadleaf forest	0.60
4	FRSD	Deciduous Needleleaf forest	0.02
5	FRDB	Deciduous Broadleaf forest	3.12
6	FRST	Mixed forest	8.32
7	RNGC	Closed shrublands	2.97
8	RNGO	Open shrublands	6.85
9	RNGW	Woody savannas	8.83
10	RNGE	Savannas	0.04
11	RNGG	Grasslands	10.52
12	WETF	Permanent wetlands	0.10
13	AGRR	Croplands	22.47
14	URMD	Urban and built-up	0.25
15	AGRL	Cropland/Natural vegetation mosaic	10.42
16	SNOW	Snow and ice	4.58
17	PAST	Barren or sparsely vegetated	19.61

SWAT Model Calibration & Validation (MODIS 2000)



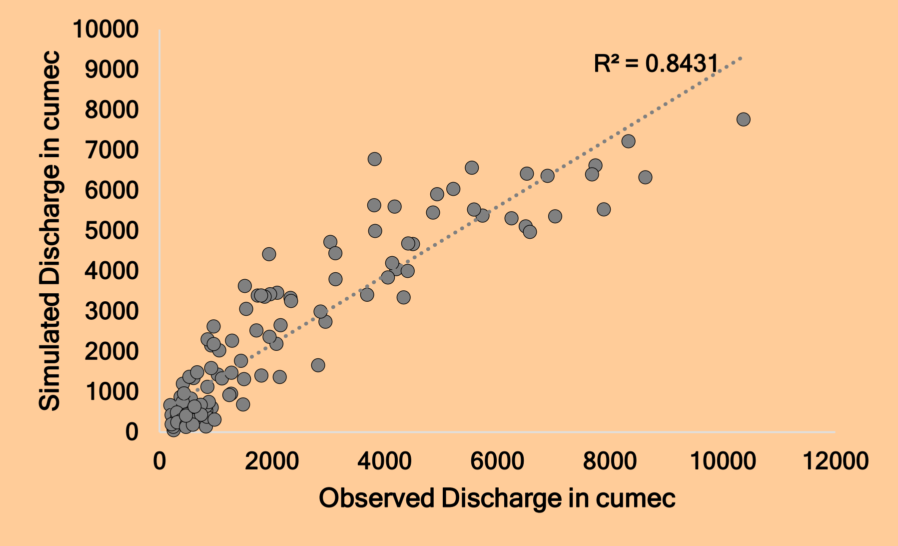
Calibration Period (1980-1990)

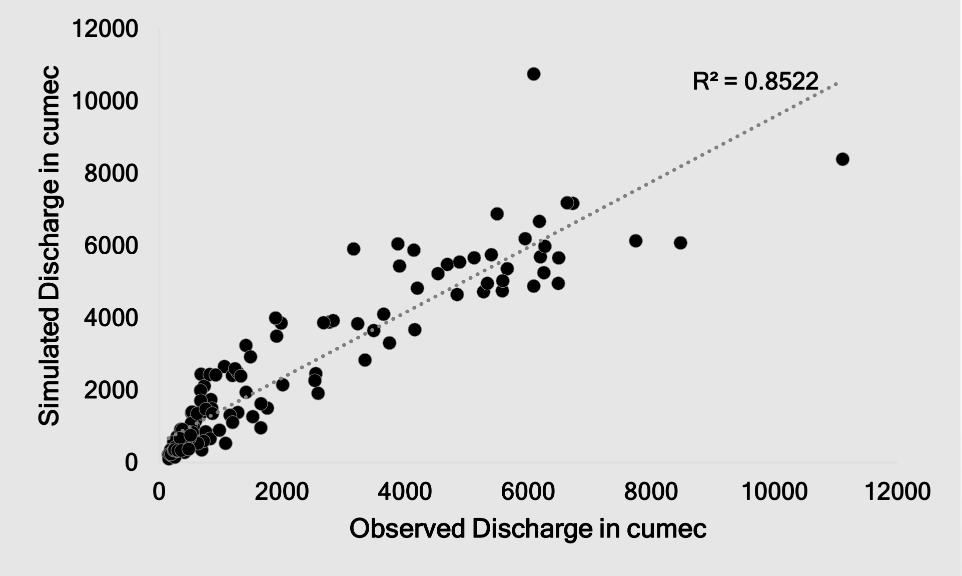


Validation Period (1991-2000)

SWAT Model Calibration & Validation (MODIS 2000)

Calibration Period (1980-1990)





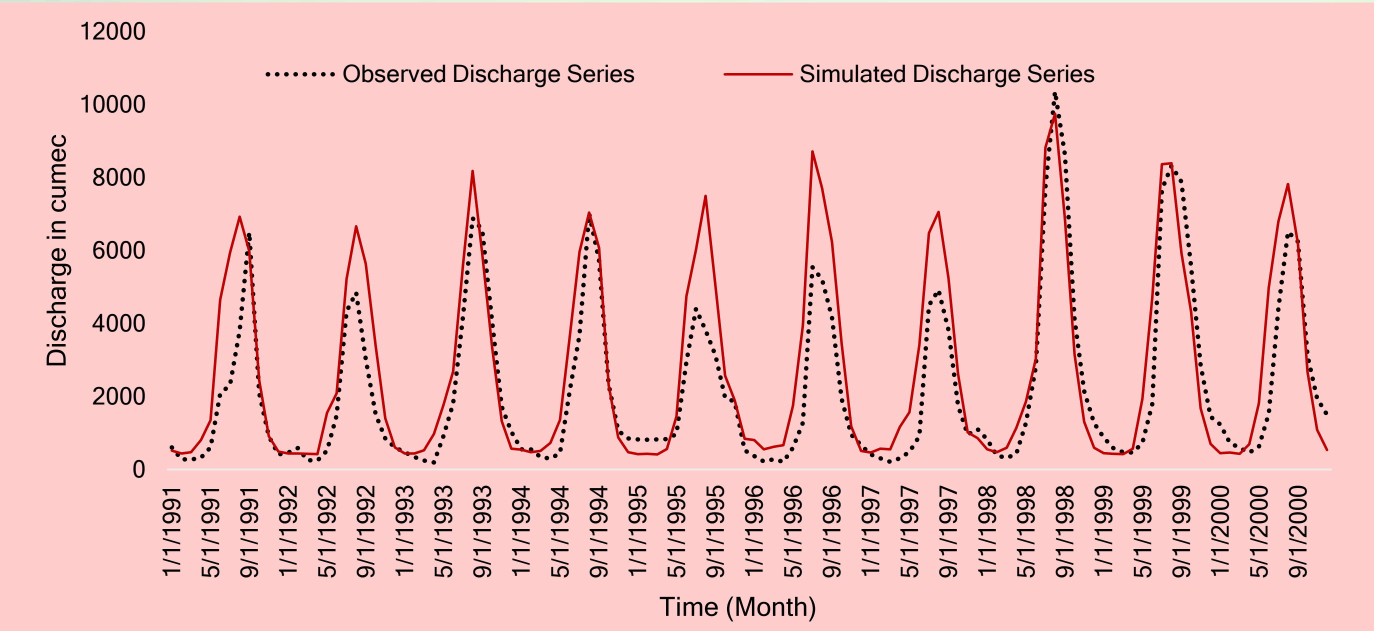
Validation Period (1991-2000)

