# Water Systems Modeling for Ganga Basin

INRM Consultants Pvt. Ltd.
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# Water Systems Modeling for Ganga Basin

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**Prepared by: INRM Consultants Pvt. Ltd.**

**In Association with:**

**Prof. A. K. Gosain**

**Professor, Department of Civil Engineering**

**Indian Institute of Technology (IIT) Delhi**

**Prof. R. Srinivasan**

**Director of Spatial Sciences Laboratory**

**Professor of Ecosystem Science and Management and Biological and Agricultural Engineering**

**Texas A&M University**

# Table of Contents

# List of Tables

# List of Figures

# List of Abbreviations

| | |
|---|---|
| ADB | Asian Development Bank |
| BL | Base Line |
| CBOD | Carbonaceous biological oxygen demand |
| CoE/NSE | Coefficient of Efficiency |
| DEM | Digital Elevation Model |
| ET | Evapotranspiration/Nash Sutcliffe efficiency |
| FAO | Food and Agriculture Organization |
| gBOD/day | Gram biological oxygen demand/day |
| GCM | Global Circulation Models |
| GHG | Green House Gas |
| GMIA | IWMI's Global Map of Irrigated Areas |
| GMLULCA | Land use: Global Map of Land Use/Land Cover Areas |
| GRDC | Global Runoff Data Centre |
| HRUs | Hydrologic Response Units |
| IMD | Indian Metrological Department |
| IPCC | Intergovernmental Panel on Climate Change |
| IWMI | International Water Management Institute |
| $km^3$ | Cubic meter |
| l/c/d | Litres per Capita per Day |
| MC | Mid Century |
| mld | Millilitres per day |
| mm | Millimetre |
| MODIS | Moderate Resolution Imaging Spectroradiometer |
| MUSLE | Modified Universal Soil Loss Equation |
| P | Percolation |
| ppm | Parts per million |
| PRECIS | Providing Regional Climates for Impact Studies |

| | |
|---|---|
| Q | Runoff |
| QR | Groundwater flow |
| QUMP | Quantifying Uncertainty in Model Predictions |
| R | Precipitation |
| R2 | Regression coefficients |
| RCM | Regional Climate Models |
| SCS | USDA Soil Conservation Service |
| sq. km | Square Kilometre |
| SRES | Special Report on Emission Scenarios |
| SRTM | Shuttle Radar Topography Mission |
| SW | Is the soil water content |
| SWAT | Soil and Water Assessment Tool |
| t/ha | Tonnes per hectare |

# Executive Summary

Ganga basin is the largest river basin in India constituting 26% of the country's land mass and supporting about 43% of its population, making it the most populated river basin in the world. Ganga basin covers 11 States of India. Total distance covered by the river is 2,525 km before its outfall into the Bay of Bengal. The Important tributaries are the Yamuna, the Ramaganga, the Gomti, the Ghagra, the Sone, the Gandak, the Burhi Gandak, the Kosi and the Mahananda. At Farakka in West Bengal the river divides into tow arms namely the Padma which flows to Bangladesh and the Bhagirathi and the Hugli which flows through West Bengal.

Out of the annual surface water potential of 525 $km^3$ in India utilizable water has been assessed to be 250 $km^3$. With about 580,000 $km^2$ of arable land (29.5% of the cultivable area of India)there is a large network of diversion canals. The most upstream diversion site is located at Haridwar, where a significant portion of the main stream is diverted into the Upper Ganga Canal. This is an irrigation channel that feeds the alluvial tract lying between the Ganga and Yamuna rivers. Diversions are also taking place from majority of tributaries of Ganga. The growth in population and industrialization has resulted in unabated increase in pollution levels in some stretches of the river. Main sources of pollution along the reach of the river are urban liquid waste (sewage), industrial liquid waste, and large scale bathing of cattle, throwing of dead bodies in the river, surface run-off from solid waste landfills and dumpsites, and surface runoff from industrial solid waste landfills or dumpsites. As per the Central Pollution Control Board estimate three-fourths of the pollution of the river comes from the discharge of untreated municipal sewage. Loss of discharge is considered as the most serious factor contributing to the rise in levels of pollution since without adequate flow toxins and bacteria cannot be flushed and degraded.

India is going through a phase of economic growth which is bringing about industrial and urban growth. A large number of projects related with water resources are being incorporated and a large number is also being proposed. The present study has been commissioned by the World Bank to help in this development process through the strategic assessment of the Ganga Basin by using the hydrological simulation methodology for Ganga Basin. The well known distributed hydrological model SWAT has been deployed for the purpose. Scenarios have been generated for assessing implications on quantity and quality of water on account of future developments.

In the present day context any water resources development can only be successfully implemented if it gets the approval of all the stakeholders. Therefore, the study also involves in producing a knowledge base on Ganga system that can be disseminated to a diversified set of stake-holders which can work very effectively towards generating consensus on future pathways.

The data available from international sources on terrain and landuse, soil have been used to set up the base SWAT model for the Ganga basin. Reanalysis weather data (1969–2001) at daily interval has been used for the Ganga basin. In order to incorporate the baseline into the simulation exercise, existing major water resources infrastructure in terms of reservoirs and diversions have been taken from the National Register of Large Dams and used into the simulation. Effort has also been made to incorporate the current management/operation practices and existing irrigation (as per crop demand). While simulating the crop management practices differentiated source of irrigation (Surface and Ground water) was incorporated so as to simulate its effect on the hydrological regime of the river system. The ArcSWAT GIS interface has been used to pre-process the spatial data for the Ganga river system. The basin has been sub-divided into 414 sub-basins to adequately account for the spatial variability of various inputs and outputs.

The model was then validated at a limited number of locations where stream flows data could become available. The validation was found to be satisfactory, thereby instilling confidence in the simulation process that is going to be the basis of development and future scenarios. Various scenarios were contemplated to evaluate the implications of the future population growth and development. Additional scenarios have also been formulated to quantify the implications of the projected climate change on quantity and quality of Ganga river. In all five main scenarios have been contemplated (Scenario A to E). The first scenario (Scenario A) is geared to capture the present baseline. This scenario is essential to understand the present status of the Ganga system. The scenario B is meant to simulate the implication of ensuring minimum stream flow (300 cumecs) at all times. This has been ensured by reducing the diversions, if required. The Scenario C is meant for capturing the implication of development during the period 2020-30. This scenario is created by adding the increased demand for domestic, industry and irrigation on top of the present demand. The Scenario D has been formulated to evaluate the implication of development of the projects in Nepal. The level of development has been taken as equivalent of 5, 10 and 50 BCM/year of diversion respectively through three sub-scenarios namely D5, D10 and D50. Lastly, Scenario E has been devised to evaluate the implication of climate change on the water resources of Ganga for periods 2020-30 and 2045-55.

The following major decisions/assumptions have been made while formulating these scenarios:

- Although there are around 206 dams/reservoirs available in the basin, only 104 structures were implemented since these were the structures with available data on the area, capacity and starting year of operation
- In the absence of the data on major canal diversions, irrigation water use as proxy was computed and used
- Current crop management practices (irrigation from Surface and Ground water) based on landuse map, irrigation source map, command area map and district-wise average irrigation (by source) information was used
- In order to incorporate the future irrigation demand, additional water demand has been calculated using agriculture demand increase for the projected population
- Point source of domestic pollution has been computed by using average BOD and the average sewer generation per capita. Consumption/Capita (l/c/d) is taken as

123.3 (ADB 2007[1]) and 80% is taken as sewage return. Per capita BOD (gBOD/day) based on 2001 population census is taken as 40.5[2]

- The future BOD load has been calculated based on future water demand using population projection[3].

The hydrologic simulation of the baseline (Scenario A) reveals that at the basin scale (although there is considerable spatial variability of hydrologic character within the basin) for the monsoon months of June through September the precipitation is larger than the water yield (blue water) and crop water requirements (green water) thus making the crop production not so much dependent on irrigation water. A good proportion of the precipitation gets stored into the soil as well as contributes to the groundwater recharge during this period. However during non-monsoon months, the evapotranspiration is higher than precipitation, suggesting that the water has to be either diverted through storage or taken from shallow to deep aquifer withdrawal to meet the crop production demand. At the annual scale 34% of the precipitation accounts for evapotranspiration from the basin and the remaining amount are distributed into water yield and ground water recharge at the basin scale. It must be mentioned here that there is considerable spatial variability of precipitation in the Ganga river basin. The average precipitation range from less than 500 mm/annum in the Chambal basins and some of the rain shadow regions of Himalayas to over 4000 mm/annum in the Kosi and Gandak sub-basins. With such variability in precipitation and other associated characteristics such as landuse and soil type the hydrologic response of these areas is also expected to be equally variable.

The most difficult part in the present simulation was the simulation of snow hydrology components of snow melt and snowfall due to the non-availability of observed precipitation data at higher elevations. In the Ganga basin the elevation range from 8000m to 2000 m at the foot hills of Himalayas. In order to get the flows observed during the lean season (mainly on account of snow and glacier melt) simulated adequately temperature lapse rate of -6.5oC/Km and precipitation lapse rate of 200 mm/Km taken from literature was used. In addition, since there were no data on spatial pattern of glacier and snow pack information, in this modelling setup it is assumed that a glacier depth of 100 m for altitudes above 4500 m elevation. These initial conditions were arrived at through an exhaustive calibration process and could achieve reasonably good validation of model for the observed flow locations in Nepal.

Another difficulty was to incorporate the water diversions in the simulation process in the absence of the availability of such data. This was also handled in an indirect way. The irrigation demand was computed based on the prevailing cropping pattern. In Ganga the major cropping pattern is Rice during Kharif season (monsoon season), Rice-Wheat

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[1] http://www.adb.org/documents/reports/Benchmarking-DataBook/default.asp

[2] http://moef.nic.in/downloads/others/M%20Karthik.pdf

[3] Census ff India 2001, Population Projections for India and States 2001-2026, Report of the Technical Group on Population Projections Constituted by the National Commission on Population, May 2006, http://nrhm-mis.nic.in/UI/Public%20Periodic/Population_Projection_Report_2006.pdf

rotation during Kharif-Rabi seasons, Sugarcane for three years, Sugarcane-Rice rotation with Sugarcane for three years and rice for one year as well as vegetables and dryland agriculture. However Rice, Wheat and Sugarcane are the dominant cropping systems and most of them are double cropping system where more irrigation water is required during Rabi (non-monsoon) season. The irrigation water in the basin is multiple sources including surface water, diversion of water from the river through barrage or dams through irrigation canals, shallow aquifer, deep aquifer and sometimes inter-basin transfer through canals and has been incorporated with respect to the available information on the source.

Another interesting exercise that was taken up was to simulate the BOD concentration in various reaches of the Ganga basin. The BOD loads as explained above were converted to concentration using the SWAT model simulated flows in each of the river reaches. Any BOD concentration of greater than 3 ppm is not good for health or environment whereas a BOD concentration of 2-3 is border-line and less than 1 ppm BOD concentration is considered safe. The analysis show that during non-monsoon season BOD concentration in most of the water bodies and river stretches exceeds the international water quality standard of 3 ppm.

On performing the simulation for the Scenarios B, C and D it was found that the Scenarios B, D5 and D10 did not produce significant change from baseline (Scenario A) therefore these scenarios were ignored for any further analysis. It was also decided to incorporate the impact of natural variability on to these analyses. Thus high, normal and low rainfall years were recognized and analyzed under various scenarios. A high year is defined in which maximum number of sub-basins experienced maximum annual rainfall in the 33 years of period, and similarly an average year and low year in which maximum number of sub-basins experienced average annual rainfall and minimum annual rainfall respectively in the 33 year period.

These scenarios have been created and analysed. On comparing the BOD concentration for Scenario C with those of Scenario A, it was found that, for high rainfall year the relative changes were not that significant and as expected due to high rainfall year the flow were high and thus even the increased population did not present major problem along the main Ganga river. However even in high rainfall year some of the major tributaries like Ramganga, Upperganga, Kandak, Kosi, Gaghra, Tons, and Sone experienced high BOD concentration of as much as 50% or more than the Scenario A. On making comparison for the average and low rainfall years the situation is worse with increase of as much as 100% change from the baseline scenario making even good river bodies in baseline scenario A would be under water quality violation due to change in irrigation demand and increased population in the year 2025.

In addition to comparing average annual BOD concentration between baseline and other scenarios, BOD concentration during monsoon and non-monsoon period were also made. It was found that even for the baseline A scenario wherein the BOD concentrations for average annual fared well, but looking it by season, during non-monsoon season the entire river reaches show very poor water quality, needing much required improvements of waste water treatment plants for almost all the stretches.

The same phenomena were observed in all the scenarios and were significantly worsening in every case for both monsoon and non-monsoon seasons. So further water resources development in the Ganga basin and future anticipated climate changes becomes reality the BOD water quality will worsen which could lead into danger of poor drinking water quality and disease spread all along the Ganga basin. So prevention of raw sewage should be the top priority to control the further deterioration. In the current study, the industrial and other forms of BOD loads were not considered, so adding this additional information will only further deteriorates the situation. Additional analysis could be done either through the modelling or externally to find the allowable carrying capacity of the river at various stretches and time period to bring the water quality to safe drinking international standards.

As part of the Scenario D50 wherein the three proposed water resources structures along the border of Nepal and India in Kosi, Gandak (Chisapani) and Ghagra (Mahakali) rivers were incorporated and the impact of removal of 50 billion cubic meters (BCM) per year by diverting to irrigation and other domestic demand was studied on BOD and sediment along the river stretches. Further deterioration of BOD concentrations in all the rivers under high to low rainfall year was experienced. Under low rainfall year the BOD concentration changes 50+% bringing the river close to 2 ppm, and thus limiting any further development in the Indian side of these rivers. It may be important to mention that the operational management of the structures was not taken into consideration explicitly.

While looking at the impact of climate change the baseline scenario of A1B was run first followed with the mid- and end-century scenarios. It is seen that in future the high rainfall years shall receive higher rainfall than the baseline. This in turn is likely to improve water quality, however, Chambal basin shows deterioration for average rainfall years in future as compared to the baseline and rest of the basin show deterioration in the low rainfall years.

Analyses were also performed with respect to the sediment yield from the basin under various scenarios. Some of the river stretches exhibit reduction in sediment yield under Scenario C when compared to Scenario A. This can be attributed to the increase in barrages and dams that help filter the sediment carried by the river. However, the various structures that have been built or are proposed on various tributaries of Ganga, are susceptible to siltation which can effectively reduce the life and efficiency of the dams built for irrigation or power generation purpose. There is a general trend of increase in sediment load in future due to the increase in intensity and magnitude of rainfall towards mid century.

The study has generated very large outputs that are not only covering a range of spatial units but also a range of temporal scales. It is not possible to present all these outputs and findings in a single report. Therefore a standalone GIS based framework has been formulated to help users to interactively explore the system in terms of various features of the Ganga system along with the SWAT outputs at various levels of details of their choice. This system shall have huge advantage as a dissemination tool for creating consensus by presenting the various options of development to the stakeholders and policy makers in an understandable manner.

# 1. Introduction

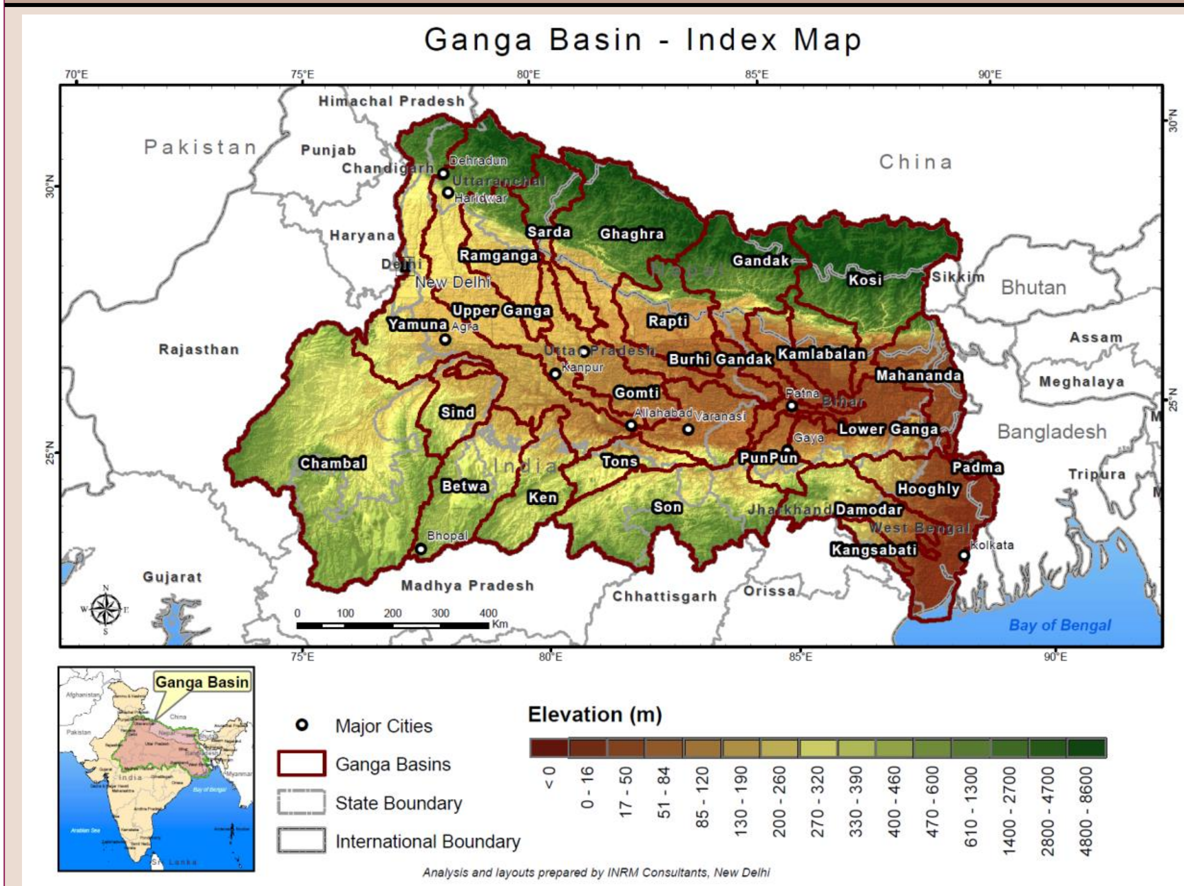
The study is aimed at supporting the strategic assessment of the Ganga Basin through the development of hydrological simulation model of Ganga Basin and generating scenarios for implications on account of future developments on quantity and quality.

The study is also intended to produce a knowledge base that can be used for independent dissemination to a much diversified set of stake-holders which can work very effectively towards generating consensus on future pathways.

## 1.1. About the Ganga basin

The Ganga basin is a part of the composite Ganga-Brahmputra-Meghna basin. The Ganga originates at an elevation of about 7010-m above mean sea level. The basin lies in China, Nepal, India and Bangladesh and drains an area of 1,086,000 sq. kms. About 79% area of Ganga basin is in India (Figure 1).

**Figure 1 Ganga Basin Index Map**



Ganga basin is the largest river basin in India in terms of catchment area, constituting 26% of the country's land mass (861,404 sq. km) and supporting about 43% of its population (448.3 million as per 2001 census), making it the most populated river basin in the world. Ganga basin covers 11 states in India namely Uttar Pradesh and Uttarakhand (294,364 sq. km), Madhya Pradesh and Chhattisgarh (198962 sq. km), Bihar and Jharkhand (143961 sq. km), Rajasthan (112,490 sq. km), West Bengal (71,485 sq. km), Haryana (34,341 sq. km), Himachal Pradesh (4,317 sq. km) and Delhi (1,484 sq. km). Total distance covered by river is 2,525 km before its outfall into the Bay of Bengal. The Important tributaries are the Yamuna, the Ramaganga, the Gomti, the Ghagra, the Sone, the Gandak, the Burhi Gandak, the Kosi and the Mahananda. The main plateau tributaries of the Ganga are the Tons, the Sone, the Damodar and the Kasai-Haldi.At Farakka in West Bengal the river divides into tow arms namely the Padma which flows to Bangladesh and the Bhagirathi and the Hugli which flows through West Bengal[4].

The important soil types found in the basin are sand, loam, clay and their combinations such as sandy loam, silty clay etc. The annual surface water potential of the basin has been assessed as 525 $km^3$ in India, out of which 250 $km^3$ is utilizable water. There is about 580,000 $km^2$ of arable land; 29.5% of the cultivable area of India. The river is diverted through canals at several sites. The most upstream diversion site is located at Haridwar, where a significant portion of the main stream is diverted into the Upper Ganga Canal. This is an irrigation channel that feeds the alluvial tract lying between the Ganga and Yamuna rivers. The upstream part is referred to as the Upper Ganga Canal. The downstream section, starting at Aligarh, is the Lower Ganga Canal. At Kanpur, the irrigation return flow re-enters the parent stream.

The level of pollution in the river depends upon the concentration of pollutants and the discharge of the river. Both concentration and discharge are affected by hydrological, geomorphologic, topographic and cultural factors. The recent survey indicate that about 8250 mld of wastewater is generated in the Ganga basin out of which treatment facilities are available only for 3500 mld of wastewater. Main sources of pollution along the reach of the river are urban liquid waste (sewage), industrial liquid waste, and large scale bathing of cattle, throwing of dead bodies in the river, surface run-off from solid waste landfills and dumpsites, and surface runoff from industrial solid waste landfills or dumpsites. The Central Pollution Control Board reports that three-fourths of the pollution of the river comes from the discharge of untreated municipal sewage Loss of discharge is considered as the most serious factor contributing to the rise in levels of pollution since without adequate flow, toxins and bacteria cannot be flushed and degraded. Industrial pollution constitutes around 20% of the total pollution load by volume. The industries represented in this river basin are sugar, paper, cloth, woollen, cotton and rayon mills, tanneries, ordinance factories, battery industries, thermal power houses, chemical plants, metal and

[4] From various documents: Status of Sewage Treatment Plant in Ganga Basin, CPCB, http://gfcc.bih.nic.in/Basin.htm, http://www.auburn.edu/~alleykd/envirolitigators/gangatext.htm, Ganga Basin NELP VII: http://www.fsi.nic.in/vegetation_map.htm, National Ganga River Basin Authority, ESMF, December 2010

steel factories, distilleries, and fertilizer corporations. Industrial unit, discharging into the river effluent having BOD load of 100 kg/day or more and/or is involved in the manufacture and use of hazardous substances, is classified as grossly polluting.

# 2. Scope of the study

Following are the specific objectives of the study:

(i) To develop a water balance model of the Ganga Basin and its use to better understand hydrologic implications of various current and future scenarios,

(ii) Construction of a shared knowledge base using the readily available and generated information, and

(iii) Preliminary assessment of spatio-temporal water pollution in the Ganga basin in India.

# 3. Methodology

The SWAT hydrological model has been used for the study. A brief description of the model is given as follows (refer Appendix I for more detailed description).

## 3.1. Brief Description of the Soil and Water Assessment Tool (SWAT) Model

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998[5], Neitsch et al., 2002[6]) is a distributed parameter and continuous time simulation model. The SWAT model has been developed to predict the response to natural inputs as well as the manmade interventions on water and sediment yields in un-gauged catchments. The model (a) is physically based; (b) uses readily available inputs; (c) is computationally efficient to operate and (d) is continuous time and capable of simulating long periods for computing the effects of management changes. The major advantage of the SWAT model is that

[5] Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998. Large-area hydrologic modeling and assessment: Part I. Model development. J. American Water Res. Assoc. 34(1): 73-89

[6] Neitsch, S. L., J. G. Arnold, J. R. Kiniry, J. R. Williams, and K. W. King. 2002a. Soil and Water Assessment Tool - Theoretical Documentation (version 2000). Temple, Texas: Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural Experiment Station.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, J. R. Srinivasan, and J. R. Williams. 2002b. Soil and Water Assessment Tool - User’s Manual (version 2000). Temple, Texas: Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural Experiment Station unlike the other conventional conceptual simulation models it does not require much calibration and therefore can be used on ungauged watersheds (in fact the usual situation).

The SWAT model is a long-term, continuous model for watershed simulation. It operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields. The model is physically based, computationally efficient, and capable of simulating a high level of spatial details by allowing the watershed to be divided into a large number of subwatersheds. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. The model has been validated for several watersheds.

In SWAT, a watershed is divided into multiple subwatersheds, which are then further subdivided into unique soil/land-use characteristics called hydrologic response units (HRUs). The water balance of each HRU in SWAT is represented by four storage volumes: snow, soil profile (0-2m), shallow aquifer (typically 2-20m), and deep aquifer (>20m). Flow generation, sediment yield, and non-point-source loadings from each HRU in a subwatershed are summed, and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet. Hydrologic processes are based on the following water balance equation:

$$SW_t = SW + \sum_{i=1}^{t} (R_{it} - Q_i - ET_i - P_i - QR_i)$$

where SW is the soil water content minus the wilting-point water content, and R, Q, ET, P, and QR are the daily amounts (in mm) of precipitation (, runoff, evapotranspiration, percolation, and groundwater flow; respectively. The soil profile is subdivided into multiple layers that support soil water processes, including infiltration, evaporation, plant uptake, lateral flow, and percolation to lower layers. The soil percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. Percolation from the bottom of the soil profile recharges the shallow aquifer. If the temperature in a particular layer is 0ºC or below, no percolation is allowed from that layer. Lateral subsurface flow in the soil profile is calculated simultaneously with percolation. The contribution of groundwater flow to the total stream flow is simulated by routing a shallow aquifer storage component to the stream (Arnold, Allen, and Bernhardt 1993[7]).

SWAT also simulates the nutrient dynamics. Sediment yield is calculated based on the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975[8]). The movement of nutrients, i.e. nitrogen and phosphorus is based on built in equations for their transformation from one form to the other. The total amounts of nitrates in runoff and

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[7] Arnold, J.G., Allen, P.M, and Bernhardt, G.T. 1993. A comprehensive surfacegroundwater flow model. Journal of Hydrology, 142: 47-69

[8] Williams, J.R. 1975. Sediment routing for agricultural watersheds. Water Resources Bulletin, 11 (5): 965-974.

subsurface flow is calculated the volume of water in each pathway with the average concentration. Phosphorus however is assumed to be a relatively less mobile nutrient, with only the top 10 mm of soil considered in estimating the amount of soluble P removed in runoff. A loading function is used to estimate the phosphorus load bound to sediments (McElroy et al, 1976[9]). SWAT calculates the amount of algae, dissolved oxygen and carbonaceous biological oxygen demand (CBOD - the amount of oxygen required to decompose the organic matter transported in surface runoff) entering the main channel with surface runoff. CBOD loading function is based on a relationship given by Thomann and Mueller (1987)[10]

## 3.2. Advantages of the SWAT model

The SWAT model possesses most of the attributes which are identified to be the desirable attributes which a hydrological model should possess.

The SWAT model is a spatially distributed physically based model. It requires site specific information about weather, soil properties, topography, vegetation, and land management practices being followed in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using these input data. This approach results in major advantages, such as

- Ungauged watersheds with no monitoring data (e.g. stream gauge data) can be successfully modeled
- The relative impact of alternative input data (e.g. changes in management practices, climate, vegetation, etc.) on water quantity, quality or other variables of interest can be quantified
- The model uses readily available inputs. The minimum data required to make a SWAT run are the commonly available data from local government agencies.
- The model is computationally efficient. Simulation of very large basins or a variety of management strategies can be performed without excessive investment of time or money.
- The model enables users to study impacts on account of human interventions which makes it very suitable for scenario generation.
- The model is also capable of incorporating the climate change conditions to quantify the impacts.

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[9] McElroy, A.D., Chiu, S.Y. and Nebgen, J.W. 1976. Loading functions for assessment of water pollution from nonpoint sources. EPA document 600/2-76-151, USEPA, Athens, GA

[10] Thomann, R.V. and J.A. Mueller. 1987. Principles of surface water quality modeling and control. Harper & Row Publishers, New York

- The model has gained a wide global acceptability. Currently 720 peer reviewed publications have been published based on the SWAT model (http://swatmodel.tamu.edu ). The current rate of publication is about 120 peer reviewed per year. There are more than 90 countries using the model for practical applications and at the least, more than 200 graduate students all over the world are using it as part of their M.S. or Ph.D. research program. In the U.S alone, more than 25 universities have adapted the model in graduate level teaching classes.
- SWAT is a public domain model actively supported by the Grassland, Soil and Water Research Laboratory (Temple, TX, USA) of the USDA Agricultural Research Service

## 3.3. Development of hydrologic model for the Ganga Basin

Mapping of a basin on to the SWAT hydrological model involves an elaborate procedure. The following paragraphs briefly describe the methodology used for mapping the Ganga river system.

### 3.3.1. Data Requirement for Modelling

The data required for modelling the Ganga basin includes both, the static data and the dynamic data. The following is the brief description of the required data and its processing:

#### 3.3.1.1. Spatial Data

Spatial data and the source of data used for the study area:

- Digital Elevation Model: GTOPO30 global digital elevation model (1996), of 1 km resolution[11]
- Drainage Network – Hydroshed[12]
- Soil maps and associated soil characteristics (source: FAO Global soil)[13]
- Land use: Global Map of Land Use/Land Cover Areas (GMLULCA), IWMI's Global Map of Irrigated Areas (GMIA) (source: IWMI )[14]

#### 3.3.1.2. Dynamic Data

The Hydro-Meteorological data pertaining to the river basin is required for modelling the basin. The data include daily rainfall, maximum and minimum temperature, solar radiation, relative humidity and wind speed. These Weather data were available as per following details

[11] http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info

[12] http://hydrosheds.cr.usgs.gov/

[13] http://www.lib.berkeley.edu/EART/fao.html

[14] http://www.iwmigiam.org/info/main/index.asp

- Reanalysis weather data (1965–2001) – 4 years of weather data was used as warmup/setup period for the Ganga basin model thus outputs were available from 1969 to 2001

Water demand and abstraction data

- Existing major water resources infrastructure, current management/operation practices, existing irrigation as per crop demand Note: Current crop management practices include irrigation sources from Surface and Ground water
- Reservoir and diversion locations and characteristics were taken from National Register of Large Dams[15]

### 3.3.2. Model Performance

Statistical parameters namely regression coefficients ($R^2$) and Nash Sutcliffe efficiency (NSE) were used to assess the model efficiency on monthly SWAT hydrologic stream flow predictions.

**Model Evaluation Statistics (Dimensionless)**

*Nash-Sutcliffe efficiency (NSE) or Coefficient of Efficiency (CoE):* The Nash-Sutcliffe efficiency (NSE) is a normalized statistic that determines the relative magnitude of the residual variance ("noise") compared to the measured data variance ("information") (Nash and Sutcliffe, 1970[16]). NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. NSE is computed as

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

where $Y_i^{obs}$ is the $i^{th}$ observation for the constituent being evaluated, $Y_i^{sim}$ is the $i^{th}$ simulated value for the constituent being evaluated, $Y^{mean}$ is the mean of observed data for the constituent being evaluated, and n is the total number of observations. NSE ranges between $-\infty$ and 1.0 (1 inclusive), with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas values <0.0 indicates that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance[17]

*Coefficient of determination ($R^2$):* Coefficient of determination ($R^2$) describes the degree of collinearity between simulated and measured data. $R^2$ describes the proportion of the variance in measured data explained by the model. $R^2$ ranges from 0 to 1, with higher

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[15] http://www.cwc.nic.in/main/downloads/National%20Register%20of%20Large%20Dams%202009.pdf

[16] Nash, J. E., and J. V. Sutcliffe. 1970. River flow forecasting through conceptual models: Part 1. A discussion of principles. J. Hydrology 10(3): 282-290

[17] Moriasi, D. N., J. G. Arnold, M. W. Van Liew, R. L. Bingner, R. D. Harmel, and T. L. Veith, 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations, Transactions of the ASABE, Vol. 50(3): 885−900 2007

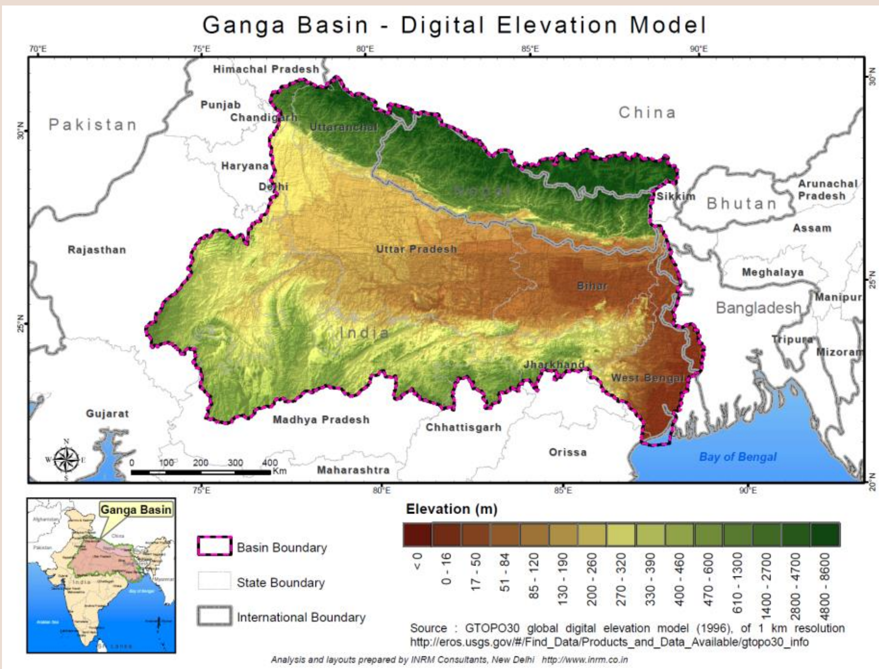
values indicating less error variance, and typically values greater than 0.5 are considered acceptable (Santhi et al., 2001[18], Van Liew et al., 2003[19]). $R^2$ is oversensitive to high extreme values (outliers) and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe, 1999[20]).

## 3.4. Mapping the Ganga System

The ArcSWAT (Winchell et al., 2007[21]) interface (Appendix I) was used to pre-process the spatial data for the Ganga river system. A brief description of the steps undertaken for pre-processing has been given below.

DEM from the GTOPO30 is used for generating the Ganga basin as shown in Figure 2.

**Figure 2 Digital Elevation Model of Ganga Basin**




[18] Santhi, C, J. G. Arnold, J. R. Williams, W. A. Dugas, R. Srinivasan, and L. M. Hauck. 2001. Validation of the SWAT model on a large river basin with point and nonpoint sources. J. American Water Resources Assoc. 37(5): 1169-1188

[19] Van Liew, M. W., J. G. Arnold, and J. D. Garbrecht. 2003. Hydrologic simulation on agricultural watersheds: Choosing between two models. Trans. ASAE 46(6): 1539-1551

[20] Legates, D. R., and G. J. McCabe. 1999. Evaluating the use of “goodness-of-fit” measures in hydrologic and hydroclimatic model validation. Water Resources Res. 35(1): 233-241

[21] Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2007. ArcSWAT interface for SWAT2005. User's Guide. BRC, TAES, USDA-ARS, Temple, TX

The topographic statistics of elevation of the Ganga River basin is given in Table 1

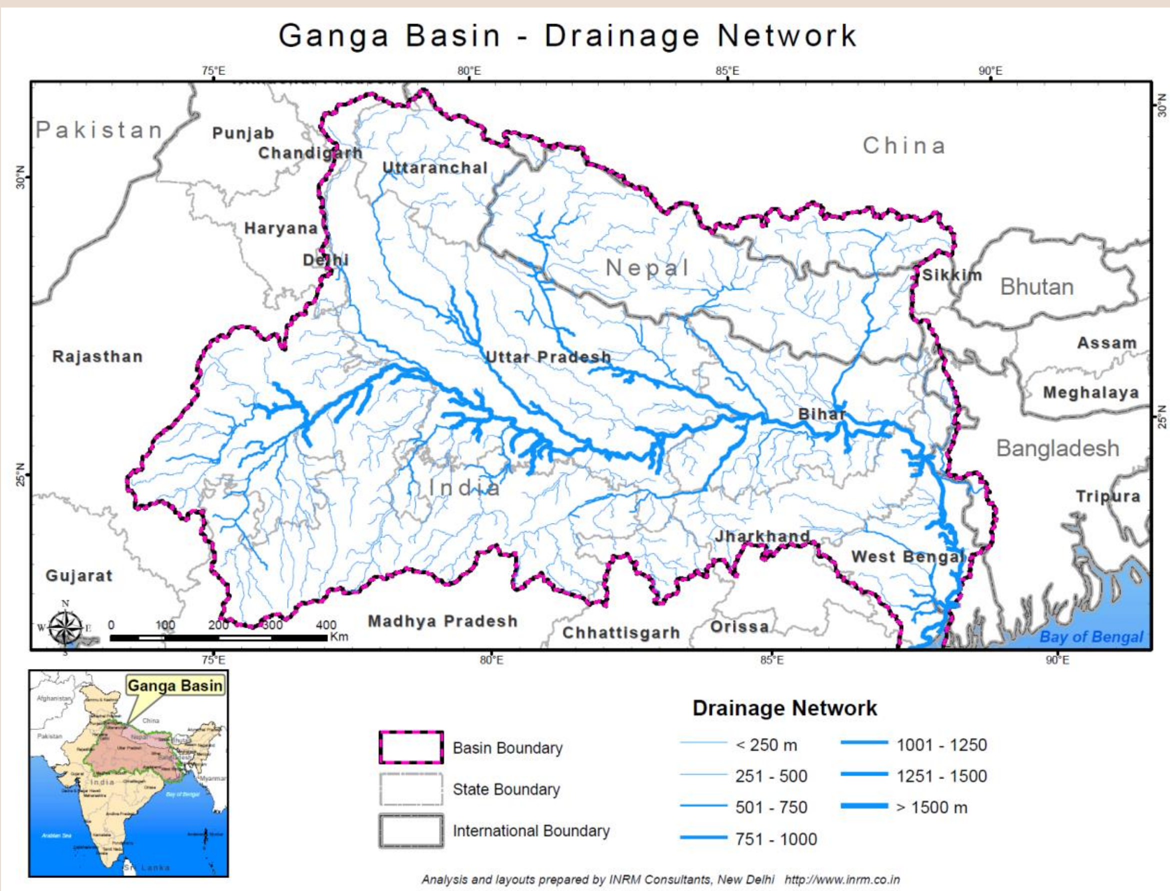
**Table 1 Elevation Summary – Ganga Basin**

| Parameter | Elevation (m) |
|---|---|
| Minimum Elevation | 1 |
| Maximum Elevation | 8752 |
| Mean Elevation | 949 |
| Standard Deviation | 3238 |

### 3.4.1.1. Basin Delineation – Ganga Basin

Figure 3 shows the automatically delineated Ganga catchment with the generated drainage network using the DEM.

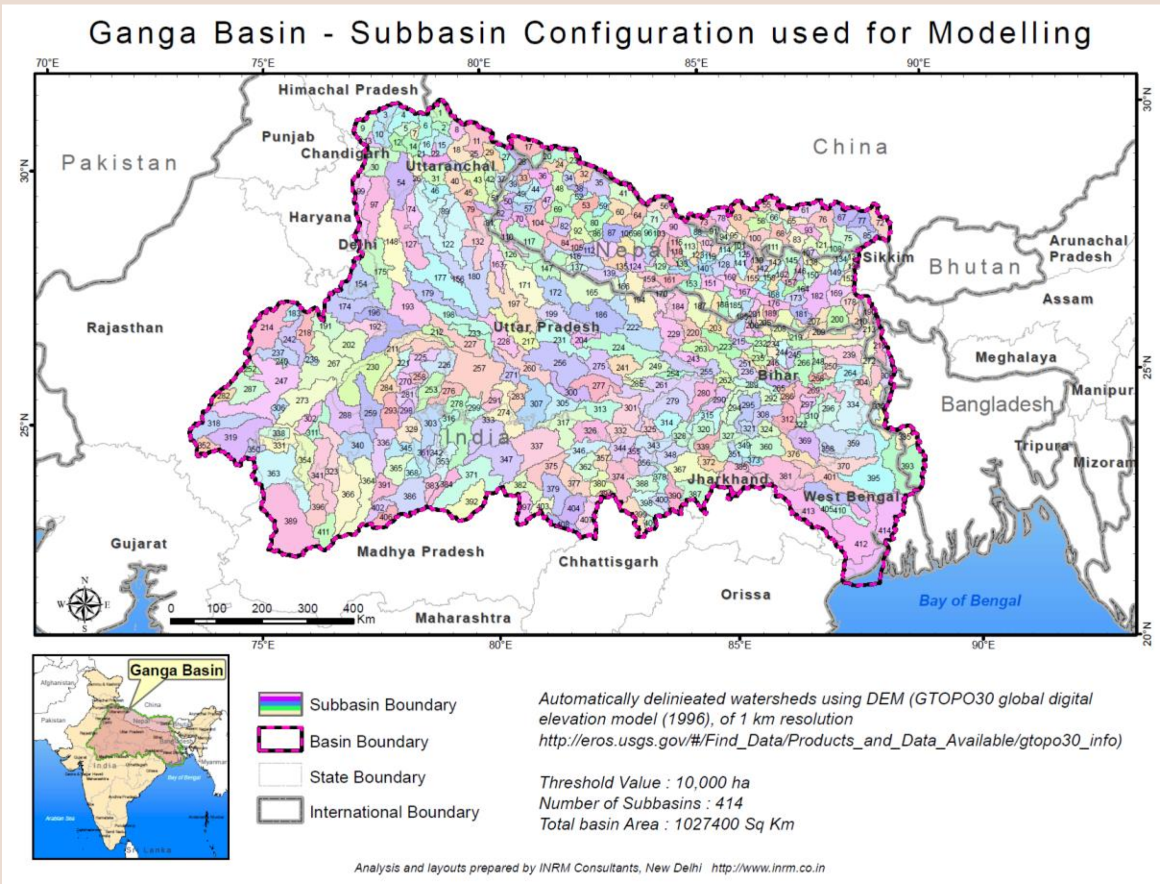
**Figure 3 Automatically delineated Basins of Ganga Basin along with Drainage network**



### 3.4.1.2. Watershed (sub-basin) Delineation – Ganga Basin

Automatic delineation of watersheds is done by using the DEM as input. The target outflow point is interactively selected. The Ganga river basin has been delineated using 10,000 ha as minimum stream threshold and has resulted in 414 sub-basins. These sub-basins are shown in Figure 4. Basin area of the Ganga up to the basin outflow point is 1,027,400 sq km. Care was also taken to incorporate the locations of major dams, reservoirs and diversion structures and major sewage disposal sites while undertaking the delineation process..

**Figure 4 Ganga Basin subbasin delineation using DEM**




### 3.4.1.3. Land Cover/Land Use Layer – Ganga Basin

Land Use/Land Cover is another important segment of data that is required for pre-processing. Merged landuse and irrigation source map from IWMI as shown in Figure 5 has been used for the present study. IWMI derived product of Ganges River Basin Irrigated Area using MODIS 500-m and AVHRR 10-km Satellite sensor Data was merged with IWMI's Global Map of Land Use/Land Cover Areas to derive a new landuse map with agriculture landuse as well as sources of irrigation

Table 2 gives the land use categories and the area covered under each category of land use for the Ganga basin.