SWAT Model Evaluation

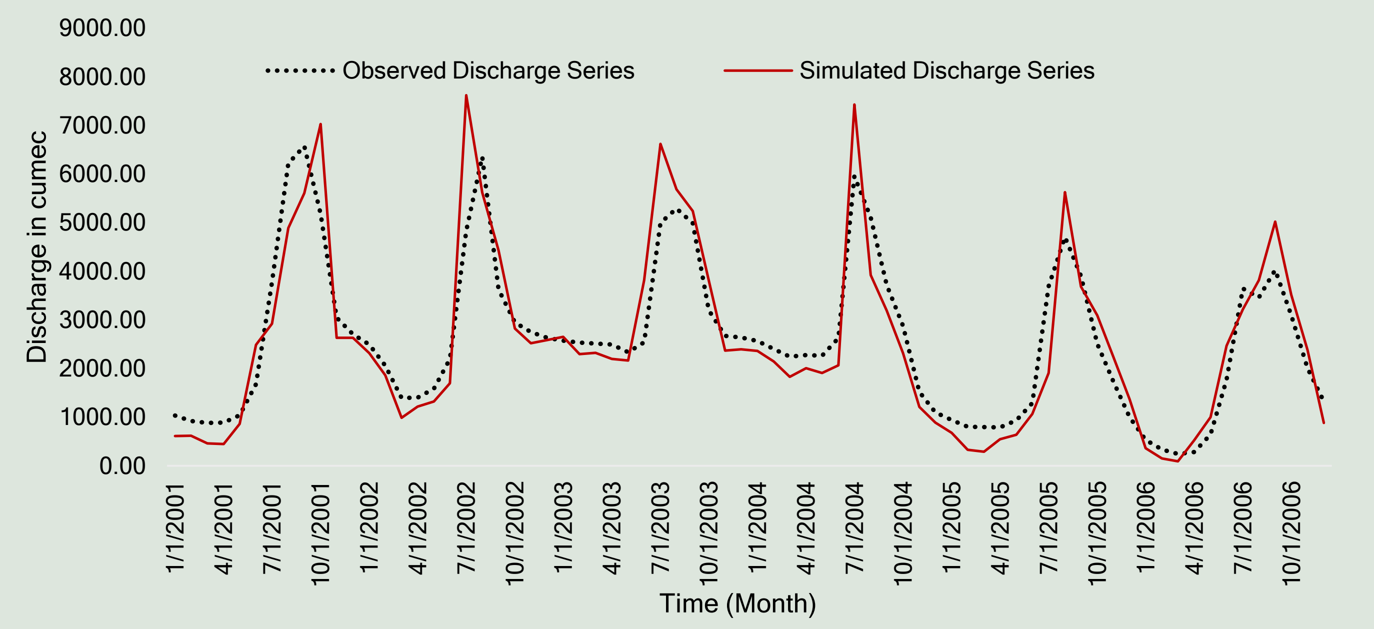
Scenario	Scenario	Calibration	Validation
1	Nash-Sutcliffe model efficiency coefficient	0.82	0.83
1	Correlation Coefficient	0.84	0.86
2	Nash-Sutcliffe model efficiency coefficient	0.82	0.81
2	Correlation Coefficient	0.84	0.85

Scenario 1: SWAT Model with MODIS Landuse/Landcover Data for the year 2000
Scenario 2: SWAT Model with MODIS Landuse/Landcover Data for the year 2006

SWAT Model Calibration & Validation (MODIS 2006)



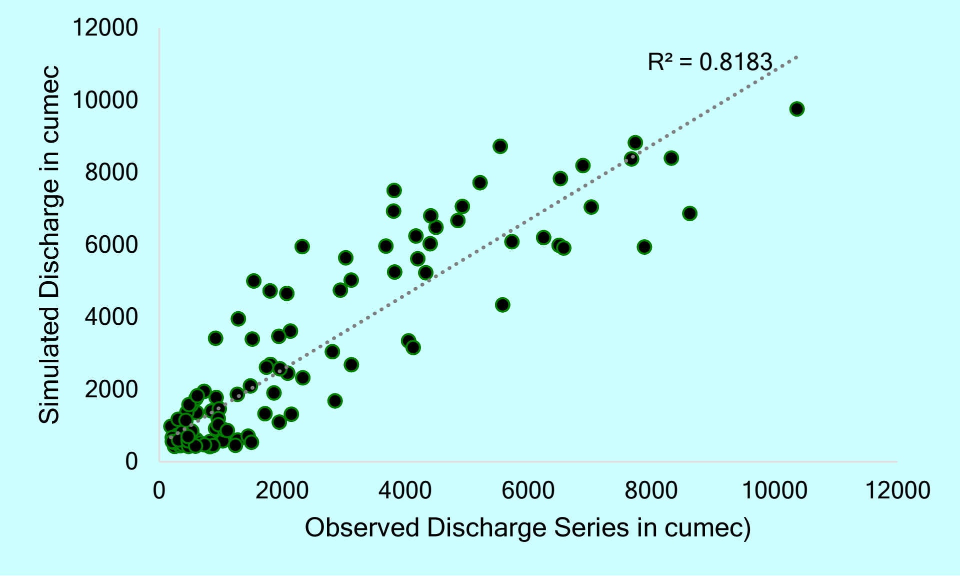
Calibration Period (1991-2000)

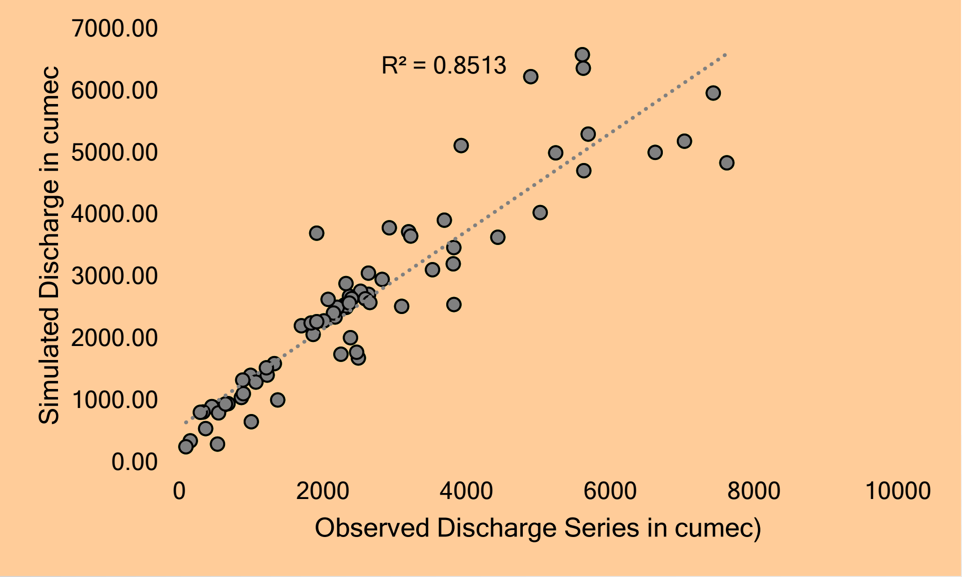


Validation Period (2001-2006)

SWAT Model Calibration & Validation (MODIS 2006)

Calibration Period (1991-2000)

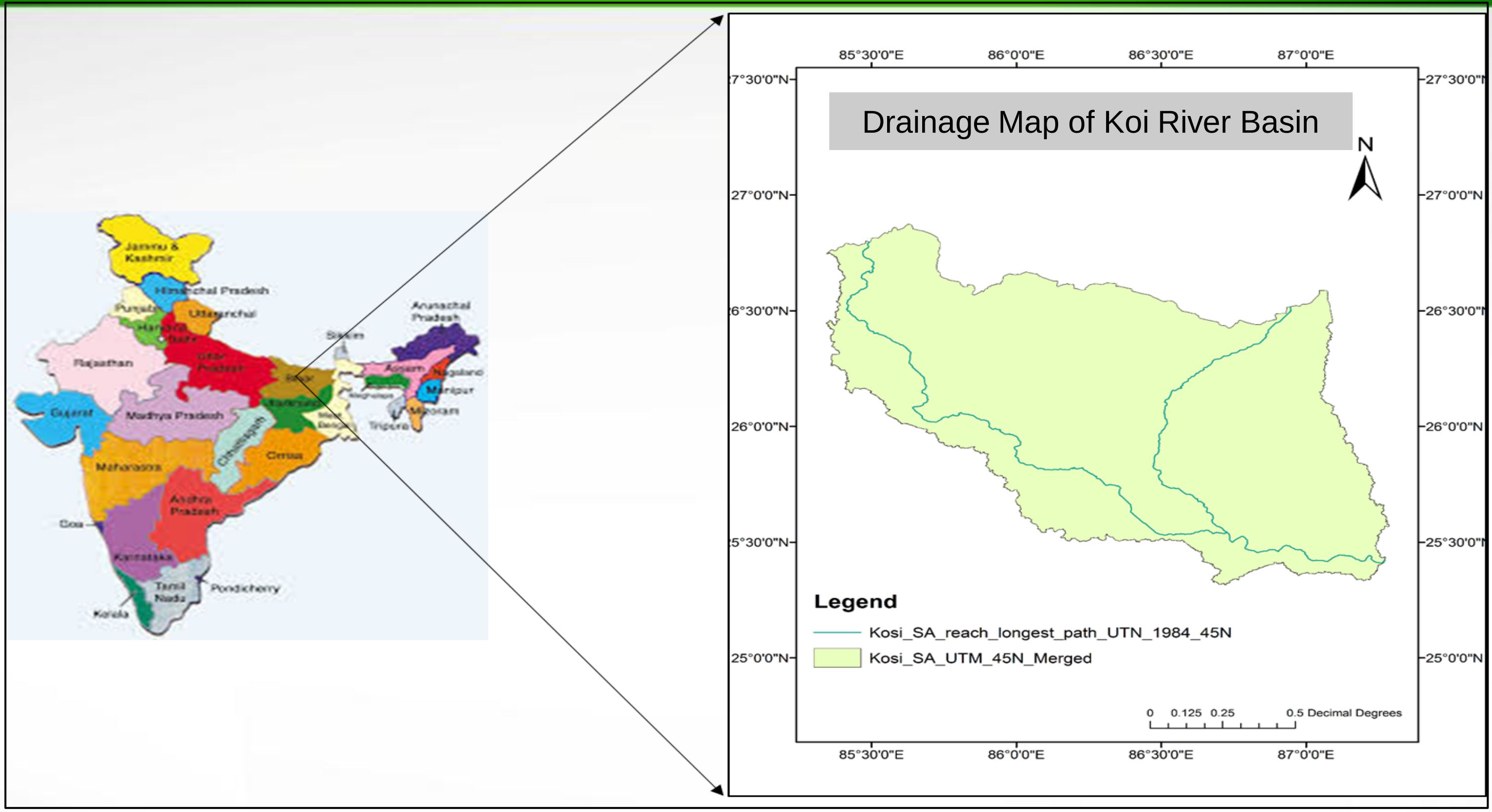




Validation Period (2001-2006)

Groundwater Hydrological Modelling

Study Area



Kosi river sub-basin, Ganges system, India.

Latitude - 25°15'41"N to 26°53'45"N

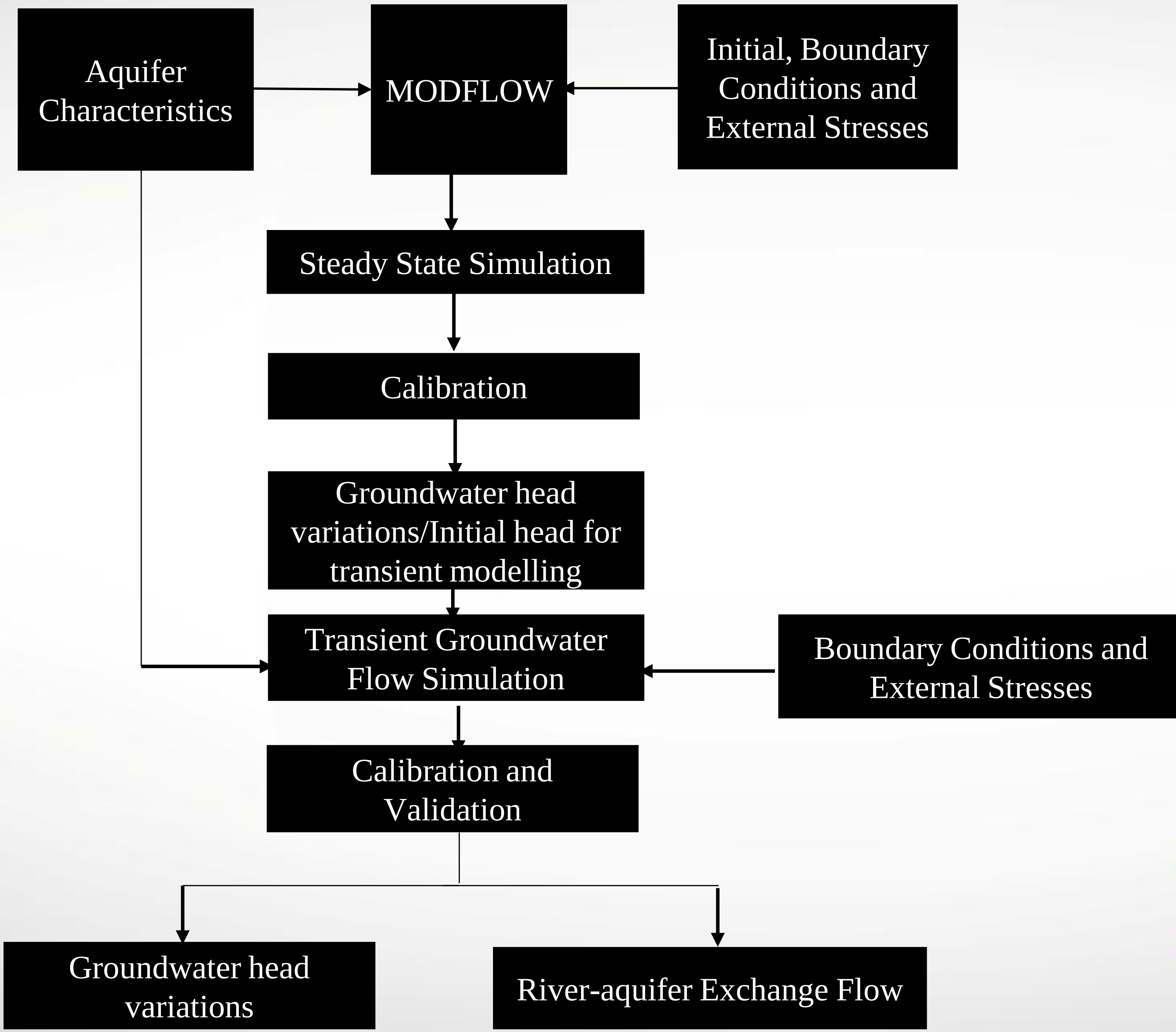
Longitudes - 85°15'3"E to 87°20'4"E

Catchment Area – 19,129 Km^2

Data Used

- **Digital Elevation Model:** USGS, SRTM (shuttle radar topography mission) (90m)
- **Aquifer Characteristics :** Aquifer characteristics such as hydraulic conductivity, specific storage, specific yield and porosity have been obtained from Central Groundwater Board (CGWB), Patna and also from literature (Heath, 1983 and Ferris *et al.* 1962)
- **Soil Characteristics:** Soil types those are existing in the study area have been obtained from fence diagram map prepared by CGWB, Patna.
- **Groundwater Draft and Recharge:** External stresses such as pumping (groundwater draft) and recharge values for the time periods 2000-06 have been obtained from CGWB,Patna
- **Evapotranspiration Information:** Evapotranspiration gridded data obtained from MODIS Satellite data (1k ×1km) was used as external stress to construct the model (Bhattacharya *et al*. 2010; Mallick *et al*. 2007)
- **Historical Groundwater Level Information:** Measured groundwater levels for the periods of 2000-2006 have been obtained from India-WRIS website (http://www.india-wris.nrsc.gov.in/GWLevelApp.html?UType=R2VuZXJhbA==?UName=).
- **Riverbed Conductance:** To calculate river bed conductance, river bed soil hydraulic conductivity and river bed thickness are taken from literature (Domenico and Schawartz, 1990). River width is taken from google earth.

Methodology



Governing Ground Water Flow Equation in Finite Difference Form

$$\frac{\partial}{\partial x}\left(K\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K\frac{\partial h}{\partial z}\right)=s_s\left(\frac{\partial h}{\partial z}\right)+w(x.y.z.t)$$

Where

h = hydraulic head (L)

S_S = specific storage (L^{-1})

K = hydraulic conductivity (LT^{-1})

t = time (T)

W (x,y,z,t) = a volumetric flux per unit volume (T^{-1})

Kxx , Kyy and Kzz are the principal components of hydraulic conductivity tensor (LT^{-1}).

Initial, Boundary and Aquifer Parameters

- Boundary Conditions:

Specified head boundary condition (Dirichlet or first-type boundary conditions) was used along all sides of the boundary

- Initial Heads or Starting Heads:

For constructing the groundwater flow model, initial or starting heads are required. For this purpose, observed averaged groundwater level variations in the study area were used to start the model.

- Soil Type Information:

There are majorly three types of soils exits at different locations at different depths in the study area. They are fine sands, medium sands and clay. Mostly fine sands percentage dominates than other two types.

Initial, Boundary and Aquifer Parameters

- Aquifer characteristics:

In the study area, aquifer characteristics for fine sands such as hydraulic conductivity, porosity specific storage and specific yield are taken as 0.017 - 43 m/d, 0.3, 0.0015m^{-1} and 0.33 respectively.

- River bed conductance:

From the literature, in the study area, there exists silty clay soil as river bed material. The hydraulic conductivity of riverbed material, river bed width and river bed thickness values used in the model were 0.8 m/d, 286-771 m and 10 m respectively.

- External stresses:

External stresses such as recharge and pumping and evapotranspiration obtained from above mentioned sources were used to construct the model.