**Figure 5 Landuse of Ganga Basin**

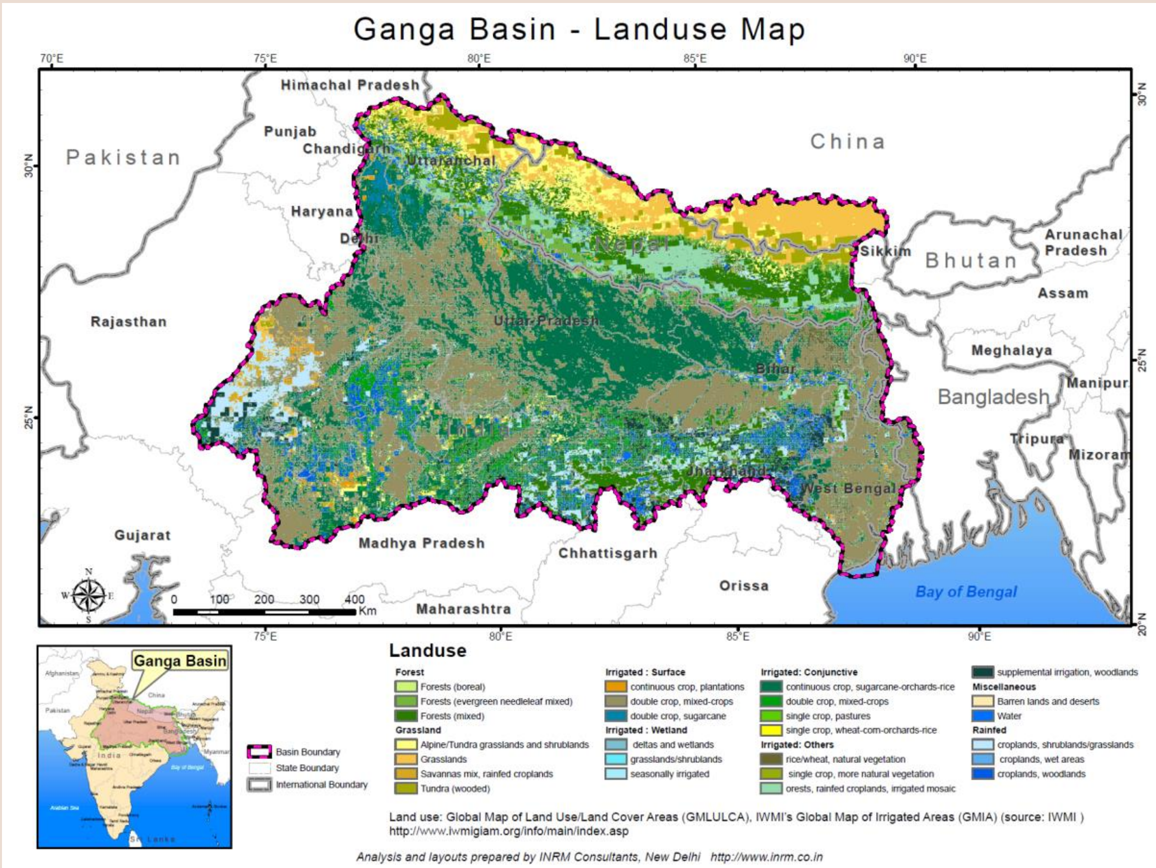



**Table 2 Landuse Categories – Ganga Basin**

| Land Use | Area (ha) | % of Watershed Area |
|---|---:|---:|
| Corn | 4170394.2 | 4.1 |
| Forest-Deciduous | 3602549.7 | 3.5 |
| Forest-Evergreen | 1402219.9 | 1.4 |
| Forest-Mixed | 8417633.4 | 8.2 |
| Grasslands, rainfed croplands | 17391.3 | 0.0 |
| Shrublands, rainfed croplands | 10536264.9 | 10.3 |

| Land Use | Area (ha) | % of Watershed Area |
|---|---:|---:|
| Tundra (wooded) | 2737166.7 | 2.7 |
| supplemental irrigation, rangelands | 519715.2 | 0.5 |
| Rice | 40261816.5 | 39.2 |
| Barren lands and deserts | 2291.9 | 0.0 |
| Spring Wheat | 1550.4 | 0.0 |
| Sugarcane | 25390142.9 | 24.7 |
| Irrigated, small scale, mixed with rangelands | 4927183.1 | 4.8 |
| Water | 690122.5 | 0.7 |
| Wetlands-Mixed | 28041.7 | 0.0 |
| Wetlands seasonally irrigated | 35524.0 | 0.0 |
| Total | 102740008.1 | 100.0 |

It may be observed from the above Table that the Ganga basin has mixed landuse with Agriculture as the major land use (about 84 %) with large portion under the irrigated agriculture.

#### 3.4.1.4. Soil Layer– Ganga Basin

Information on the soil profile is also required for simulating the hydrological character of the constituent space of the basin. Global soil map based on FAO has been used for the modelling of Ganga basin. Soil units' details are given in Table 3. The soil map of the basin is shown in Figure 6.

**Figure 6 Soils of Ganga Basin**

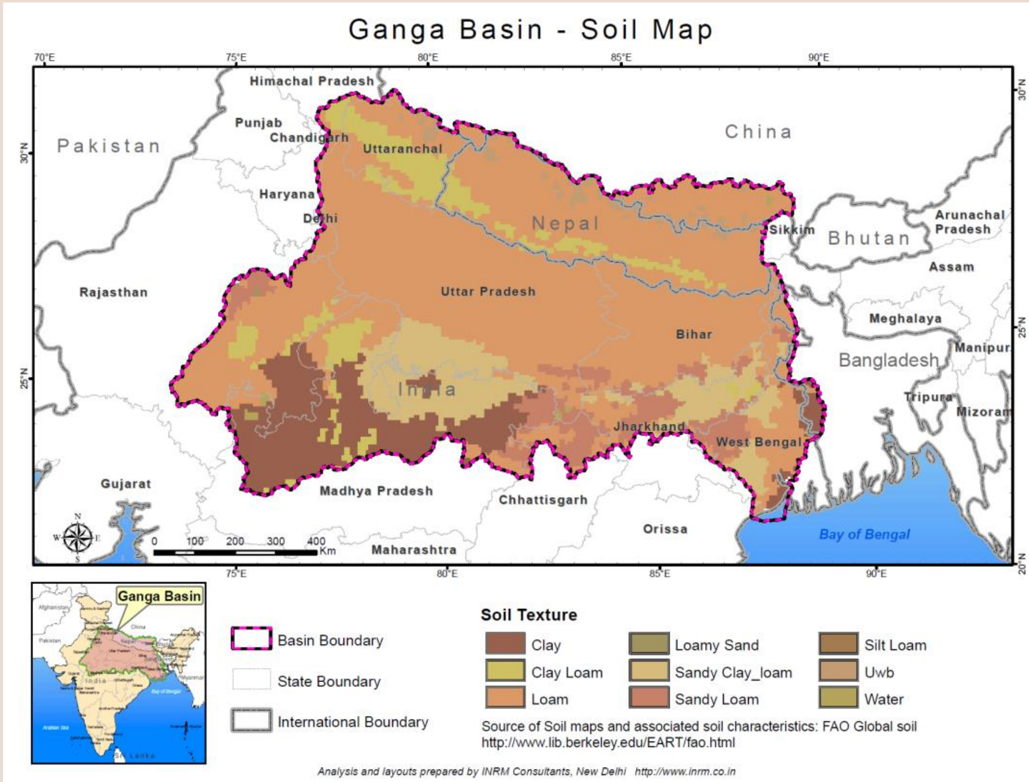



**Table 3 Soil Type – Ganga Basin**

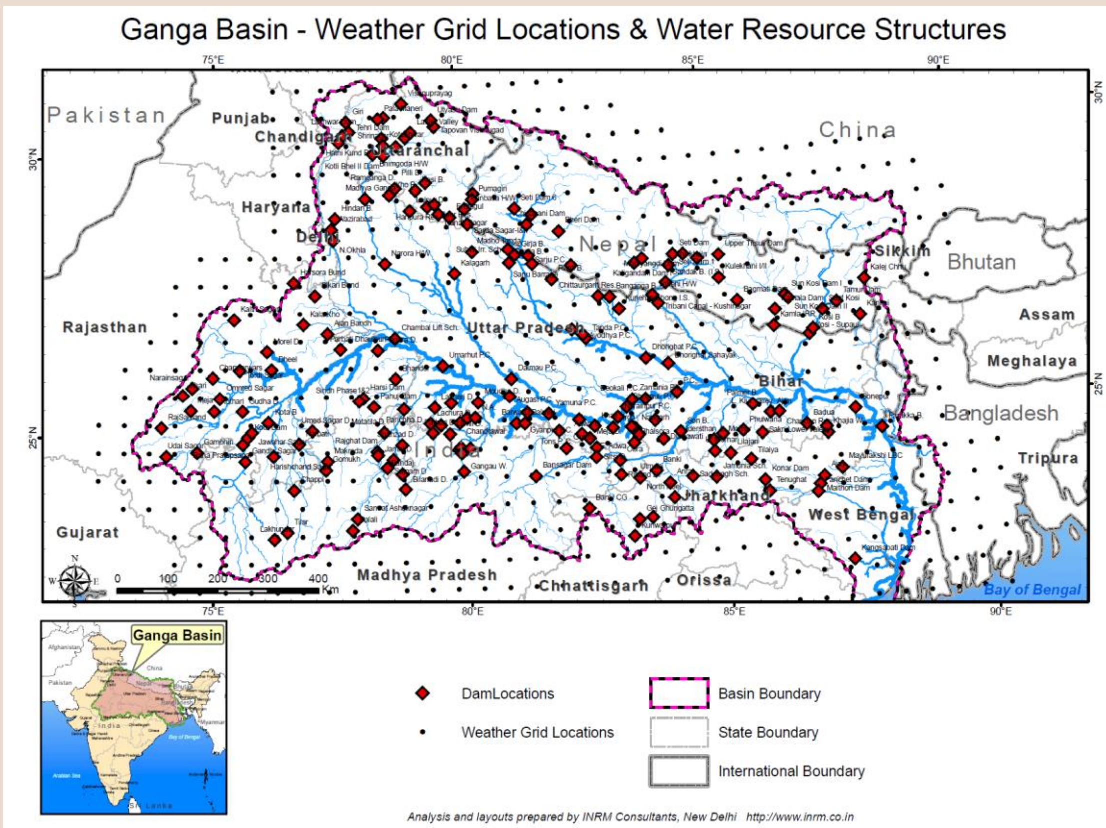
| Soil Texture | | Area (ha) | % of Watershed Area |
|---|---|---|---|
| **Main** | **No of Subtype** | | |
| Clay | 8 | 12477074.2 | 12.2 |
| Clay_Loam | 7 | 7627208.0 | 7.4 |
| Loam | 41 | 63271717.7 | 61.6 |
| Loamy_Sand | 1 | 76373.2 | 0.1 |
| Sandy_Clay_Loam | 13 | 10836702.0 | 10.5 |
| Sandy_Loam | 9 | 6654578.9 | 6.5 |
| Silt_Loam | 1 | 11998.6 | 0.0 |

The soil is predominantly loamy however; sandy clay loam and sandy loam are also prevalent. There are about 41 soil sub types in the loamy soil.

### 3.4.1.5. Hydro-Meteorological and Water resources structures data

The daily reanalysis and re-gridded weather data (rainfall, temperature, wind speed and solar radiation) has been used. The rainfall data at is at a resolution of 0.5° X 0.5° latitude by longitude grid points (represented by black dots in Figure 7). In the absence of other daily weather data on relative humidity that is an important parameter; long term statistics have been used to generate data for this weather parameter from IMD $1^o x 1^o$ resolution for the Indian part of the basin. Since a single point precipitation value is really not representative of the volume of precipitation falling over subbasin area, precipitation values were converted to areal estimates using the Thiessen (Thiessen, 2011[22]) polygon method[23]. The weather grids were superimposed on the sub basins for deriving the weighted means of the inputs for each of the sub basins. The centroid of each sub basin is then taken as the location for the weather station to be used in the SWAT model.

**Figure 7 Weather Grids along with Water resources structure locations of Ganga Basin**




[22] Thiessen, A. H. (1911) Precipitation for large areas. Monthly Weather Review 39, 1082-1084

[23] The Thiessen polygon method is a graphical technique which calculates station weights based on the relative areas of each measurement station in the Thiessen polygon network. The individual weights are multiplied by the station observation and the values are summed to obtain the areal average precipitation.

# 4. Baseline (Scenario A) Analysis

Having set up the model and validating it to the extent possible in the wake of the limited data availability of the stream flows, various scenarios were contemplated to evaluate the implications of the future population growth and development. Scenarios have also been formulated to quantify the implications on account of the projected climate change. In all five main scenarios have been contemplated (Scenario A to E) for implementation. The first scenario (Scenario A) is geared to capture the present baseline. This scenario is essential to understand the present status of the Ganga system so as to evaluate the sustainability of the future developments with and without the climate change impacts. Table 4 gives a brief outline of the scenarios.

**Table 4 Scenarios used in the study**

| Scenario | Years Representing | Major Water Infrastructure | Operation | Diversions |
|---|---|---|---|---|
| Current Baseline Scenario A | 1965-2001 | Existing | Current | Existing diversion estimates |
| Min Flow Scenario B | 1965-2001 | Existing | Ensure min flow in Yamuna & Ganga mainstem at all times | Reduced diversions to ensure min flow |
| Business as Usual Scenario C | 2020-30 | Existing | Current | Increased diversions (for domestic, industry, irrigation) |
| Dams in Nepal Scenario D5 Scenario D10 Scenario D50 | 2020-30 | Separately for Mahakali, Kosi, Chisapani and in combination | Various operating rules (to optimize hydropower, flood mgmt, and lowflow augmentation separately and a Balanced operating rule) | Additional diversions (x BCM/yr) where x=5,10,50 BCM/yr split in rabi, summer & kharif |
| Climate Change Scenario | 2020-30, 2045-55 | Baseline & Separately for Mahakali, | Balanced operating rule | Additional diversions (x BCM/yr) where x=5,10,50 BCM/yr split |

| | | | | |
|---|---|---|---|---|
| E50A1BBL Scenario E50A1BMC | | Kosi, Chisapani and in combination | | in rabi, summer & kharif |
| Major Water Infrastructure | Baseline: out of 206 dams/reservoirs available 104 structures were implemented as major structures with available data on the area, capacity and operation starting year, diversions: major canal diversions as irrigation water use was implemented<br><br>Future: Planned projects in India and Nepal (Mahakali, Kosi, Chisapani) | | | |
| Operation | Baseline: Current management/operation practices, existing crop water demand through irrigation. Note: Current crop management practices (irrigation from Surface and Ground water) based on landuse map, irrigation source map, command area map and districtwise average irrigation by source information<br><br>Future: Additional water demand calculated using population projection and agriculture demand increase<br><br>Water use calculation was based on increase of 16 BCM[24] for the agriculture area spread over 12 months of 70 % non Kharif (October-March) and 30 % Kharif (June – September ) | | | |
| Diversions | Baseline: current Irrigation water diversion as irrigation water use<br><br>Future: Nepal additional diversions from 3 planned structures @ 5, 10, 50 BCM/yr | | | |
| Point Source | Point source (average BOD and the average sewer generation per capita and converting total load based on subbasin population). Calculation as per following procedure:<br><br>Consumption/Capita (l/c/d) is taken as 123.3 (ADB 2007)[25],Assumption: 80% supply as sewer return, 20% is removed from the system - Baseline<br><br>Per capita BOD (gBOD/day) based on 2001 population census is taken as 40.5[26]<br><br>Future: BOD calculated based on future water demand calculated using population projection | | | |

[24] Sharma B.R., U. A Amarasinghe and Alok Sikka, 2008, Indo-Gangetic River Basins: Summary Situation Analysis, International Water Management Institute, New Delhi Office, New Delhi, India, cpwfbfp.pbworks.com/f/IGB_situation_analysis.pdf

[25] http://www.adb.org/documents/reports/Benchmarking-DataBook/default.asp

[26] http://moef.nic.in/downloads/others/M%20Karthik.pdf

The next legitimate step is to carry forward the SWAT simulation process started with the pre-processing of the Ganga Basin by incorporating all the water resources structures and their operation rules as well as the irrigation commands. This incorporation shall result in realising the implementation of Scenario A. The following sections provide details of the implementation.

#### 4.1.1.1. SWAT model setup - Scenario A

SWAT model was setup using daily rainfall data for the period 1965-2001. Due to the lack of streamflow observations in the main part of Ganga basin, it was not possible to attempt any calibration or validation of the model. However the model was verified with some of the gauges from Nepal that were provided by the World Bank. These gauges are mainly on the snow and glacier fed streams and with little or no major abstractions other than hydropower structures. The verification of the SWAT model results agreed well with long-term monthly observed data and are shown later in this chapter.

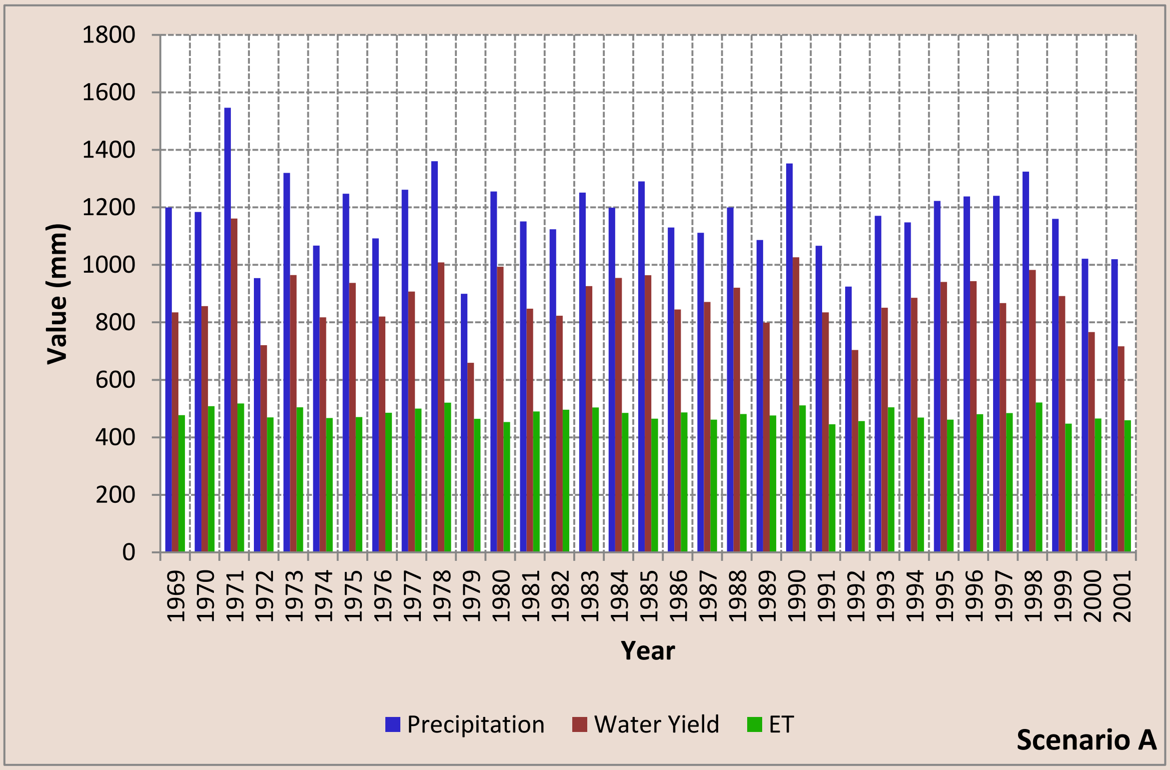
In the absence of precipitation data availability for higher elevation areas, elevation corrections were applied for rainfall and temperature to simulate snow hydrology. Maps of canal command area, irrigation source and district crop production were used to arrive at close representation of current crop management practices to be incorporated for crop simulation in the SWAT model.

After setting up the model for the present conditions (Scenario A), simulation runs were made for a period of 33 years (1969-2001). The model has been run on continuous basis at daily interval for all the sub-basins the Ganga system has been divided into. The outputs provided by the model are very exhaustive covering all the components of water balance spatially and temporally. The sub components of the water balance that are more significant and were used for analyses, include:

- Total flow (Water yield) consisting of surface runoff, lateral and base flow
- Precipitation
- Actual evapotranspiration (Actual ET)

The outputs can be depicted in many ways depending on the focus and requirement of the user. Figure 8 presents the snapshot long-term variability of the key water balance elements for the whole Ganga basin as a single unit. These components are expressed in terms of total annual depth of water in mm over the total watershed area. In other words, the total water yield is the equivalent depth in mm, of flow past the outlet of the watershed on average annual basis. Figure 8 to Figure 10 show the annual, average annual and average monthly water balance components for the Ganga basin.

**Figure 8 Annual Water Balance Components – Ganga**




As shown in Figure 8, inter annual variation of rainfall for the period of analysis from 1969-2001 was 900 to 1550 mm, while inter annual variation of water yield was 659 to 1161 mm for the same period. This shows there is great degree of fluctuations in the rainfall and runoff pattern even in such large basin like Ganga.

**Figure 9 Average Monthly Water Balance Component (Ganga)**

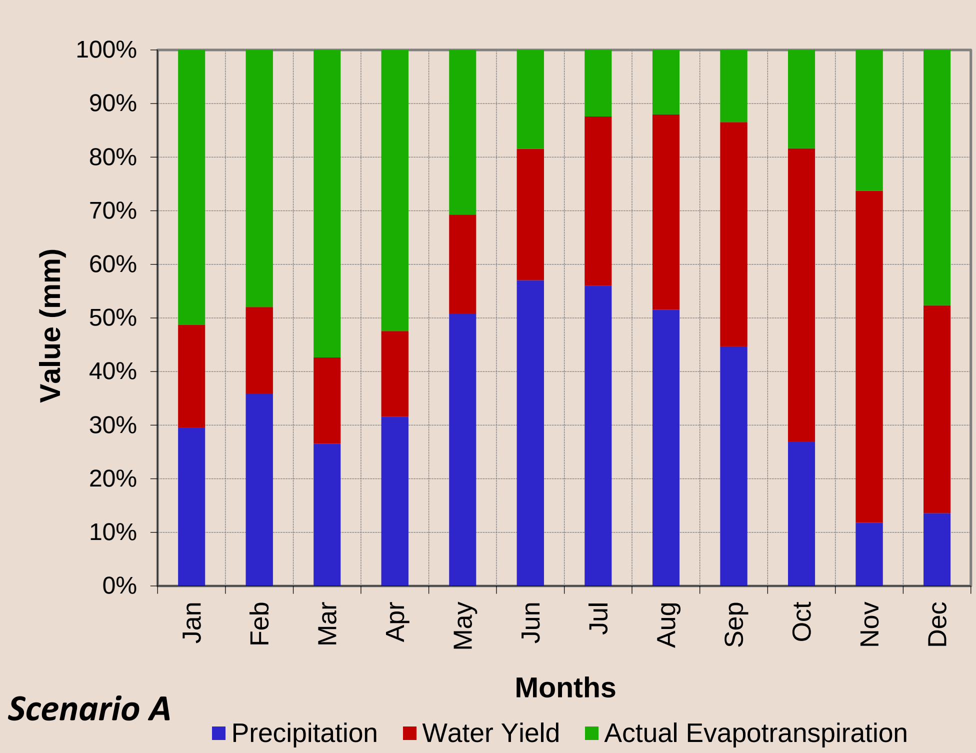
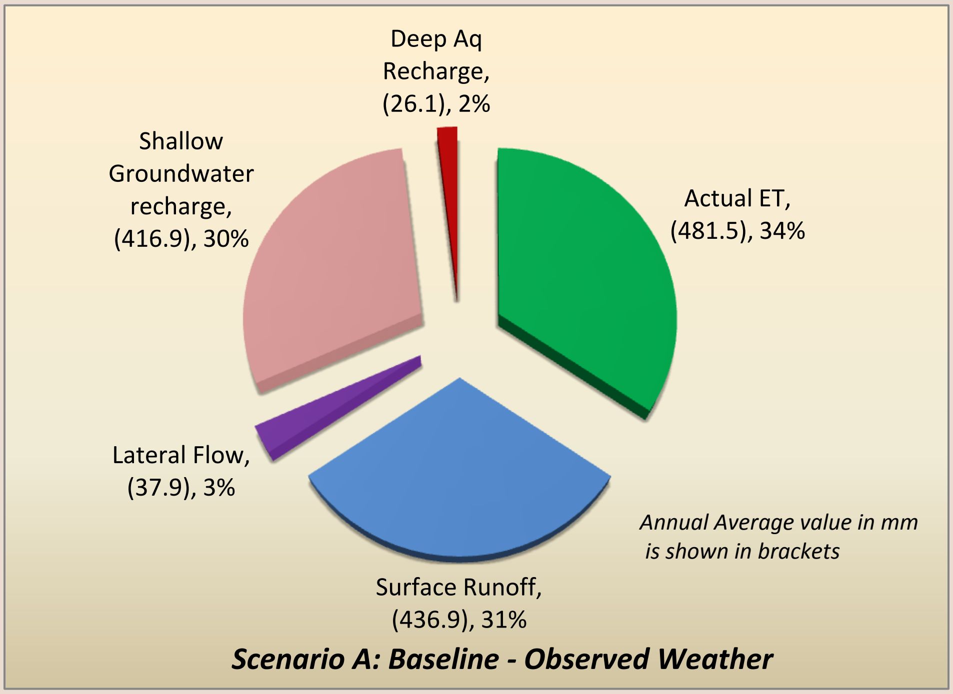



Figure 9 shows the average model simulated monthly water balance components for the period of 1969-2001. During monsoon months of June through September the rainfall is higher than the water yield and able to meet most of the crop water requirements. However during non-monsoon months, the evapotranspiration is higher than rainfall, suggesting the water has been either diverted through storage or shallow to deep aquifer withdrawal to meet the crop production demand.

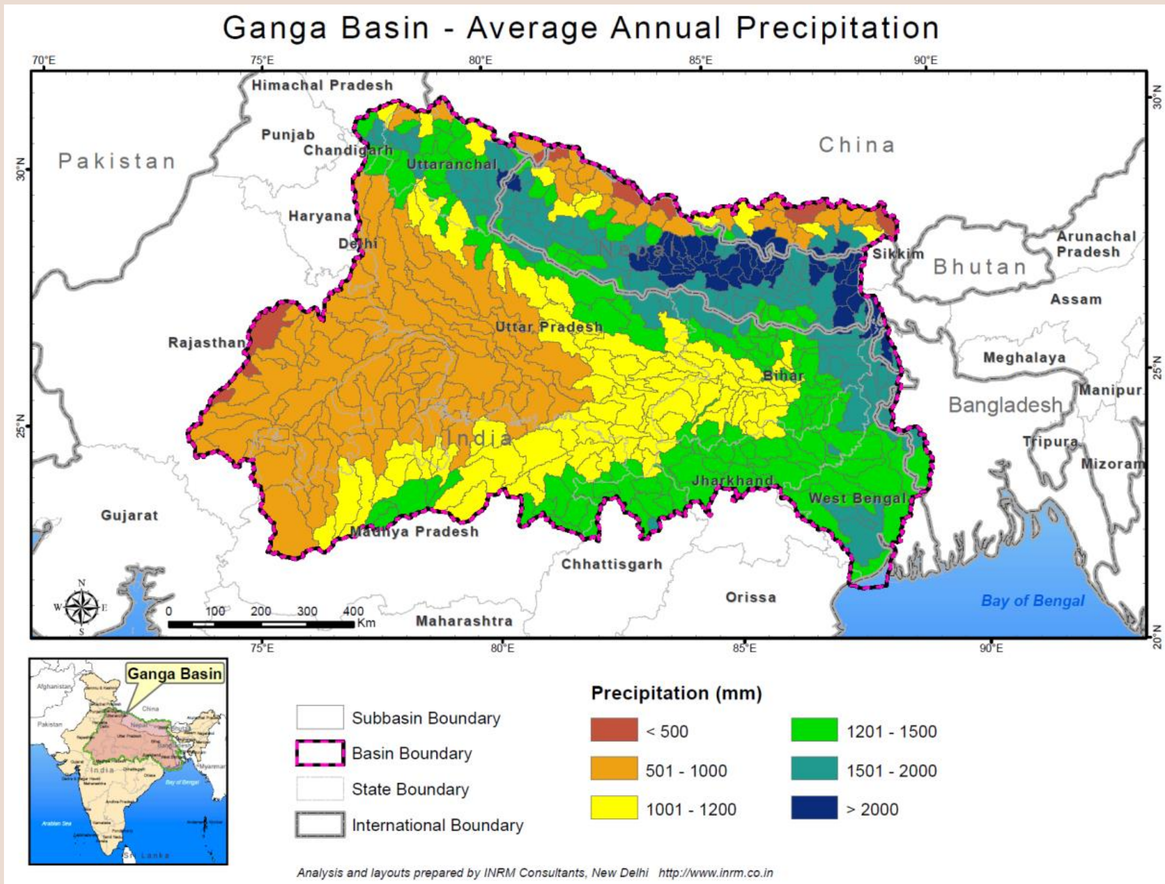
**Figure 10 Average Annual Water Balance Component (Ganga)**




The Figure 10 shows that between ET and ground water contribution, almost 66% of the available water is utilized leaving only about 34% as runoff/streamflow in the river resulted due to rainfall or snow/glacier melt from the Himalayan Mountains.

The average annual (1969-2001) precipitation, water yield, actual evapotranspirarion and soil water recharge as simulated by the model over the Ganga basin has been depicted in Figure 11-15 as a GIS layer so as to display the spatial variability of these water budget components.

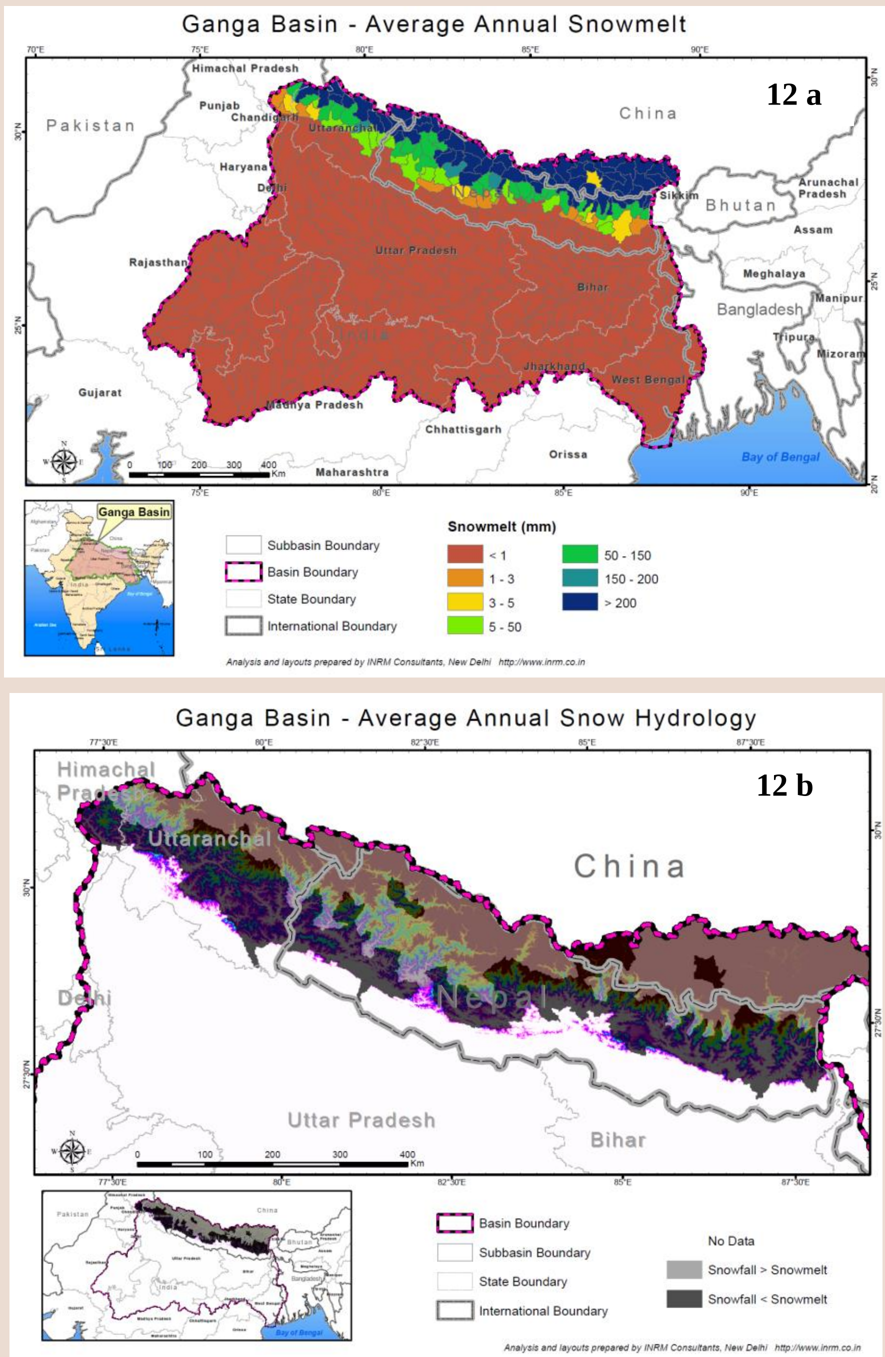
**Figure 11 Spatial distribution of Average Annual Precipitation (Ganga)**

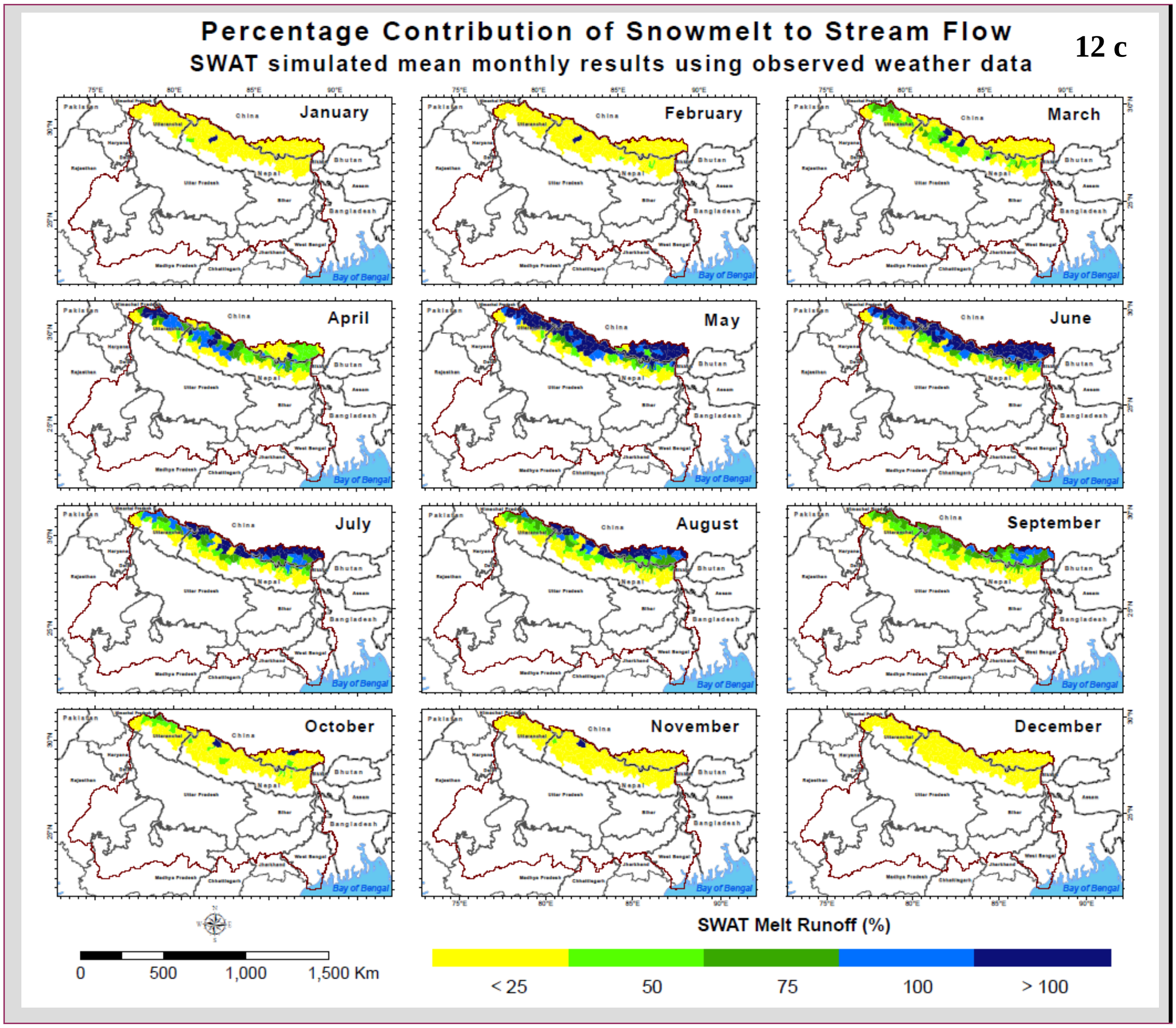



The precipitation varies both spatially and temporally. The average precipitation was shown in Figure 11, ranging from less than 500 mm/annum in the Chambal basins and some of the rain shadow regions of Himalayas to over 4000 mm/annum in the Kosi and Gandak basins. The average rainfall for the entire basin is about 1176 mm. The general spatial trend is evident that rainfall increases as you move from west to east of the Ganga basin.

Figure 12a and 12b show the SWAT model simulated snow hydrology components of snow melt and snowfall. The model is capable of using elevation band to adjust the temperature and rainfall as the altitude changes. In the Ganga basin the elevation range from 8000m to 2000 m at the foot hills of Himalayas. Hence, all the subbasins above 2000 m elevation, an elevation band and corresponding area that fall within the elevation band were incorporated in the model subbasin input files. In addition a literature value of -6.5$^{o}$C/km raise was used as temperature lapse rate and 200 mm/Km was used as precipitation lapse rate for those subbasin where the elevation bands were incorporated. These correction factors are necessary to account of change in precipitation and temperature at higher altitudes since the observation of rainfall and temperatures were very limited. In addition, there were no data that depicts the spatial pattern of glacier depth and snow pack information. In this modelling setup it is assumed a glacier depth of 100 m for altitudes about 4500 m elevation. The model can provide the glacier depth over time to account of loss of glacier due to climatic factors including climate change.

**Figure 12 Spatial distribution of Average Annual Snowmelt & Snow hydrology**






As shown in Figure 12a, significant streamflow was generated due to the snow and glacier melt where altitudes about 4000m elevation has significant snow fall and melt.

Figure 12b shows the regions where snowmelt exceeds the snowfall, these are the areas where in addition to snow evaporation/sublimation the glacier may also be contributing to the streamflow during the peak summer season. However there is also evidence that in the upper part of the Himalays the balance of snow fall and melt may be evening out thus preserving the glacier. However individual years there may be contribution from the glacier due to lack of snowfall or higher temperature. Mean monthly contribution of the snowmelt to the stream flow as percentage is shown in 12c. It can be seen that the maximum melt contribution occur during the summer months.

**Figure 13 Spatial distribution of Average Annual Water Yield (Ganga)**

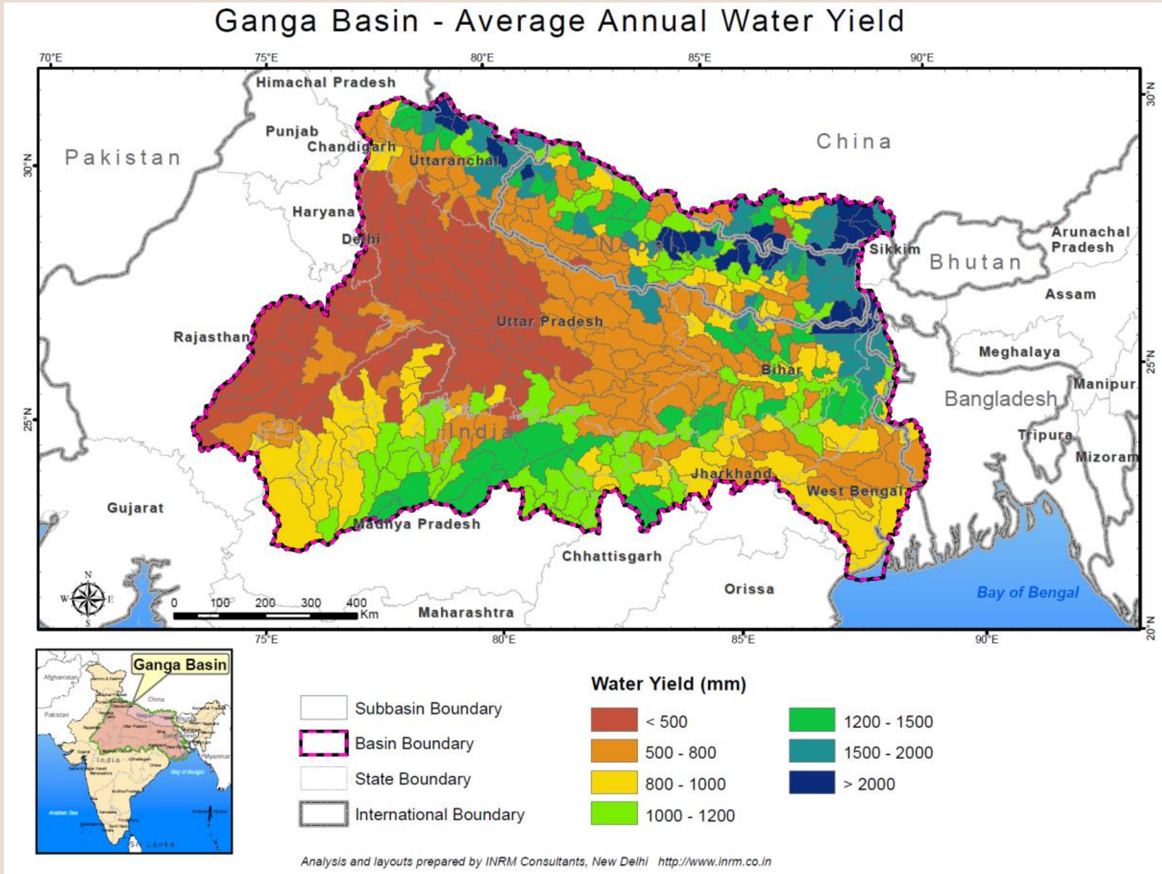



Figure 13, shows spatial distribution of water yield across the Ganga basin. As expected the dry and semi-arid region of Chambal and part of Yamuna the water yield is less than 500m and high water yield of 1500mm+ in Tons and Sone basins along with the subbasins that are in high altitudes in the Himalayan region. This is clearly evident in the case of Kosi basins with significant contribution of the water yield throughout the basin.

Figure 14 shows the SWAT model simulated average annual actual evapotranspiration over the Ganga basin. Like other hydrological components, there is quite a spatial variation of ET in the basin ranging from 100s of mm to well over 900 mm in some parts of the basin. Since Ganga basin has significant agricultural cultivation and the agricultural land gets irrigation water from either the snow/glacier fed streams through storages, local rainfall during monsoon season and supplemented by ground water pumping during non-monsoon season or where surface storage is not adequate. The actual ET shows the overall water requirement for the Ganga basin of both cultivated and natural landscapes such as grass land and forest etc.

**Figure 14 Spatial distribution of Average Annual Actual Evapotranspiration (Ganga)**

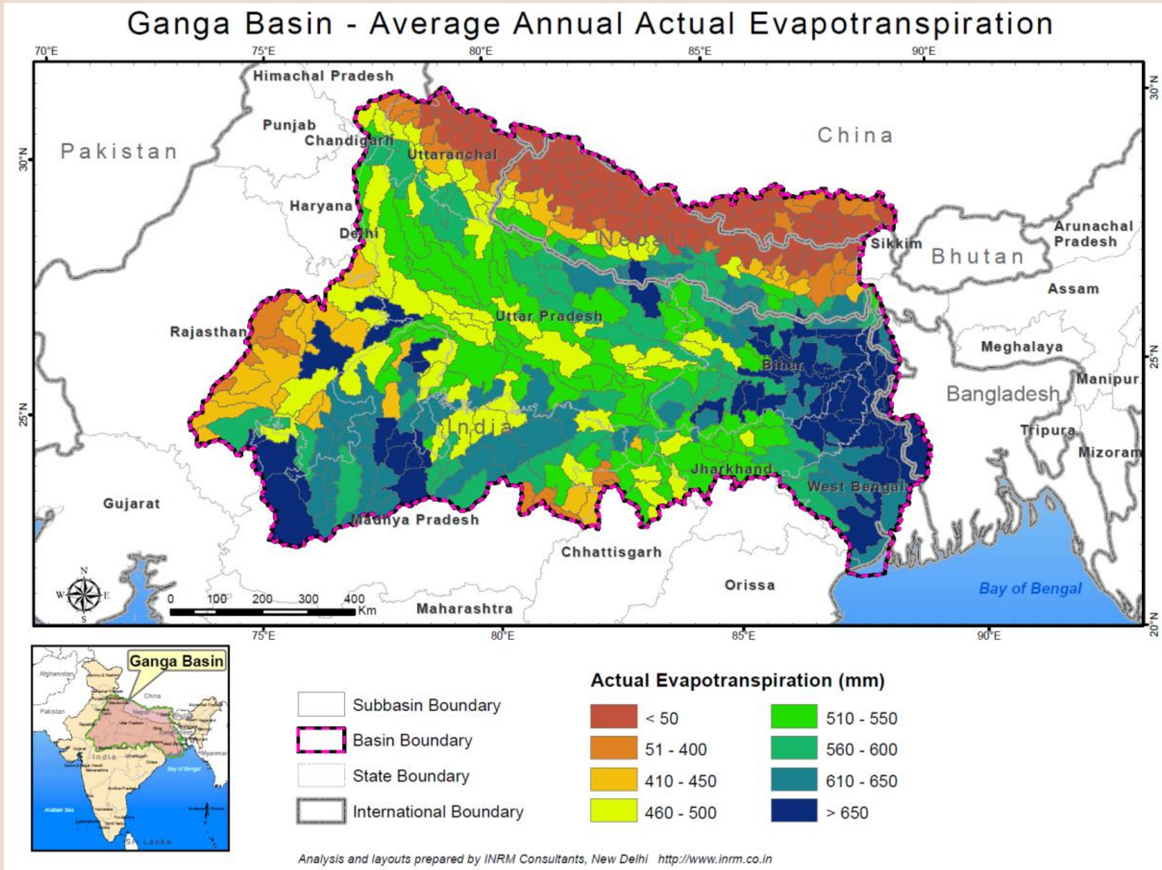


**Figure 15 Spatial distribution of Average Annual Ground Water Flow (Ganga)**

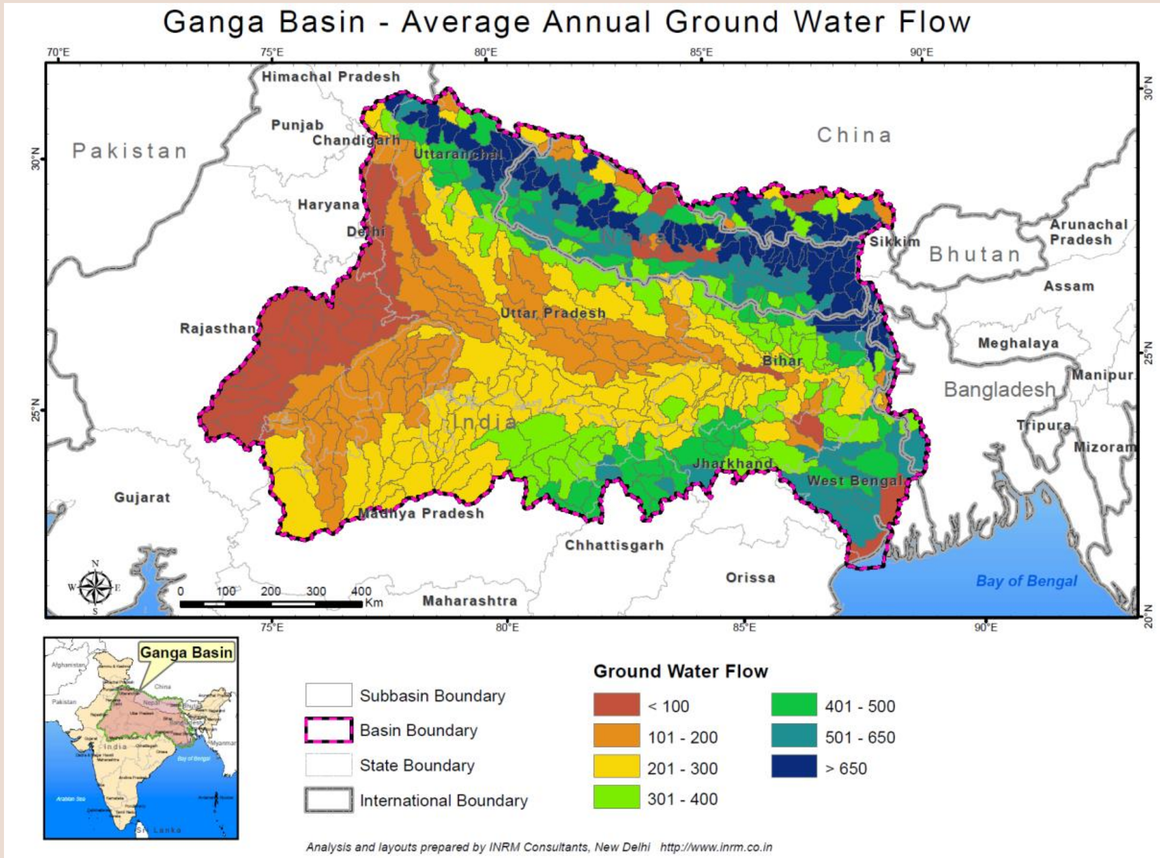
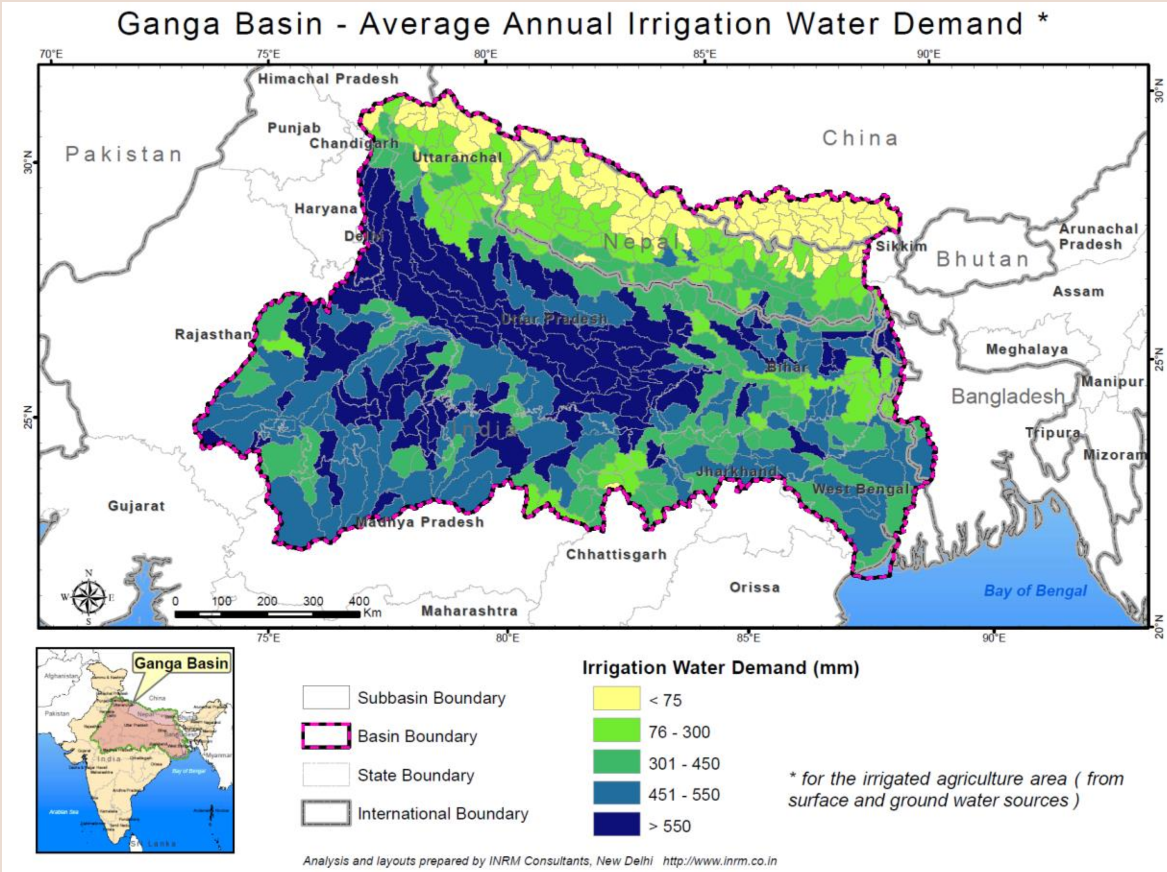



Figure 15 shows the amount of water returned through shallow aquifer as return or baseflow contribution to the river. Again in the alluvial plains and where the command area cultivation with flood irrigation was practiced the groundwater return flows were high. However the model was not calibrated or tested with actual data hence this output need to be verified using monitored flow data to validate the model estimation.

**Figure 16 Spatial distribution of Average Annual Irrigation Water Demand (Ganga)**



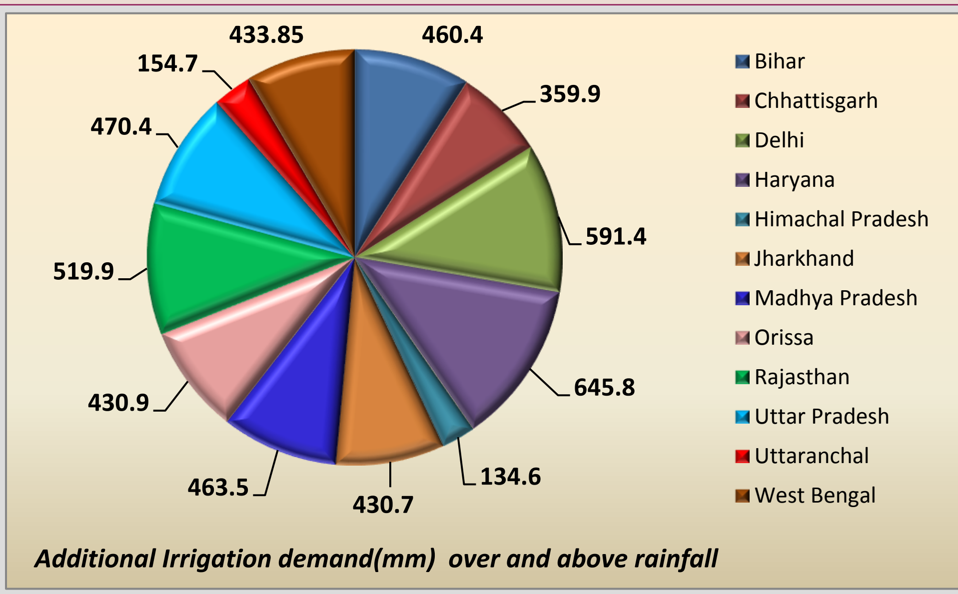



Figure 16 shows the irrigation demand based on the cropping patten. In Ganga the major cropping patterns are Rice during Karif season (monsoon season), Rice-Wheat rotation during karif-rabi seasons, Sugarcane for three years, Sugarcane-Rice rotation with Sugarcane for three years and rice for one year as well as vegetables and dryland agriculture. However Rice, Wheat and Sugarcane are the dominant cropping systems and most of them was double cropping system where more irrigation water was required during Rabi (non-monsoon) season. The irrigation water can be multiple sources including surface water, diversion of water from the river through barrage or dams through irrigation canals, shallow aquifer, deep aquifer and sometimes inter-basin transfer through canals. Figure 16 shows spatial pattern of the irrigation water requirement from all sources of available water over the Ganga basin for agricultural irrigable croplands only. Average irrigation water demand in mm for the States falling in the Ganga basin is also depicted in Figure 16. This irrigation demand is above the crop water demand met by the rainfall.

**Figure 17 Spatial distribution of Average Annual Sediment Yield (Ganga)**

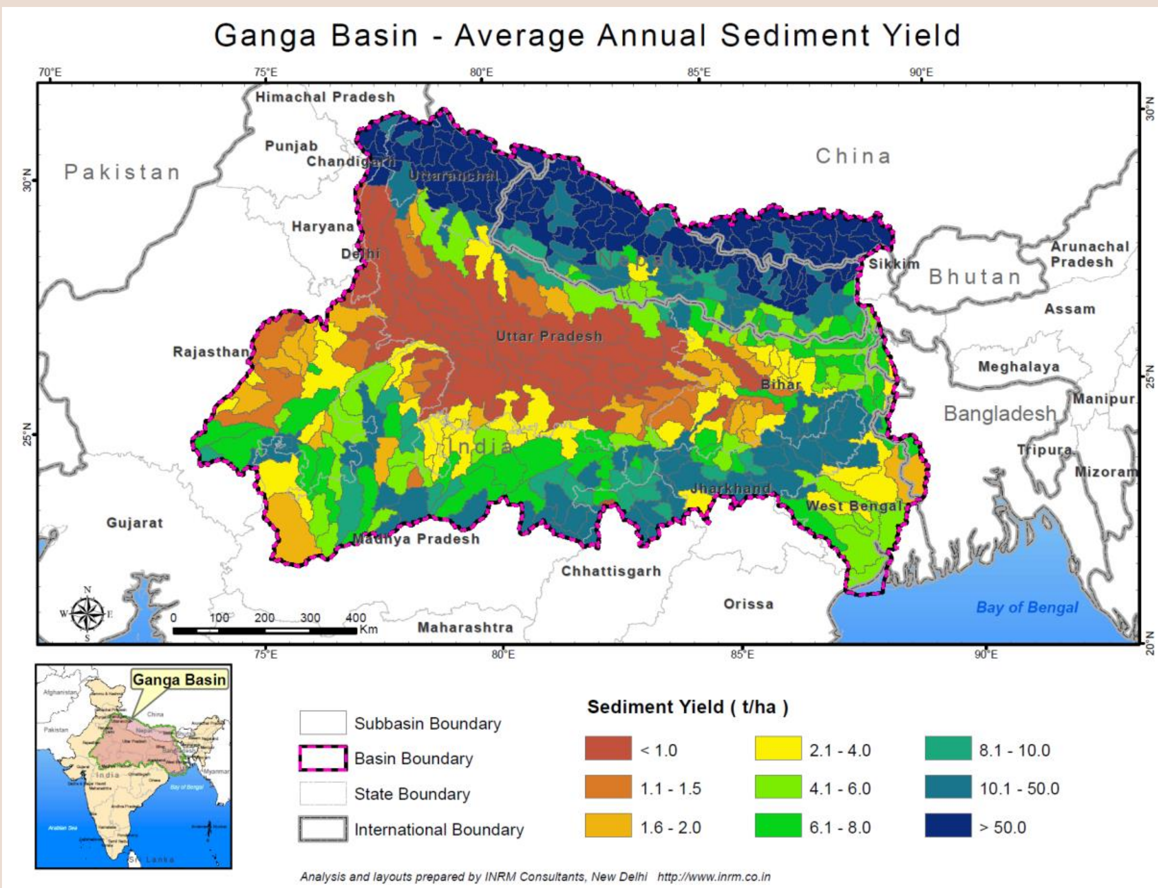
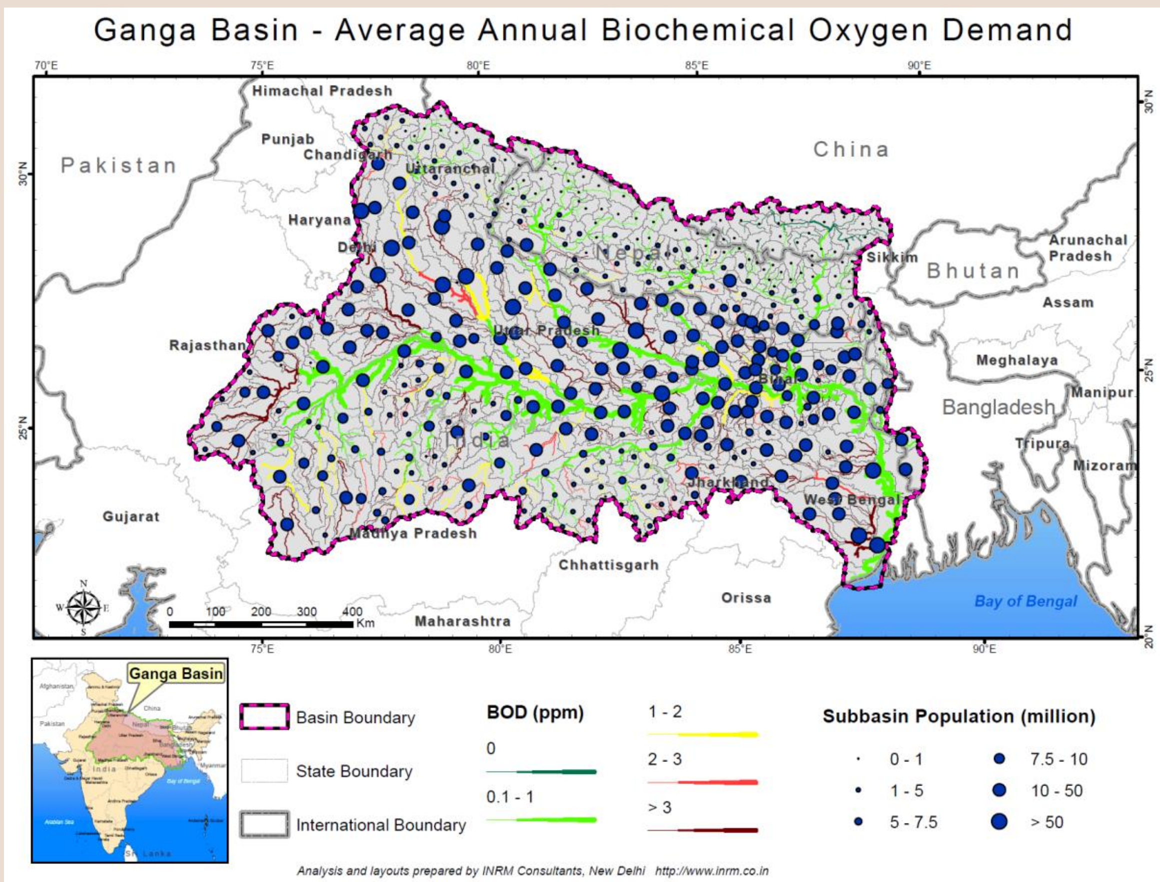



Figure 17 shows the preliminary sediment delivery from the subbasin to the rivers. Again this data was not validated and thus should be used with caution. The general pattern looks good with high erosion in the mountainous regions and low or less sediment from the plains. However the magnitude of the sediment was not checked with any of the observation data and thus should be used with caution. There are several other factors including the land management can alter the sediment delivered to the streams, currently no detailed land management were incorporated in the model setup and thus limits the use of this results.

In addition to the sediment analysis, BOD analysis was also performed in this study for the Ganaga basin (Figure 18). As presented in Table 4, in the baseline model setup, BOD loading was considered based on the population within each subbasin as shown in Figure 18. Population of all the cities within a subbasin were added and literature value was used to estimate the per capita BOD (Table 4) loading to the main streams within the subbasin.

**Figure 18 Spatial distribution of Average Annual BOD Load (Ganga)**




These BOD loads were converted to concentration using the SWAT model simulated flows in each of the river reaches. The flows will increase as move from upstream to downstream, thus at any given location the streamflow is cumulative flow from all the drainage area above that reach/subbasin. Figure 18 shows the various concentration of the BOD in ppm by reach by reach. As per international water quality standards any BOD concentration of greater than 3 ppm is not good for health or environment. A BOD concentration of 2-3 is border-line or impaired water bodies. Less than 1 ppm BOD concentration is considered safe. As seen from Figure 18, most of the head watersheds are either border-line or already impacted with higher BOD concentration of greater than 2 ppm. Due to the abundance of snow/glacier fed Perennial River of the main stem of the Ganga, the concentration of BOD is relatively safe. However structures along the river main stem can impact the availability of water to dilute the higher concentration of BOD. It should be noted with caution the information presented here was average annual concentration, however individual months and days, especially non-monsoon seasons most of the waterbodies and river stretches exceeds the international water quality standard of 3 ppm. Later in this chapter it is shown both monsoon and non-monsoon seasonal impact of BOD concentrations along the river in the Ganga basin.

## 4.2. SWAT Model Performance for Ganga Basin

Watershed models can be used in two ways, either absolute or relative quantification of the impact. If one does not have enough monitored data spatially distributed and long enough records, the model can be setup with the best available data and the scenarios can be run to analyze the relative impact of the scenarios compared with baseline model run. Even in this case, the model output at a gross level such as evapotranspiration, expected runoff, baseflow and crop yield should be verified with available literature data. However if one wants to use absolute number for making decision, then it is highly advised to calibrate and validate the model for two separate time periods with proper statistical confidences and then extend this analysis to all the scenarios. However in most cases having luxury of monitored data both space and time for various hydrological components of a watershed model is often difficult. Hence, it was advised to verify the various hydrologic and biologic components and perform model comparison with observed data where data available, thus the scenarios results can be extended with more realism.

In this study, through World Bank-Nepal there were about 14 stream flow monitoring stations were made available. In addition through global runoff database by GRDC[27] additional 23 stations stream flow data were obtained for various time periods. In general GRDC data were available until 1993, whereas the data obtained by WB from Nepal hydro-meteorological department were available until 2006. Most of the data were available at the monthly scale, thus the comparison were performed at monthly scale only. Before performing any of the statistical comparison, the model was setup to the best of the inputs available as discussed in the chapter 3, and the results from the model for general evapotranspiration, runoff, base flow/return flow, and crop yields against district averages were analyzed and found satisfactory. Since most of the stream flow data were available in the Nepal-India border, they capture most of the snow hydrology components of the model with limited or no abstraction or structures above these locations. There is very limited agriculture or any significant landuse above these gauge locations (Figure 19).

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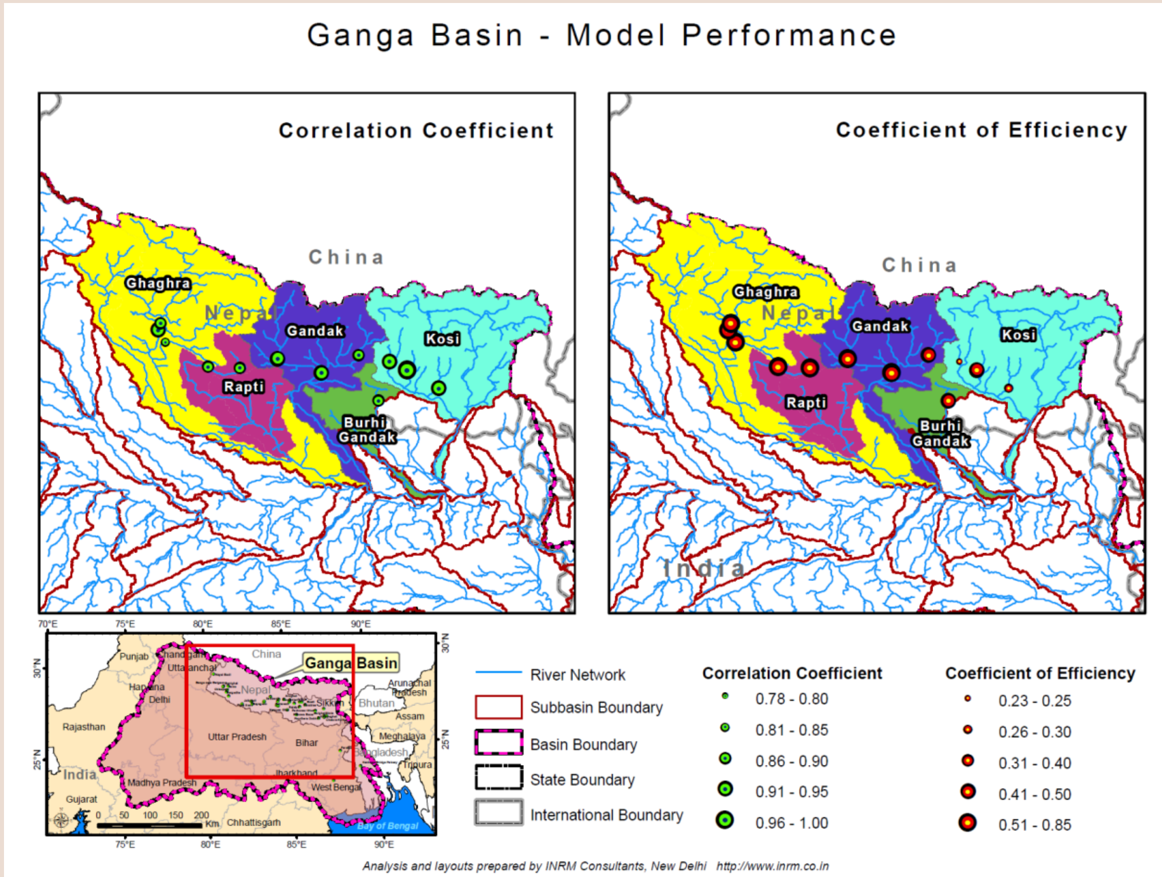
27 http://www.bafg.de/cln_007/nn_293846/GRDC/EN/01__GRDC/03__Database/database__node.html?__nnn=true

**Figure 19 Stream flow Gauge Locations used for SWAT model verification**




Hence, only the snow hydrological components of snowfall, snowmelt, sublimation, snow/glacier depth were the outputs that were able to verify through these comparison of modeled and observed datasets for a fairly long-term period providing significant confidence in the model prediction for this study. While setting up the model, some of the specific site locations were not available thus unable to coincide the subbasin outlets with that of all the available monitoring stations. Hence, for this study only 12 stations were compared and analyzed and their results and time series plots were made available in Table 5 and Figure 20. As it can be seen the SWAT model as setup in this study with proper elevation bands, temperature and precipitation lapse rates along with proper glacier depth produced statistically significant comparison results with observed data at various location for 10+ years and the timing of snow hydrology components were very satisfactory. The long-term simulation means at all drainage area levels were on par with observed means, the $R^2$ and Coefficient of efficiency were above literature acceptable ranges from 0.84 to 0.97 and 0.41 to 0.83 respectively.

Given the importance of glacier and snow hydrology from Himalayas for Ganaga basin, with additional resources and time a more in-depth analysis could be extended and gain significant confidence in the models ability to simulate and thus able to apply various scenarios including climate change aspects. One of the outputs that the SWAT model can produce is the remaining depth of glacier/snow at various elevation bands at each time step of the model. So using time series remote sensing methods, available ground based snow and glacier data, available additional long-term gauge monitoring data with proper SWAT model setup, a study can bring out even more quantified availability of water resources. For basin like the Ganga that span across four countries, having accurate accountability of perennial water resources is very important for inter-country negotiations, water resources development, infrastructure (such as dams and bridges protection), flooding and drought management and understanding impact of climate change on these permanent water resources. So it is highly advisable to extend a more thorough study on these aspects to gain further confidence in the decision processes.

**Table 5 SWAT output comparison Locations and model efficiency parameters**

| Gauge Site | River | Drainage Area (at Observation) (Sq km) | Start Year | End Year | COE* | Correlation coefficient | Area** Difference (%) | Volume Bias (%) |
|---|---|---|---|---|---|---|---|---|
| **Ghagra Basin** | | | | | | | | |
| Jamu | Bheri | 12290 | 1969 | 2001 | 0.533 | 0.874 | -8.79 | -27.48 |
| Chisapani | Karnali | 42890 | 1969 | 1993 | 0.597 | 0.942 | -8.16 | -25.81 |
| Bargadha | Babai (Sarju) | 3000 | 1969 | 1986 | 0.67 | 0.841 | -17.47 | 26.84 |
| **Gandak Basin** | | | | | | | | |
| Narayan Ghat/ Devghat | Narayani | 31100 | 1969 | 2001 | 0.834 | 0.948 | -20.45 | -0.70 |
| Setibeni | Kali Gandaki | 6630 | 1969 | 1993 | 0.543 | 0.919 | -8.14 | 10.44 |
| Betrawati | Trishuli | 4110 | 1969 | 2001 | 0.444 | 0.891 | -11.56 | 1.04 |
| **Bhuri Gandak Basin** | | | | | | | | |
| Pandhera Dobhan | Bagmati | 2700 | 1969 | 2001 | 0.494 | 0.896 | -0.37 | 36.22 |
| **Rapti Basin** | | | | | | | | |
| Jalkundi | Rapti | 5150 | 1969 | 1985 | 0.713 | 0.870 | -1.28 | 5.17 |
| Bagasoti Gaon | Jhimruk Khola | 3380 | 1976 | 1985 | 0.602 | 0.858 | -1.33 | 10.79 |
| **Kosi Basin** | | | | | | | | |
| Rabuwar Bazar | Dudh Kosi | 4100 | 1969 | 1985 | 0.289 | 0.948 | 0.39 | 26.29 |
| Busti | Tamakosi | 2753 | 1971 | 1987 | 0.050 | 0.966 | 75.21 | 68.96 |
| Jalbire | Balephi Khola | 629 | 1978 | 1990 | 0.231 | 0.913 | -10.35 | 14.29 |

*Nash-Sutcliffe coefficient, ** Difference in Drainage Area (at Observation) and Drainage Area (modelled).

**Figure 20 SWAT output comparison Locations and model efficiency parameters**

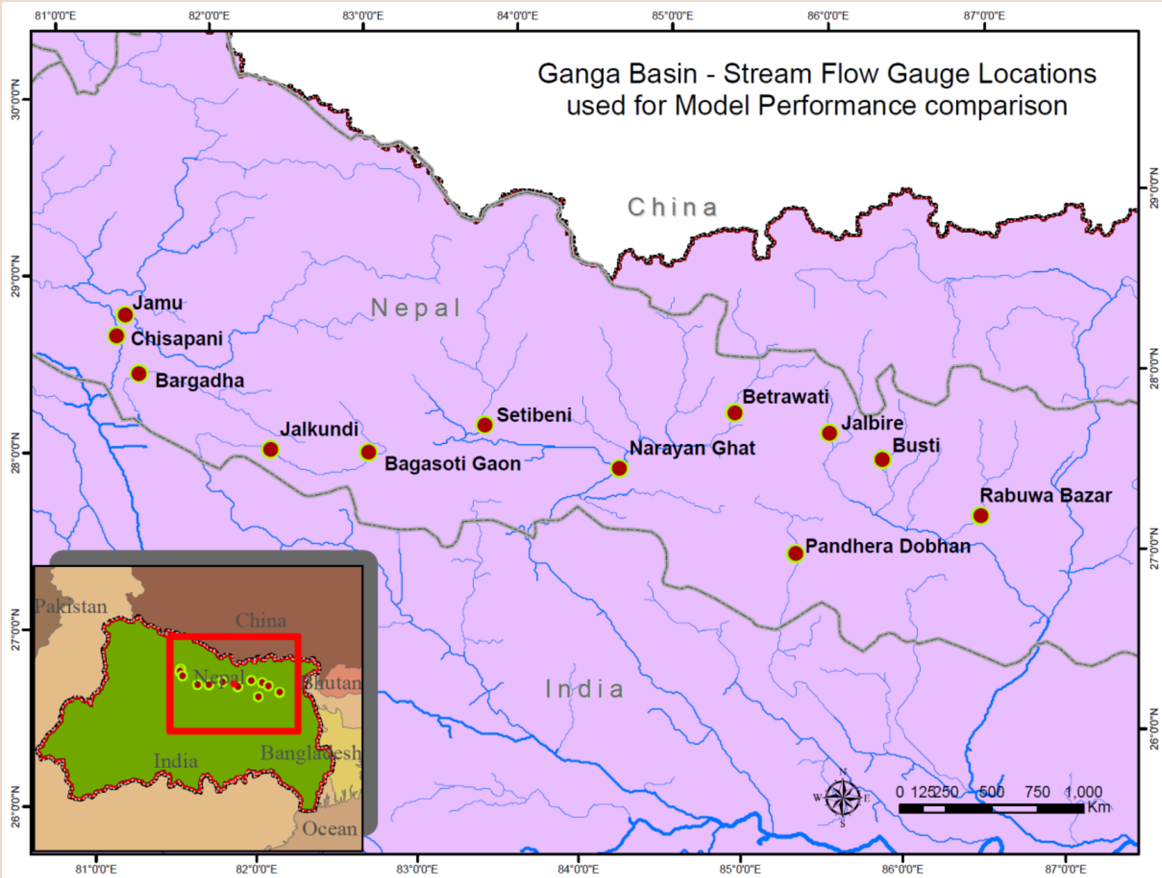
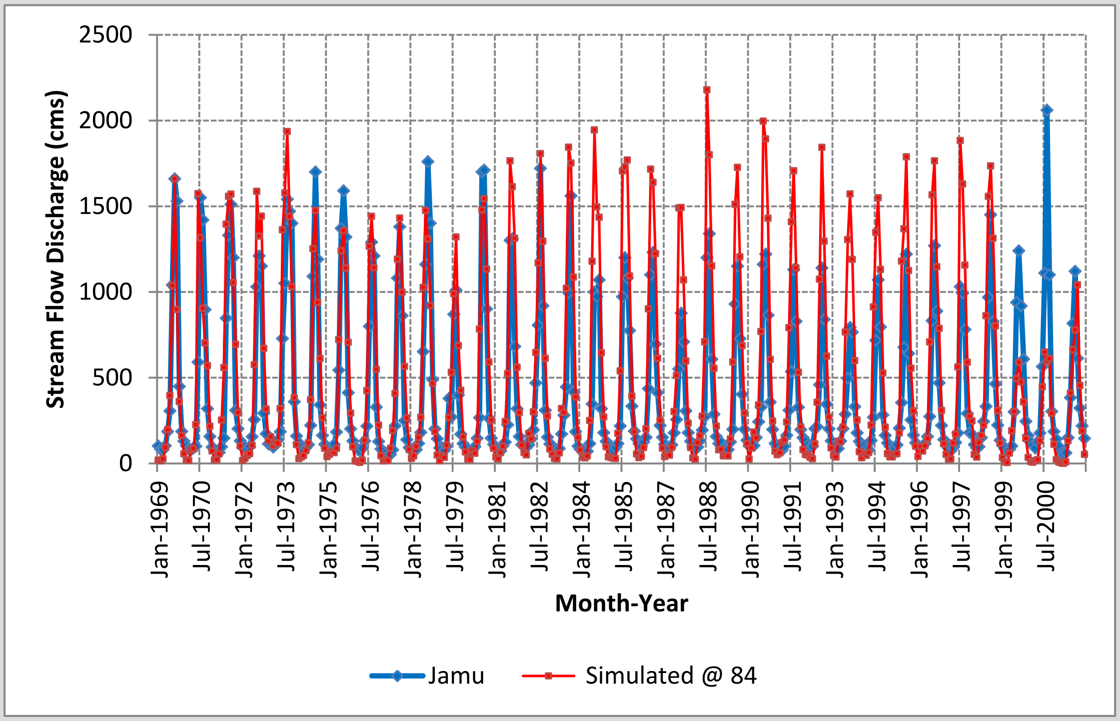


**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Jamu on Bheri river Catchment area 12,290 sq km. Comparison period: 1969 - 2001



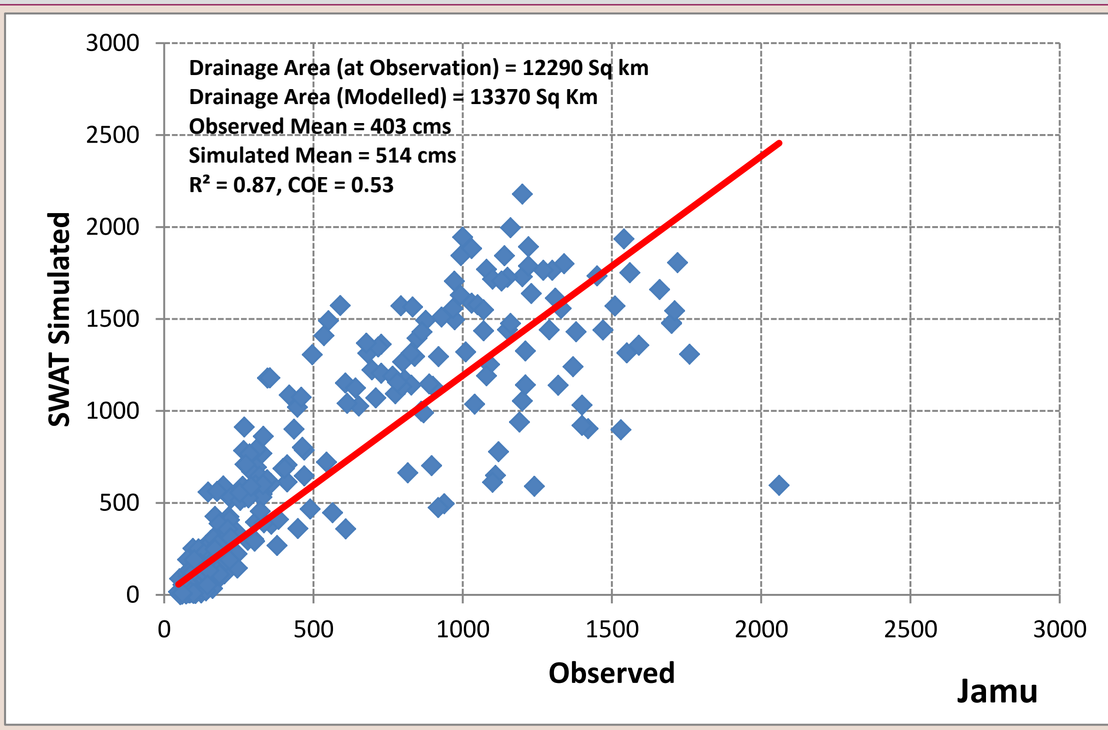
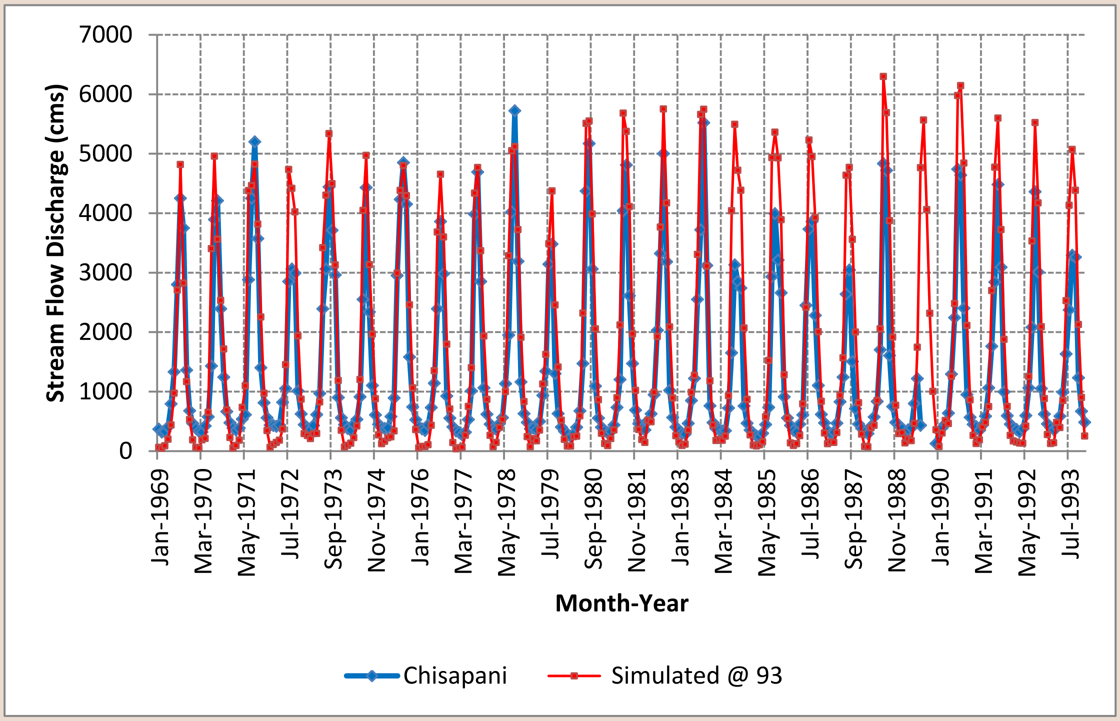



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Chisapani on Karnali river Catchment area 42,890 sq km. Comparison period: 1969 - 1993



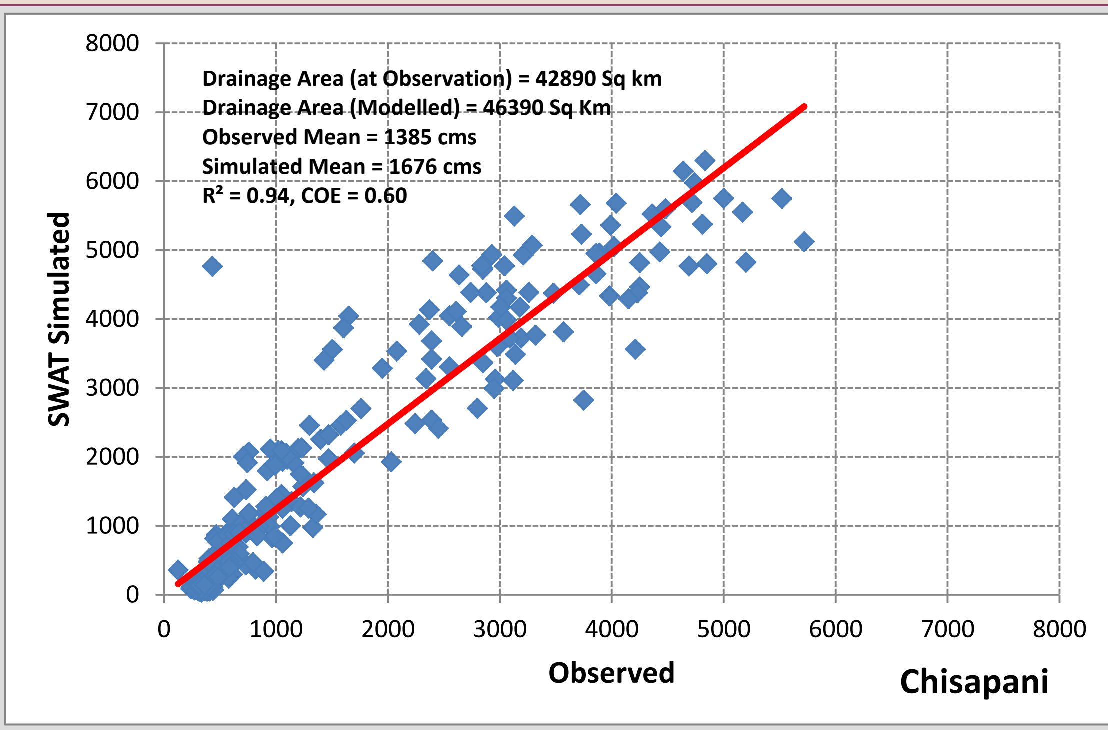
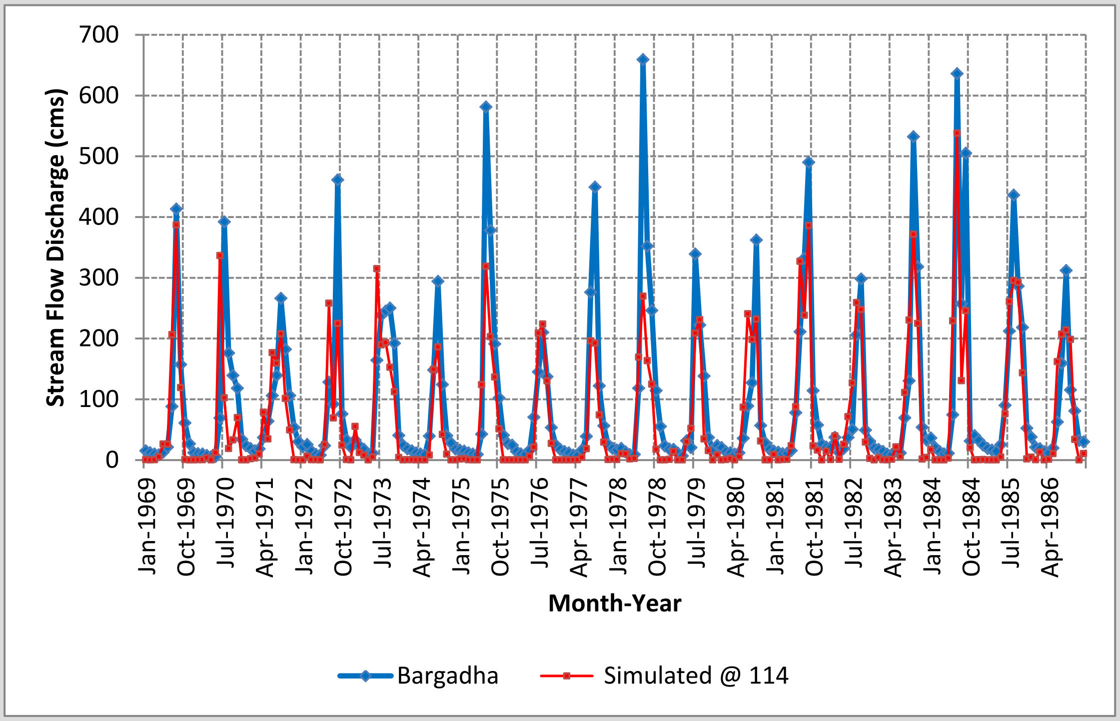



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Bargadha on Babai river Catchment area 3,000 sq km. Comparison period: 1969 - 1986