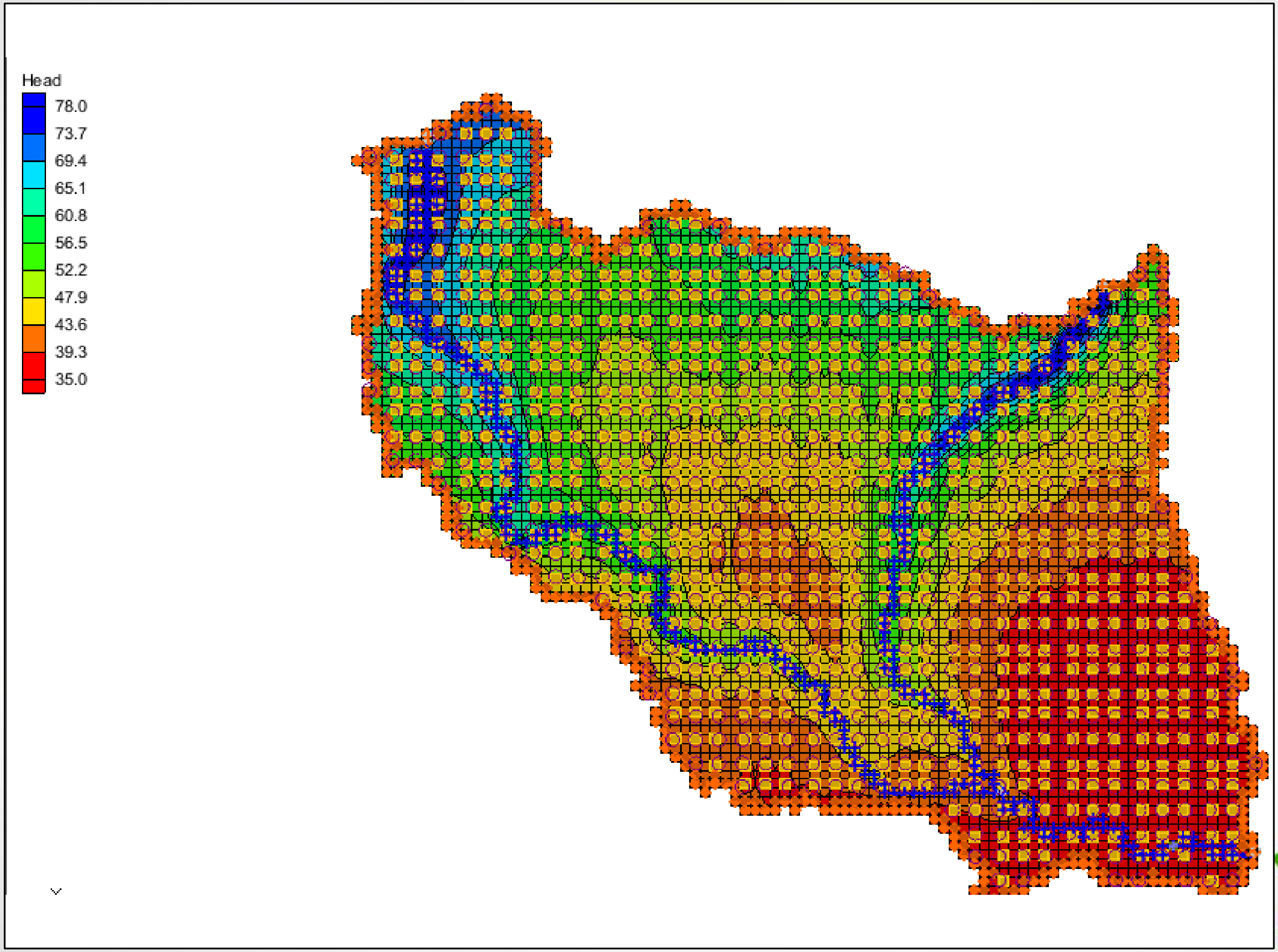
- Aquifer Top Elevations and Bottom Elevations:

SRTM 90m × 90m gridded Digital elevation model was used to obtained top elevations in the study area and bottom elevations were estimated using top elevations and soil strata layer depths.

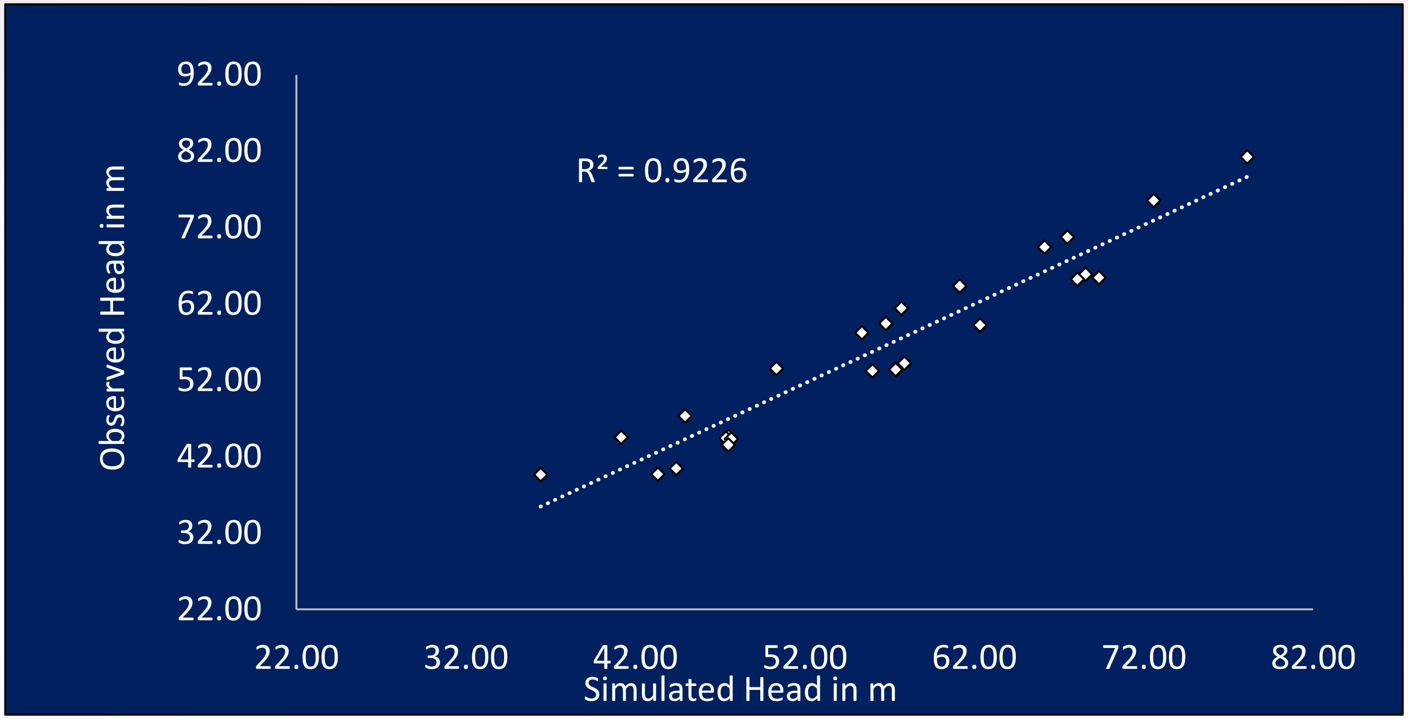
Steady State Simulation

- Steady state simulation of groundwater flow model of Kosi river basin was constructed by considering the above information
- The model was discretized into 100 × 100 grid cells using conceptual approach
- The groundwater draft (pumping) was uniformly distributed by considering hypothetical wells (758 numbers) throughout the watershed.
- External stress values for recharge, pumping and evapotranspiration were taken as 0.002 m/d, 8640 m3/d per well and 0.0018m/d respectively.
- Model was calibrated using calibration parameters (hydraulic conductivity 15m/d and river bed conductance 66 $m^2/d/m$)

Groundwater Flow Contours



Calibration of Steady State Simulation



Scatter plot between observed head and simulated head for steady state model calibration for the month of January. 2000 at Darbanga

Simulated head results ranges from 31m to 85m whereas, observed head variation ranges from 30-78 m

Transient Simulation

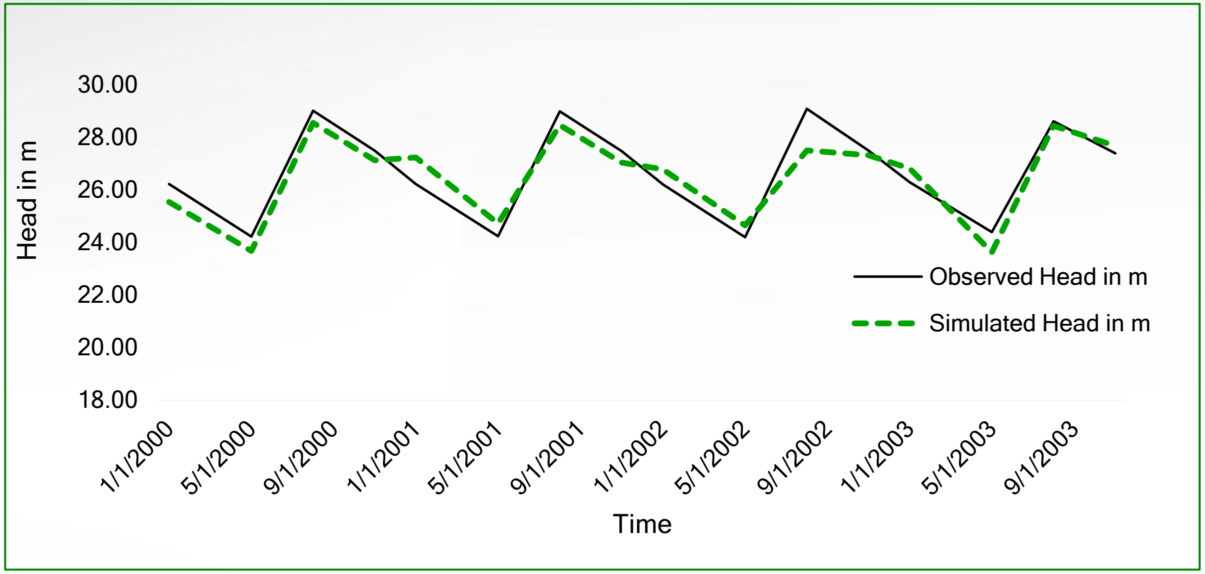
- Transient groundwater flow modelling was performed to get seasonal groundwater head variations with above information mentioned using conceptual approach.

- External stresses: groundwater draft, recharge and evapotranspiration for the time periods 2000-06 for 4 seasons i.e. January (post monsoon Rabi), May (pre monsoon), August (Monsoon) and November (post monsoon Kharif) were taken to develop the model

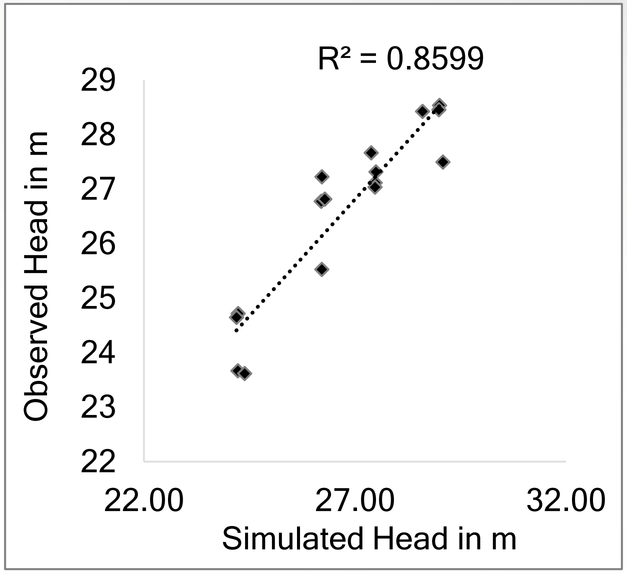
- The model was calibrated and with observed groundwater level variations.

- The model calibration parameters were hydraulic conductivity (10 m/day for Clay, 25 m/day for Fine sand and 120 m/day for medium sand) with and riverbed conductance (24-66 m^2/d/m).

Calibration of Transient Simulation



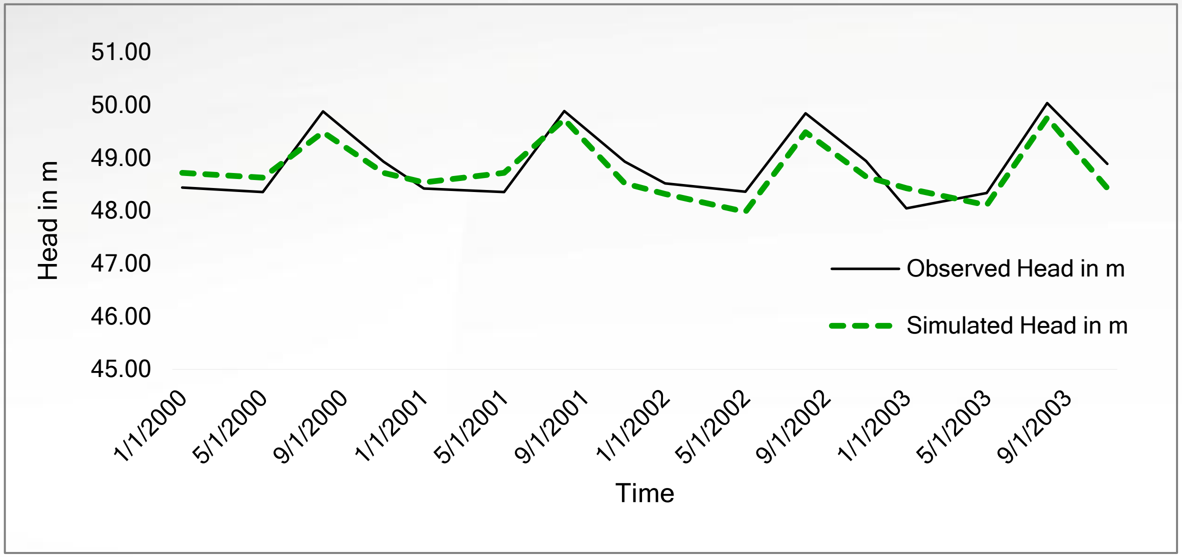
Piezometric head variations at Kursela station for calibration period 2000-03

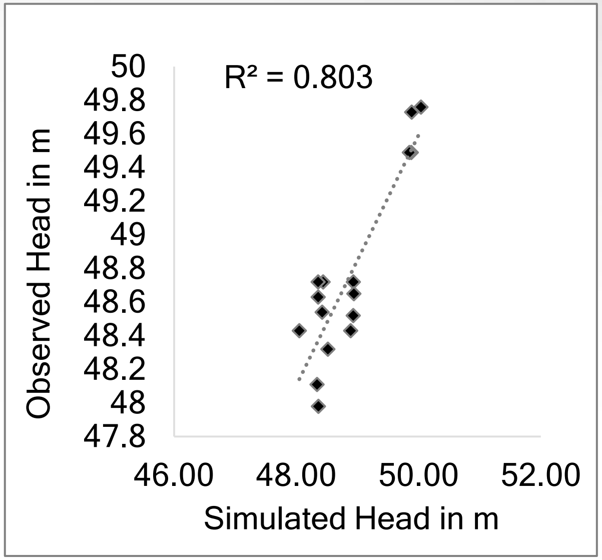


Scatter plot between observed and simulated heads at Kursela for calibration period 2000-03

Observed head ranges from 24.1- 30.5 m whereas, simulated head ranges from 23.6- 29.4m

Calibration of Transient Simulation



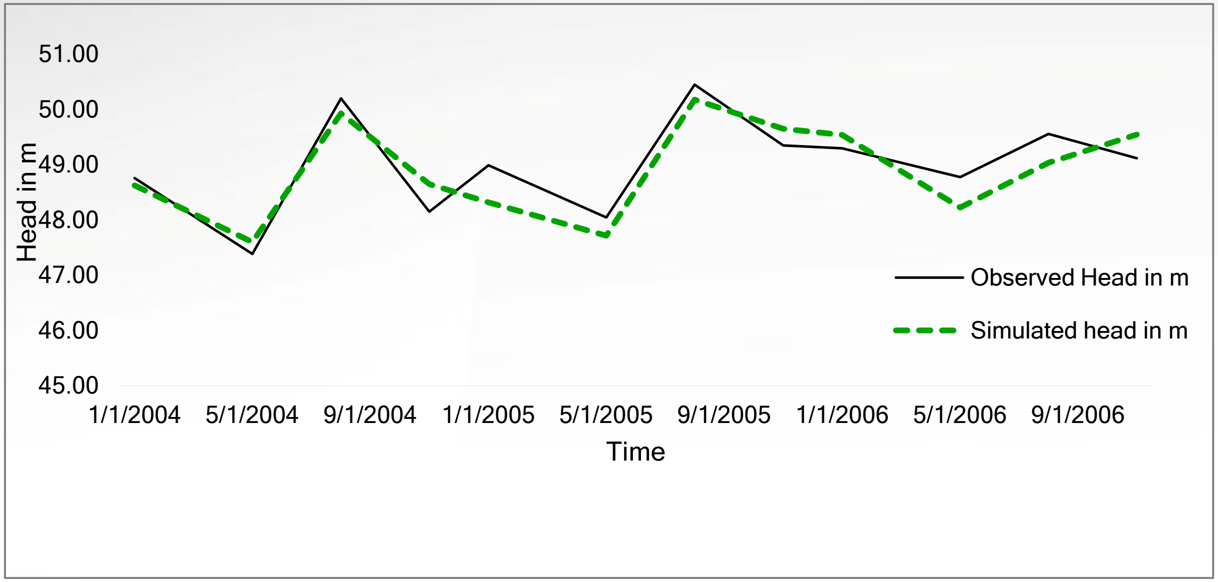


Piezometric head variations at Darbanga station for calibration period 2000-03

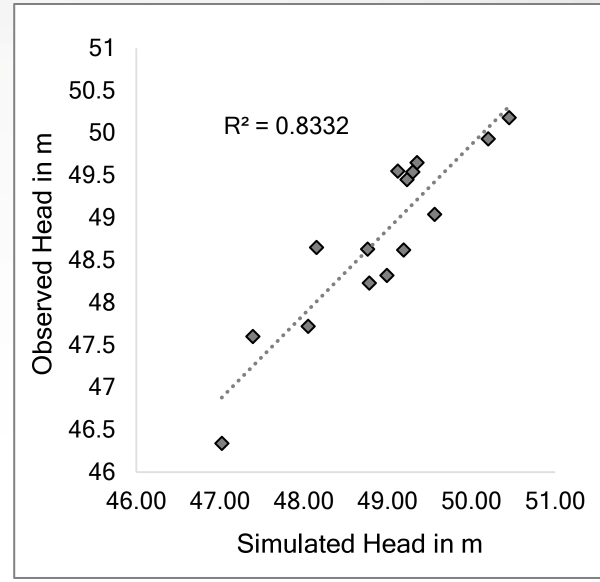
Scatter plot between observed and simulated heads at Darbanga for calibration period 2000-03