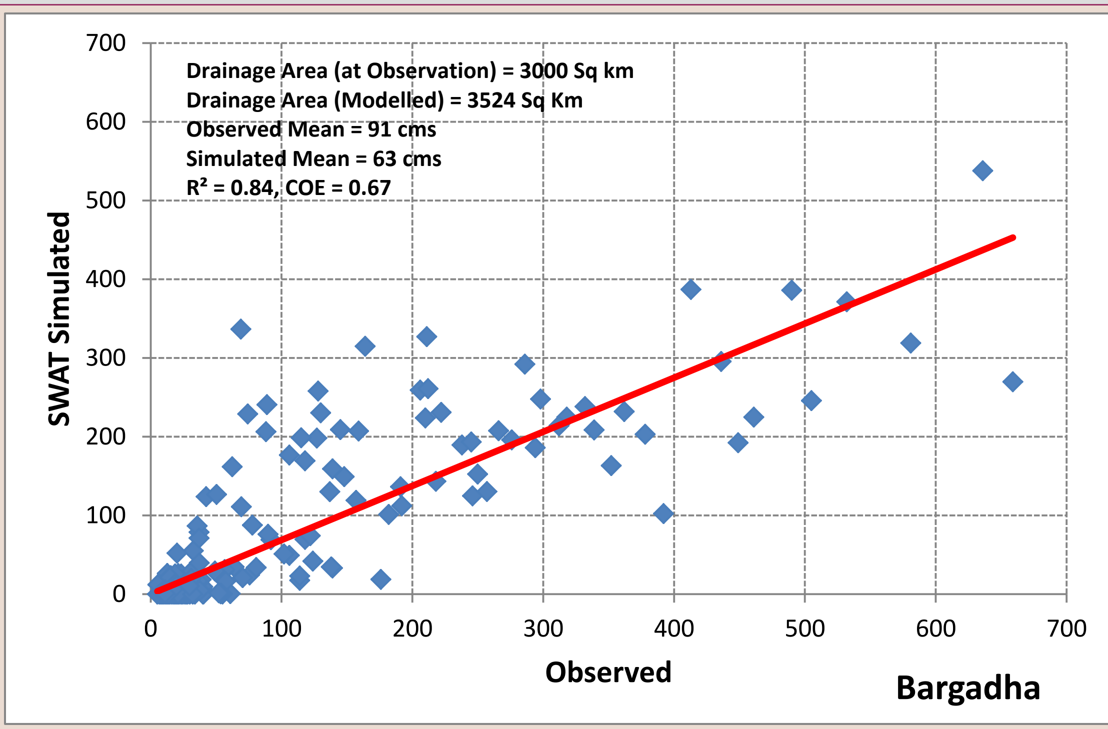
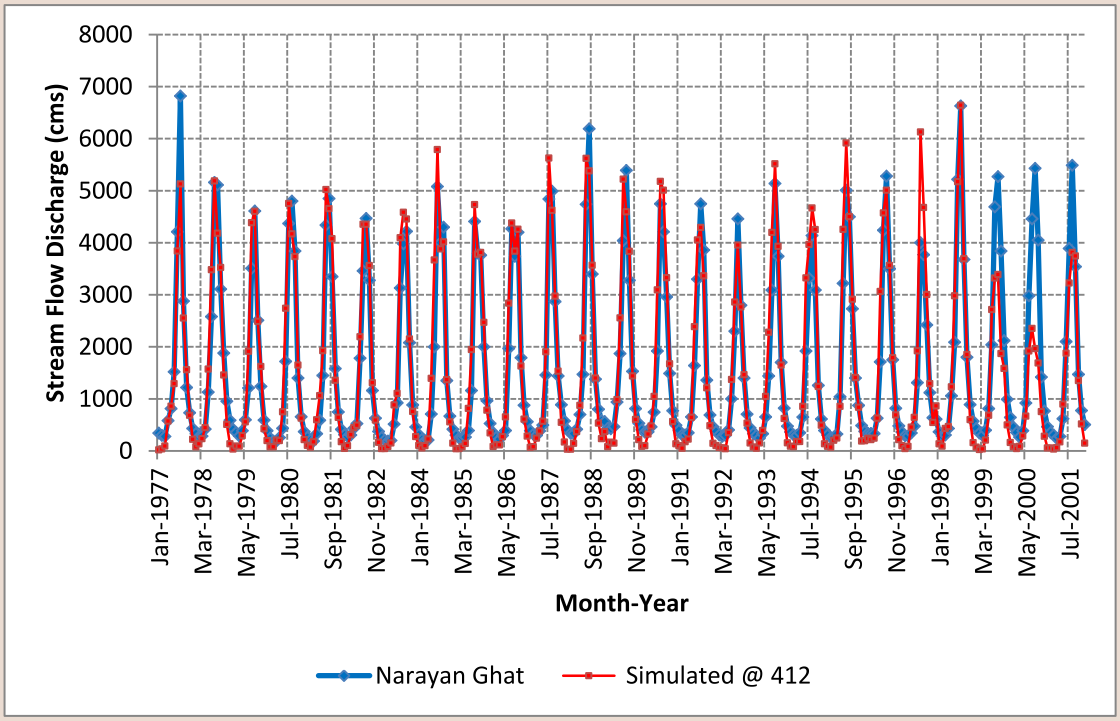



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Narayan Ghat on Narayani river Catchment area 31,100 sq km. Comparison period: 1969 - 2001



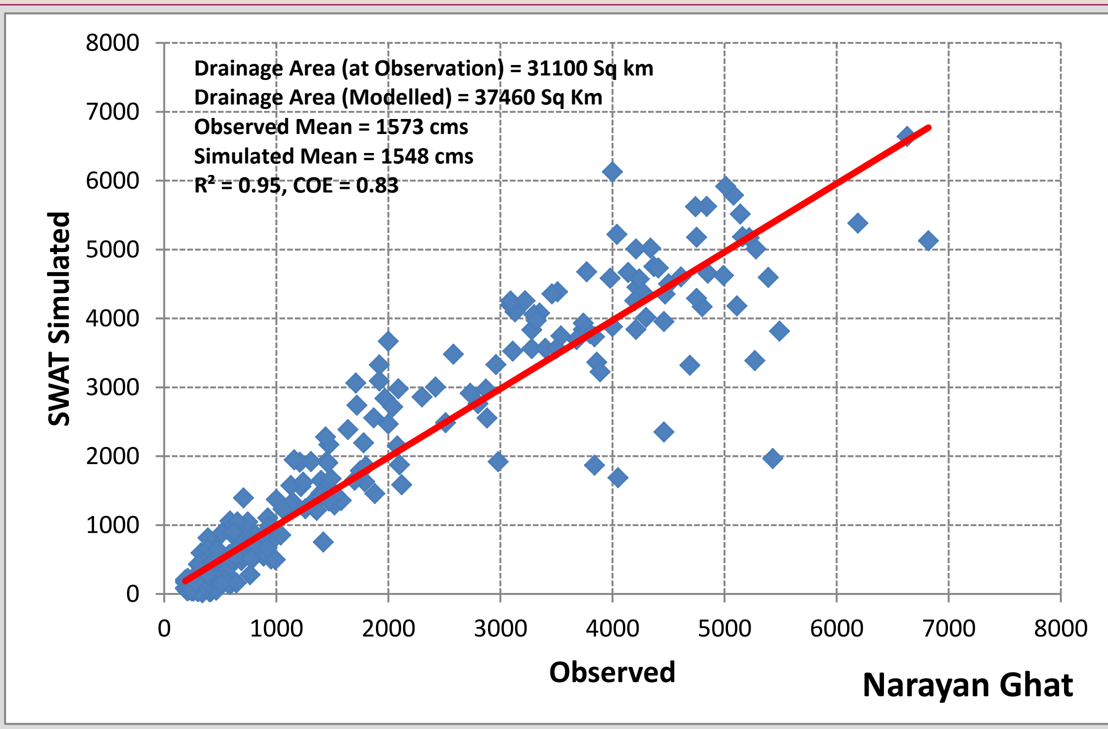
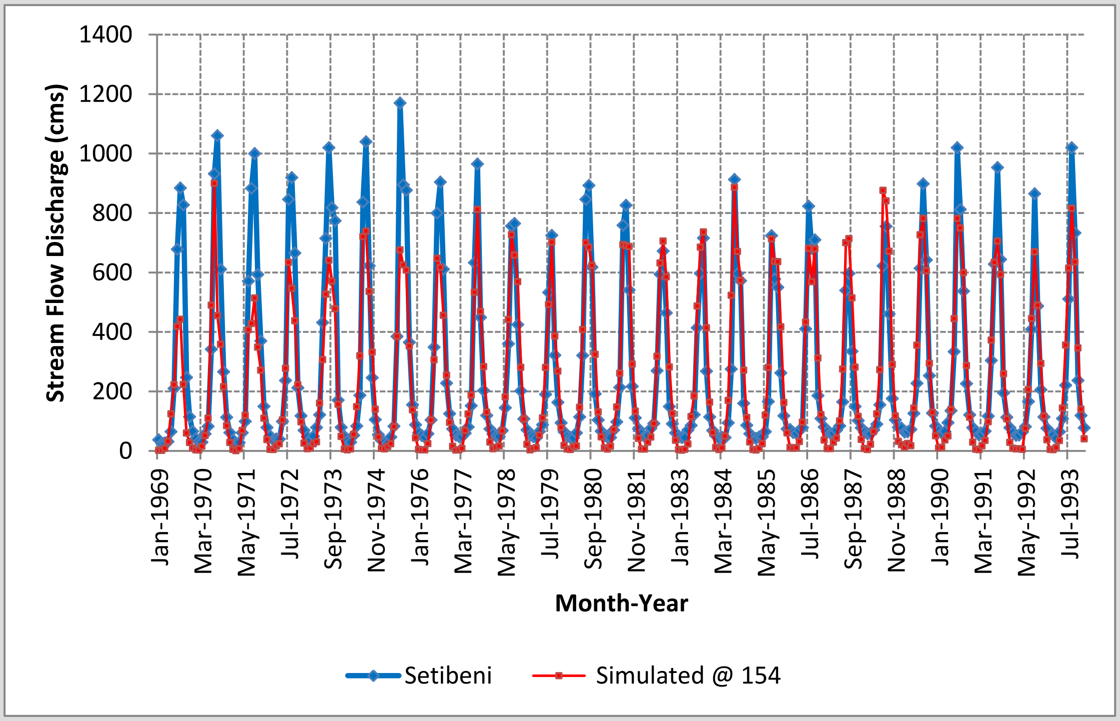



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Setibeni on Kali Gandaki river Catchment area 6,630 sq km. Comparison period: 1969 - 1993



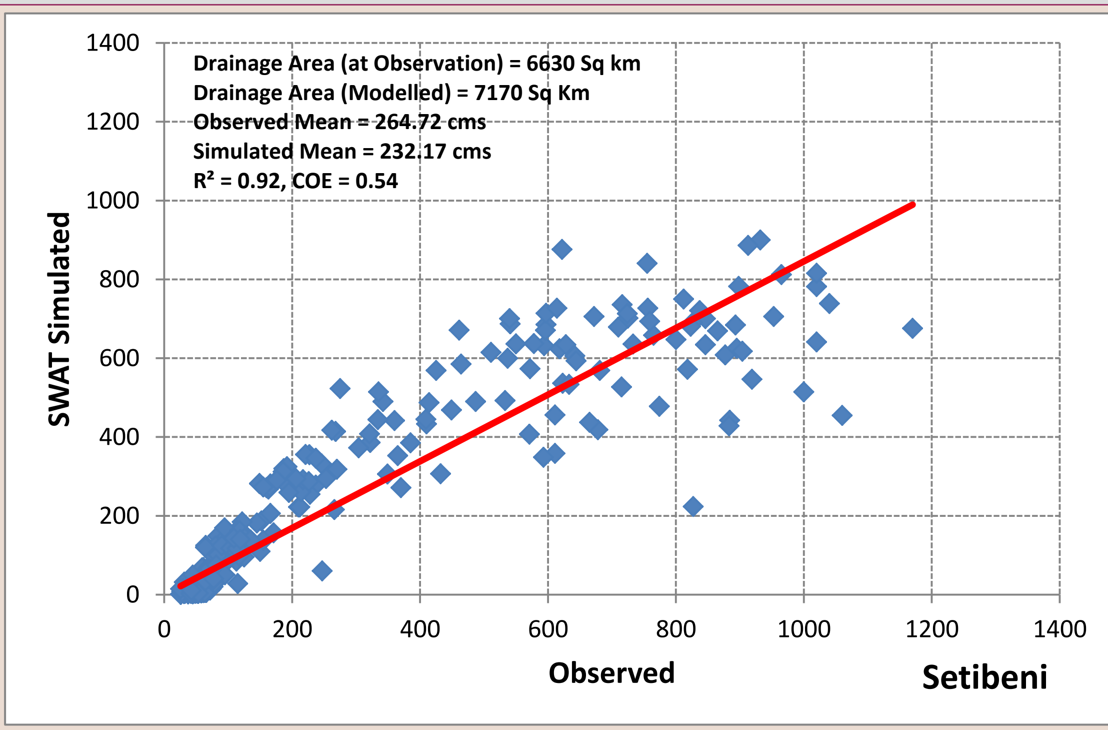
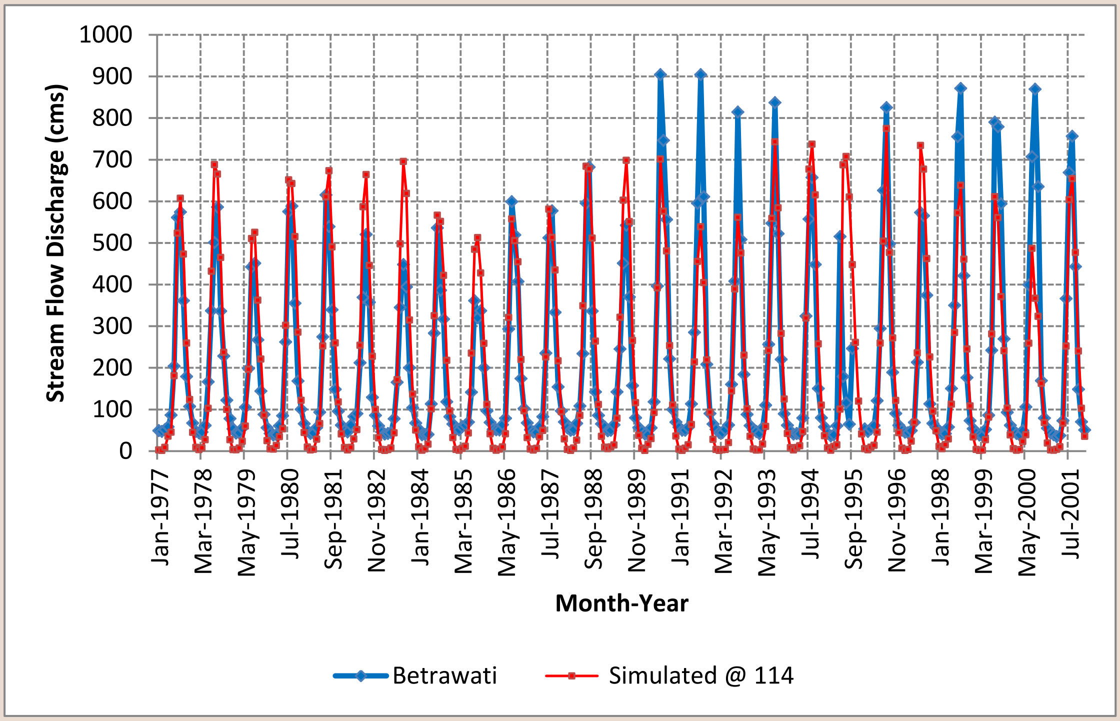



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Betrawati on Trishuli river Catchment area 4,110 sq km. Comparison period: 1969 - 2001



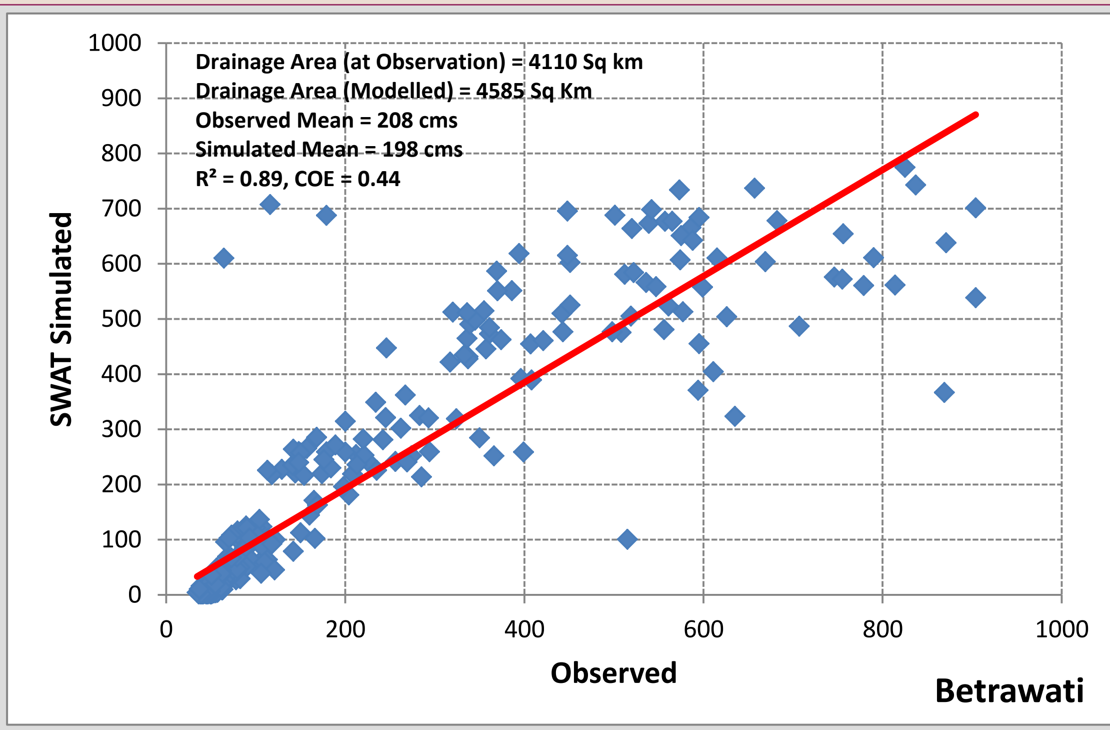
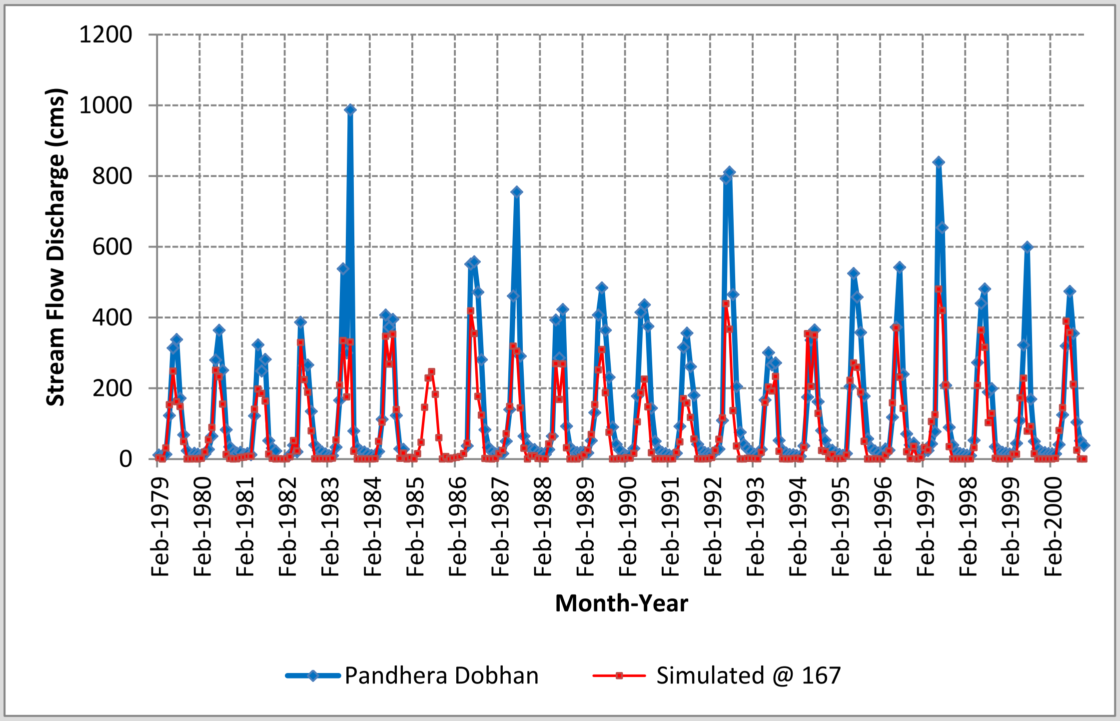



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Pandhera Dhoban on Bagmati river Catchment area 2,700 sq km. Comparison period: 1969 - 2001



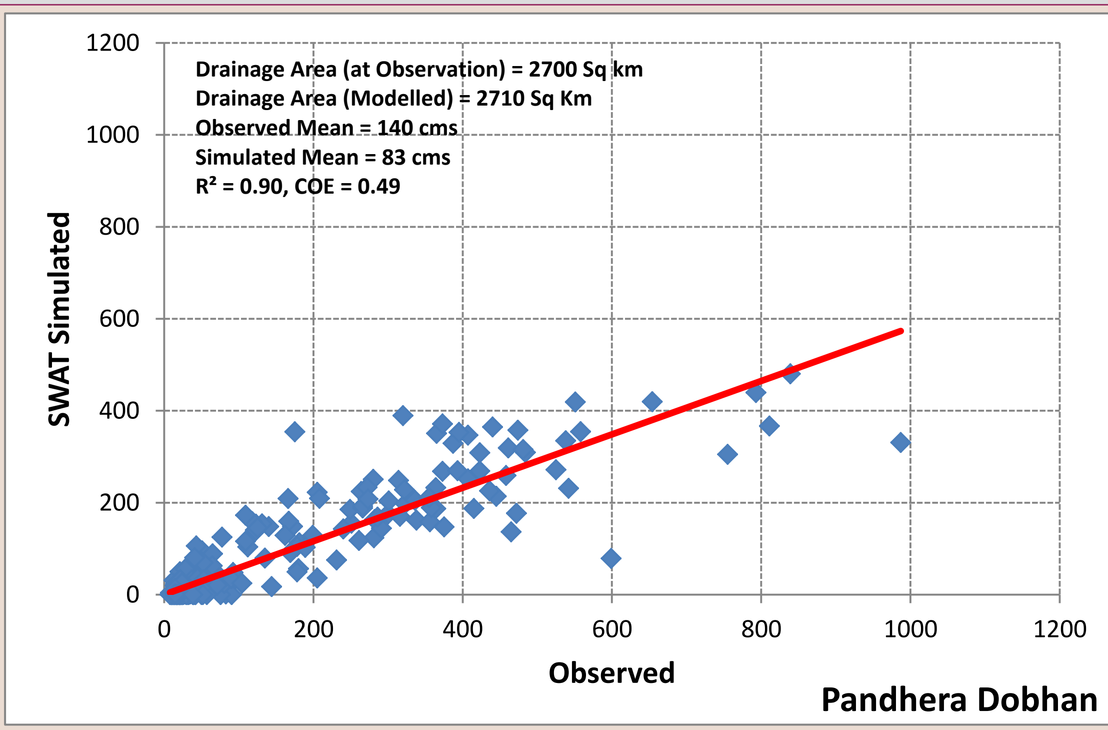
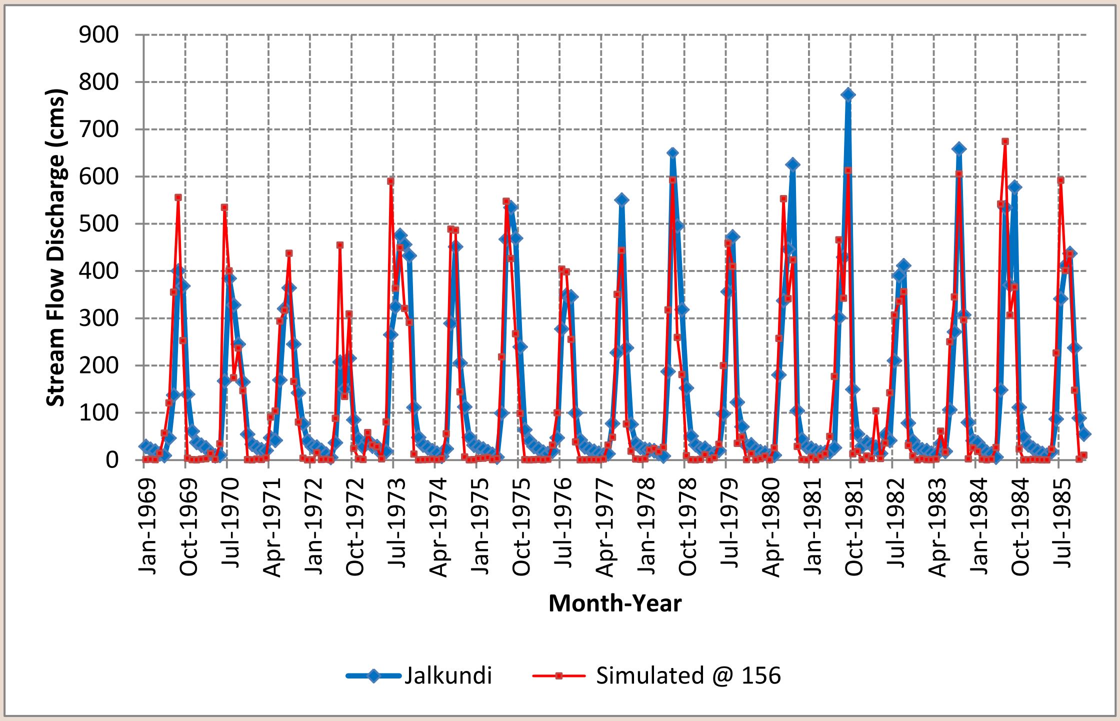



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Jalkundi on Rapti river Catchment area 5,150 sq km. Comparison period: 1969 – 1985



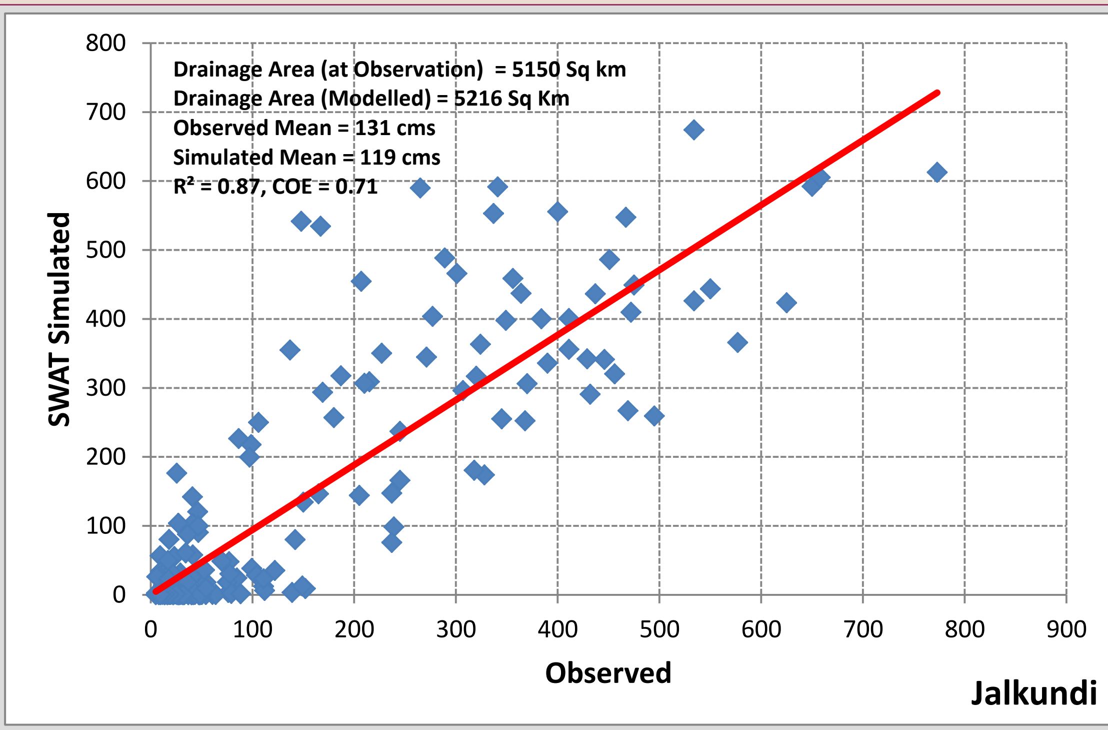
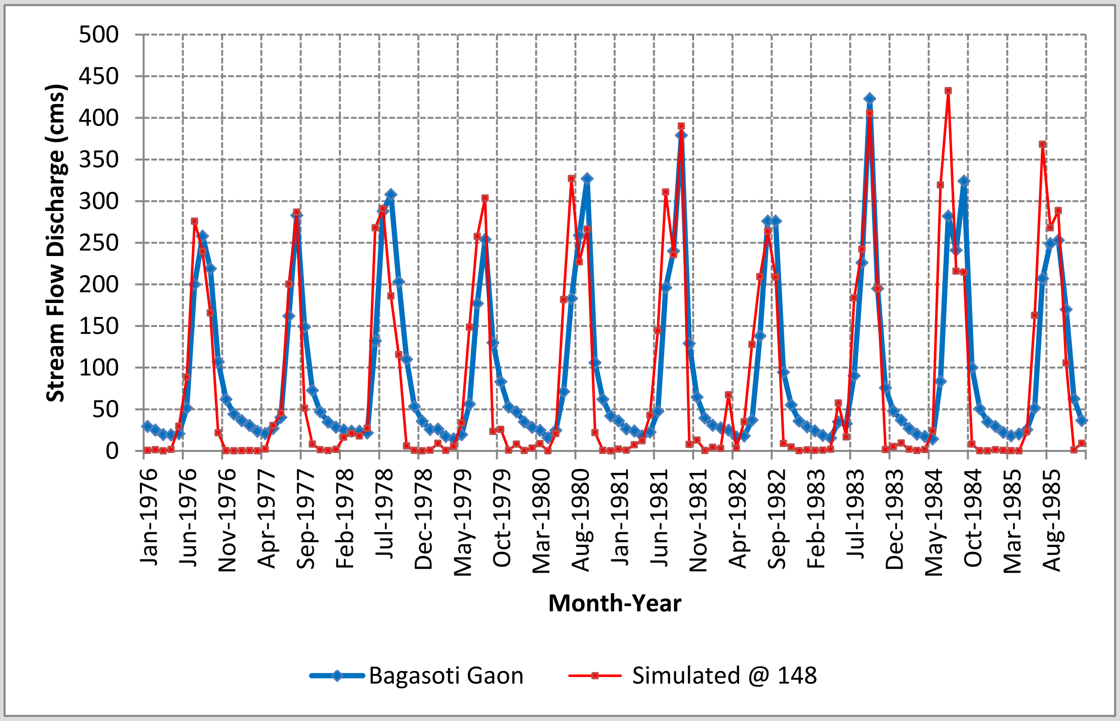



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

BagasotiGaon on Jhimruk river Catchment area 3,380 sq km. Comparison period: 1976 - 1985



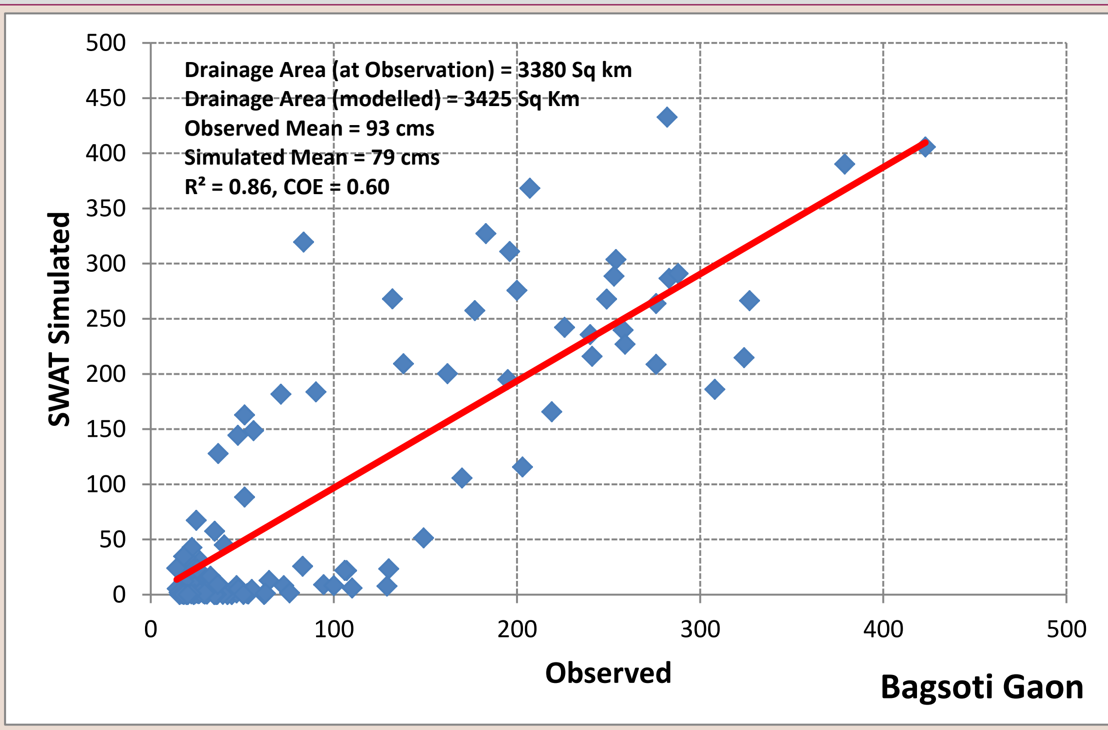
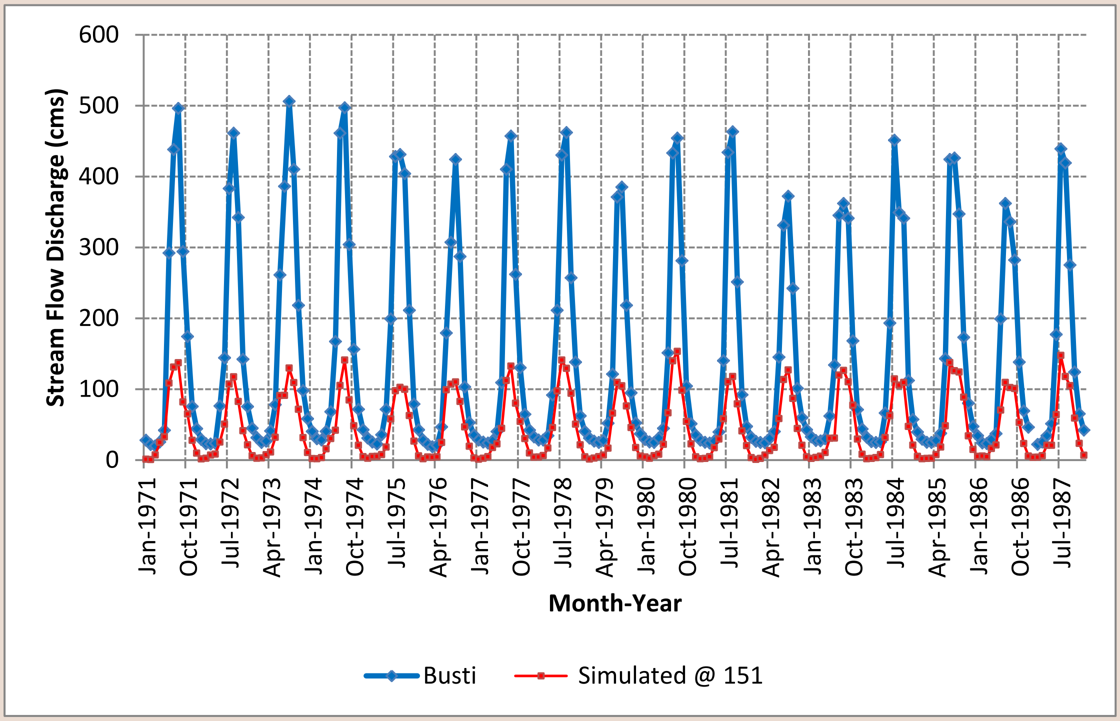
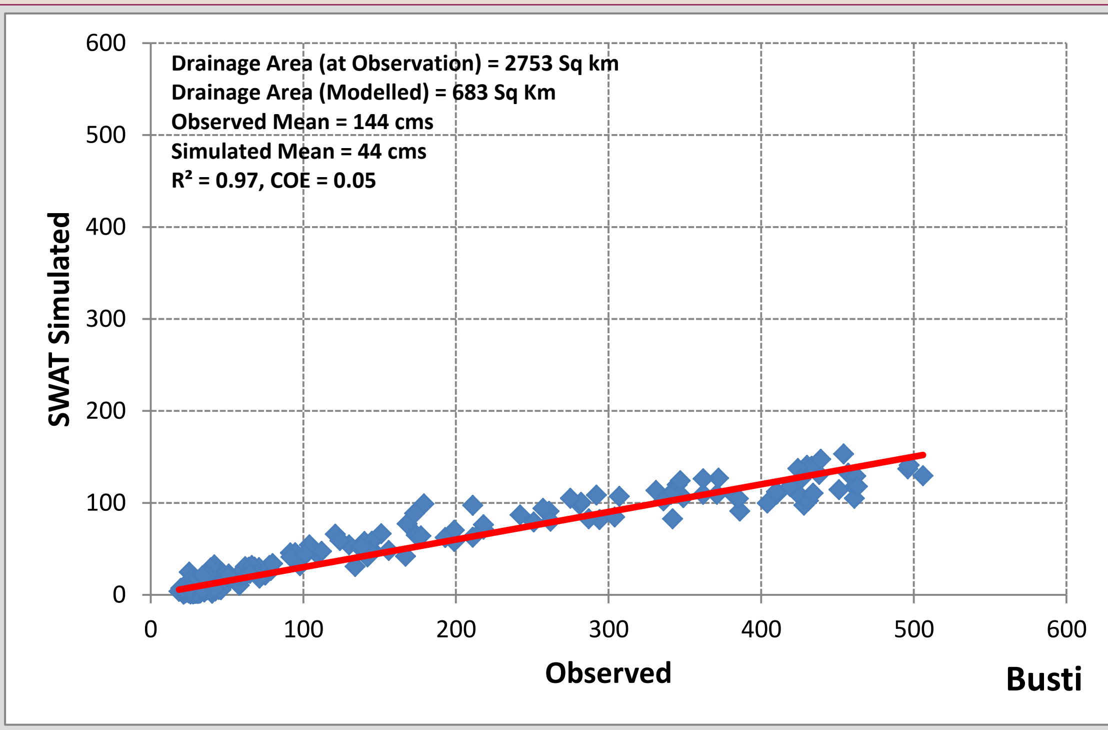



**Figure 20 SWAT output comparison Locations and model efficiency parameters**

Busti on Tamakosi river Catchment area 2,753 sq km. Comparison period: 1971 - 1987



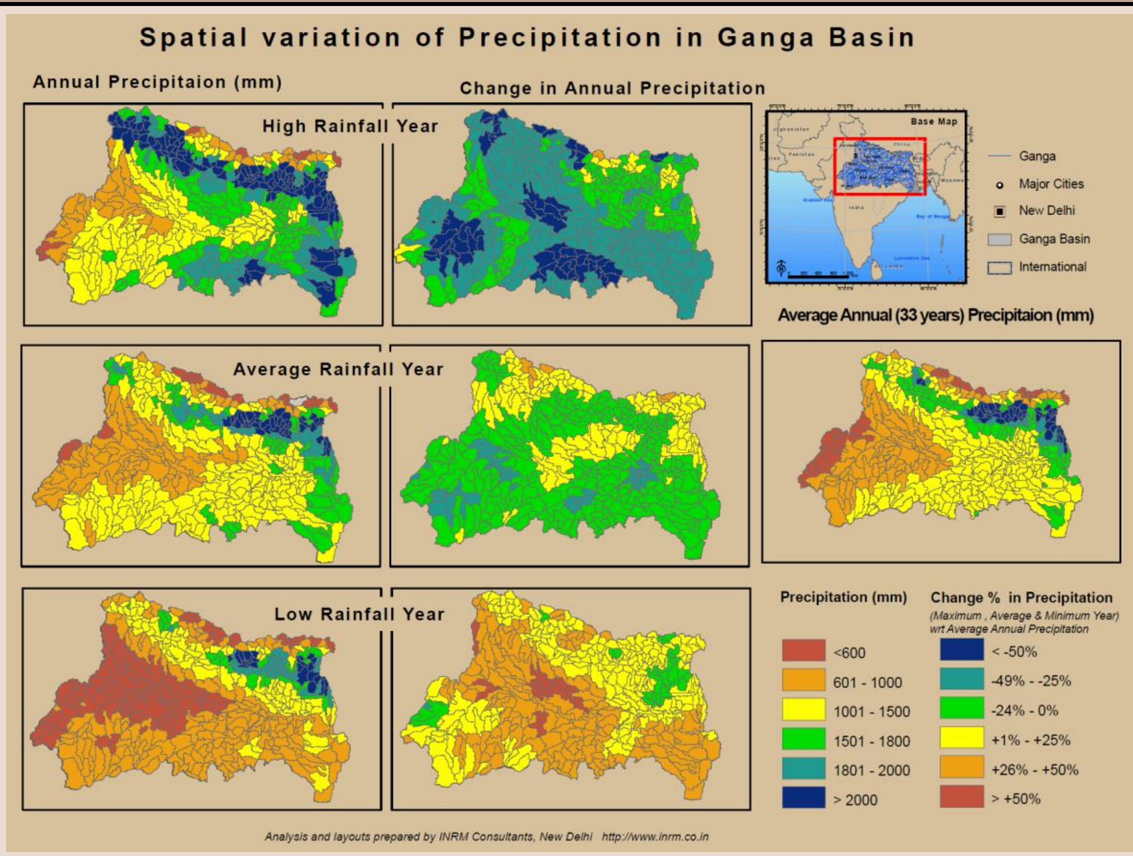



# 5. Scenarios Analysis

In the present study five scenario (Table 4) model runs (Scenario A to E) were implemented. Analysis of the model results are presented in the following paragraphs. Scenarios B, D5 and D10 did not produce significant change from baseline (Scenario A), hence the analysis outputs for these are not presented.

Average annual range was picked up using the high, normal and low rainfall year for the analysis. Figure 21 shows the spatial variation of high (year in which maximum number of subbasins experienced maximum annual rainfall in the 33 years period), average (year in which maximum number of subbasins experienced average annual rainfall in the 33 year period) and low (year in which maximum number of subbasins experienced minimum annual rainfall in the 33 year period) rainfall years and the change in the annual rainfall for these three years from the average annual (33 years average). However, some of the subbasins may be significantly higher or lower than the other basins thus some of these subbasins might not be representative of high, average or low rainfall years. Hence readers of this report should keep this in mind while analysing all the results in this chapter.

**Figure 21 Spatial Variation of Annual average precipitation and the change in annual precipitation for high, average and low rainfall – Scenario A (Baseline)**



For the same years the average water yield and change in average water yield was mapped (Figure 22).