Observed head ranges from 47.39- 50.2 m whereas, simulated head ranges

Validation of transient Simulation



Piezometric head variations at Darbanga station for validation time period 2004-06



Scatter plot between observed and simulated heads at Darbanga for validation period 2004-06

Observed head ranges from 47- 50.2 m whereas, simulated head ranges from 46.3- 50.1m

Landuse/Land Cover Change Analysis using MODIS Satellite Products

Analysis of Evapotranspiration Datasets

- Land Evapotranspiration (ET) is a fundamental process in the climate system and a terrestrial link among the water, energy and carbon cycles.
- Several methods are there for estimating Evapotranspiration.
- In this study Evapotranspiration was estimated using satellite data (MODIS) of Indian continental datasets (2000 to 2006)) by energy balance method.

Analysis of Evapotranspiration Datasets

- Actual evapo-transpiration (AET) (hereafter referred as ET) can be estimated from latent heat fluxes (λE or LE) and latent heat (L) of evaporation
- Latent heat flux (λE) is generally computed as a residual of surface energy balance
- A single (soil-vegetation complex as single unit) source surface energy balance can be written as,

$$R_n = H + G + \lambda E + M + S$$

Where- R_n = net radiation (Wm^{-2})

H = sensible heat flux (Wm-2)

G = ground heat flux (Wm^{-2})

M= Energy Component for metabolic activities

S= Canopy Storage component

$$\lambda E = R_n - G - H$$

$R_n - G$ = net available energy (Q) in Wm^{-2}

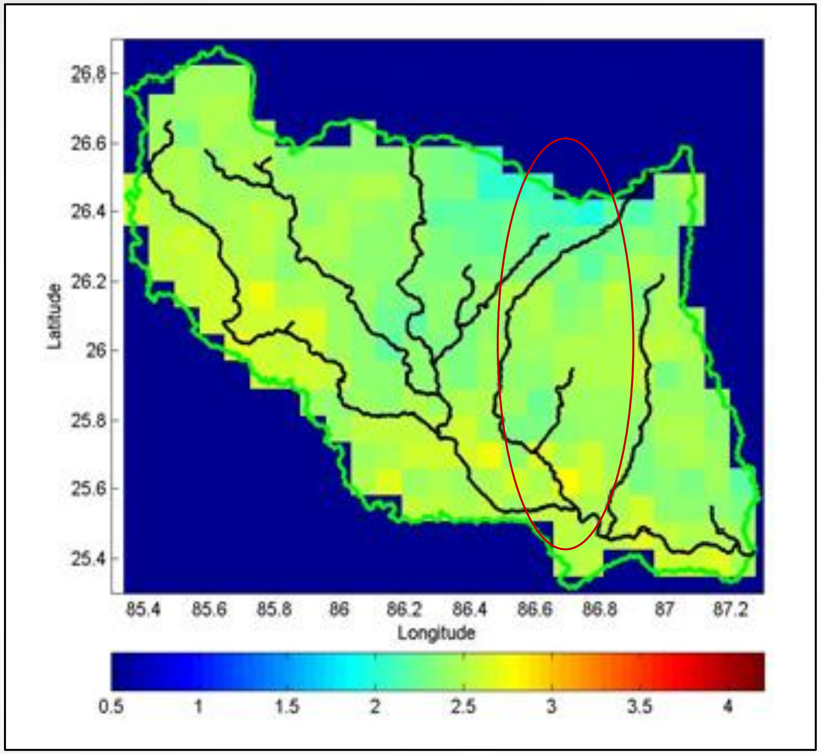
The combination of evaporative fraction $\left(\frac{\lambda E}{Q}\right)$ and Q results into λE estimates

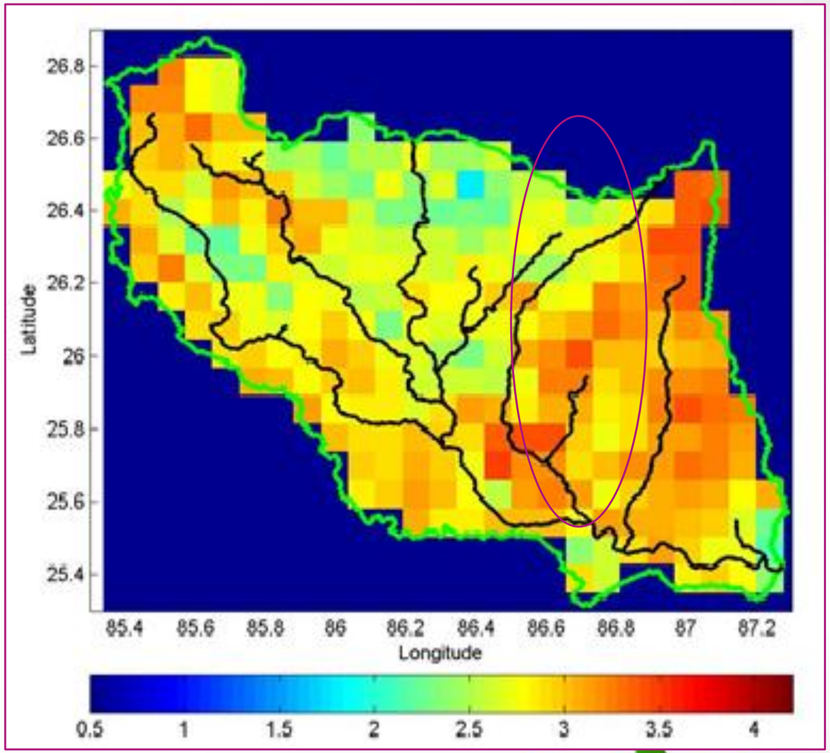
$$\boxed{\lambda E = Q \cdot \Lambda = (R_n - G) \cdot \Lambda}$$

Λ - evaporative fraction

$$ET = \left(\lambda E_d \frac{dl}{24}\right) C$$

Evapotranspiration Spatio-Temporal Variations



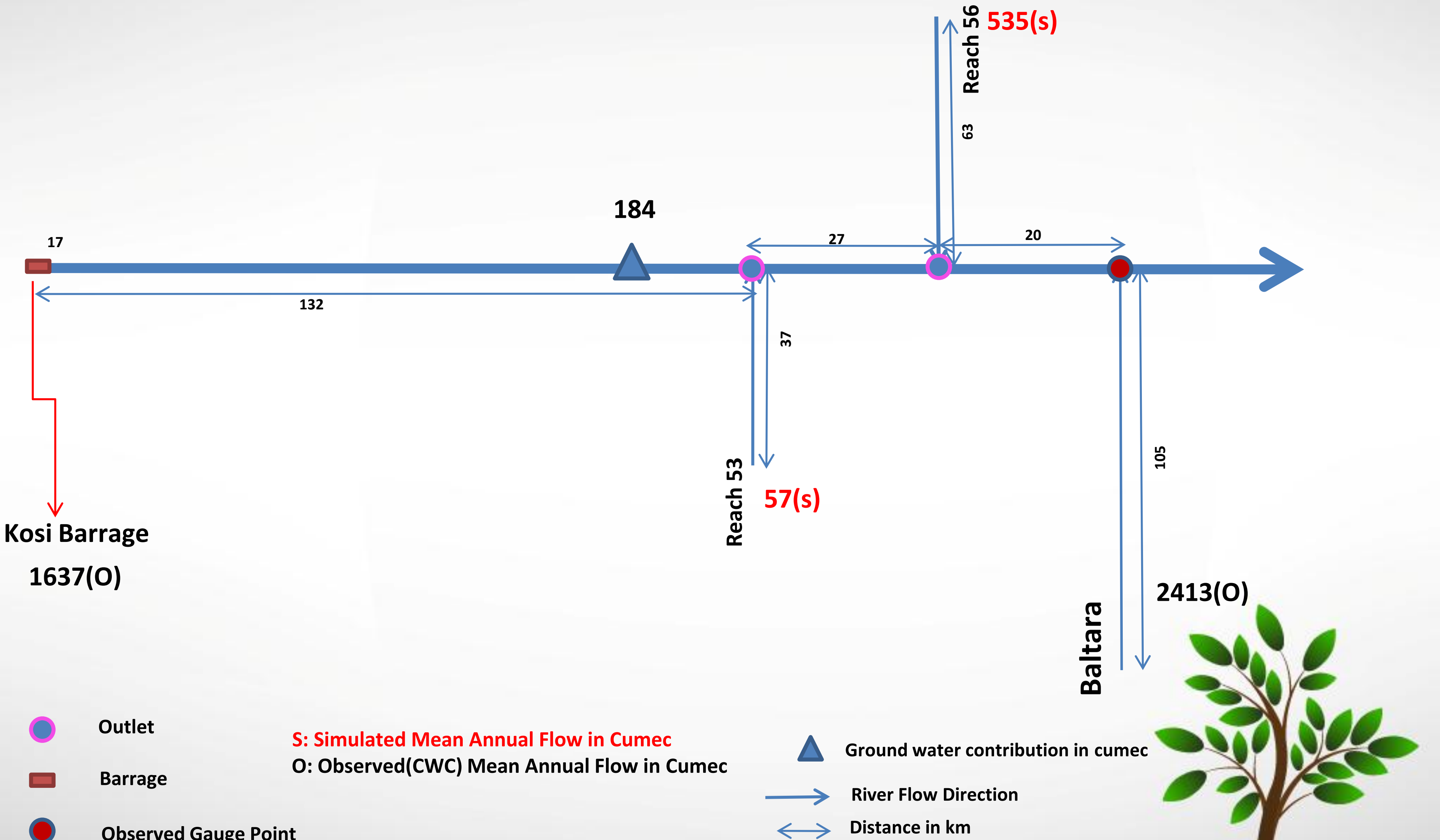


2000

2006

Water Balance Study

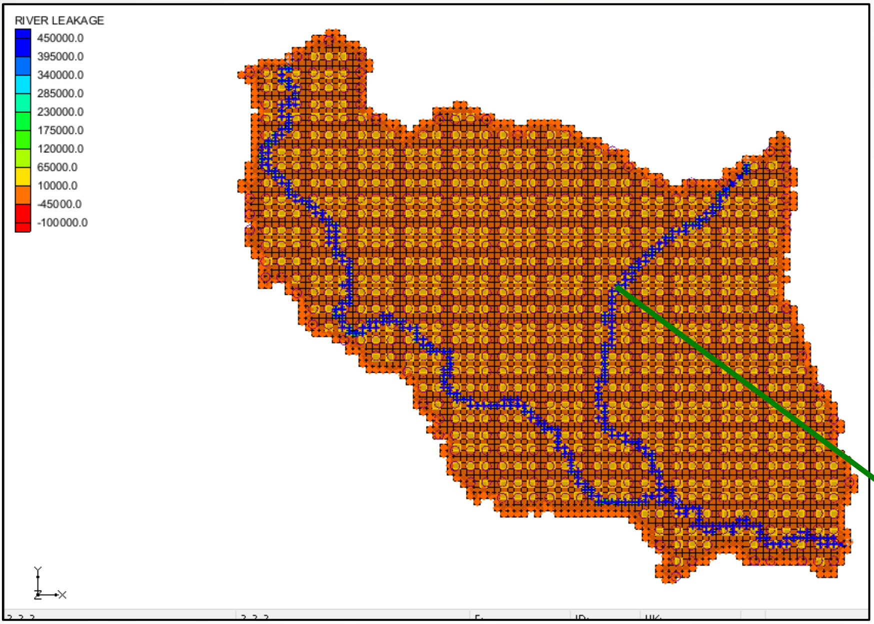
(2000)
Annual



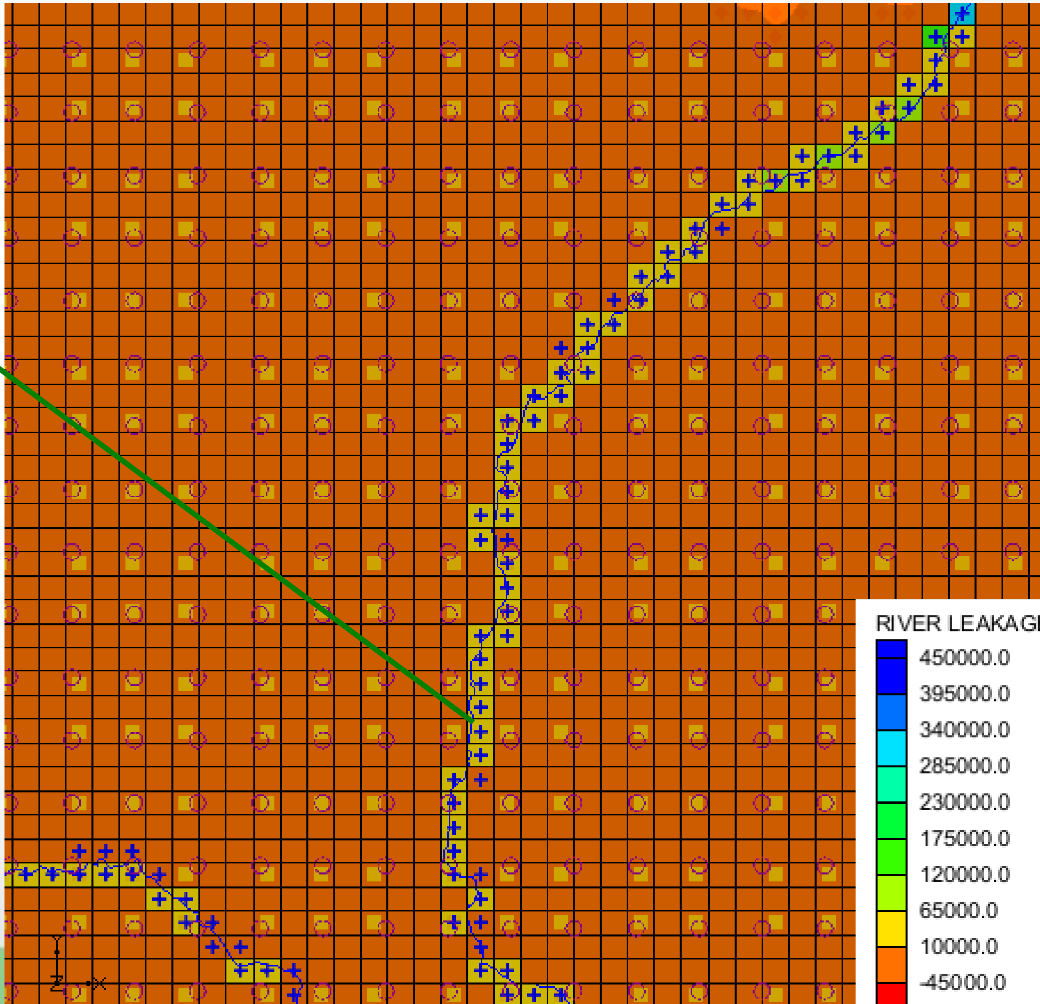
NOTE: ALL MEASUREMENTS ARE IN KM & NOT UPTO SCALE

Effluent or Influent River Reaches

(2000) Annual



Gaining Stream

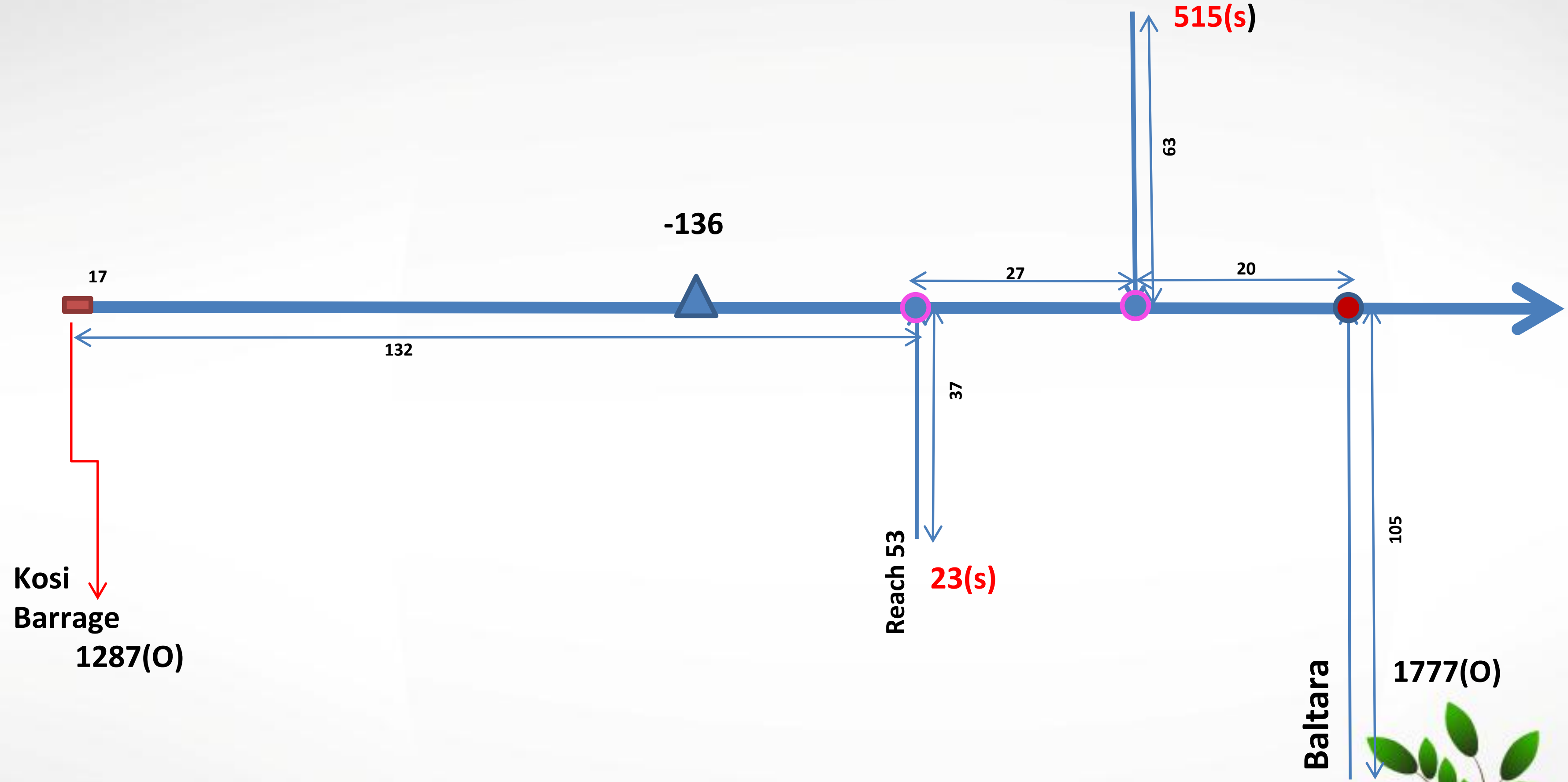


Kosi river leakage

River was gaining in nature during the time period (2000)

Water Balance Study

(2006)
Annual



Barrage

Observed Gauge Point

S: Simulated Mean Annual Flow in Cumec
O: Observed(CWC) Mean Annual Flow in Cumec

Ground water contribution in cumec

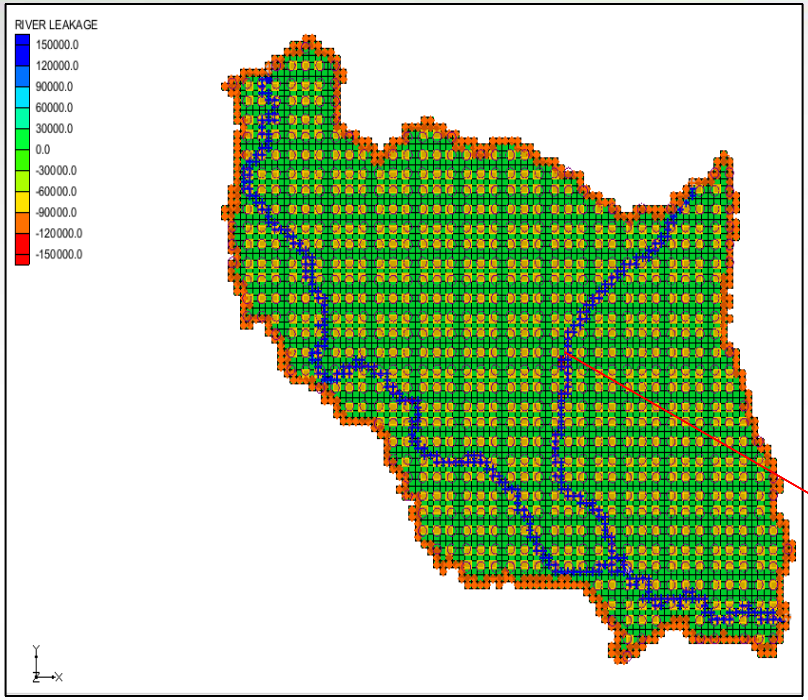
River Flow Direction

Distance in km

NOTE: ALL MEASUREMENTS ARE IN KM & NOT UPTO SCALE

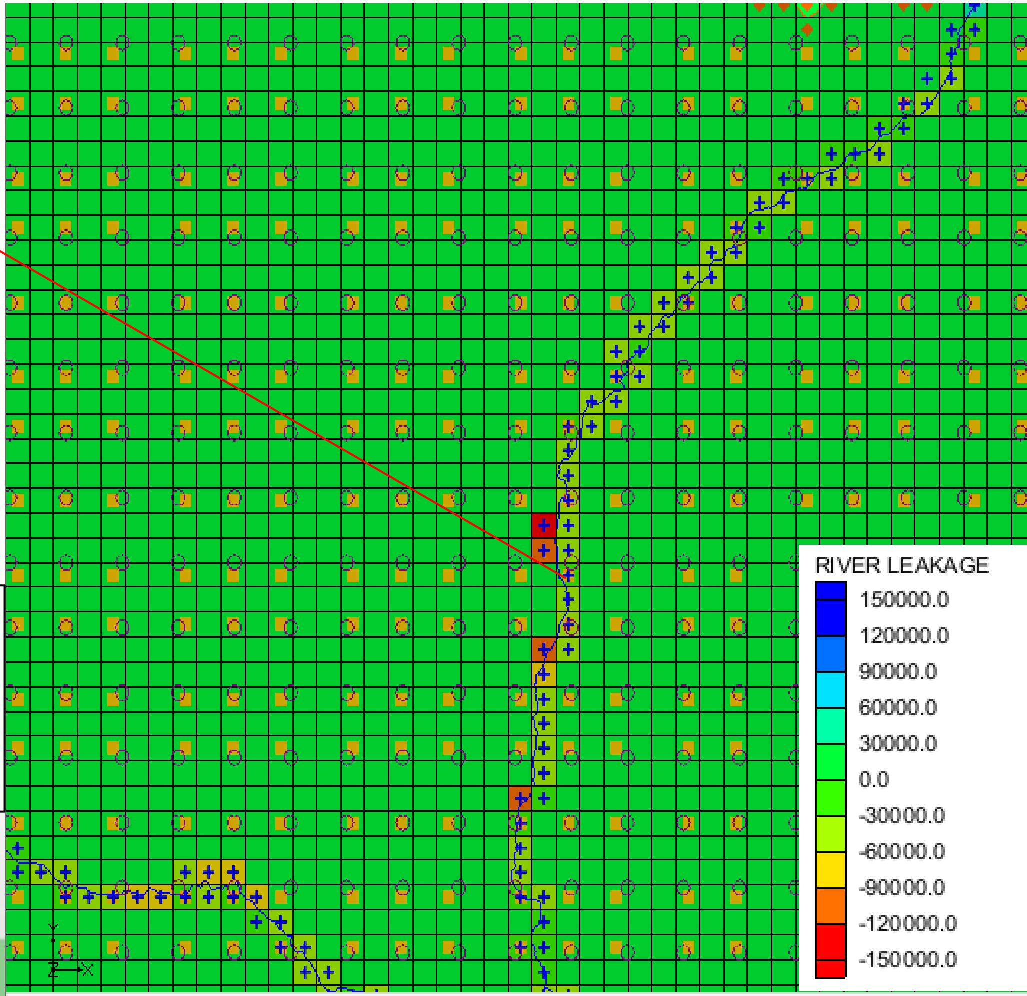
Effluent or Influent River Reaches

(2006) Annual



Kosi river leakage

Loosing Stream



River was partially gaining and loosing in nature. Overall, river was stream loosing during this time period (2006) and also reconfirmed with MODFLOW

Conclusions

- Surface water hydrological model was well calibrated and validated. Groundwater delay and soil slope length were found to be most sensitive parameters.
- Sub-surface hydrological model was set up with landuse/land cover changes by incorporating evapotranspiration variations and calibrated followed by validation. Hydraulic conductivity and river bed conductance were found to be most sensitive parameters.
- As an initial tool, a simple water balance was carried out with SWAT Model to understand the interaction exchange varied annual scale level.
- Using MODFLOW, river-aquifer interaction exchange was evaluated and compared the trends for the same time periods with water balance study
- Through the water balance study, significant change was observed in the river-aquifer interaction exchange from the year 2000-2006 and it was reflected for the landuse/land cover changes incorporated in the MODFLOW.
- The combination of surface and sub-surface hydrological model can be used to understand the effect of LULC on Surface and groundwater interaction exchange process.

ACKNOWLEDGEMENT

- And we also thankful to Ganga River Basin Environmental Plan Management Project Team, Central Groundwater Board, Patna and Central Water Commission, Patna for providing valuable data for hydrological modelling.

- We are very thankful to Dr.Bimal Bhattacharya, Space Application Centre, Ahmedabad for his support in providing Evapotranspiration data sets for Bihar State.

THANK YOU

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