**Figure 22 Spatial Variation of Annual average water yield and the change in annual yield for high, average and low rainfall year**

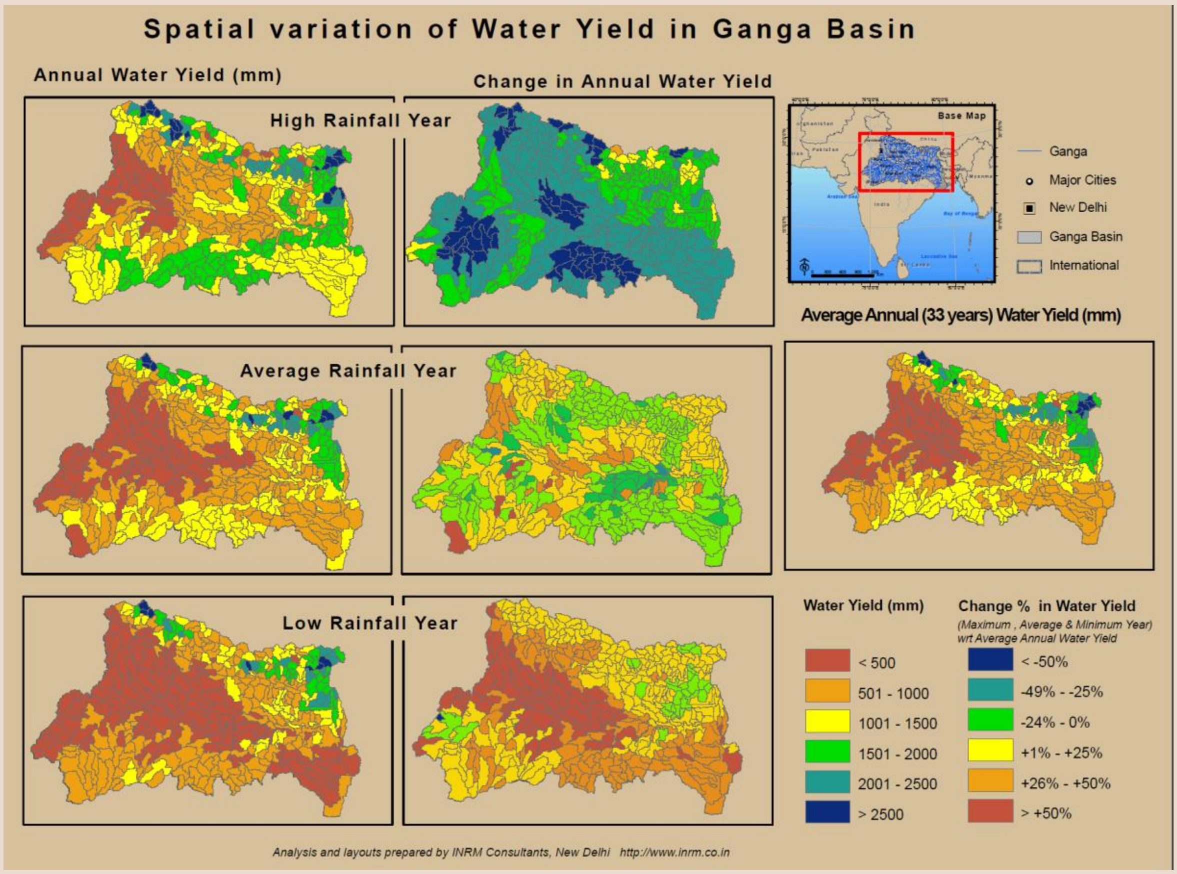
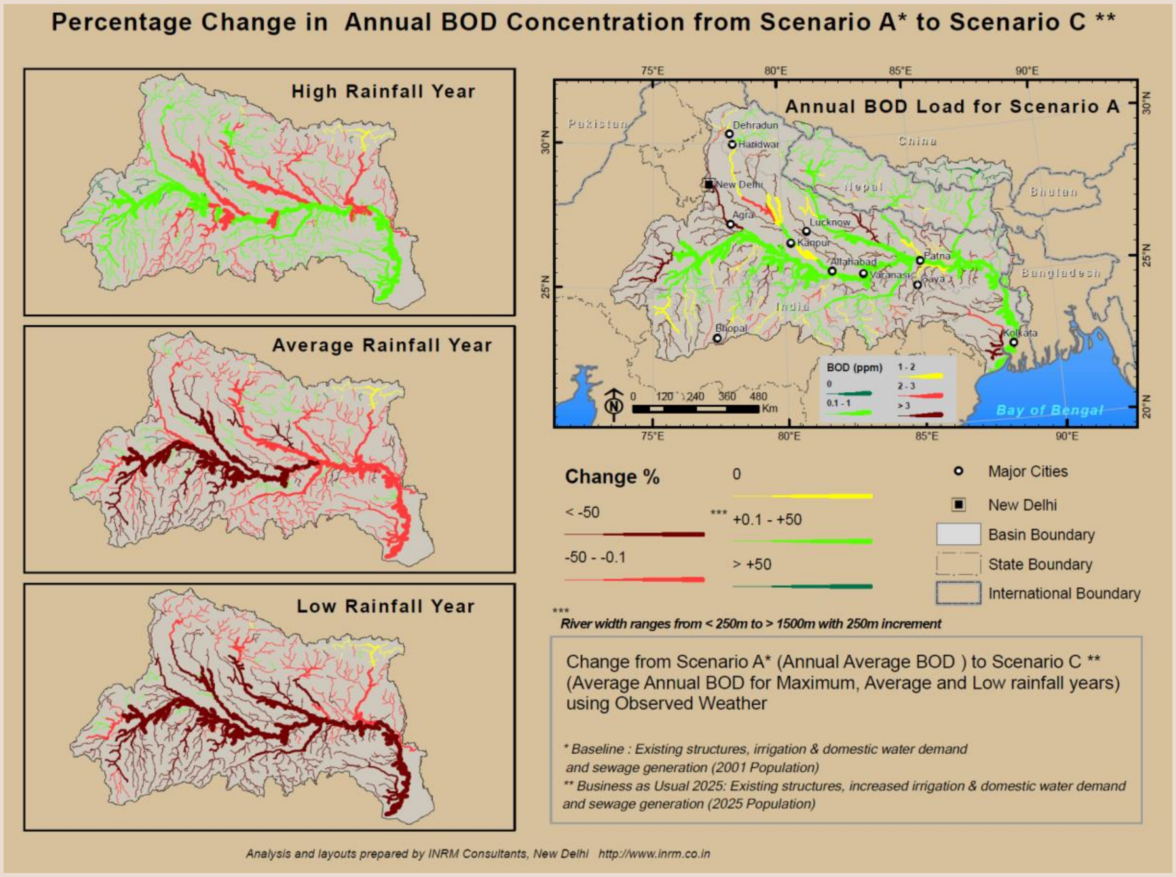



Figure 23 shows the average annual percent change of BOD concentration between Scenario A to C. As explained in table 4, the Scenario C has projection of water use for year 2025 due to increase irrigation and population demand. So naturally the water in the river will be spatially removed due to the additional demand in the year 2025. Comparing the BOD concentration between the average BOD values in baseline scenario A with high rainfall year, average rainfall year and low rainfall year in scenario C is shown in Figure 23.

**Figure 23: Average Annual Percent Change of BOD concentration from Scenario A to C**

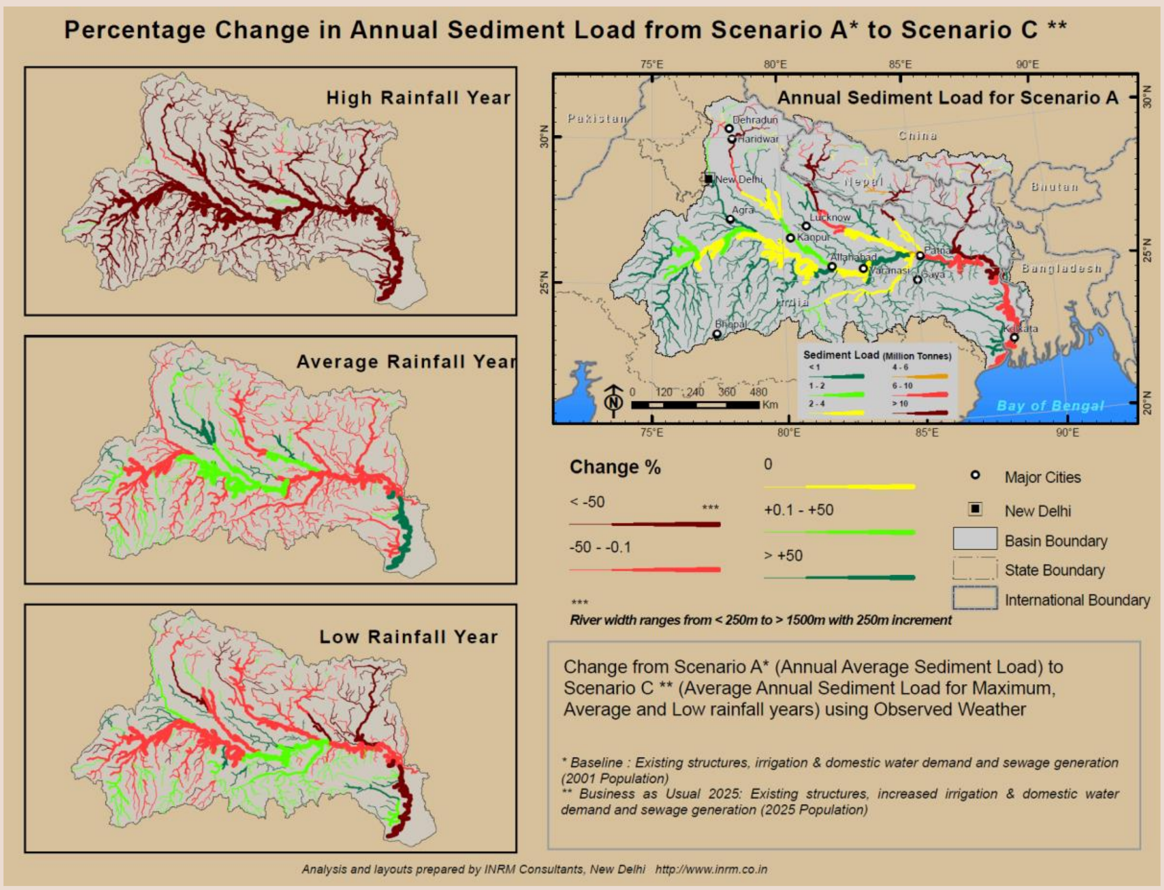



In the baseline scenario A, most of the reaches along the main step is healthy with less than 3 ppm BOD. However there are some stretches in the Upperganga, Ramganga, Yamuna and Chambal basins the BOD levels are at or higher than internationally allowed 3 ppm. Again this was annual average, any given time period it can be even higher due to low flow or no water in the river. There is also several head water reaches in almost all basins also above 3 ppm thus causing concern about the level of BOD in those stretches. When comparing the modelled BOD concentration for Scenario C with average BOD load of Scenario A, for high rainfall year the relative changes were not that significant and as expected due to high rainfall year the flow were high and thus even the increased population did not present major problem along the main ganga river. However even in high rainfall year some of the major tributaries like Ramganga, Upperganga, Kandak, Kosi, Gaghra, Tons, and Sone all experienced high BOD concentration of as much as 50% or more. This would be a major concern without regard to controlling the source of the BOD which is mainly treatment of sewer disposal to the river.

While comparing the average and low rainfall years the situation is worse with significant change as much as 100% change from the baseline scenario making even good river bodies in baseline scenario A were under water quality violation due to change in irrigation demand and increased population in the year 2025. So the urgency of cleaning the river and improving the waste water discharge becomes very crucial immediately.

Figure 24 shows the percentage change of sediment between Scenarios A and C. Under the baseline scenarios some of the river stretches goes from very high to medium or low sediment due to two reasons; either the channel is very flat thus the sediments are getting deposited or there is barrage or dams that help to filter the sediment carried by the river. This is clearly evident wherever the water is getting diverted or dams are present that less sediment is getting transported. Even otherwise the amounts of sediment from the upper reaches of Ganga especially at the foothills of Himalayas are significant due to high slopes and less vegetation.

**Figure 24: Average Annual Percent Change of Sediment load from Scenario A to C**




While comparing the simulated sediment outputs with that of the baseline scenario A and scenario C, during high rainfall year as expected the amount of sediment in the main river is greater than 50%, while it is somewhat low during average and low rainfall years as expected due to less rain and less runoff. This is even evident even in high slope and mountainous regions where the sediment is less compare to baseline scenario under low rainfall year. These results are important given the various structures that have been built-in in various tributaries of Ganges where siltation can effectively reduce the life and efficiency of the dams for irrigation or power generation

In addition to comparing average annual BOD concentration between baseline and other scenarios, BOD concentration of monsoon and non-monsoon period data (Figure 25) were also equally important. In Figure 25, for each scenario of A, C, D and E scenarios, the BOD concentrations of both monsoon and non-monsoon seasons for high, average and low rainfall years are shown. It is clearly evident from these data, that even though average annual fared well for the baseline A scenario, but looking it by season, only during the monsoon period the water quality is better along the main stem of the Ganga river. Still some of the first and second order tributaries during monsoon season still did not perform well with high BOD concentration above international safety standards of 3 ppm. During non-monsoon season the entire river reaches were shown very poor water quality, needing much required improvements of waste water treatment plants for almost all the stretches.

**Figure 25 Average monthly BOD concentration during Monsoon and non monsoon months for high, average and low rainfall year (baseline-Scenario A)**

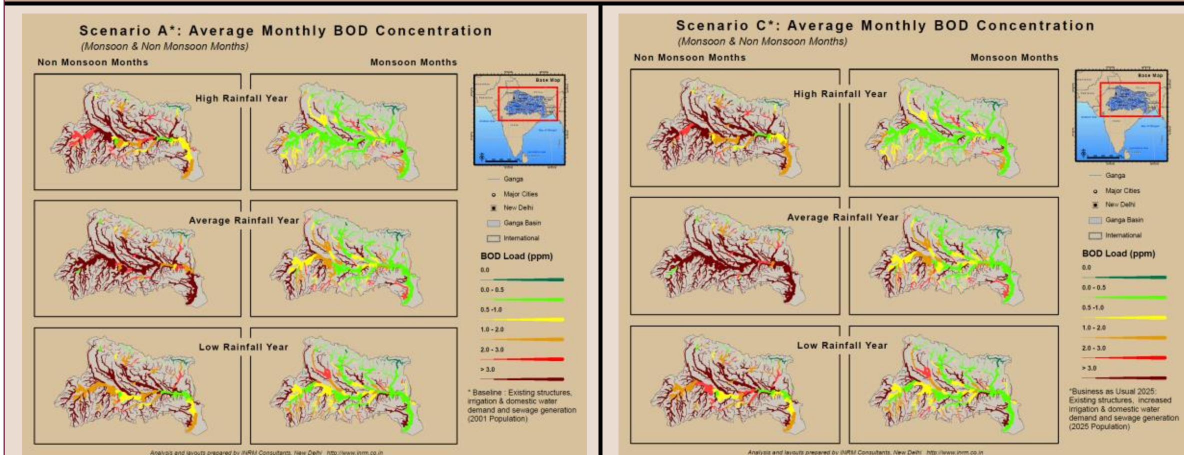
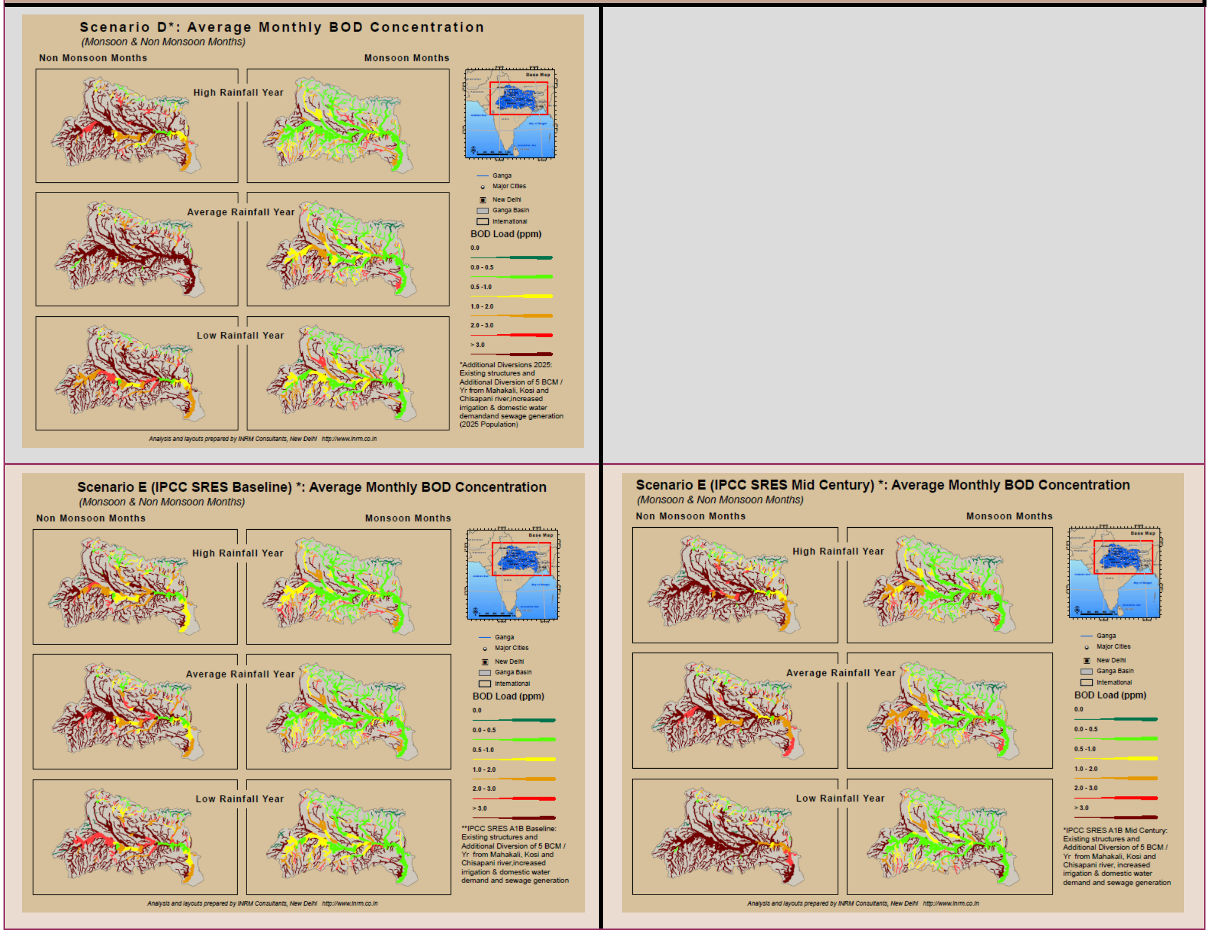


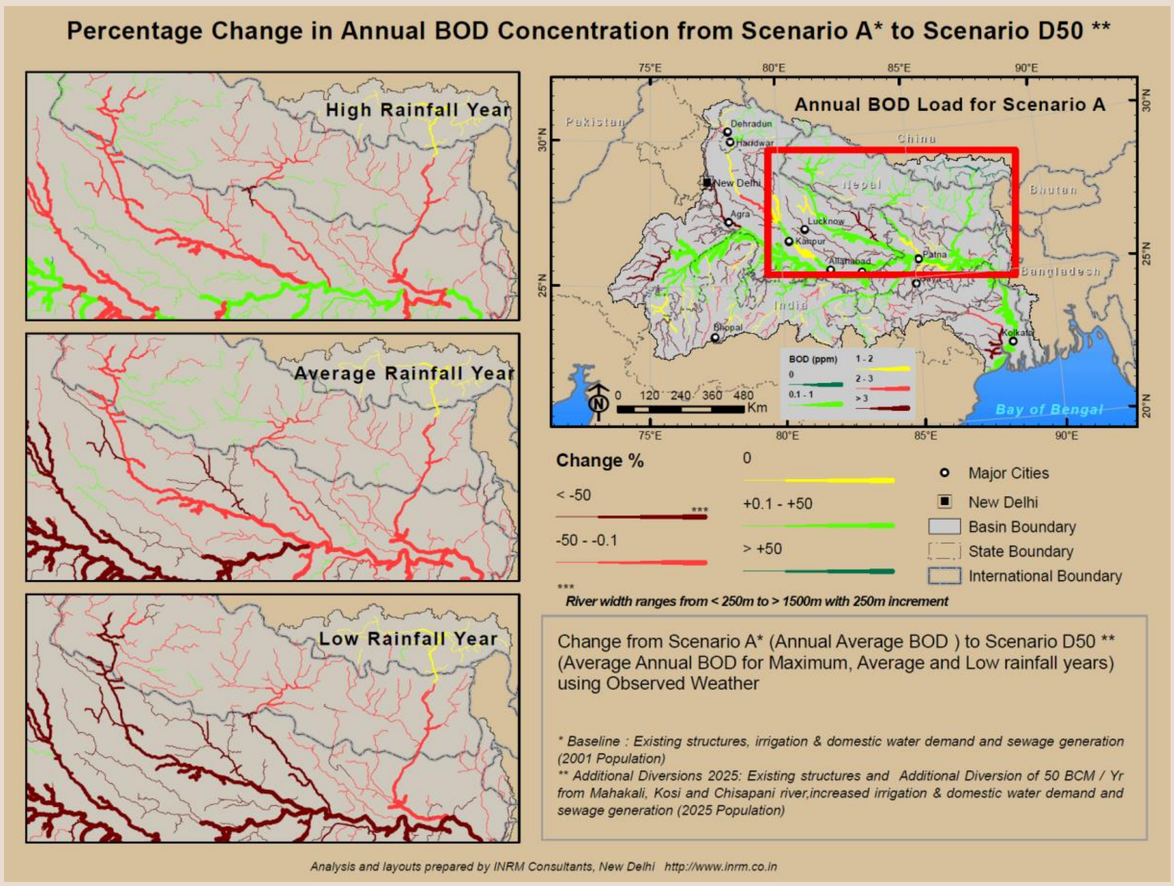
**Figure 25 Average monthly BOD concentration during Monsoon and non monsoon months for high, average and low rainfall year (baseline-Scenario A)**




The same phenomena were observed in all the scenarios and were significantly worsening in every case for both monsoon and non-monsoon seasons. So further water resources development in the Ganga basin and future anticipated climate changes becomes reality the BOD water quality will worsen which could lead into danger of poor drinking water quality and disease spread all along the Ganga basin. So prevention of raw sewage should be the top priority to control the further deterioration. In the current study, the industrial and other forms of BOD loads were not considered, so adding this additional information will only further deteriorates the situation. Additional analysis could be done either through the modelling or externally to find the allowable carrying capacity of the river at various stretches and time period to bring the water quality to safe drinking international standards.

As part of the future scenario (D50) where if all the three future water resources structures along the border of Nepal and India were realized in Kosi, Gandak (Chisapani) and Ghagra (Mahakali) rivers, the impact of removal 50 billion cubic meters per year (BCM) were diverted to irrigation and other domestic demand the impact of BOD and sediment along these river stretches are shown in Figures 26 and 27.

**Figure 26 Change (%) in Annual BOD Concentration from Scenario A to Scenario D50**

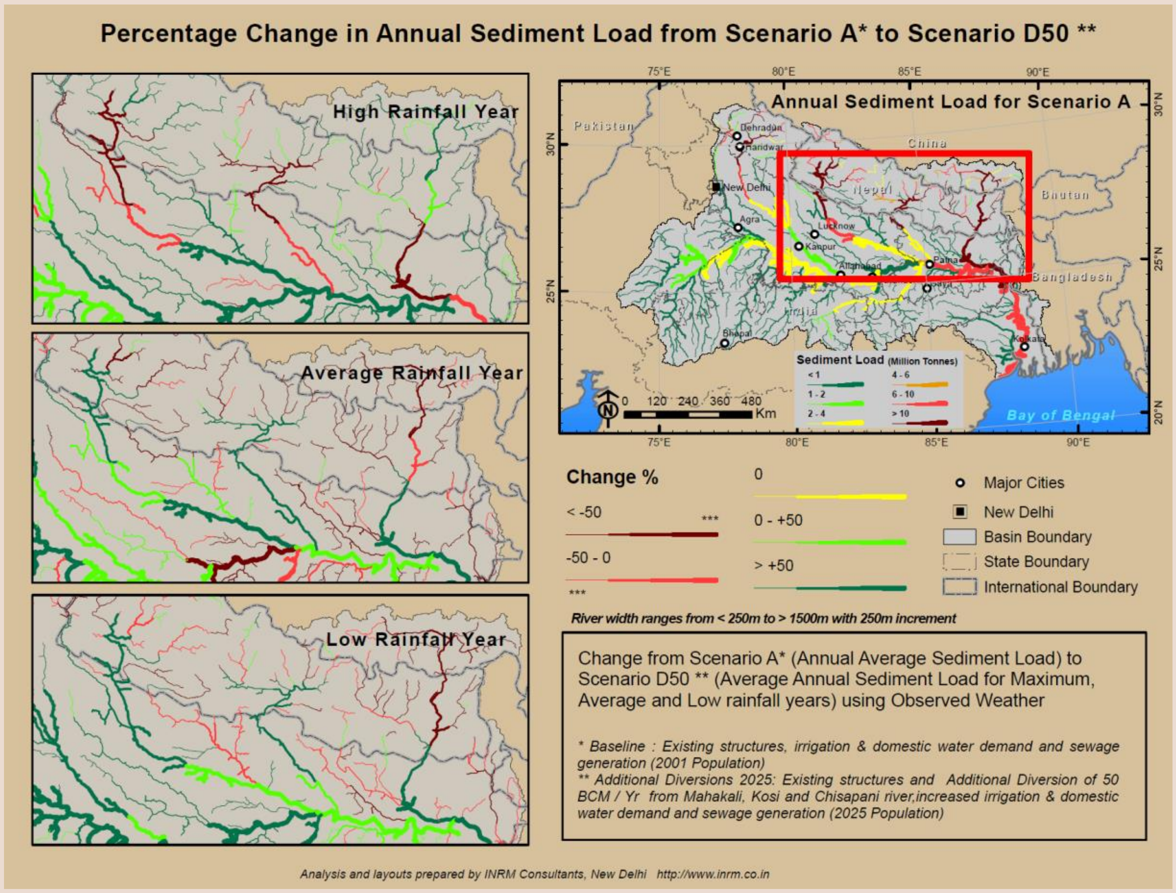



**Note: Left to right drainage: Ghagra (Mahakali), Gandak (Chisapani) and Kosi*

Future construction of dams and removal of 50BCM from these structures for water resources development in Nepal show (Figure 26) further deterioration of BOD concentrations in all the rivers under high to low rainfall year. Under low rainfall year the BOD concentration changes 50+% making the river close to 2 ppm, and thus limiting any further development in the India side of these rivers. Of course the management of the structures were not fully taken into account in this study, ie hydropower vs irrigation water supplies during non-monsoon etc. were not considered explicitly.

However as shown in Figure 27, the impact of adding three structures and removal of 50 BCM showed less sediment in the river, thus the potential for less flooding and delta formation. Again this results will depend on how much of the sediment will be retained in these structures vs let go based on the type and management of structures that were proposed to build in the three rivers.

**Figure 27 Change (%) in Annual Sediment Load from Scenario A to Scenario D50**



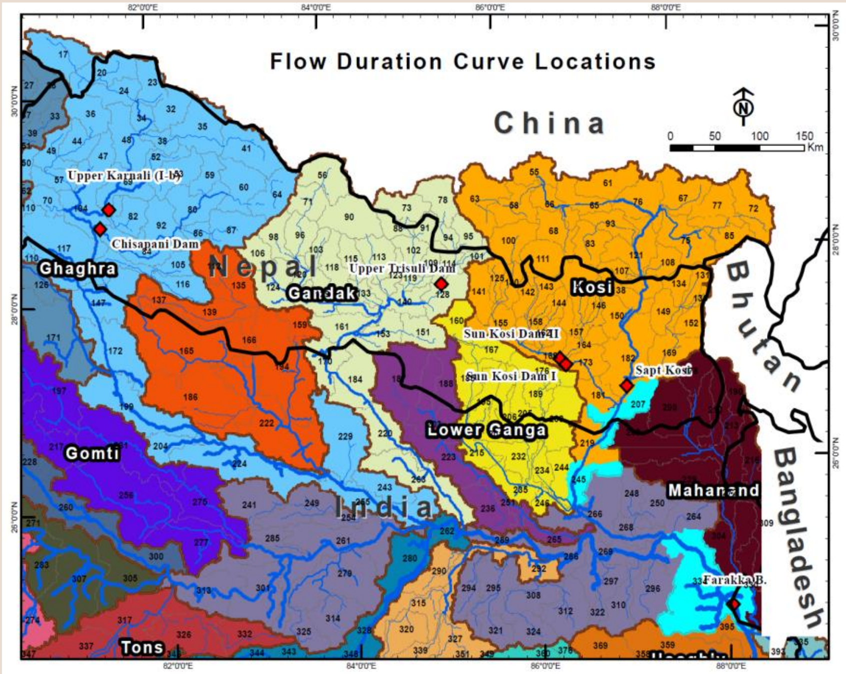

**Note: Left to right drainage: Ghagra (Mahakali), Gandak (Chisapani) and Kosi*

These positive effects were shown (Figure 27) only in the average and low rainfall year. Still the high rainfall year may not help to reduce any sediment as shown in Figure 27.

### 5.1.1. Average monthly comparisons for the Kosi at the confluence of Kosi with main Ganga with and without upstream dams in Nepal

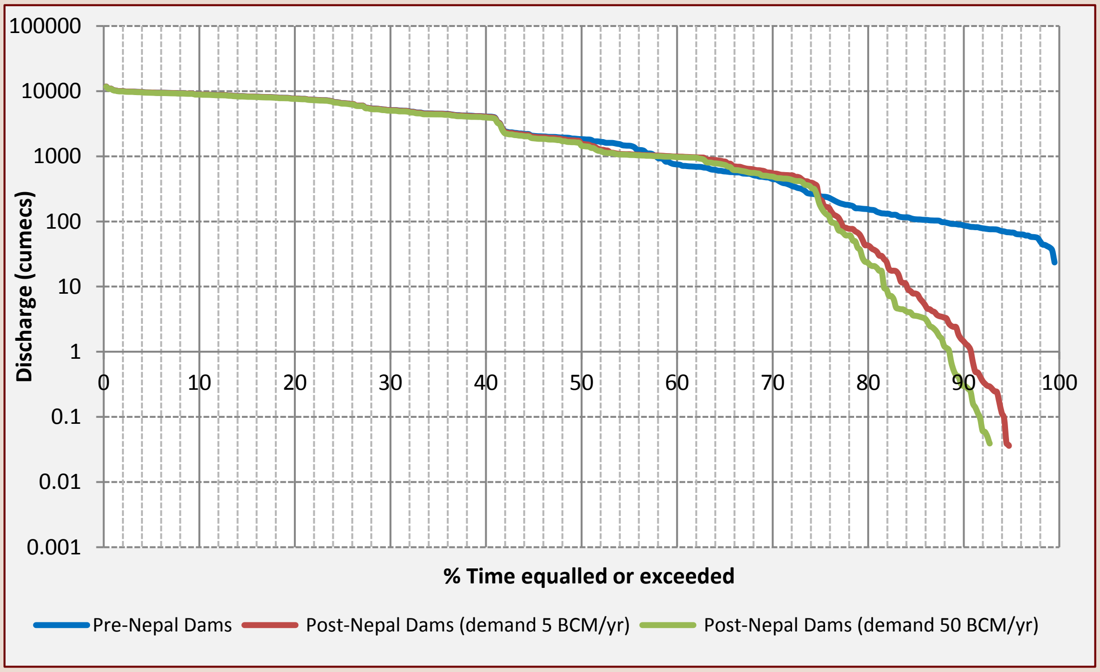
Effect of upstream reservoir on the downstream flow has been analysed as flow duration curve and mean monthly flow at three locations (a) Kosi at India Nepal Border, (b) Kosi before the confluence with main Ganga and (c) at Farakka. Figure 28 shows the locations where comparison of flow is made. Assumption were made while implementation reservoir drawdown and release were not optimized for flood prevention or irrigation water use during non-monsoon season. A non uniform target monthly release was used.

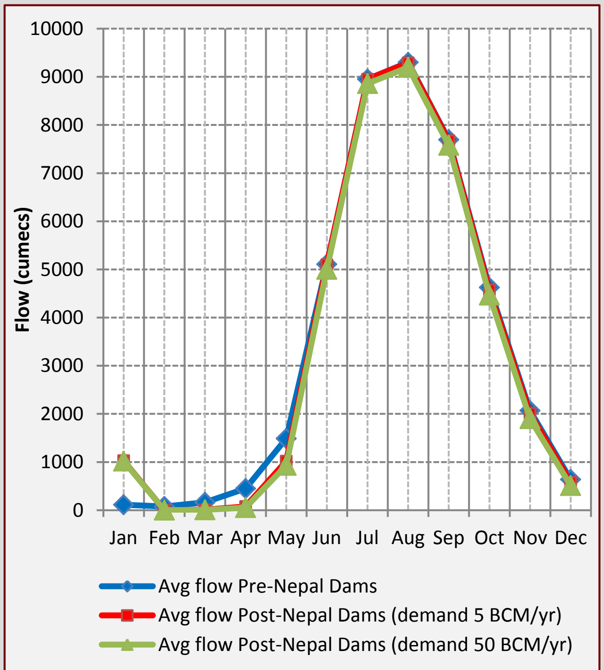
**Figure 28 Locations for comparison of flow**



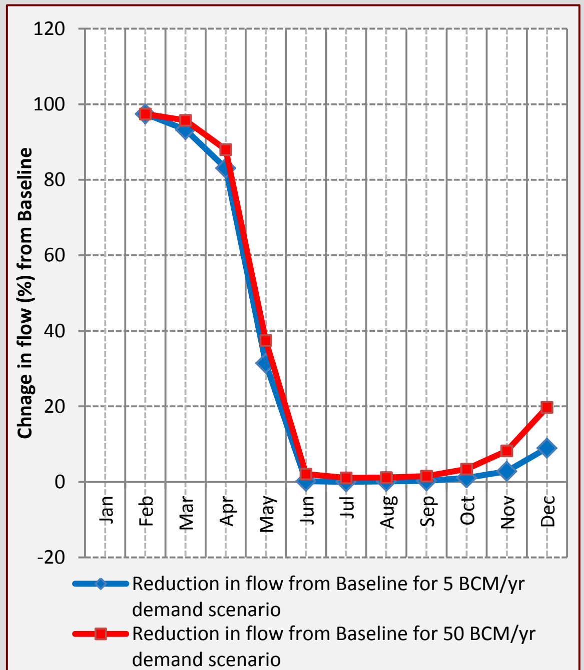

Figures 29 depict the flow duration curve and mean monthly flows on Kosi at India Nepal Border.

**Figure 29 Flow comparison on Kosi at India Nepal Border**



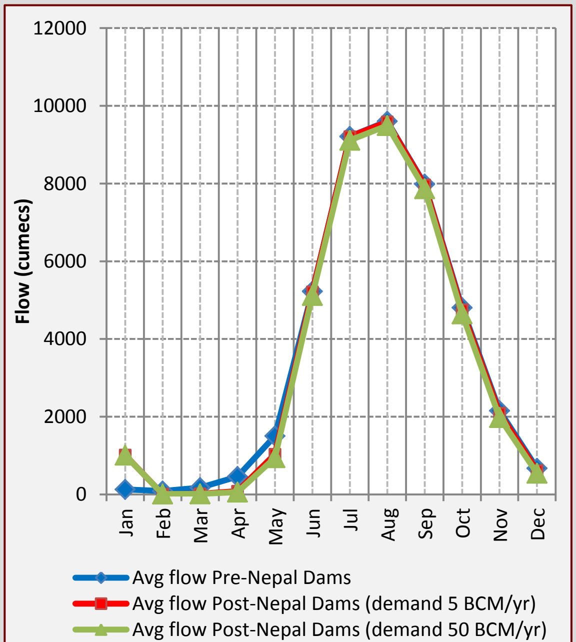



*Average Monthly Reduction in Flow at India Nepal Border due to presence of upstream dams in Nepal*

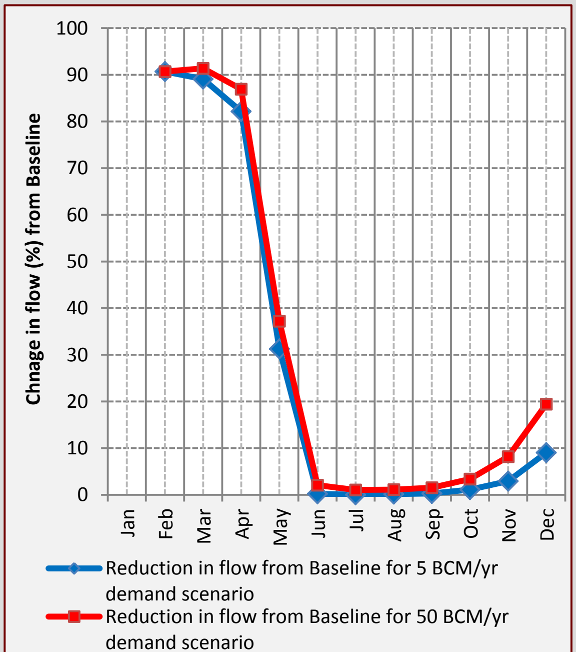



*Average Monthly Reduction in Flow at India Nepal Border due to presence of upstream dams in Nepal*

**Figure 30 Flow comparison on Kosi before the confluence with main Ganga**

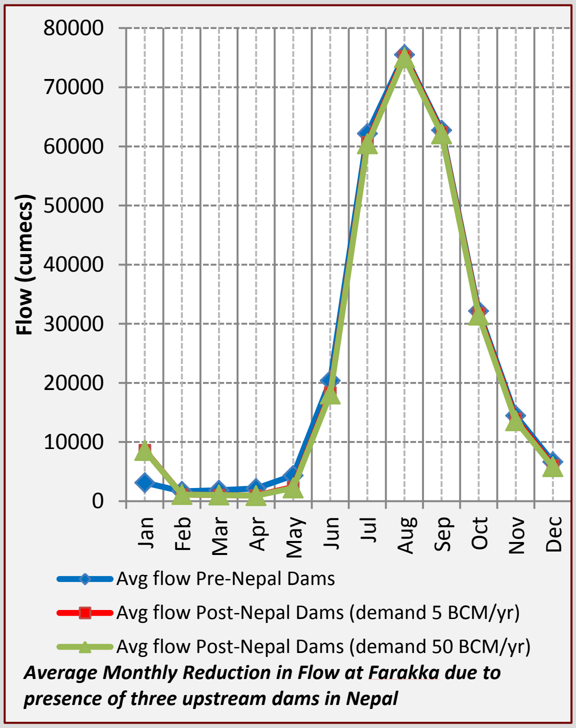


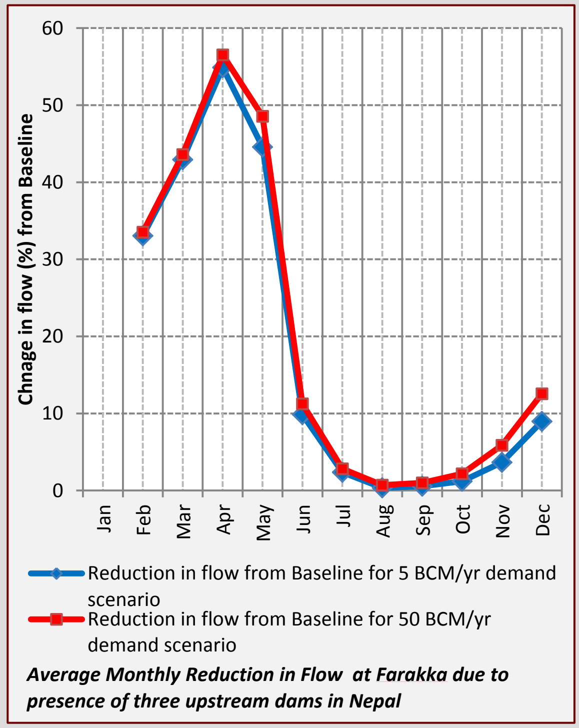

***Average Monthly Reduction in Flow in Kosi due to presence of upstream dams in Nepal***




***Average Monthly Reduction in Flow in Kosi due to presence of upstream dams in Nepal***

## Figure 31 Flow comparison at Farakka




It can be observed form Figures 29, 30 and 31 that there is a reduction in low flow due to presence of dams/reservoirs upstream of Kosi in Nepal with 2 demand scenarios of 5 BCM/yr and 50 BCM/yr from these reservoirs and similar reduction is observed at Farakka.

Scenario E was implemented using the IPCC SRES A1B scenario (Appendix II) weather outputs for the hydrological model SWAT. The current study uses the conditions under the PRECIS[28] A1B, which is a mid path scenario, a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies, with the development balanced across energy sources. The details of the scenario used are: A1B baseline (1961–1990) and mid century (2021-2050) derived using Q14 QUMP (Quantifying Uncertainty in Model Predictions).

[28] PRECIS (Providing Regional Climate for Impact Studies) is the Hadley Centre portable regional climate model, developed to run on a PC with a grid resolution of 0.44° x 0.44°. PRECIS simulation datasets is provided by the Indian Institute of Tropical Meteorology, Pune

**Figure 32 Change (%) in Annual BOD Concentration from IPCC SRES A1B scenario Baseline to IPCC SRES A1B scenario Mid Century**

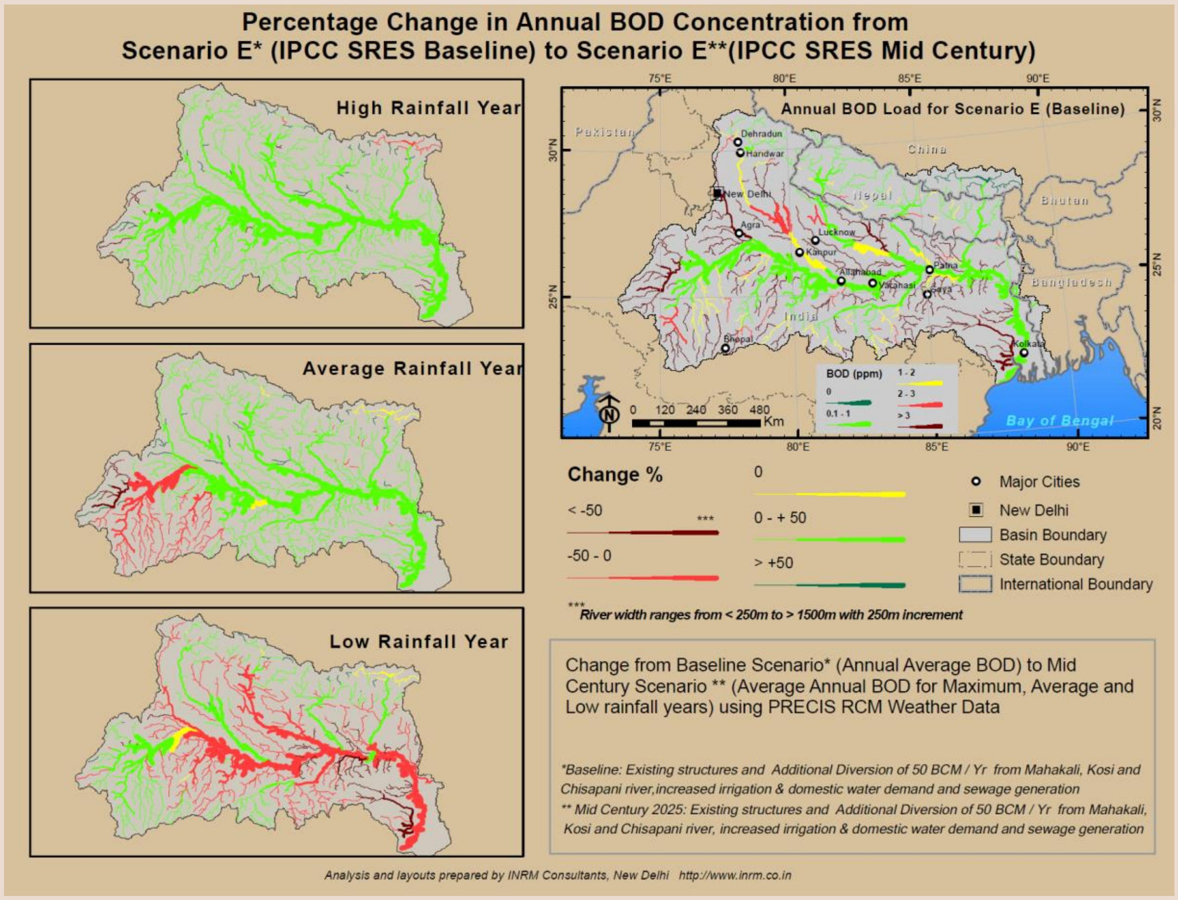
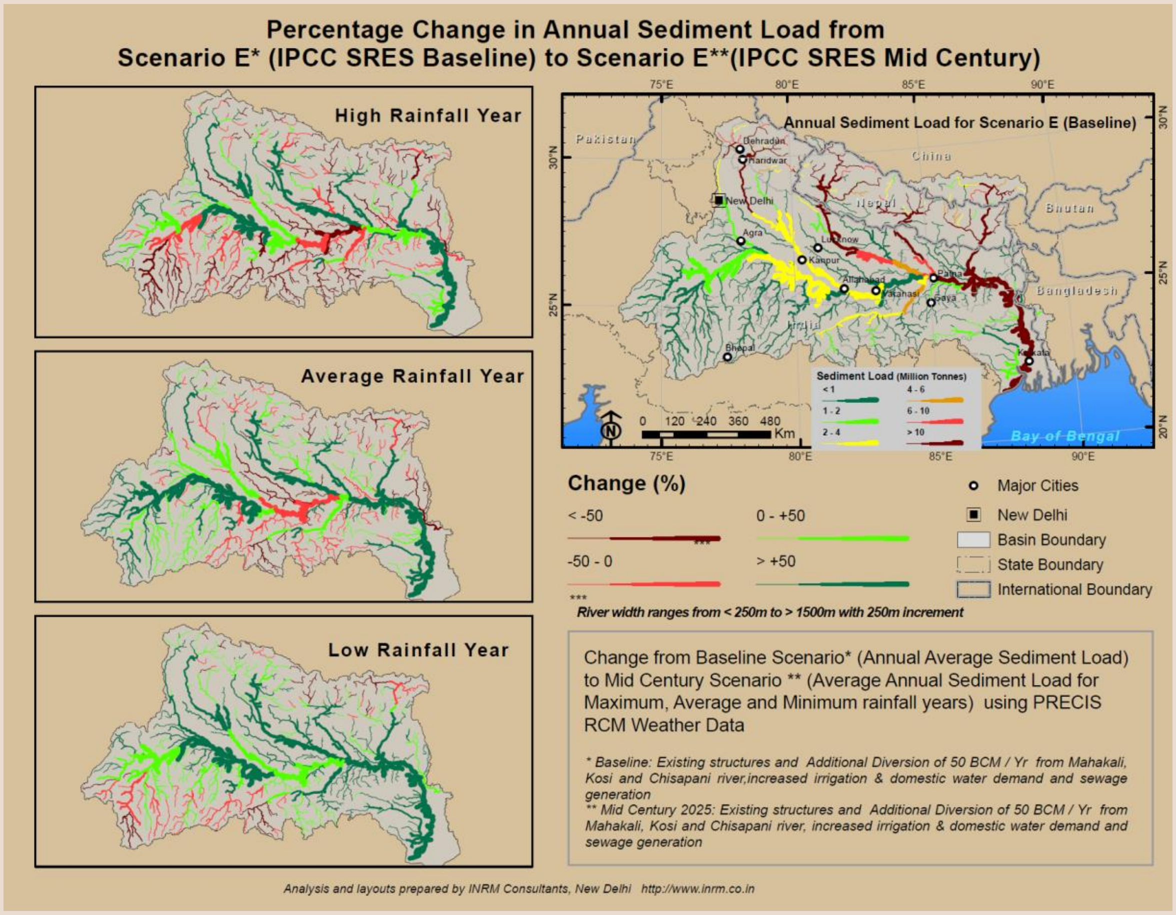



Figure 32 shows the change in annual BOD concentration from climate change baseline to mid century scenario. Climate change baseline was run with the same setup as current baseline (Scenario A) except for the daily weather data. It can be seen that in future the high rainfall years get higher rainfall than the baseline which in turn improves water quality, however, Chambal basin shows deterioration for average rainfall years in future as compared to the baseline and rest of the basin show deterioration in the low rainfall years.

Sediment load increases in future due to increase in intensity and magnitude of rainfall towards mid century (Figure 33).

**Figure 33 Change (%) in Annual Sediment Load from IPCC SRES A1B scenario Baseline to IPCC SRES A1B scenario Mid Century**



# 6. Limitations of the Study and Future Prospects

## 6.1. Assumptions

A few assumptions were made for running the scenarios using the hydrological model for the Ganga basin. The following major decisions/assumptions have been made while formulating these scenarios:

- Although there are around 206 dams/reservoirs available in the basin, only 104 structures were implemented since these were the structures with available data on the area, capacity and starting year of operation
- In the absence of the data on major canal diversions, irrigation water use as proxy was computed and used
- Current crop management practices (irrigation from Surface and Ground water) based on landuse map, irrigation source map, command area map and district-wise average irrigation (by source) information was used
- In order to incorporate the future irrigation demand, additional water demand has been calculated using agriculture demand increase for the projected population
- Point source of domestic pollution has been computed by using average BOD and the average sewer generation per capita. Consumption/Capita (l/c/d) is taken as 123.3 (ADB 2007[29]) and 80% is taken as sewage return. Per capita BOD (gBOD/day) based on 2001 population census is taken as 40.5[30]
- The future BOD load has been calculated based on future water demand using population projection[31].
- No change in future landuse.

## 6.2. Data Limitations

- Lack of detailed data on:
- Soils: Absence of high resolution Indian soil map and soil profiles
- Landuse: Absence of high resolution Indian landuse specially the cropping pattern map
- Weather data: Actual observed station data on rainfall, temperature at daily scale, absence of high altitude weather station locations, spatial distribution issues to address the spatial variability of weather parameters, use of weather generator for

[29] http://www.adb.org/documents/reports/Benchmarking-DataBook/default.asp

[30] http://moef.nic.in/downloads/others/M%20Karthik.pdf

[31] Census of India 2001, Population Projections for India and States 2001-2026, Report of the Technical Group on Population Projections Constituted by the National Commission on Population, May 2006, http://nrhm-mis.nic.in/UI/Public%20Periodic/Population_Projection_Report_2006.pdf

generating weather parameters of wind speed, relative humidity etc. Absence to weather data in Nepal, Tibet

- Water diversion: Canal command area, canal network, time series canal diversions and discharges
- Point sources location, load, type of pollutants
- Snow and Glacier: assumption on elevation bands on where is the snow and glacier and initial glacier depth, depth and spread of glacier, precipitation and temperature lapse rates to represent the orographic effect
- Ground Water: initial depth of shallow and deep aquifer.
- Irrigation assumptions on the source and amount of irrigation, cropping pattern

## 6.3. Model limitations

- Initialization of various model input parameters such as initial soil nutrient levels, soil moisture, groundwater levels, residue, specific crop growth parameters and related databases have uncertainties. Most of these parameters were initialized by running the model warm-up or setup period for five years to bring the model to an equilibrium stage.
- Due to the size of the subbasins the climatic data were interpolated to assign one weather station per subbasin, where the model assumes uniform input for the entire subbasin. However everyone knows the weather is very dynamic in spatial and temporally scales. This could add to uncertainties to model inputs and thus model predictions and outputs.
- In the current SWAT 2009 model, only basin level snow melt parameters are available, however it is understood that the snow process simulations are very complex and highly spatially variable taking into account of slope, depth of snow, aspect, location of snow line and initialization of glacier depth.
- The exact specific irrigation sources, amounts and frequencies for specific crop is not known throughout the basin, hence data available from various sources were compiled and used as average irrigation schedules across the basin.
- Fertilizer and manure applications were also quite different over the space, due to lack of information SWAT model automatic fertilizer option was used in some of the subbasins and crops, then in the other areas where data were available the typical application date and amount were used.
- Reuse of the water from irrigation was not totally captured in the upstream/downstream irrigation schemes, which is a difficult process to capture at the basin scale modelling and required very detailed inputs and irrigation command area which were not available at the Ganga basin scale levels.
- No observed data were available inside India for any detailed calibration or validation, hence significant portion of the basin was not validated, but, where ever the data were available especially in Nepal and India border, the model was verified and agreed well.

## 6.4. Future Studies

- The model was able to represent the snow melt process reasonably well despite using one set of parameters for the entire basin. A new model has been in the process of development where the snow parameters can be adjusted by subbasin and by elevation bands along with glacier and snow depths. This gives great flexibility to simulate the snow processes in detail and able to accurately account for the streamflow generated by snow processes and also estimate snow melt and glacier melt separately and quantify the glacier depth overtime. One of the greatest threats in the Ganga basin is availability of fresh water from the glacier and snow melt under current and future climate change conditions. There is always an expectation in the scientific community that glacier will be melted away in the next 100 to 200 years under climate change conditions, however no one has clearly documented the level of impact or average thickness of glacier loss under current and future conditions. This is very important in Ganga basin as this will affect more than 300 million population and agriculture livelihood. In addition, it is anticipated the climate change will accelerate the glacier melt process in the near future increasing the flooding threat more so in already flood savage areas in Ganga basin. However, at a later date, due to less snow and glacier melt, the fresh water availability and storage will be less for agriculture which can turn the area into frequent drought prone area due to monsoon dependability like elsewhere in India due to lack of storage like Himalayas in other parts of India. So studying the upper part of Ganga above 3000m is very important in detail under current and future conditions to assess the impact of snow/glacier melt as well as understand the consequences and develop adaptation strategies of frequent flood and drought cycles. In addition, this permanent contribution has implication of linking rivers project that are planned from north to south in India.
- We are in the process of obtaining detailed monitoring data at various main stem location of Ganga, it is important that the water quality impact is studied in detail using actual data instead of typical pollution and treated water as assumed in this study. It may be difficult to study the entire Ganga due to the size and non-uniform availability of data, however a small stretch or section of the main or tributaries can be undertaken for more detailed study to look at the impact of urban, agricultural and industrial pollutions and mitigation strategies.
- In the current study detailed water diversions were not introduced, this is very important to assess the availability of water downstream as most water from the main stem of the river gets diverted. Given the time and resources, the data can be collected and more realistic diversions inputs can be incorporated in the entire Ganga model to simulate its effect on water quantity and quality under current and future (including climate change scenarios). These diversions are considered to be one of the most important factors for the water quality problems during non-monsoon seasons. With the limited data input in the current study it has been clearly documented under current and future scenarios the water quality is getting

worse due to non-flowing rivers or very little baseflow in the Ganga and its tributaries.

# Appendix I

The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998, Neitsch et al., 2002) is a distributed parameter and continuous time simulation model. The SWAT model has been developed to predict the response to natural inputs as well as the manmade interventions on water and sediment yields in un-gauged catchments. The model (a) is physically based; (b) uses readily available inputs; (c) is computationally efficient to operate and (d) is continuous time and capable of simulating long periods for computing the effects of management changes. The major advantage of the SWAT model is that unlike the other conventional conceptual simulation models it does not require much calibration and therefore can be used on ungauged watersheds (in fact the usual situation).

The SWAT model is a long-term, continuous model for watershed simulation. It operates on a daily time step and is designed to predict the impact of management on water, sediment, and agricultural chemical yields. The model is physically based, computationally efficient, and capable of simulating a high level of spatial details by allowing the watershed to be divided into a large number of subwatersheds. Major model components include weather, hydrology, soil temperature, plant growth, nutrients, pesticides, and land management. The model has been validated for several watersheds.

## *Distributed Behaviour of the SWAT model*

SWAT allows a number of different physical processes to be simulated in a watershed. For modeling purposes, a watershed may be partitioned into a number of sub-watersheds or sub-basins. The use of sub-watersheds in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils different enough in properties to impact hydrology. By partitioning the watershed into sub-watersheds, the user is able to relate different areas of the watershed to one another spatially.

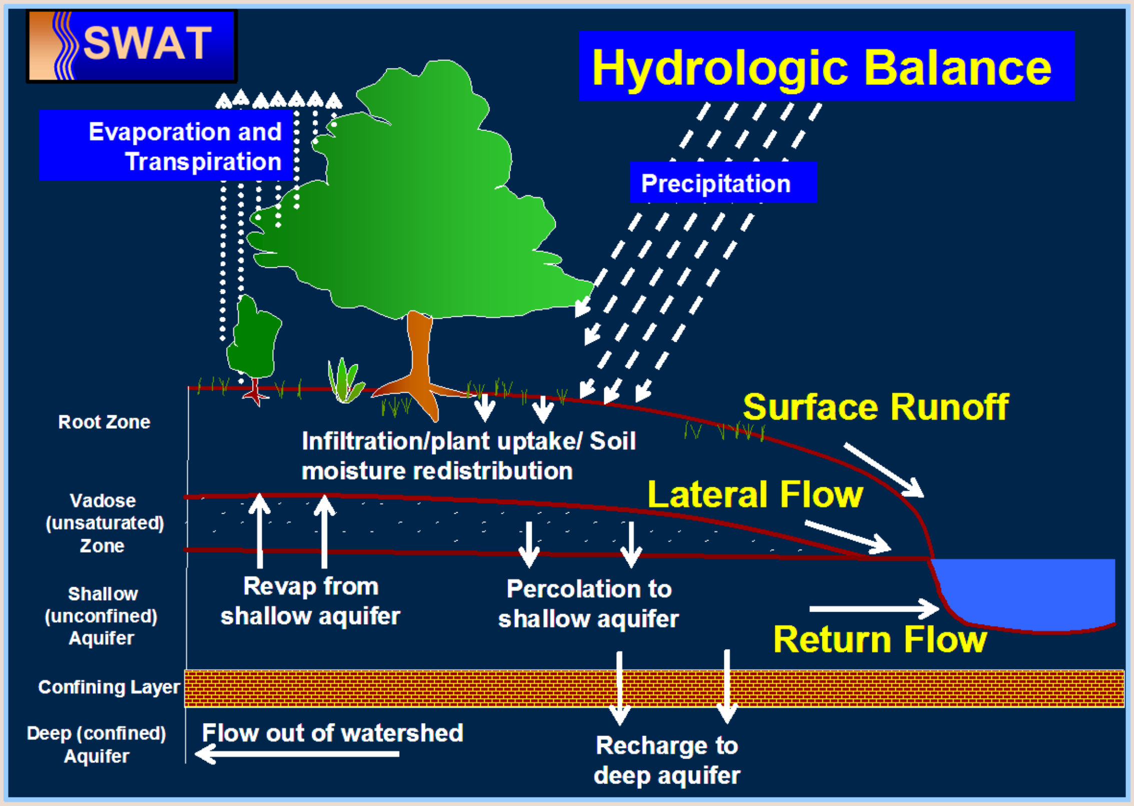
Input information for each sub-watershed can further be subdivided into unique areas of land cover, soil, and management within the sub-watersheds (known as hydrologic response units or HRUs). This facility provides complete distributed behaviour to the model.

No matter what type of problem is studied with SWAT, water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of water, sediments or nutrients, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed.

## *Brief Theoretical Basis of the SWAT model*

In the SWAT model, simulation of the hydrology of a watershed can be separated into two major segments. The first segment is the land phase of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-watershed. The second segment is the routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet. Figure i depicts the major processes modelled in SWAT.

**Figure i Processes modelled by SWAT Hydrological model**




## *Landphase of the Hydrologic Cycle*

As precipitation descends, it may be intercepted and held in the vegetation canopy or fall on the soil surface. Water on the soil surface will infiltrate into the soil profile or flow overland as runoff. Runoff moves relatively quickly toward a stream channel and contributes to short-term stream response. Infiltrated water may be held in the soil and later evapotranspired or it may slowly make its way to the surface-water system via underground paths.

***Canopy Storage*** Canopy storage is the water intercepted by vegetative surfaces (the canopy) where it is held and made available for evaporation. When using the curve number method to compute surface runoff, canopy storage is taken into account in the surface runoff calculations. However, if methods such as Green & Ampt are used to model infiltration and runoff, canopy storage must be modeled separately. SWAT allows the user to input the maximum amount of water which can be stored in the canopy at the maximum leaf area index for the land cover. This value and the leaf area index are used by the model to compute the maximum storage at any time in the growth cycle of the land cover/crop. When evaporation is computed, water is first removed from canopy storage.

***Infiltration:*** Infiltration refers to the entry of water into a soil profile from the soil surface. As infiltration continues, the soil becomes increasingly wet, causing the rate of infiltration to decrease with time until it reaches a steady value. The initial rate of infiltration depends on the moisture content of the soil prior to the introduction of water at the soil surface. The final rate of infiltration is equivalent to the saturated hydraulic conductivity of the soil.

***Redistribution:*** Redistribution refers to the continued movement of water through a soil profile after input of water (via precipitation or irrigation) has ceased at the soil surface. Redistribution is caused by differences in water content in the profile. Once the water content throughout the entire profile is uniform, redistribution will cease. The redistribution component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow, or percolation, occurs when field capacity of a soil layer is exceeded and the layer below is not saturated. The flow rate is governed by the saturated conductivity of the soil layer. Movement of water from a subsurface layer to an adjoining upper layer may occur when the water content of the lower layer exceeds field capacity. The soil water to field capacity ratios of the two layers regulates the upward movement of water. Redistribution is also affected by soil temperature. If the temperature in a particular layer is $^{0}$C or lower, no redistribution is allowed from that layer.

***Evapotranspiration:*** Evapotranspiration is a collective term for all processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. Evapotranspiration includes evaporation from rivers and lakes, bare soil, and vegetative surfaces; evaporation from within the leaves of plants (transpiration); and sublimation from ice and snow surfaces. The model computes evaporation from soils and plants separately as described by Ritchie[32] (1972). Potential soil water evaporation is estimated as a function of potential evapotranspiration and leaf area index. Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant transpiration is simulated as a linear function of potential evapotranspiration and leaf area index.

***Potential Evapotranspiration:*** Potential evapotranspiration is the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation which has access to an unlimited supply of soil water. This rate is assumed to be unaffected by micro-climatic processes such as advection or heat-storage

[32] Ritchie, J.T. 1972. A model for predicting evaporation from a row crop with incomplete cover. Water Resour. Res. 8:1204-1213.

effects. The model offers three options for estimating potential evapotranspiration: Hargreaves (Hargreaves and Samani[33], 1985), Priestley-Taylor (Priestley and Taylor[34], 1972), and Penman-Monteith (Monteith[35], 1965).

***Lateral Subsurface*** Flow: Lateral subsurface flow, or interflow, is streamflow contribution which originates below the surface but emerges above the zone where rocks are saturated with water. Lateral subsurface flow in the soil profile (0-2m) is calculated simultaneously with redistribution. A kinematic storage model is used to predict lateral flow in each soil layer. The model accounts for variation in conductivity, slope and soil water content. It also allows for flow upward to an adjacent layer or to the surface.

***Surface Runoff:*** Surface runoff, or overland flow, is flow that occurs along a sloping surface. Using daily rainfall amounts, SWAT simulates surface runoff volumes and peak runoff rates for each HRU.

Surface runoff volume is computed using a modification of the SCS curve number method (USDA Soil Conservation Service[36], 1972). The curve number varies non-linearly with the moisture content of the soil. The curve number drops as the soil approaches the wilting point and increases to near 100 as the soil approaches saturation. SWAT includes a provision for estimating runoff from frozen soil where a soil is defined as frozen if the temperature in the second soil layer is less than 0°C. The model increases runoff for frozen soils but still allows significant infiltration when the frozen soils dry up.

***Peak runoff rate:*** predictions are made with a modification of the rational method. In brief, the rational method is based on the idea that if a rainfall of intensity i begins instantaneously and continues indefinitely, the rate of runoff will increase until the time of concentration, tc, when all of the sub-basin is contributing to flow at the outlet. In the modified Rational Formula, the peak runoff rate is a function of the proportion of daily precipitation that falls during the time of concentration of the subbasin tc, and the daily surface runoff volume. The proportion of rainfall occurring during the subbasin tc is estimated as a function of total daily rainfall using a stochastic technique. The subbasin time of concentration is estimated using Manning's Formula considering both overland and channel flow.

***Ponds/Tanks***: Ponds/Tanks are water storage structures located within a subbasin which intercept surface runoff. The catchment area of a pond is defined as a fraction of the total area of the subbasin. When the catchment area fraction is equal to 1.00, the pond is

[33] Hargreaves, G.H. and Z.A. Samani. 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1:96-99.

[34] Priestley, C.H.B. and R.J. Taylor. 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100:81-92.

[35] Monteith, J.L. 1965. Evaporation and the environment. p. 205-234. In The state and movement of water in living organisms. 19th Symposia of the Society for Experimental Biology. Cambridge Univ. Press, London, U.K.

[36] USDA Soil Conservation Service. 1972. National Engineering Handbook Section 4 Hydrology, Chapters 4-10.

assumed to be located at the outlet of the subbasin on the main channel. If the catchment area fraction is less than 1.00, the pond is assumed to be located on a minor tributary within the subbasin. Pond water storage is a function of pond capacity, daily inflows and outflows, seepage and evaporation. Ponds are assumed to have only emergency spillways. Required inputs are the storage capacity and surface area of the pond when filled to capacity. Surface area below capacity is estimated as a non-linear function of storage.

***Tributary Channels:*** Two types of channels are defined within a subbasin: the main channel and tributary channels. Tributary channels are minor or lower order channels branching off the main channel within the subbasin. Each tributary channel within a subbasin drains only a portion of the subbasin and does not receive groundwater contribution to its flow. All flow in the tributary channels is released and routed through the main channel of the subbasin.

***Transmission Losses:*** Transmission losses are losses of surface flow via leaching through the streambed. This type of loss occurs in ephemeral or intermittent streams where groundwater contribution occurs only at certain times of the year, or not at all. SWAT uses Lane's method (USDA Soil Conservation Service[37], 1983) to estimate transmission losses. Water losses from the channel are a function of channel width and length and flow duration. Both runoff volume and peak rate are adjusted when transmission losses occur in tributary channels. Return Flow Return flow, or base flow, is the volume of stream flow originating from groundwater. SWAT partitions groundwater into two aquifer systems: a shallow, unconfined aquifer which contributes return flow to streams within the watershed and a deep, confined aquifer which contributes return flow to streams outside the watershed (Arnold et al.[38], 1993). Water percolating past the bottom of the root zone is partitioned into two fractions—each fraction becomes recharge for one of the aquifers. In addition to return flow, water stored in the shallow aquifer may replenish moisture in the soil profile in very dry conditions or be directly removed by plant uptake (only trees may uptake water from the shallow aquifer). Water in the shallow aquifer may also seep into the deep aquifer or be removed by pumping. Water in the deep aquifer may be removed by pumping.

***Land Cover/Plant Growth:*** SWAT utilizes a single plant growth model to simulate all types of land covers. The model is able to differentiate between annual and perennial plants. Annual plants grow from the planting date to the harvest date or until the accumulated heat units equal the potential heat units for the plant. Perennial plants maintain their root systems throughout the year, becoming dormant after frost. They resume growth when the average daily air temperature exceeds the minimum, or base temperature required. The plant growth model is used to assess removal of water and nutrients from the root zone, transpiration, and biomass/yield production.

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[37] USDA Soil Conservation Service. 1983. National Engineering Handbook Section 4 Hydrology, Chapter 19.

[38] Arnold, J.G., P.M. Allen, and G. Bernhardt. 1993. A comprehensive surface-groundwater flow model. J. Hydrol. 142:47-69.

***Potential Growth:*** The potential increase in plant biomass on a given day is defined as the increase in biomass under ideal growing conditions. The potential increase in biomass for a day is a function of intercepted energy and the plant's efficiency in converting energy to biomass. Energy interception is estimated as a function of solar radiation and the plant's leaf area index.

***Erosion:*** Erosion and sediment yield are estimated for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams[39], 1975). While the USLE uses rainfall as an indicator of erosive energy, MUSLE uses the amount of runoff to simulate erosion and sediment yield. The substitution results in a number of benefits: the prediction accuracy of the model is increased, the need for a delivery ratio is eliminated, and single storm estimates of sediment yields can be calculated. The hydrology model supplies estimates of runoff volume and peak runoff rate which, with the subbasin area, are used to calculate the runoff erosive energy variable. The crop management factor is recalculated every day that runoff occurs. It is a function of above-ground biomass, residue on the soil surface, and the minimum C factor for the plant. Other factors of the erosion equation are evaluated as described by Wischmeier and Smith[40](1978).

***Management Practices:*** SWAT model allows the user to define management practices taking place in every HRU. The user may define the beginning and the ending of the growing season, specify timing and amounts of fertilizer, pesticide and irrigation applications as well as timing of tillage operations. At the end of the growing season, the biomass may be removed from the HRU as yield or placed on the surface as residue.

In addition to these basic management practices, operations such as grazing, automated fertilizer and water applications, and incorporation of every conceivable management option for water use are available. The latest improvement to land management is the incorporation of routines to calculate sediment and nutrient loadings from urban areas.

***Crop Rotations:*** The dictionary defines a rotation as the growing of different crops in succession in one field, usually in a regular sequence. A rotation in SWAT refers to a change in management practices from one year to the next. There is no limit to the number of years of different management operations specified in a rotation. SWAT also does not limit the number of land cover/crops grown within one year in the HRU. However, only one land cover can be growing at any one time.

***Water Use:*** The two most typical uses of water are for application to agricultural lands or use as a town's water supply. SWAT allows water to be applied on an HRU from any water source within or outside the watershed. Water may also be transferred between reservoirs, reaches and subbasins as well as exported from the watershed.

## *Routing Phase of the Hydrologic Cycle*

[39] Williams, J.R. 1975. Sediment routing for agricultural watersheds. Water Resour. Bull. 11(5):965-974.

[40] Wischmeier, W.H., and D.D. Smith. 1978. Predicting rainfall losses: A guide to conservation planning. USDA Agricultural Handbook No. 537. U.S. Gov. Print. Office, Washington, D. C.

Once SWAT determines the loadings of water, sediment, nutrients and pesticides to the main channel, the loadings are routed through the stream network of the watershed using a command structure similar to that of HYMO (Williams and Hann[41], 1972). In addition to keeping track of mass flow in the channel, SWAT models the transformation of chemicals in the stream and streambed.

### *Snow simulation in SWAT*

Snowfall-snowmelt process has great impact on hydrologic simulation. SWAT classifies precipitation as rain or freezing rain/snow using the average daily temperature.

Snow cover module in SWAT allows non-uniform cover due to shading, drifting, topography and land cover by defining a threshold snow depth above which snow coverage will always extend over 100% of the area. As the snow depth in sub-basin decreases below this value, the snow coverage is allowed to decline non-linearly based on an areal depletion curve. Snow melt is controlled by the air and snow pack temperature, the melting rate, and the areal coverage of snow. If snow is present, it is melted on days when the maximum temperature exceeds 00C using a linear function of the difference between the average snow pack maximum air temperature and the base or threshold temperature for snow melt. Melted snow is treated the same as rainfall for estimating runoff and percolation. For snow melt, rainfall energy is set to zero and the peak runoff rate is estimated assuming uniformly melted snow for 24 hour duration. SWAT allows the subbasin to be split into a maximum of ten elevation bands. Snow cover and snow melt are simulated separately for each elevation band. By dividing the subbasin into elevation bands, the model is able to assess the differences in snow cover and snow melt caused by orographic variation in precipitation and temperature. Soil temperature impacts water movement and the decay rate of residue in the soil. Daily average soil temperature is calculated at the soil surface and the center of each soil layer. The temperature of the soil surface is a function of snow cover, plant cover and residue cover, the bare soil surface temperature, and the previous day’s soil surface temperature. The temperature of a soil layer is a function of the surface temperature, mean annual air temperature and the depth in the soil at which variation in temperature due to changes in climatic conditions no longer occurs. This depth, referred to as the damping depth, is dependent upon the bulk density and the soil water content. More detailed descriptions of the model can be found in Arnold et al. 1998.

The SWAT model is available with various interfaces, such as DOS, GRASS, ArcView, and ArcGIS. The most versatile is ArcSWAT interface on ArcGIS and the same has been used in the present study.

[41] Williams, J.R. and R.W. Hann. 1972. HYMO, a problem-oriented computer language for building hydrologic models. Water Resour. Res. 8(1):79-85.

## *Brief Description of ArcSWAT Interface*

This interface is created to facilitate pre-processing before running of the SWAT model and is known as ArcSWAT. The model requires a large amount of formatted inputs to be generated. The pre-processor is incorporated to handle all the inputs and also to graphically represent the model outputs after successful run of the model, as a post processing activity. The ArcSWAT interface consists of three segments, main interface, a pre processor and a post processor (Winchell[42] et. al., 2007)

The Main Interface - handles creating new swat project, opening an existing project, copying an existing project, deleting an existing project.

The Pre processor - is the backbone of the interface. SWAT model (run from executable file) requires extensive input files in their respective formats. Pre processor helps the user in creating the same in a user friendly way. The basic input required is the Digital Elevation Model (DEM) for the area under consideration. Pre processor generates the Stream Network, identifies the outlet points for a given threshold value, delineates the main watershed and sub watersheds within it, if desired. Watershed characteristics like area, slope, perimeter and channel characteristics are also calculated. Land use and soil grids are then overlaid and the basic modeling units are extracted. The other input files (soil, water use, management practices, pesticide, water quality etc.) for each subbasins are written. Default values are used in many files, which could be modified using the EDIT FILES menu. The sequence of input data creation is well followed using the enable/disabled menu item. SWAT model is run using SWAT RUN menu.

Post – Processor - Reads the results of the simulation run for the watershed as basin file and channel routing file in tabular form and helps in viewing the output created after SWAT model run. The basin table and channel routing table are viewed (at daily, monthly, yearly frequency).

[42] Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2007. ArcSWAT interface for SWAT2005. User's Guide. BRC, TAES, USDA-ARS, Temple, TX.

# Appendx II - Climate Change Scenarios

The present study is an attempt to quantify the impact of the climate change on the water resources of the river Ganga. The SWAT model has been used on the basin with the weather inputs taken fromvarious scenarios of the PRECIS (Providing REgional Climates for Impacts Studies) regional climate model's daily weather outputs. The simulation determines the water availability in space and time under different scenarios (of present and future) without incorporating current development such as dams, diversions, etc. While predicting the impact of climate change on the water resources an assumption has been made that the land use shall not change over time. A total of 88 years of simulation over Ganga river basins has been conducted; 30 years belonging to control (baseline representing 1961-1990), 30 years belonging to GHG mid century (representing 2021-2050) and the remaining 28 years belonging to GHG end century(representing 2071-2098) scenario. While modelling river basin has been further subdivided into reasonable sized sub-basins so as to account for spatial variability of inputs. Detailed analyses have been performed over each sub-basin to quantify the possible impacts on the hydrological regime on account of the climate change. It has been observed that the impacts of climate change are not spatially and temporally uniform and are varying across the river basin as well as sub-basins.

It may be pertinent to discuss about the PRECIS regional climate scenarios that have served as the base input to the hydrological modelling.

## *Regional Climate Scenarios for India Using PRECIS*

Climate models are mathematic models used to simulate the behaviour of climate system. They incorporate information regarding climate processes, current climate variability and the response of the climate to the human-induced drivers. These models range from simple one dimensional models to complex three dimensional coupled models. The latter, known as Global Circulation Models (GCM), incorporate oceanic and atmospheric physics and dynamics and represent the general circulation of the planetary atmosphere or ocean. The GCMs are usually run at very course grid (about $3^0$ X$3^0$) resolution whereas the processes that are of interest for studies such as this one, such as precipitation, are highly influenced by the local features namely orography and land use. These local characteristics are not properly represented at the coarse scale of GCM and contribute to prediction errors on the impact of climate change at the sub-grid scale. Therefore, these GCMs are strengthened with the incorporation of local factors and downscaled, in general with a grid resolution of about $0.5^0$X$0.5^0$ or less. The downscaling can be of dynamic or statistical type. These models are referred to as Regional Climate Models (RCM) and improve the quality of climatic prediction for specific local areas.

A Regional Climate Model is a model of the atmosphere and land surface which has high horizontal resolution and consequently covers a limited area of the earth's surface. A regional climate model can not exist without a 'parent' GCM to provide the necessary inputs. The regional climate models (RCMs) provide an opportunity to dynamically downscale global model simulations to superimpose the regional detail of specified region.

PRECIS (Providing Regional Climate for Impact Studies) is the Hadley Centre portable regional climate model, developed to run on a PC with a grid resolution of 0.44° x 0.44°. High-resolution limited area model is driven at its lateral and sea-surface boundaries by output from global coupled atmosphere-ocean (HadCM3) and global atmospheric (HadAM3) general circulation models. PRECIS captures important regional information on summer monsoon rainfall missing in its parent GCM simulations.

The IPCC scenarios provide a way to assess the potential impact on climate change. Global emission scenarios were first developed by the IPCC in 1992 and were used in global general circulation models to provide estimates for the full suite of greenhouse gases and the potential impacts on climate change. Since then, there has been greater understanding of possible future greenhouse gas emissions and climate change as well as considerable improvements in the general circulation models. The IPCC, therefore, developed a new set of emissions scenarios, published in the IPCC Special Report on Emission Scenarios (IPCC SRES November 2000). These scenarios provided input into the Third and Fourth Assessment Reports and were the basis for evaluating climatic and environmental consequences of different levels of future greenhouse gas emissions and for assessing alternative mitigation and adaptation strategies. These scenarios refer to the predictions made for future conditions mainly related to precipitation, sea level rise and temperature changes based on 'storylines' of the alternate greenhouse gas emissions. There are four storylines (A1, A2, B1 and B2) identifying alternate states of future economic and technological development that takes place over the next few decades as summarized in Table i.

**Table i Summaries of IPCC SRES Scenarios**

| **IPCC SRES Scenarios** | |
|---|---|
| A1<br>World: Market Oriented<br>Economy: Rapid economic growth.<br>Population: Peaks in 2050 and then gradually declines.<br>Governance: A convergent world - income and way of life converge between regions. Extensive social and cultural interactions worldwide.<br>Technology: There are three subsets to the A1 family<br>A1FI - fossil-fuels intensive.<br>A1B - balanced on all energy sources. | A2<br>World: Divided World<br>Economy: Regionally oriented, lowest per capita income<br>Population: Continuously increasing population.<br>Governance: independently operating, self-reliant nations<br>Technology: Slower and more fragmented |

| | |
|---|---|
| A1T - non-fossil energy sources. | |
| B1<br>World: Convergent<br>Economy: service and information based, lower growth than A1<br>Population: Same as A1.<br>Governance: global solutions to economic, social and environmental stability<br>Technology: clean and resource efficient technologies | B2<br>World: Local Solutions<br>Economy: Intermediate levels of economic development<br>Population: Continuously increasing population, but at a slower rate than in A2.<br>Governance: local solutions to economic, social and environmental stability<br>Technology: more rapid A2, less rapid more diverse A1/B1 |
| Source: IPCC 4th Assessment Report (2007) | |

The data available from the IITM regional climate model simulations are derived from a number of GCMs and scenarios which provide a range of plausible future climate scenarios for use in assessing the range of potential impact of a changing climate.

The current study uses the conditions under the PRECIS A1B, which is a mid path scenario, a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies, with the development balanced across energy sources. The details of the scenario used are: A1B baseline (1961–1990, BL_61-90) and mid century (2021-2050, MC_21-50) derived using Q14 Qump (Quantifying Uncertainty in Model Predictions).

Having discussed the RCM scenarios that have been deployed as input to the hydrological model SWAT, results of simulation have been discussed below.

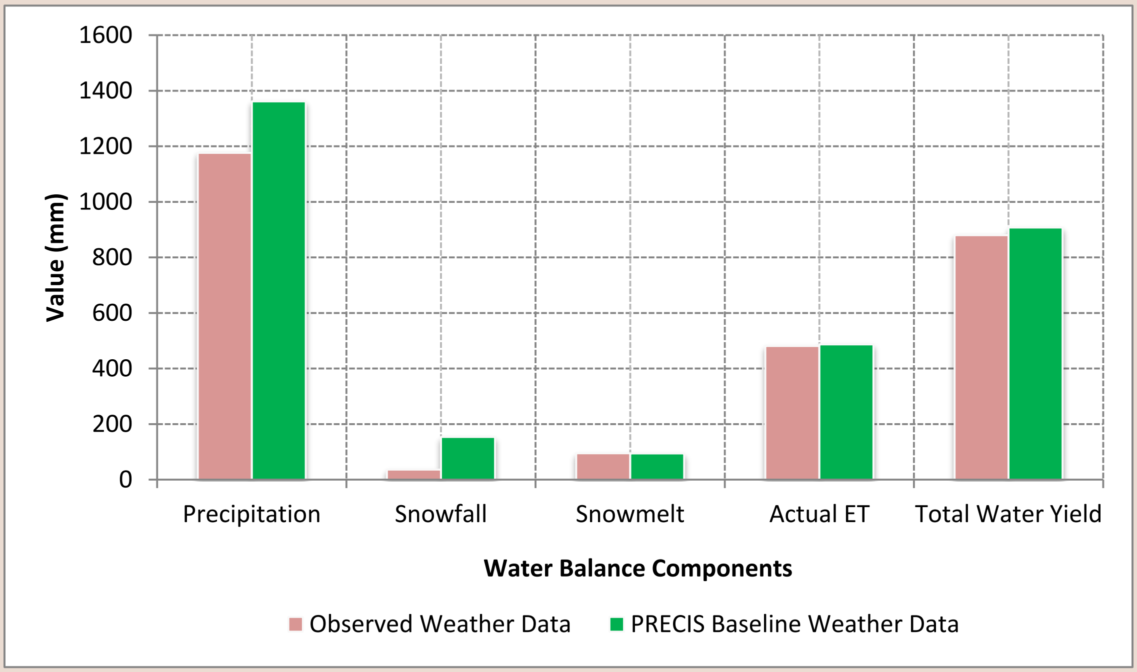
## The Hydrologic Simulation with Climate Change Scenarios

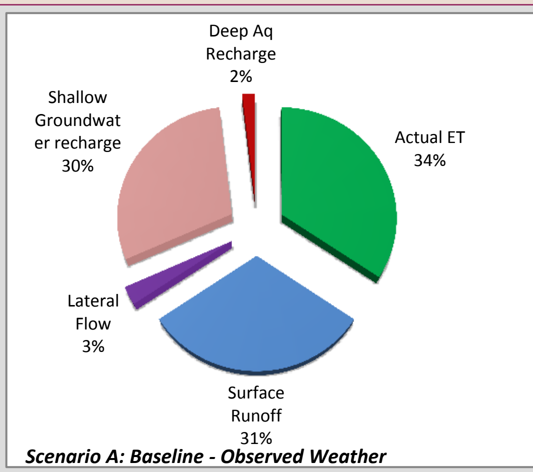
The model has been run using PRECIS GHG climate scenarios A1B baseline (BL_61-90), and GHG mid century (MC_21-50) scenarios without changing the land use. The outputs of the GHG scenarios have been analyzed with respect to the possible impacts on the runoff, precipitation and actual evapotranspiration.

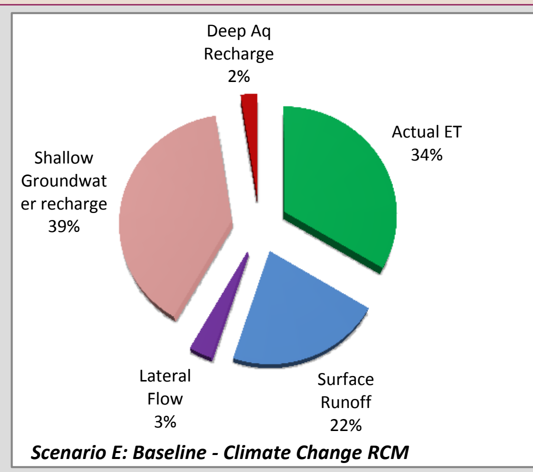
The Figure 31 shows the plot of these average annual water balance components for the simulated using observed weather data (1969-2001) and PRECIS baseline weather data (1961-1990) for the Ganga river basin. This analysis has been done to have a comparison of how well the baseline of the PRECIS RCM model compares with the observed data and the simulations made using the observed data. It may be observed that the PRECIS model is over simulating the precipitation corresponding to the baseline period (although these are not exactly concurrent periods). The contribution of precipitation to water yield (surface runoff + shallow groundwater + lateral flow) is presented as pie diagram shows similar percentage contribution for the two comparisons.

Another significant observation is the misrepresentation of the baseline precipitation simulation of the PRECIS model when compared to the observed precipitation data (Figure ii). The baseline average annual precipitation of 1362 mm is over simulated when compared to the less than 1200 mm observed average annual precipitation.

**Figure ii Average annual water balance components simulated using Observed and climate change baseline data for the Ganga river basin**

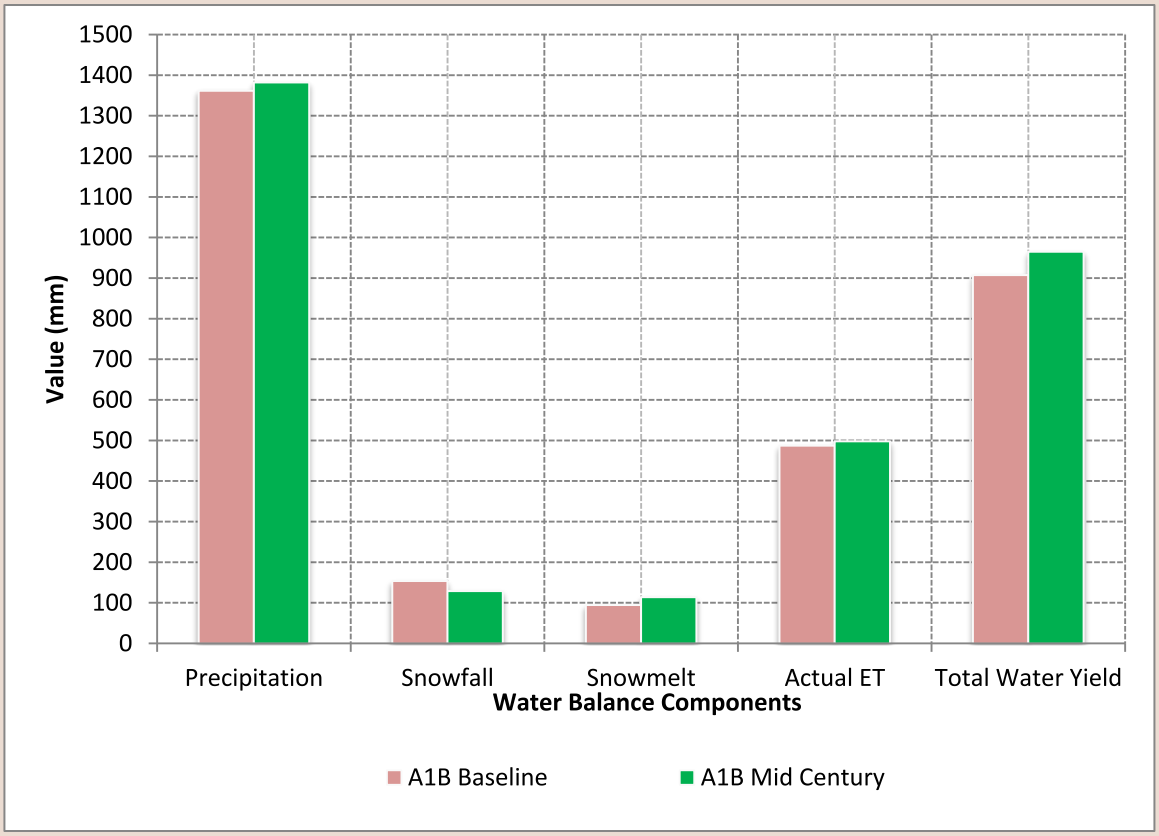


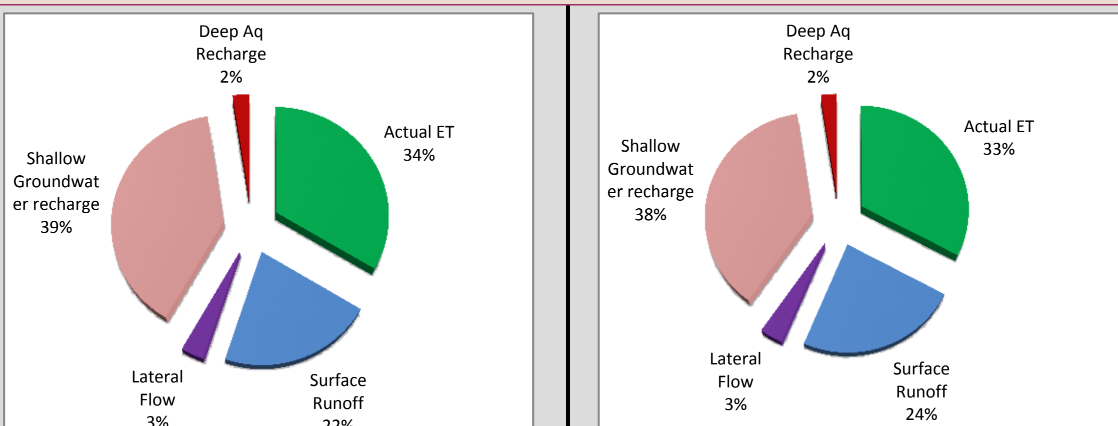



The Figure iii shows the plot of the average annual water balance components for the baseline and GHG climate scenarios for the Ganga river basin. Figure iii and Table ii depict change in water balance components from baseline scenario of A1B to Mid Century scenarios.

**Figure iii Average annual water balance components for the baseline and GHG climate scenarios for the Ganga river basin**




*Scenario E: Baseline - Climate Change RCM*

*Scenario E: Mid Century - Climate Change RCM*

A close examination of the results reveals that there is a slight increase in precipitation (about 1.5%) in the MC scenario over the baseline. One may also observe that the corresponding increase in the total water yield for the MC scenarios is 6.3%. It may further be observed that the surface runoff, which is a sub-component of the total water yield, has increased to about 15.2% under MC scenario. This may be attributed to more intense precipitation in the GHG scenarios. There is a slight increase in ground water recharge by 1% under MC scenario.

The other significant change that may be noted is the reduction in the snowfall component of the precipitation that is predicted to reduce by 16% under the MC scenario. This is mainly on account of higher temperatures during the GHG scenarios.

**Table ii Trend in water balance for IPCC SRES A1B Baseline and Mid Century climate scenarios**

| Water Balance Components (mm) | A1B Baseline (1960-1990) | A1B Mid Century (2021-2050) | Change % wrt Baseline* |
|---|---|---|---|
| Precipitation | 1361.5 | 1382.0 | -1.5 |
| Total Water Yield | 907. 6 | 965.1 | -6.3 |
| AET | 487.2 | 498.0 | -2.2 |
| Snowfall | 153.9 | 128.9 | 16.2 |
| Surface Runoff Q | 312.9 | 360.6 | -15.2 |
| Groundwater recharge | 569.0 | 575.1 | -1.0 |
| * Negative change indicates an increase towards mid century as compared to baseline | | | |

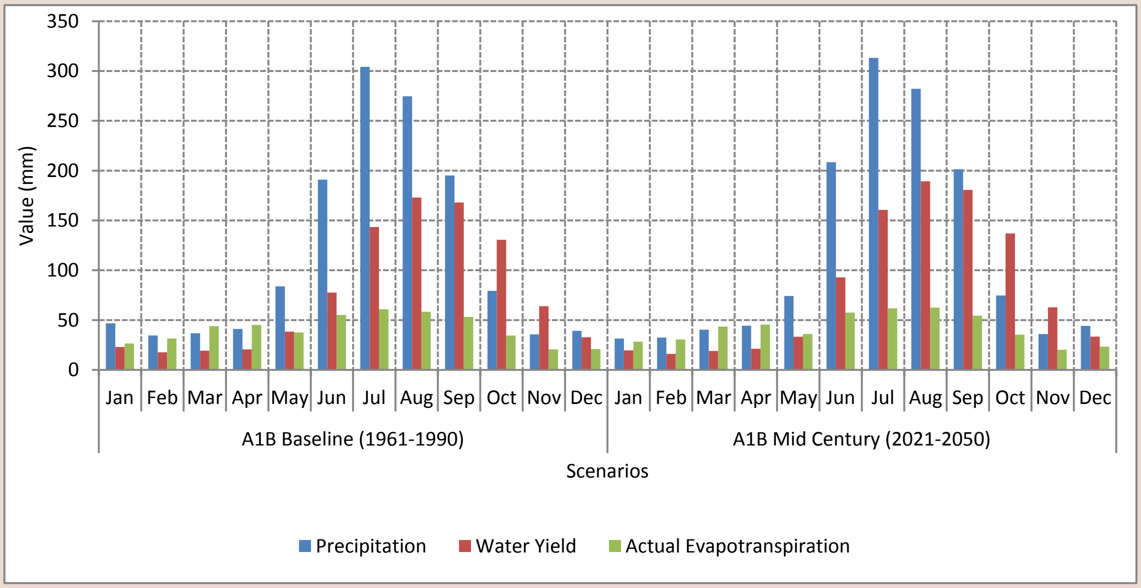
The Table iii has been provided to ascertain the impact of climate change on the hydrological character of the system. It shows what will be the change in the runoff coefficient under different scenarios. It may be seen that the proportion of runoff is likely to be higher for MC scenario. The change in the actual evapotranspiration is only marginally higher under the MC scenario that is likely due to slight increase in temperature and the precipitation.

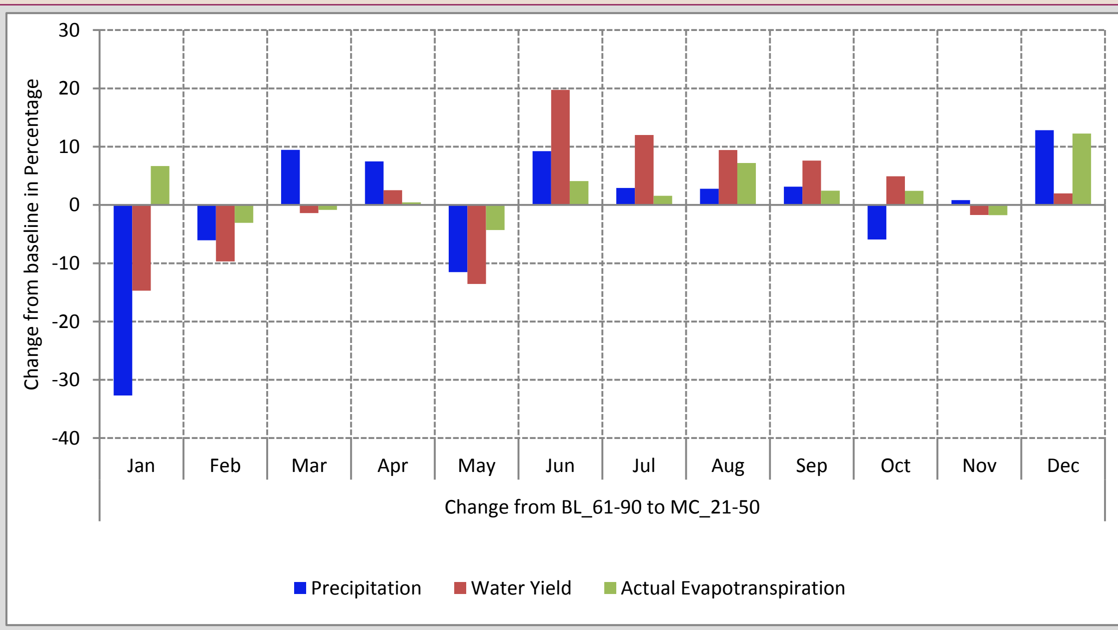
**Table iii Water Balance Components as % of rainfall for IPCC SRES A1B Baseline, Mid and End Century climate scenarios**

| Scenario | Rainfall mm | Water Yield mm | As proportion of Rainfall | Actual ET mm | As proportion of Rainfall |
|---|---|---|---|---|---|
| BL_61-90 | 1361.5 | 907.5 | 66.6 | 487.2 | 35.7 |
| MC_21-50 | 1382.0 | 965.1 | 69.8 | 498.0 | 36.0 |

The results of hydrological simulation have been depicted in Figures iv in terms of long term monthly average by picking up three major elements of water balance i.e., precipitation, water yield and actual evapotranspiration. The Figure iv shows these components in terms of depth for the Ganga basin for baseline and mid century scenario respectively and also the same elements in terms of change from the baseline to the mid century.

**Figure iv Mean monthly water balance (mm) for IPCC SRES A1B Baseline and Mid Century climate scenarios for Ganga basin**



It may be observed that increase in precipitation has been predicted in almost all months under the MC scenario but for the months of January, May and October, where decrease has been predicted. The change in the total water yield in the MC scenario is inconsistent. There is appreciable increase in the month of June but marginal increase in the months of monsoon. The months of February and May show decrease under the MC scenario. The response in evapotranspiration is similar and only differs in magnitude. The GHG scenarios display a reduction in the non-monsoon months of April and May. The reduction in ET for April and May is very likely due to reduction in the available moisture content and the resultant reduction in ET.

The spatial variability of the water balance entities is also depicted by showing the variations through the GIS layers with the precipitation, water yield and evapotranspiration as the base entities. Figures v shows the percent change in these entities from baseline BL to MC scenarios for various subbasins of Ganga.

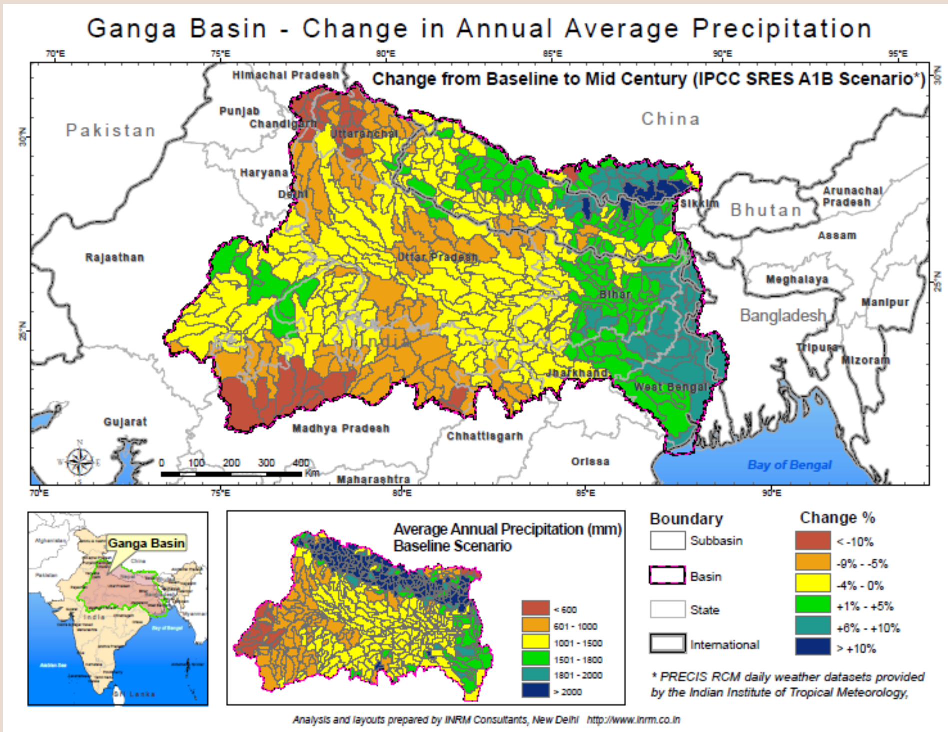
## Spatial distribution of water balance components

Effect of climate change on the water balance components has been analysed spatially with respect to the sub-bsins of Ganga river. The spatial distribution of precipitation, total water yield and evapotranspirationhas been plotted as GIS layer in terms of percent change over the baseline scenario.

In Figure 33 the change in precipitation is more in North-west, Central and Southern part of the basin under the MC scenario. The percent change in water yield for these areas is also shown in the Figure iv It may be observed from the figure that the maximum variation under the MC scenario is about 20%. There are few areas where there has been some marginal decrease in the water yield.

The increase in the evapotranspiration under MC scenario is more uniform over the Ganga Basin but for the Northern part of the area in Nepal as shown in Figure v.

**Figure v Percent change in mean annual water balance components from IPCC SRES A1B Baseline to Mid Century climate scenarios for Ganga**



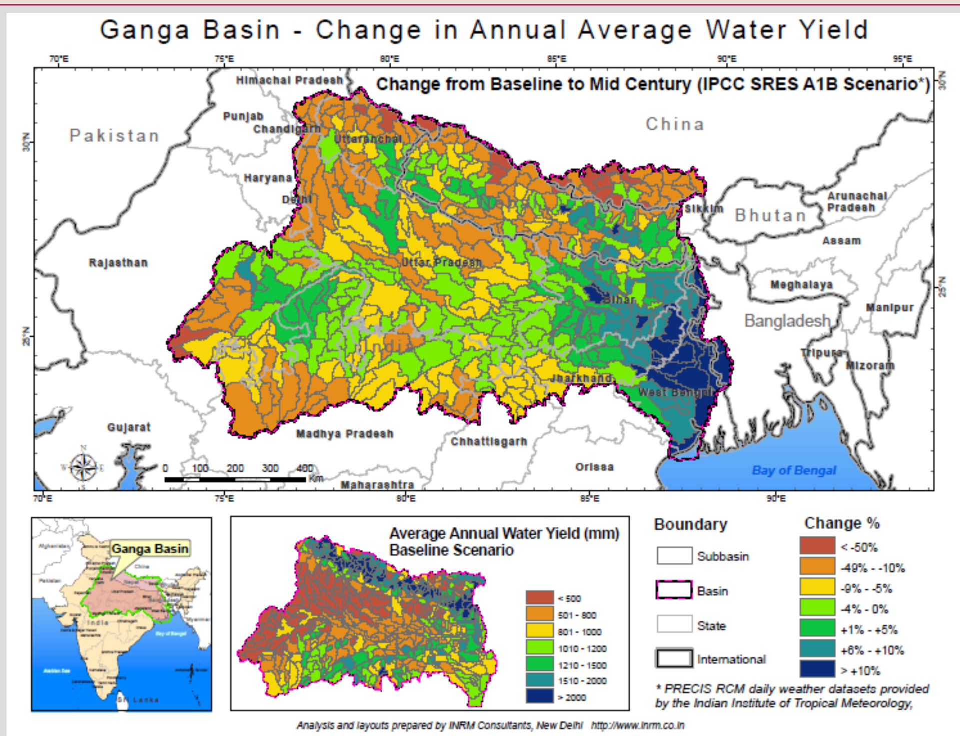
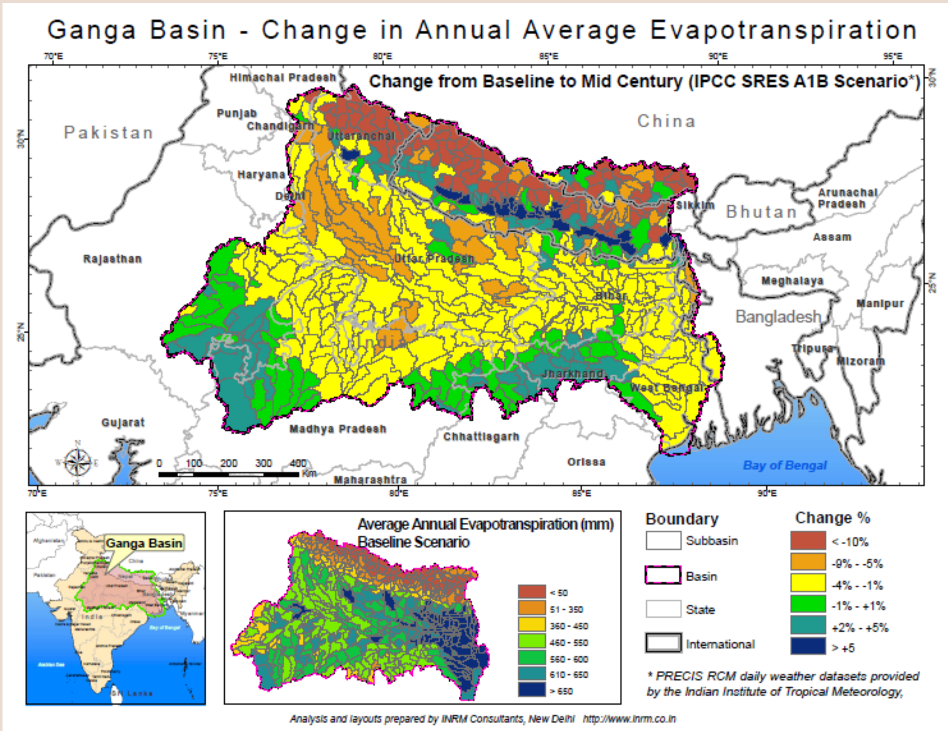



**Figure v Percent change in mean annual water balance components from IPCC SRES A1B Baseline to Mid Century climate scenarios for Ganga**



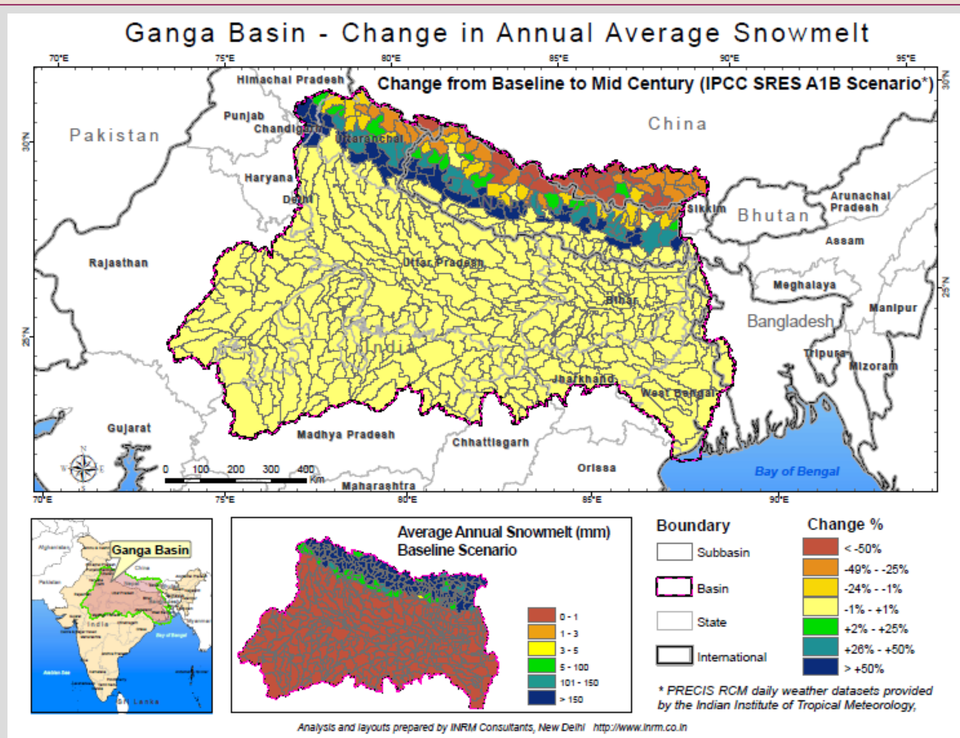
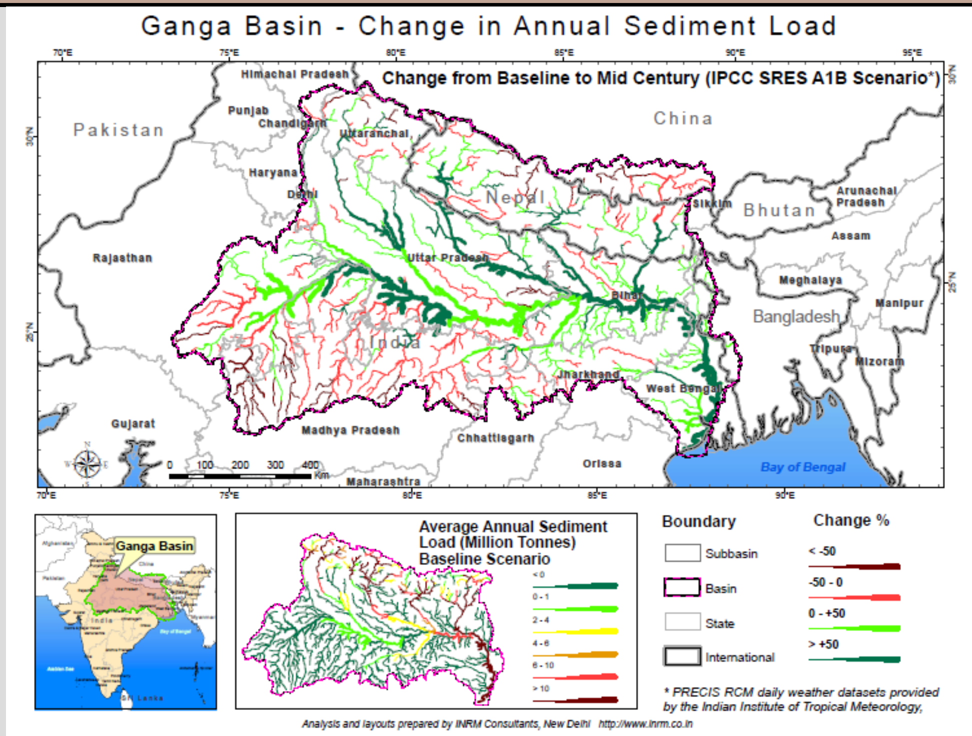



**Figure v Percent change in mean annual water balance components from IPCC SRES A1B Baseline to Mid Century climate scenarios for Ganga**



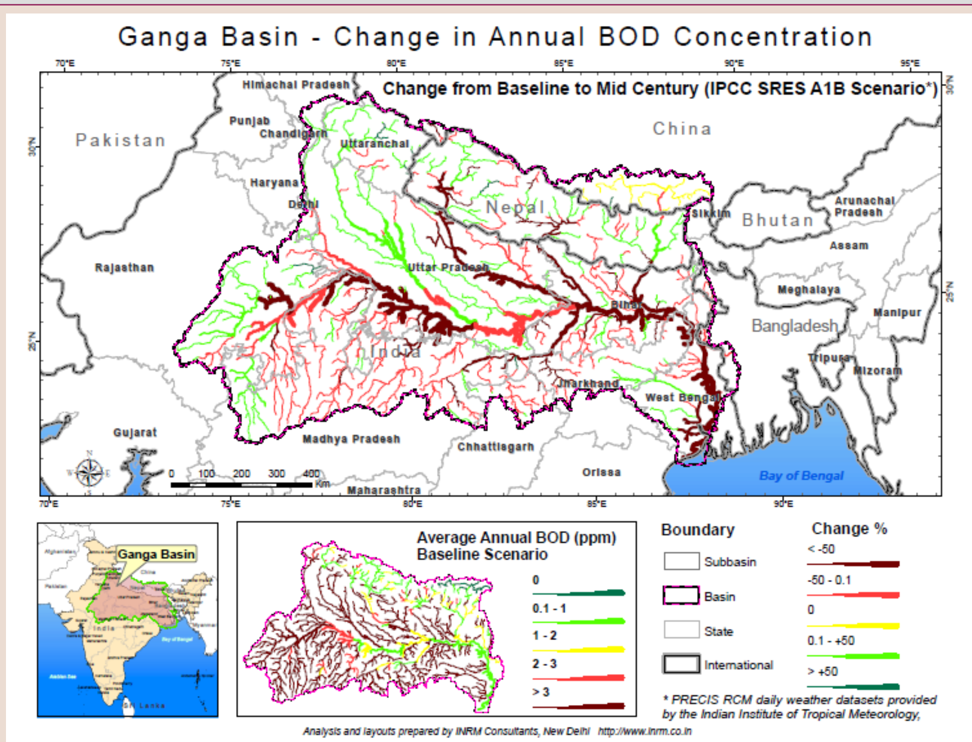
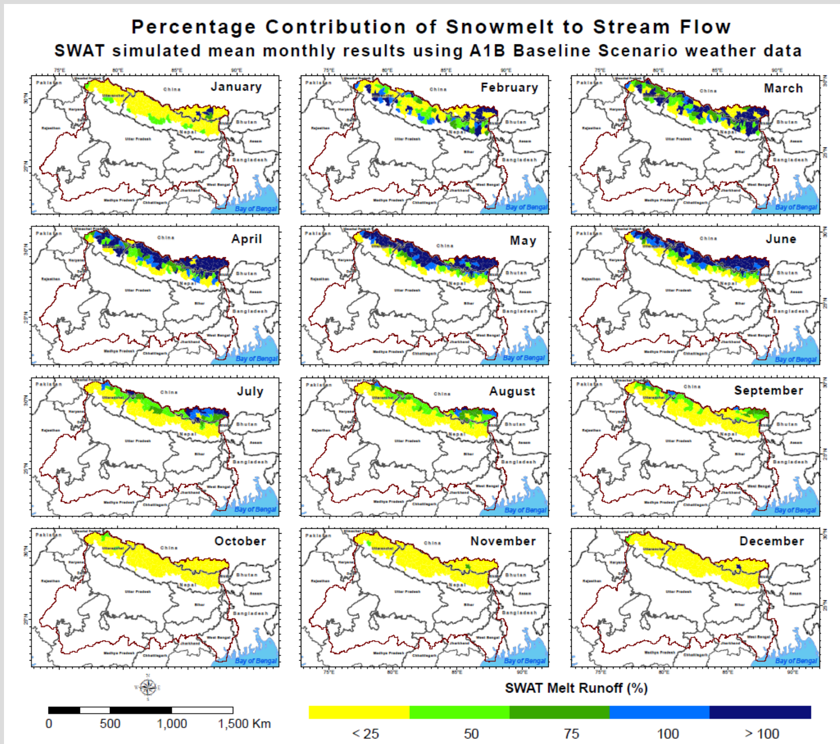
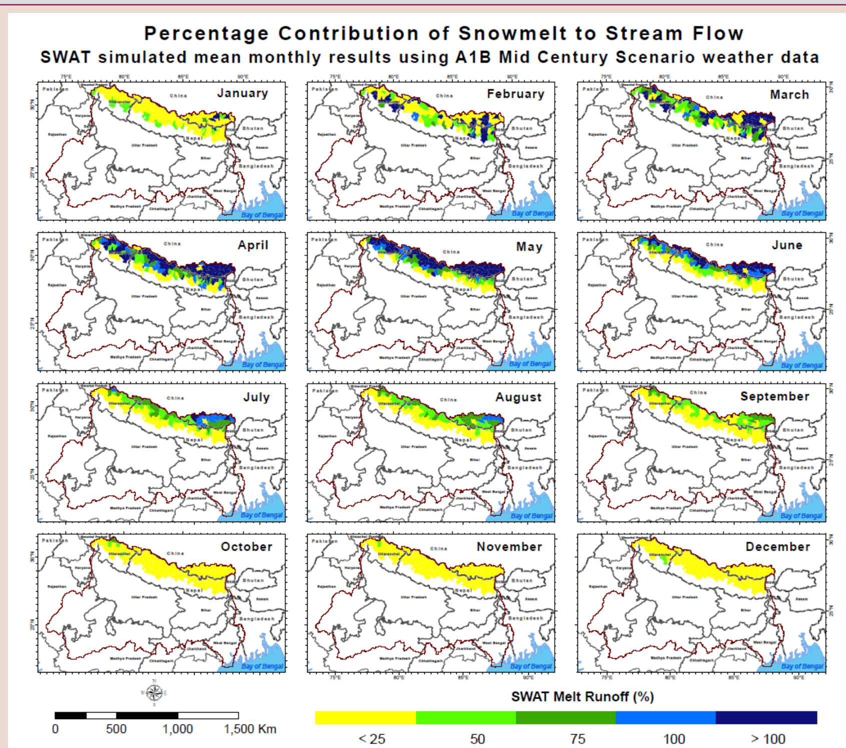



**Figure v Percent change in mean annual water balance components from IPCC SRES A1B Baseline to Mid Century climate scenarios for Ganga**



# Appendx III - Ganga Basin Knowledgebase

The study has generated very large outputs that are not only covering a range of spatial units but also a range of temporal scales. It is not possible to present all these outputs and findings in a single report. Therefore a standalone GIS based framework has been formulated to help users to interactively explore the system in terms of various features of the Ganga system along with the SWAT outputs at various levels of details of their choice. This system shall have huge advantage as a dissemination tool for creating consensus by presenting the various options of development to the stakeholders and policy makers in an understandable manner.

## Features

The interface for the knowledgebase has the following features:

- User Friendly
- Open source GIS
- View spatial distribution of Hydrological model SWAT outputs
- View time series data as Graphs
- Add new Shape file
- Export selection as new GIS layer
- Export attribute to excel
- Query and thematic map creation

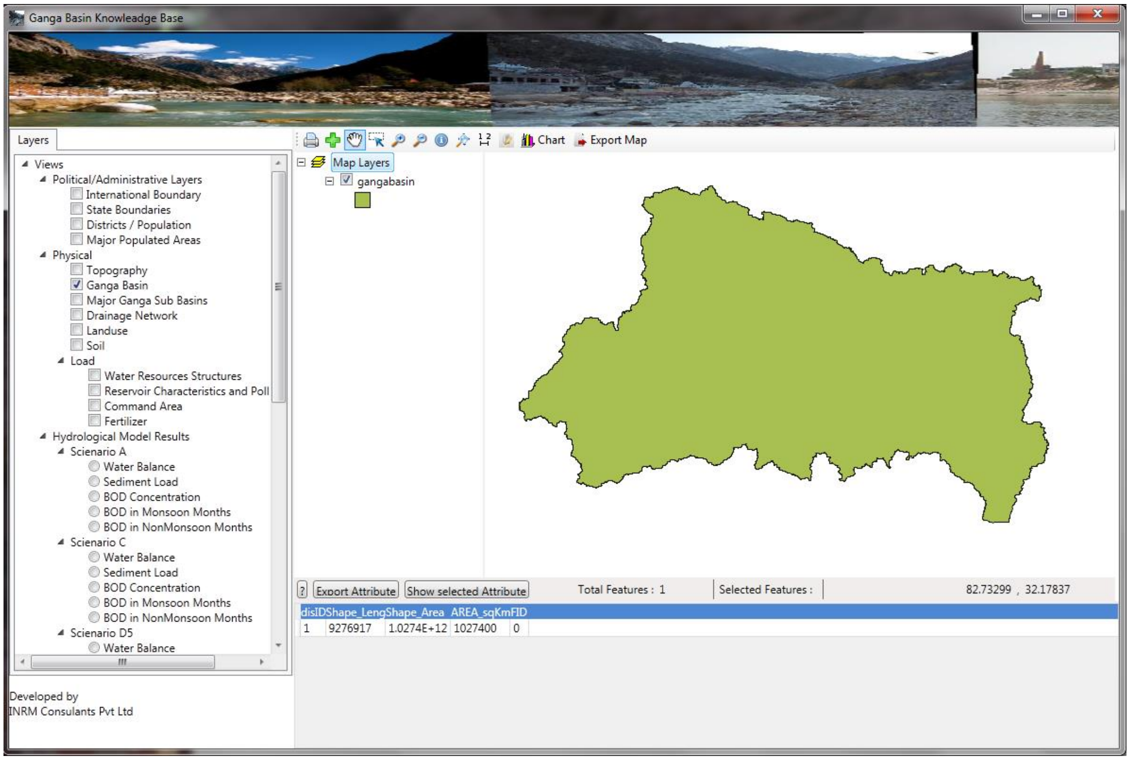
## Technology Used

Interface is designed using Microsoft. dotNet framework and WPF (windows presentation foundation). Open source GIS namely MapWindow 6.0 GIS[43] is used to GIS operations. The Ms Access database is used to link the SWAT model outputs to the GIS layers. GIS tool is used to view and analyze the SWAT simulated outputs of various hydrological components for Ganga Basin under Business as usual (baseline) and future scenarios.The interface also provides the users to generate export and print customized reports and charts.

## Interface

This is the front end or interface users will work with, as shown in the figure below

[43] http://mapwindow6.codeplex.com/

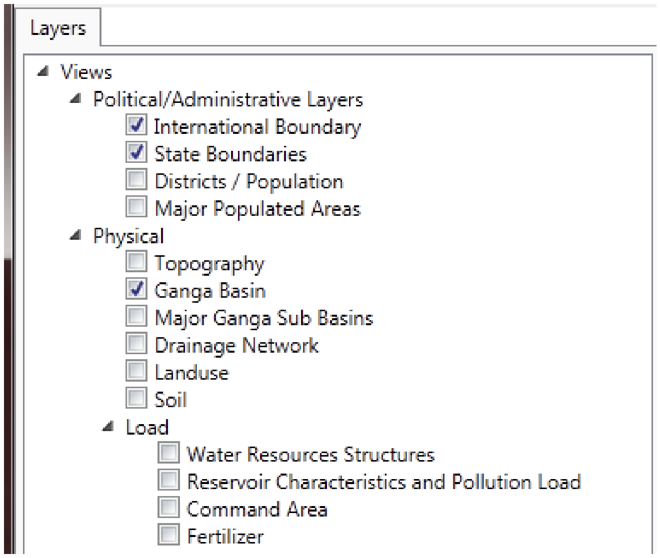


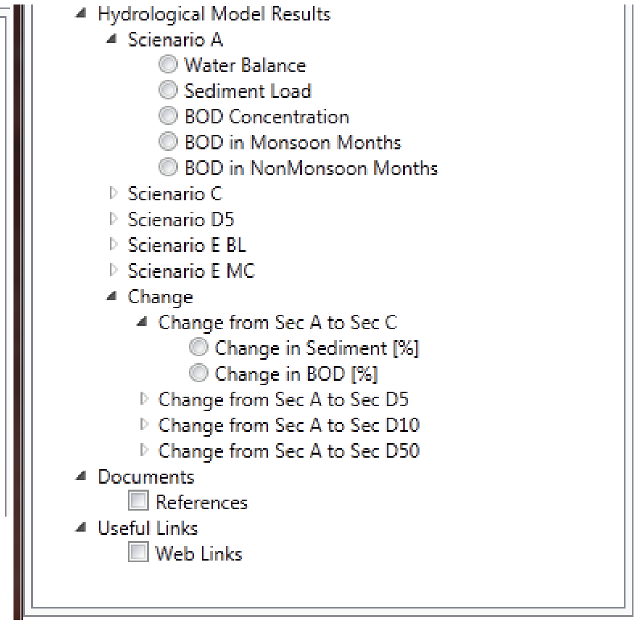

The interface consists of 4 divisions

1. Layers – Enlists available data (Shape files)
2. Map layers – Enlists the layers displayed in the map area
3. Map Area - Displays the loaded layers
4. Attribute Table – shows the attribute table of the layer selected in the map layers.

**Layers:**

The left panel enlists the available shapefiles, click on the check box beside the name of the shapefile to load it in the Map layer panel.



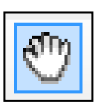




## Map Layers

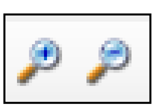
Upper left corner of the map layer panel has a toolbar with several functions


Print Map


Adds Shape file (WGS 84 projection)

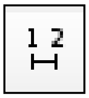

Pan (Move View)


Select (feature)


Zoom In , Zoom Out


Identify features


Zoom to Full Extent




Measure Distance between to places

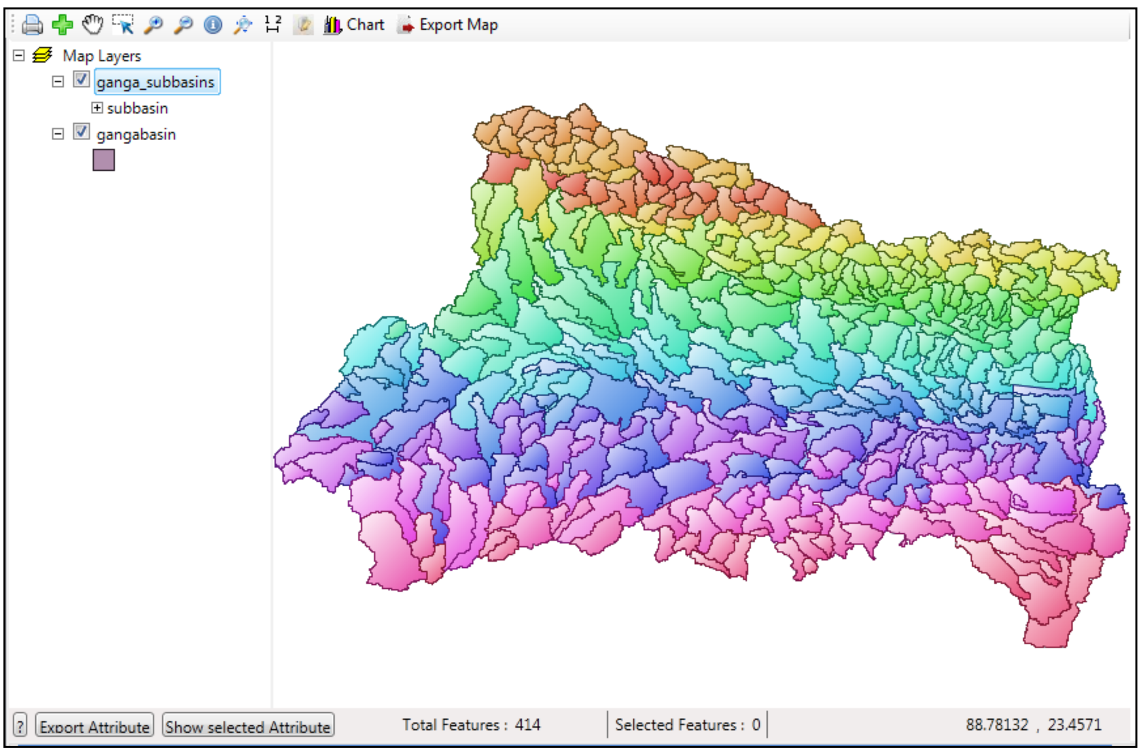
Query Tool to analyze spatial data


Brings pop menu to create customized Charts

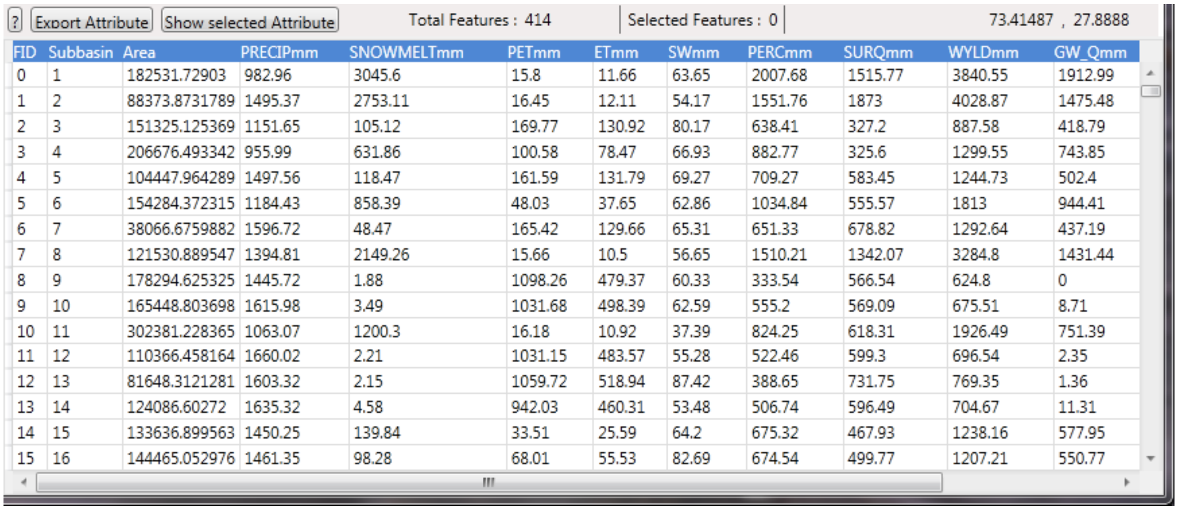

Exports the shape file to desired location

**Map Area**

Map area displays the layers loaded in the Map layer. The bottom panel of the map area displays the total number of features, features selected and geographic coordinates of the location.




The bottom panel shows the attribute table of the selected shape file. The attribute table can be exported as csv file by clicking on Export Attribute button. The selected records can be filtered by clicking on Show Selected Attribute button.

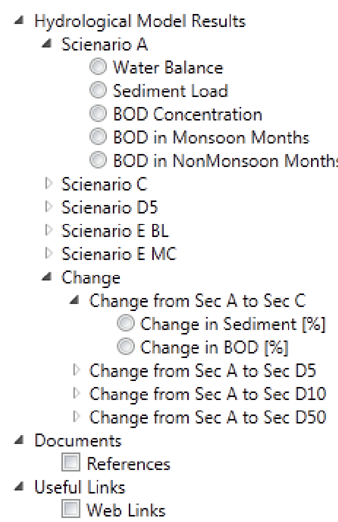


? | Export Attribute | Show selected Attribute | Total Features : 414 | Selected Features : 0 | 73.41487 , 27.8888

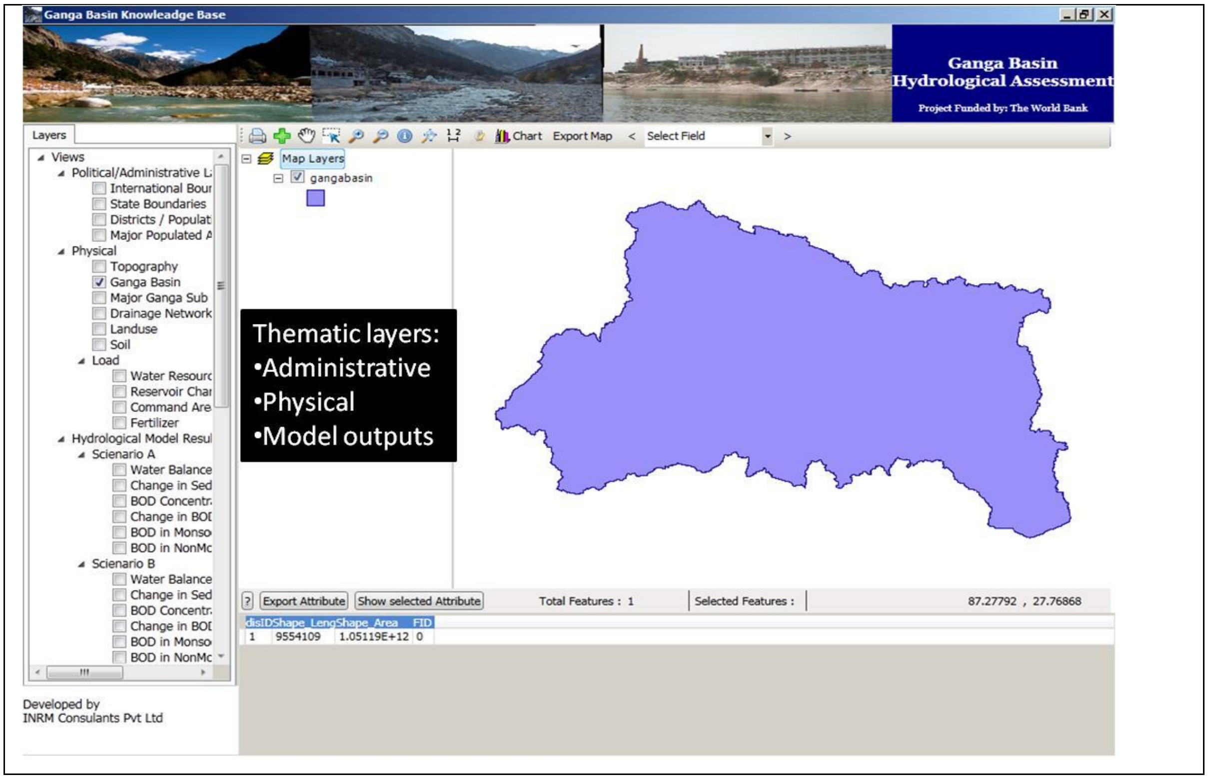
| FID | Subbasin | Area | PRECIPmm | SNOWMELTmm | PETmm | ETmm | SWmm | PERCmm | SURQmm | WYLDmm | GW_Qmm |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 182531.72903 | 982.96 | 3045.6 | 15.8 | 11.66 | 63.65 | 2007.68 | 1515.77 | 3840.55 | 1912.99 |
| 1 | 2 | 88373.8731789 | 1495.37 | 2753.11 | 16.45 | 12.11 | 54.17 | 1551.76 | 1873 | 4028.87 | 1475.48 |
| 2 | 3 | 151325.125369 | 1151.65 | 105.12 | 169.77 | 130.92 | 80.17 | 638.41 | 327.2 | 887.58 | 418.79 |
| 3 | 4 | 206676.493342 | 955.99 | 631.86 | 100.58 | 78.47 | 66.93 | 882.77 | 325.6 | 1299.55 | 743.85 |
| 4 | 5 | 104447.964289 | 1497.56 | 118.47 | 161.59 | 131.79 | 69.27 | 709.27 | 583.45 | 1244.73 | 502.4 |
| 5 | 6 | 154284.372315 | 1184.43 | 858.39 | 48.03 | 37.65 | 62.86 | 1034.84 | 555.57 | 1813 | 944.41 |
| 6 | 7 | 38066.6759882 | 1596.72 | 48.47 | 165.42 | 129.66 | 65.31 | 651.33 | 678.82 | 1292.64 | 437.19 |
| 7 | 8 | 121530.889547 | 1394.81 | 2149.26 | 15.66 | 10.5 | 56.65 | 1510.21 | 1342.07 | 3284.8 | 1431.44 |
| 8 | 9 | 178294.625325 | 1445.72 | 1.88 | 1098.26 | 479.37 | 60.33 | 333.54 | 566.54 | 624.8 | 0 |
| 9 | 10 | 165448.803698 | 1615.98 | 3.49 | 1031.68 | 498.39 | 62.59 | 555.2 | 569.09 | 675.51 | 8.71 |
| 10 | 11 | 302381.228365 | 1063.07 | 1200.3 | 16.18 | 10.92 | 37.39 | 824.25 | 618.31 | 1926.49 | 751.39 |
| 11 | 12 | 110366.458164 | 1660.02 | 2.21 | 1031.15 | 483.57 | 55.28 | 522.46 | 599.3 | 696.54 | 2.35 |
| 12 | 13 | 81648.3121281 | 1603.32 | 2.15 | 1059.72 | 518.94 | 87.42 | 388.65 | 731.75 | 769.35 | 1.36 |
| 13 | 14 | 124086.60272 | 1635.32 | 4.58 | 942.03 | 460.31 | 53.48 | 506.74 | 596.49 | 704.67 | 11.31 |
| 14 | 15 | 133636.899563 | 1450.25 | 139.84 | 33.51 | 25.59 | 64.2 | 675.32 | 467.93 | 1238.16 | 577.95 |
| 15 | 16 | 144465.052976 | 1461.35 | 98.28 | 68.01 | 55.53 | 82.69 | 674.54 | 499.77 | 1207.21 | 550.77 |

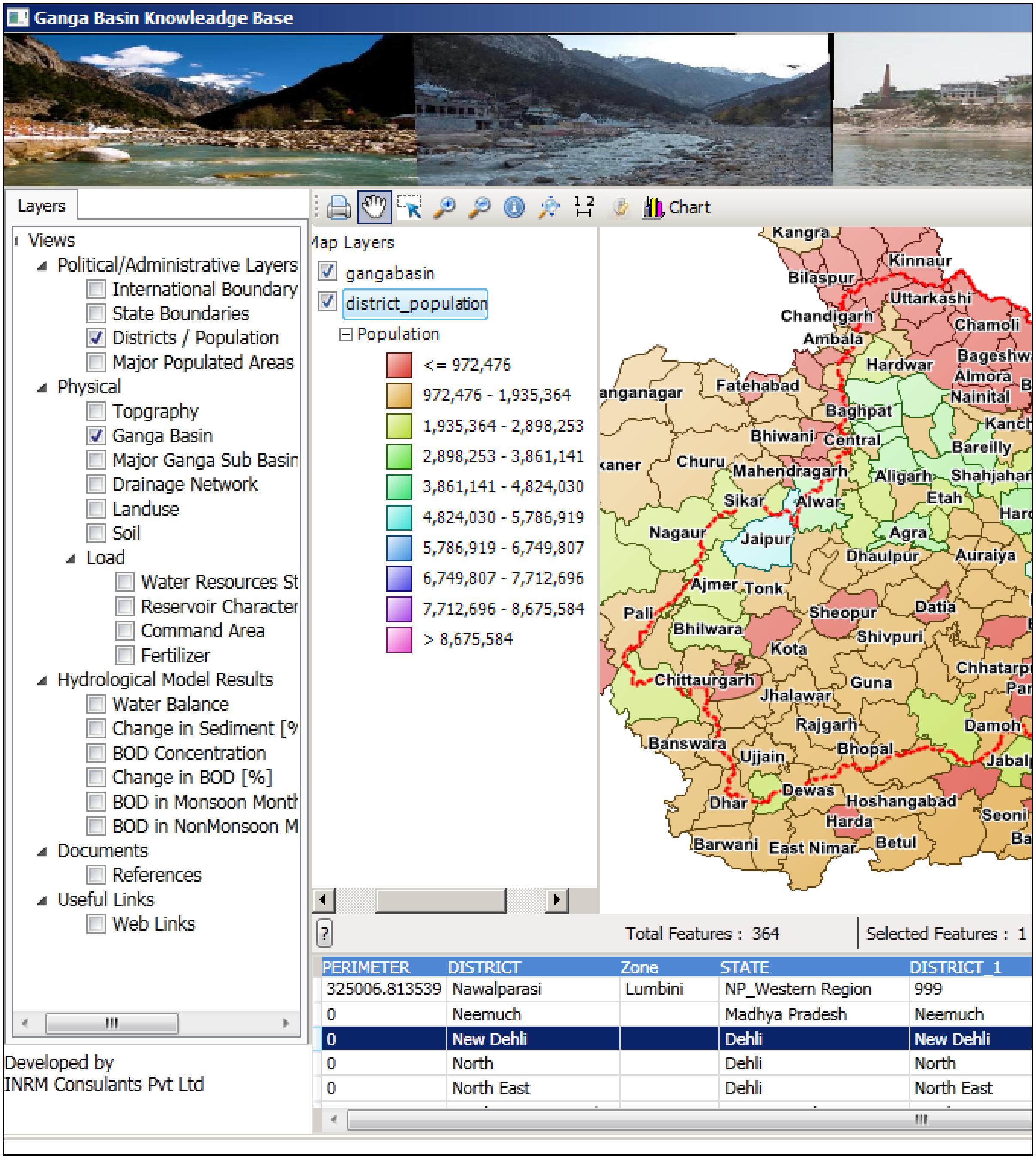
## Viewing Hydrological Model Results

SWAT modelled outputs on all the Scenarios (Scenario A, C, D and E, refer the main document for the scenario details) can be viewed by clicking the radio buttons on the left panel. The change from the baseline to other scenarios are also available for viewing from the left panel.

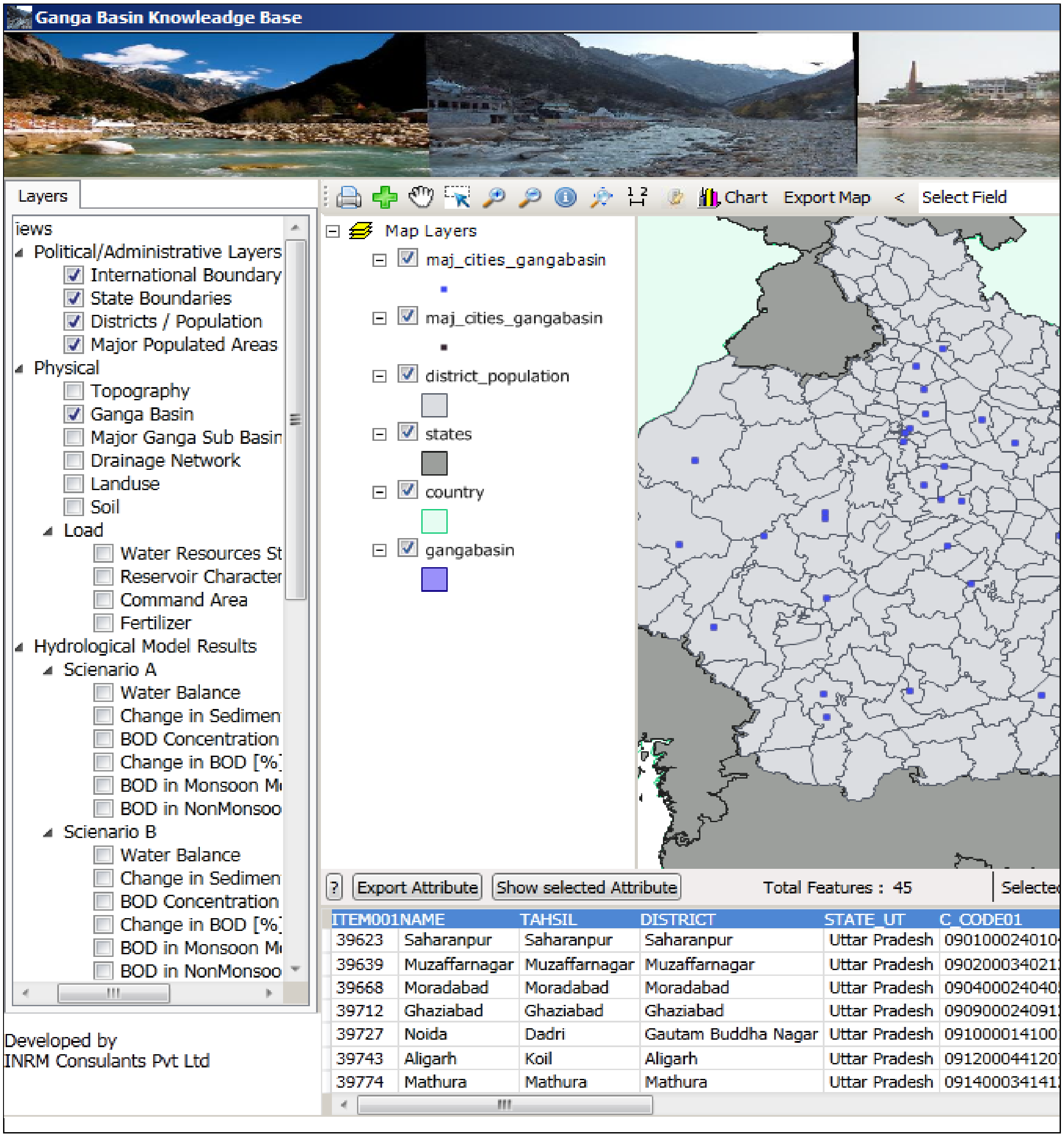


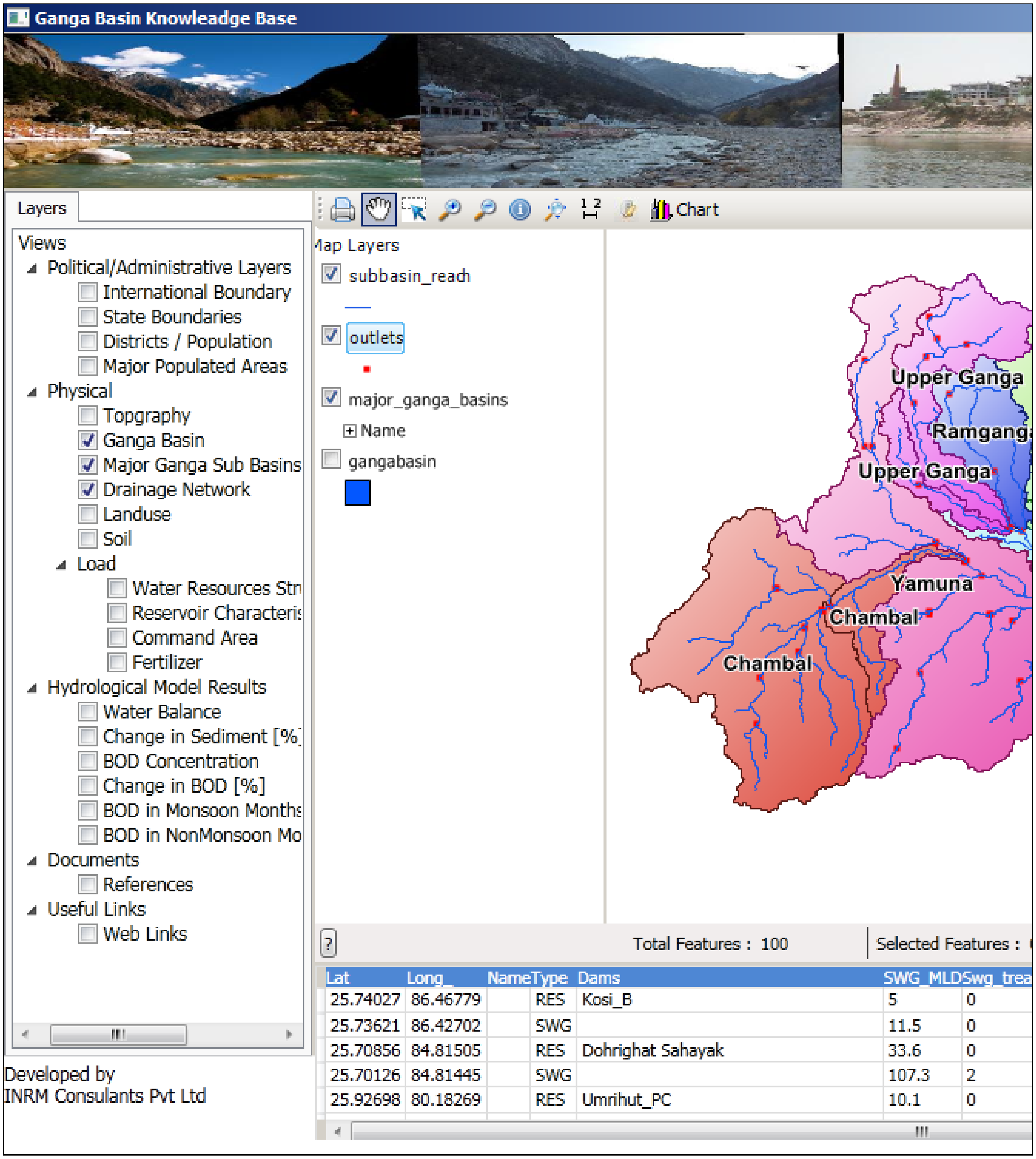

Screen shots of some of the functions are given below.

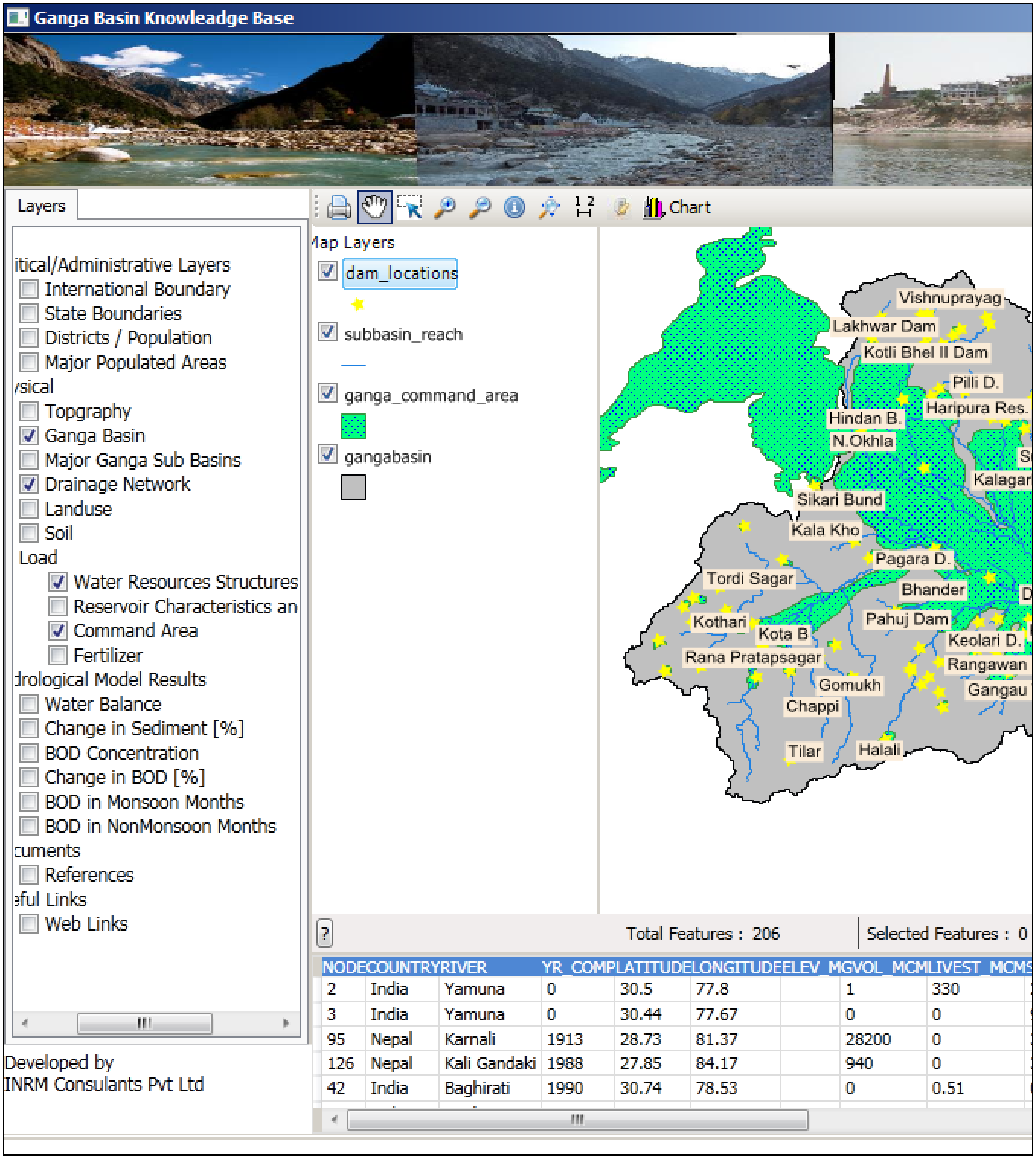

Ganga Basin Knowleadge Base
Ganga Basin
Hydrological Assessment
Project Funded by: The World Bank
Layers
Views
Political/Administrative L
International Bour
State Boundaries
Districts / Populat
Major Populated A
Physical
Topography
Ganga Basin
Major Ganga Sub
Drainage Network
Landuse
Soil
Load
Water Resourc
Reservoir Char
Command Are
Fertilizer
Hydrological Model Resul
Scienario A
Water Balance
Change in Sed
BOD Concentr
Change in BOD
BOD in Monso
BOD in NonMc
Scienario B
Water Balance
Change in Sed
BOD Concentr
Change in BOD
BOD in Monso
BOD in NonMc
Chart
Export Map
Select Field
Map Layers
gangabasin
Thematic layers:
•Administrative
•Physical
•Model outputs
Export Attribute
Show selected Attribute
Total Features : 1
Selected Features :
87.27792 , 27.76868
disID Shape_Leng Shape_Area FID
1 9554109 1.05119E+12 0
Developed by
INRM Consulants Pvt Ltd

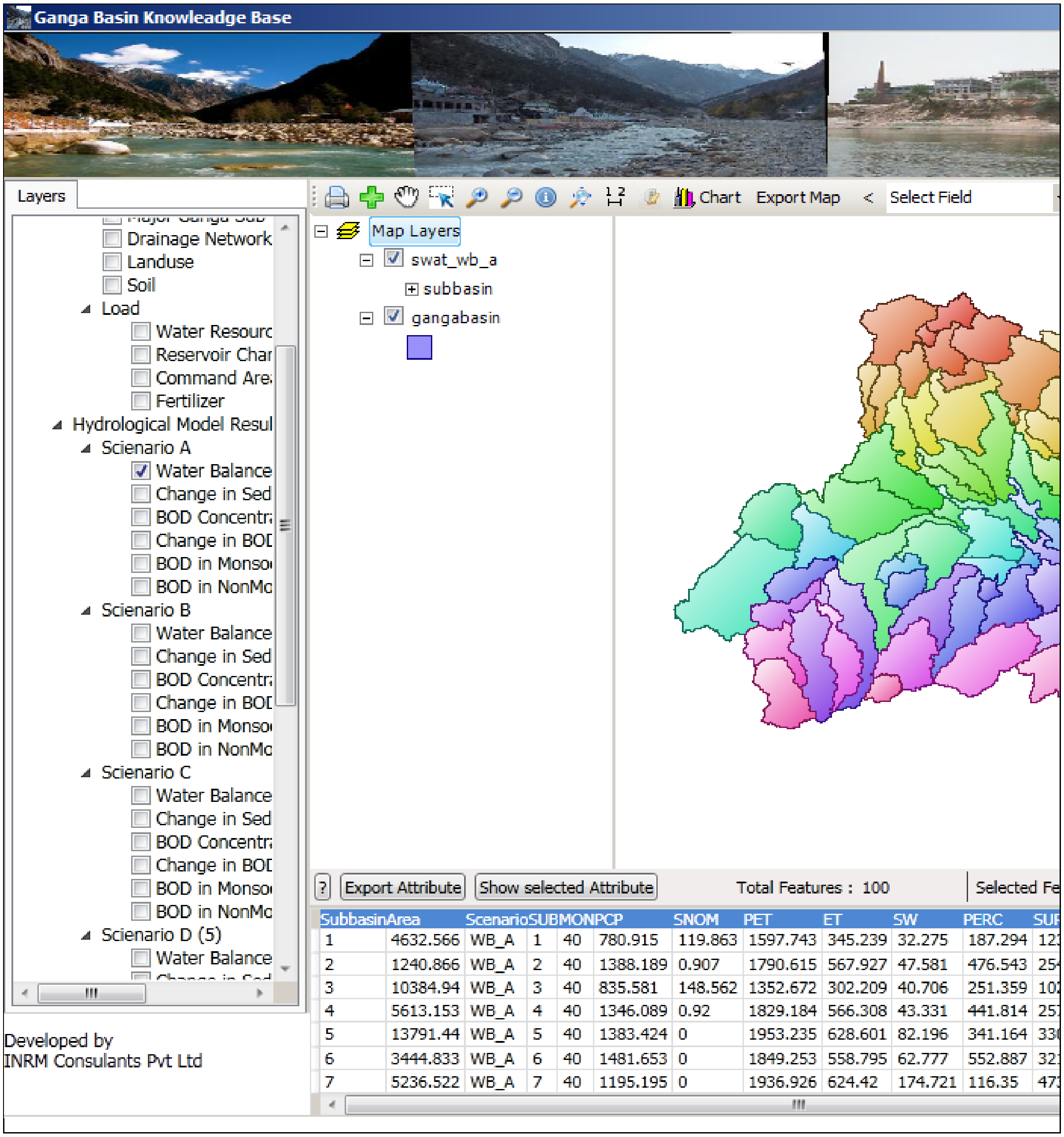


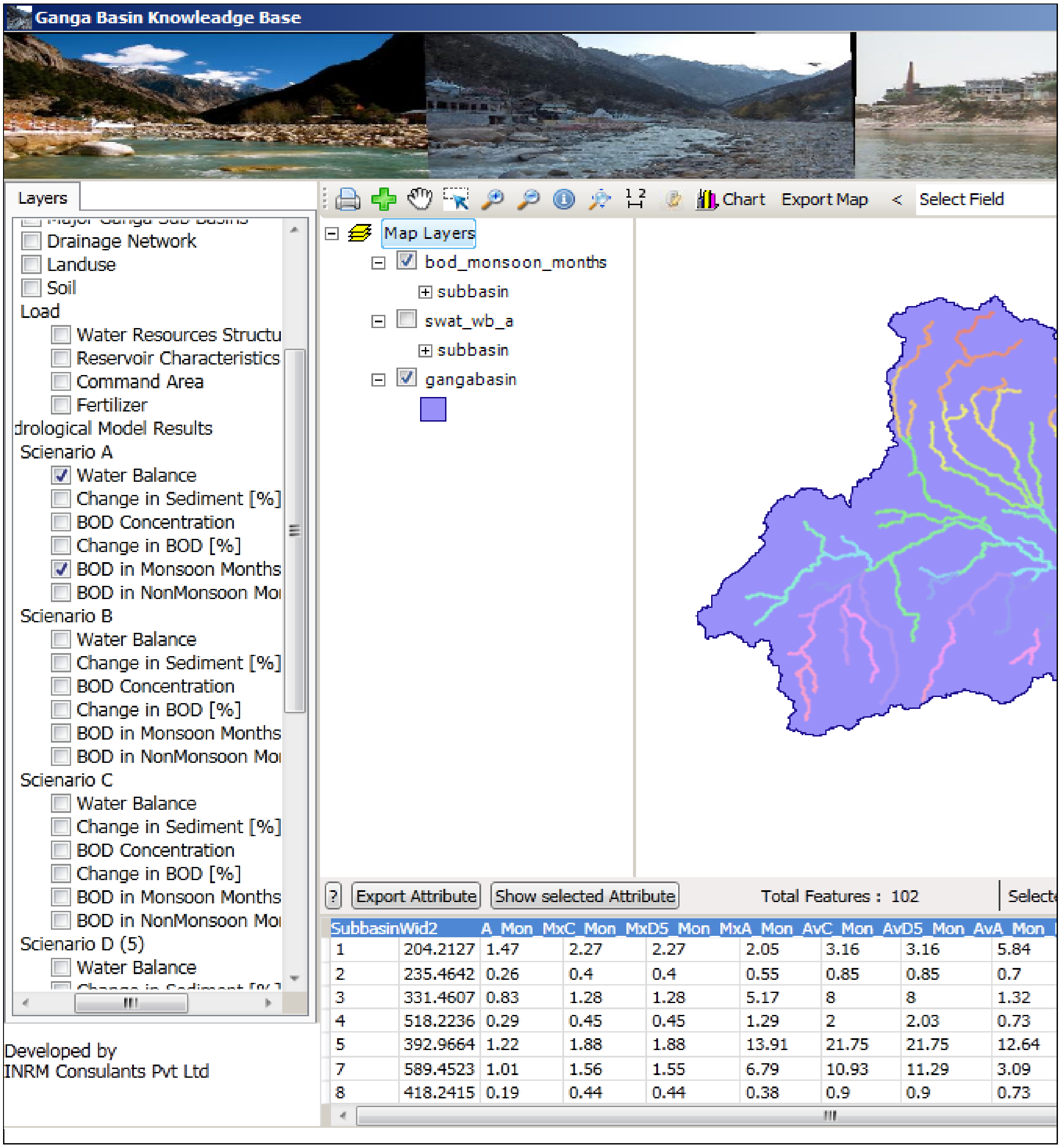
Ganga Basin Knowleadge Base
Layers
Views
Political/Administrative Layers
International Boundary
State Boundaries
Districts / Population
Major Populated Areas
Physical
Topgraphy
Ganga Basin
Major Ganga Sub Basin
Drainage Network
Landuse
Soil
Load
Water Resources St
Reservoir Character
Command Area
Fertilizer
Hydrological Model Results
Water Balance
Change in Sediment [%
BOD Concentration
Change in BOD [%]
BOD in Monsoon Month
BOD in NonMonsoon M
Documents
References
Useful Links
Web Links
Developed by
INRM Consulants Pvt Ltd
Chart
Map Layers
gangabasin
district_population
Population
<= 972,476
972,476 - 1,935,364
1,935,364 - 2,898,253
2,898,253 - 3,861,141
3,861,141 - 4,824,030
4,824,030 - 5,786,919
5,786,919 - 6,749,807
6,749,807 - 7,712,696
7,712,696 - 8,675,584
> 8,675,584
Total Features : 364
Selected Features : 1
PERIMETER | DISTRICT | Zone | STATE | DISTRICT_1
325006.813539 | Nawalparasi | Lumbini | NP_Western Region | 999
0 | Neemuch | | Madhya Pradesh | Neemuch
0 | New Dehli | | Dehli | New Dehli
0 | North | | Dehli | North
0 | North East | | Dehli | North East
Kangra
Kinnaur
Bilaspur
Uttarkashi
Chandigarh
Chamoli
Ambala
Bageshw
Hardwar
Almora
Fatehabad
Nainital
Baghpat
Bhiwani
Central
Bareilly
Churu
Mahendragarh
Aligarh
Shahjahan
Sikar
Alwar
Etah
Nagaur
Jaipur
Agra
Dhaulpur
Auraiya
Ajmer
Tonk
Pali
Sheopur
Datia
Bhilwara
Shivpuri
Kota
Chittaurgarh
Guna
Jhalawar
Rajgarh
Damoh
Banswara
Ujjain
Bhopal
Dewas
Hoshangabad
Dhar
Harda
Seoni
Barwani
East Nimar
Betul

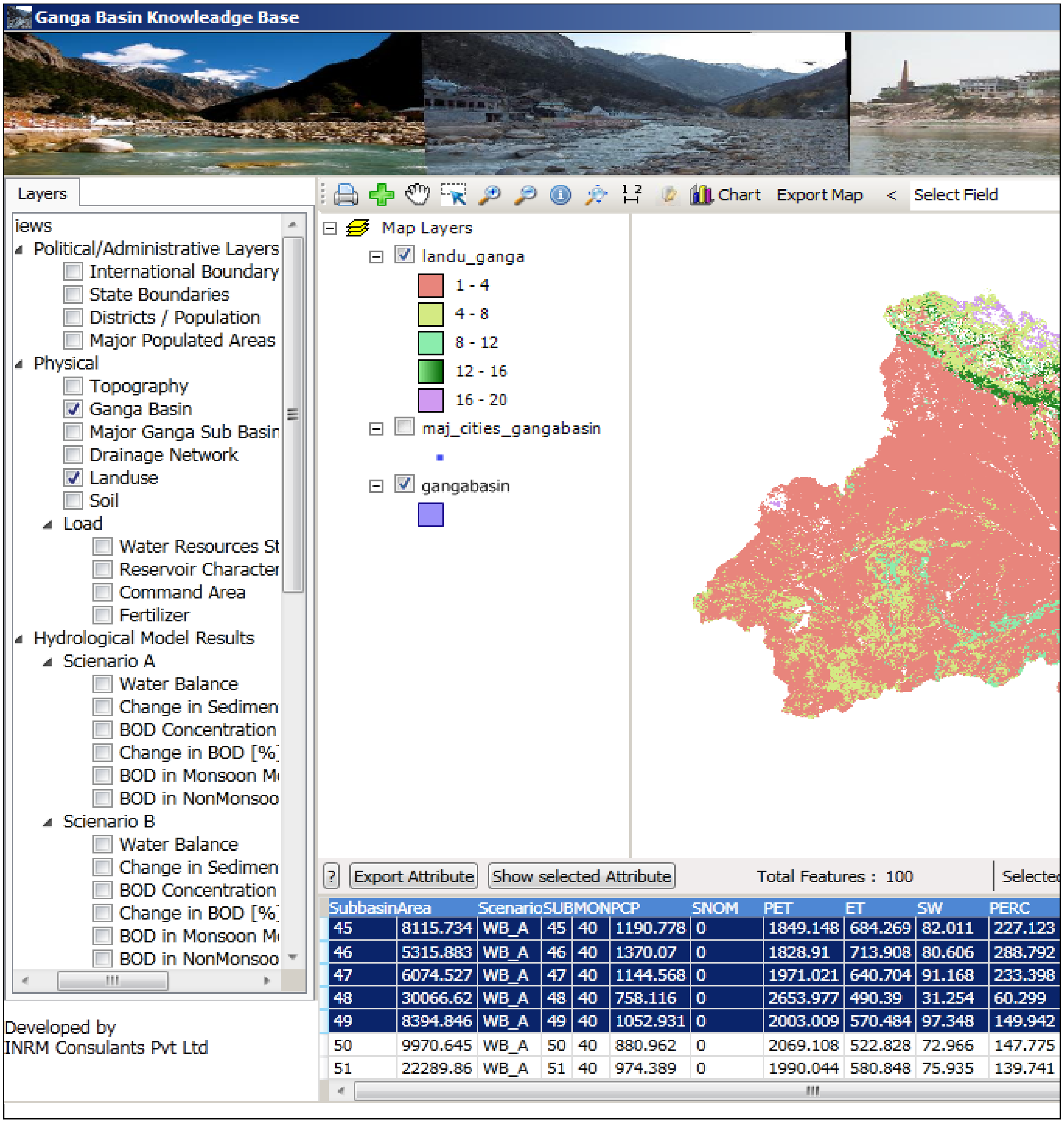

Ganga Basin Knowleadge Base
Layers
iews
Political/Administrative Layers
International Boundary
State Boundaries
Districts / Population
Major Populated Areas
Physical
Topography
Ganga Basin
Major Ganga Sub Basin
Drainage Network
Landuse
Soil
Load
Water Resources St
Reservoir Character
Command Area
Fertilizer
Hydrological Model Results
Scienario A
Water Balance
Change in Sedimen
BOD Concentration
Change in BOD [%]
BOD in Monsoon M
BOD in NonMonsoo
Scienario B
Water Balance
Change in Sedimen
BOD Concentration
Change in BOD [%]
BOD in Monsoon M
BOD in NonMonsoo
Developed by
INRM Consulants Pvt Ltd
Chart
Export Map
Select Field
Map Layers
maj_cities_gangabasin
maj_cities_gangabasin
district_population
states
country
gangabasin
Export Attribute
Show selected Attribute
Total Features : 45
ITEM001NAME TAHSIL DISTRICT STATE_UT C_CODE01
39623 Saharanpur Saharanpur Saharanpur Uttar Pradesh
39639 Muzaffarnagar Muzaffarnagar Muzaffarnagar Uttar Pradesh
39668 Moradabad Moradabad Moradabad Uttar Pradesh
39712 Ghaziabad Ghaziabad Ghaziabad Uttar Pradesh
39727 Noida Dadri Gautam Buddha Nagar Uttar Pradesh
39743 Aligarh Koil Aligarh Uttar Pradesh
39774 Mathura Mathura Mathura Uttar Pradesh


Ganga Basin Knowleadge Base
Layers
Views
Political/Administrative Layers
International Boundary
State Boundaries
Districts / Population
Major Populated Areas
Physical
Topgraphy
Ganga Basin
Major Ganga Sub Basins
Drainage Network
Landuse
Soil
Load
Fertilizer
Hydrological Model Results
Water Balance
BOD Concentration
Change in BOD [%]
Documents
References
Useful Links
Web Links
Developed by
INRM Consulants Pvt Ltd
Chart
subbasin_reach
outlets
major_ganga_basins
Name
gangabasin
Upper Ganga
Upper Ganga
Yamuna
Chambal
Chambal
Total Features : 100
Lat
NameType
Dams
25.74027
86.46779
RES
Kosi_B
5
0
25.73621
86.42702
SWG
11.5
0
25.70856
84.81505
RES
Dohrighat Sahayak
33.6
0
25.70126
84.81445
SWG
107.3
2
25.92698
80.18269
RES
Umrihut_PC
10.1
0


Ganga Basin Knowleadge Base
Layers
itical/Administrative Layers
International Boundary
State Boundaries
Districts / Population
Major Populated Areas
/sical
Topgraphy
Ganga Basin
Major Ganga Sub Basins
Drainage Network
Landuse
Soil
Load
Water Resources Structures
Reservoir Characteristics an
Command Area
Fertilizer
drological Model Results
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
BOD in NonMonsoon Months
cuments
References
eful Links
Web Links
Developed by
INRM Consulants Pvt Ltd
Chart
Map Layers
dam_locations
subbasin_reach
ganga_command_area
gangabasin
Vishnuprayag
Lakhwar Dam
Kotli Bhel II Dam
Pilli D.
Haripura Res.
Hindan B.
N.Okhla
Kalagar
Sikari Bund
Kala Kho
Pagara D.
Tordi Sagar
Bhander
Kothari
Kota B
Pahuj Dam
Keolari D.
Rana Pratapsagar
Rangawan
Gomukh
Gangau
Chappi
Tilar
Halali
Total Features : 206
Selected Features : 0
NODE COUNTRY RIVER YR_COMPL ATITUDE LONGITUDE ELEV_M GVOL_MCM LIVEST_MCM
2 India Yamuna 0 30.5 77.8 1 330
3 India Yamuna 0 30.44 77.67 0 0
95 Nepal Karnali 1913 28.73 81.37 28200 0
126 Nepal Kali Gandaki 1988 27.85 84.17 940 0
42 India Baghirati 1990 30.74 78.53 0 0.51


Ganga Basin Knowleadge Base
Layers
Drainage Network
Landuse
Soil
Load
Water Resourc
Reservoir Char
Command Are
Fertilizer
Hydrological Model Resul
Scienario A
Water Balance
Change in Sed
BOD Concentr
Change in BOD
BOD in Monso
BOD in NonMo
Scienario B
Water Balance
Change in Sed
BOD Concentr
Change in BOD
BOD in Monso
BOD in NonMo
Scienario C
Water Balance
Change in Sed
BOD Concentr
Change in BOD
BOD in Monso
BOD in NonMo
Scienario D (5)
Water Balance
Developed by
INRM Consulants Pvt Ltd
Chart
Export Map
Select Field
Map Layers
swat_wb_a
subbasin
gangabasin
Export Attribute
Show selected Attribute
Total Features : 100
Selected Fe
SubbasinArea
ScenarioSUBMONPCP
SNOM
PET
ET
SW
PERC
1 4632.566 WB_A 1 40 780.915 119.863 1597.743 345.239 32.275 187.294
2 1240.866 WB_A 2 40 1388.189 0.907 1790.615 567.927 47.581 476.543
3 10384.94 WB_A 3 40 835.581 148.562 1352.672 302.209 40.706 251.359
4 5613.153 WB_A 4 40 1346.089 0.92 1829.184 566.308 43.331 441.814
5 13791.44 WB_A 5 40 1383.424 0 1953.235 628.601 82.196 341.164
6 3444.833 WB_A 6 40 1481.653 0 1849.253 558.795 62.777 552.887
7 5236.522 WB_A 7 40 1195.195 0 1936.926 624.42 174.721 116.35


Ganga Basin Knowleadge Base
Layers
Drainage Network
Landuse
Soil
Load
Water Resources Structu
Reservoir Characteristics
Command Area
Fertilizer
drological Model Results
Scienario A
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
BOD in NonMonsoon Mo
Scienario B
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
BOD in NonMonsoon Mo
Scienario C
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
BOD in NonMonsoon Mo
Scienario D (5)
Water Balance
Chart
Export Map
Select Field
Map Layers
bod_monsoon_months
subbasin
swat_wb_a
subbasin
gangabasin
Export Attribute
Show selected Attribute
Total Features : 102
SubbasinWid2 A_Mon MxC_Mon MxD5_Mon MxA_Mon AvC_Mon AvD5_Mon AvA_Mon
1 204.2127 1.47 2.27 2.27 2.05 3.16 3.16 5.84
2 235.4642 0.26 0.4 0.4 0.55 0.85 0.85 0.7
3 331.4607 0.83 1.28 1.28 5.17 8 8 1.32
4 518.2236 0.29 0.45 0.45 1.29 2 2.03 0.73
5 392.9664 1.22 1.88 1.88 13.91 21.75 21.75 12.64
7 589.4523 1.01 1.56 1.55 6.79 10.93 11.29 3.09
8 418.2415 0.19 0.44 0.44 0.38 0.9 0.9 0.73
Developed by
INRM Consulants Pvt Ltd


Ganga Basin Knowleadge Base
Layers
iews
Political/Administrative Layers
International Boundary
State Boundaries
Districts / Population
Major Populated Areas
Physical
Topography
Ganga Basin
Major Ganga Sub Basin
Drainage Network
Landuse
Soil
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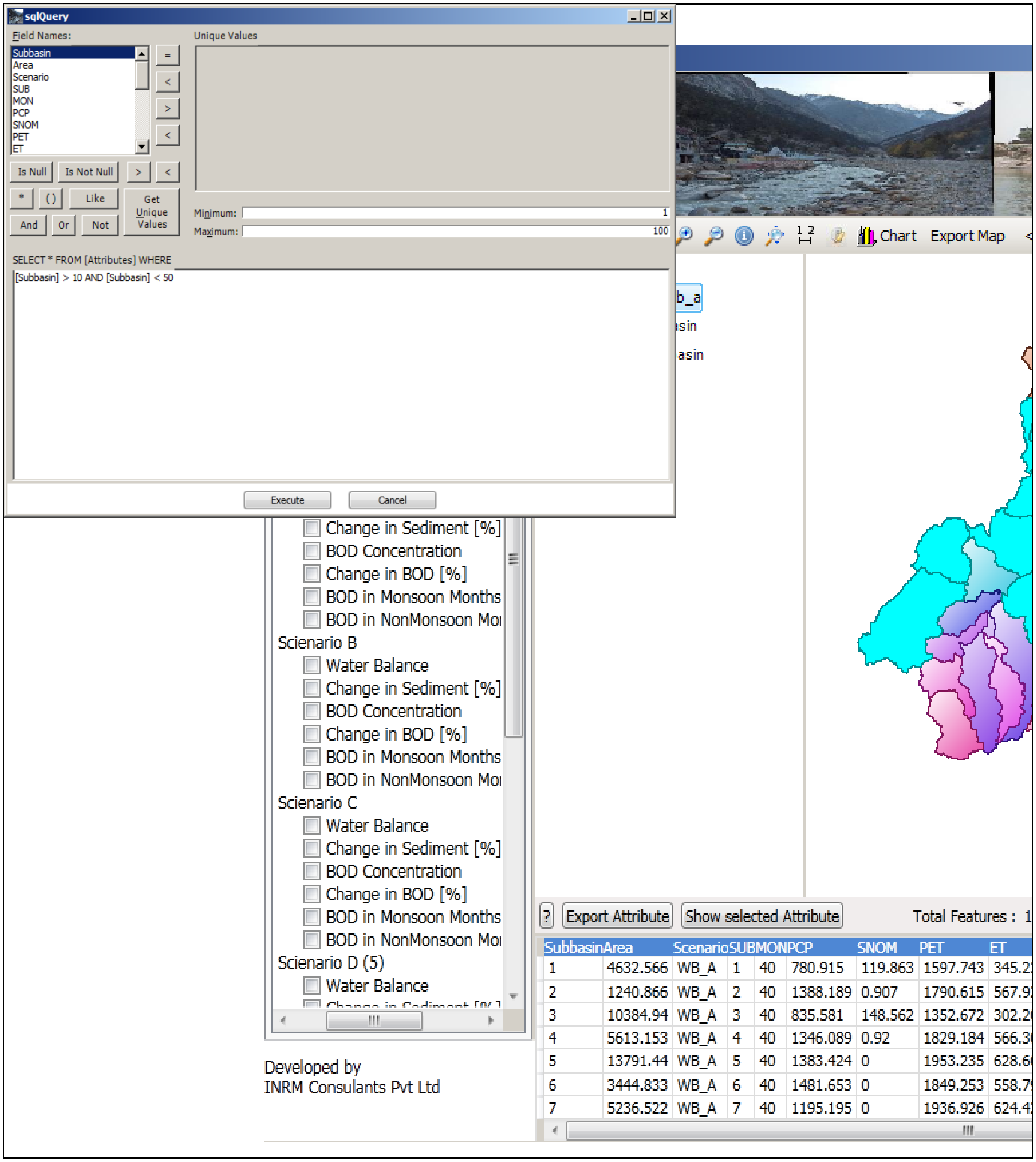
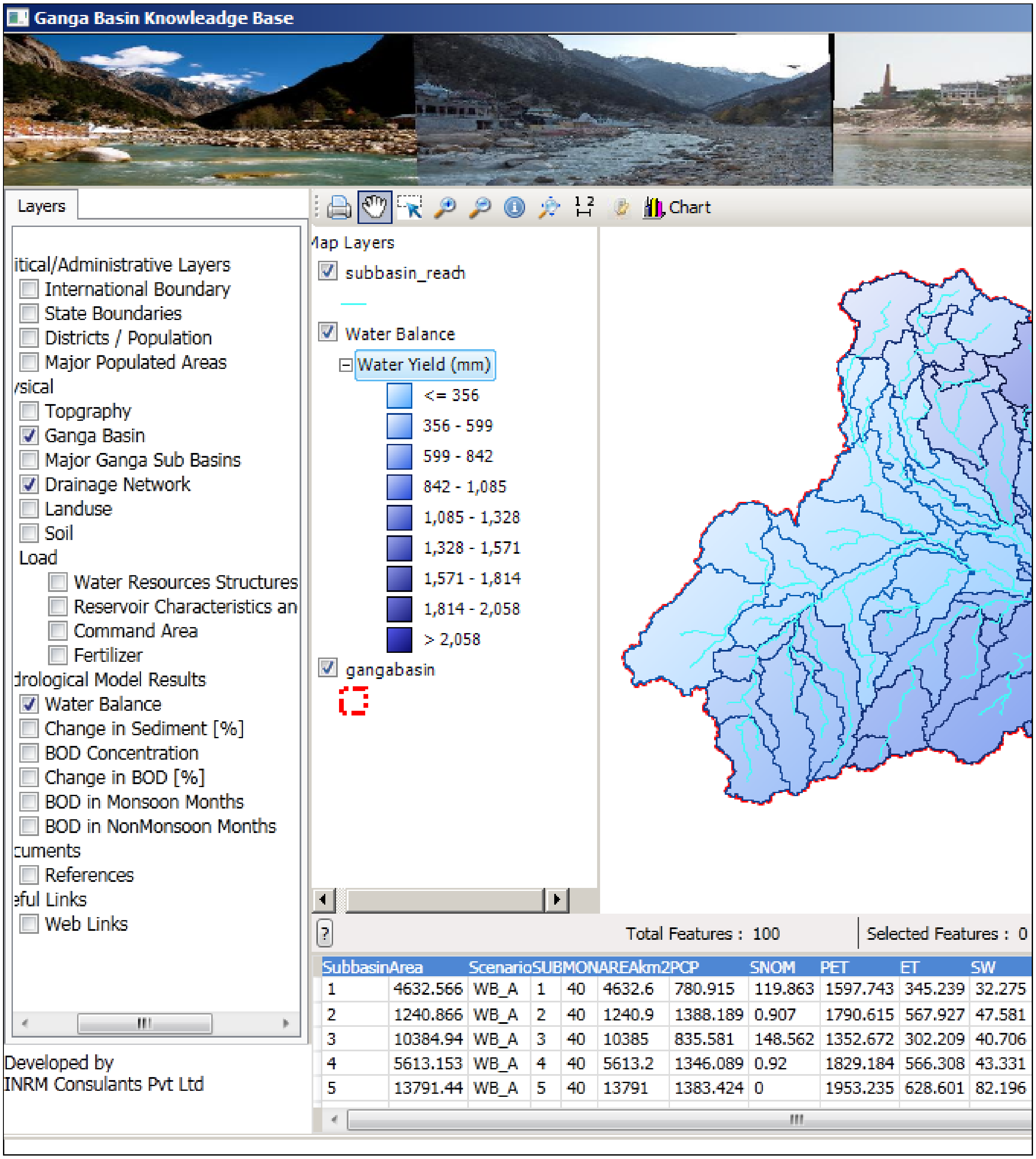
Water Resources St
Reservoir Character
Command Area
Fertilizer
Hydrological Model Results
Scienario A
Water Balance
Change in Sedimen
BOD Concentration
Change in BOD [%]
BOD in Monsoon M
BOD in NonMonsoo
Scienario B
Water Balance
Change in Sedimen
BOD Concentration
Change in BOD [%]
BOD in Monsoon M
BOD in NonMonsoo
Developed by
INRM Consulants Pvt Ltd
Chart
Export Map
Select Field
Map Layers
landu_ganga
1 - 4
4 - 8
8 - 12
12 - 16
16 - 20
maj_cities_gangabasin
gangabasin
Export Attribute
Show selected Attribute
Total Features : 100
Selected
SubbasinArea ScenarioSUBMONPCP SNOM PET ET SW PERC
45 8115.734 WB_A 45 40 1190.778 0 1849.148 684.269 82.011 227.123
46 5315.883 WB_A 46 40 1370.07 0 1828.91 713.908 80.606 288.792
47 6074.527 WB_A 47 40 1144.568 0 1971.021 640.704 91.168 233.398
48 30066.62 WB_A 48 40 758.116 0 2653.977 490.39 31.254 60.299
49 8394.846 WB_A 49 40 1052.931 0 2003.009 570.484 97.348 149.942
50 9970.645 WB_A 50 40 880.962 0 2069.108 522.828 72.966 147.775
51 22289.86 WB_A 51 40 974.389 0 1990.044 580.848 75.935 139.741


sqlQuery
Field Names:
Subbasin
Area
Scenario
SUB
MON
PCP
SNOM
PET
ET
Unique Values
Is Null
Is Not Null
Like
Get Unique Values
And
Or
Not
Minimum:
1
Maximum:
100
SELECT * FROM [Attributes] WHERE
[Subbasin] > 10 AND [Subbasin] < 50
Execute
Cancel
Chart
Export Map
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
Scienario B
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
Scienario C
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
Scienario D (5)
Water Balance
Developed by
INRM Consulants Pvt Ltd
Export Attribute
Show selected Attribute
Total Features :
SubbasinArea ScenarioSUBMONPCP SNOM PET ET
1 4632.566 WB_A 1 40 780.915 119.863 1597.743
2 1240.866 WB_A 2 40 1388.189 0.907 1790.615
3 10384.94 WB_A 3 40 835.581 148.562 1352.672
4 5613.153 WB_A 4 40 1346.089 0.92 1829.184
5 13791.44 WB_A 5 40 1383.424 0 1953.235
6 3444.833 WB_A 6 40 1481.653 0 1849.253
7 5236.522 WB_A 7 40 1195.195 0 1936.926


Ganga Basin Knowleadge Base
Layers
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International Boundary
State Boundaries
Districts / Population
Major Populated Areas
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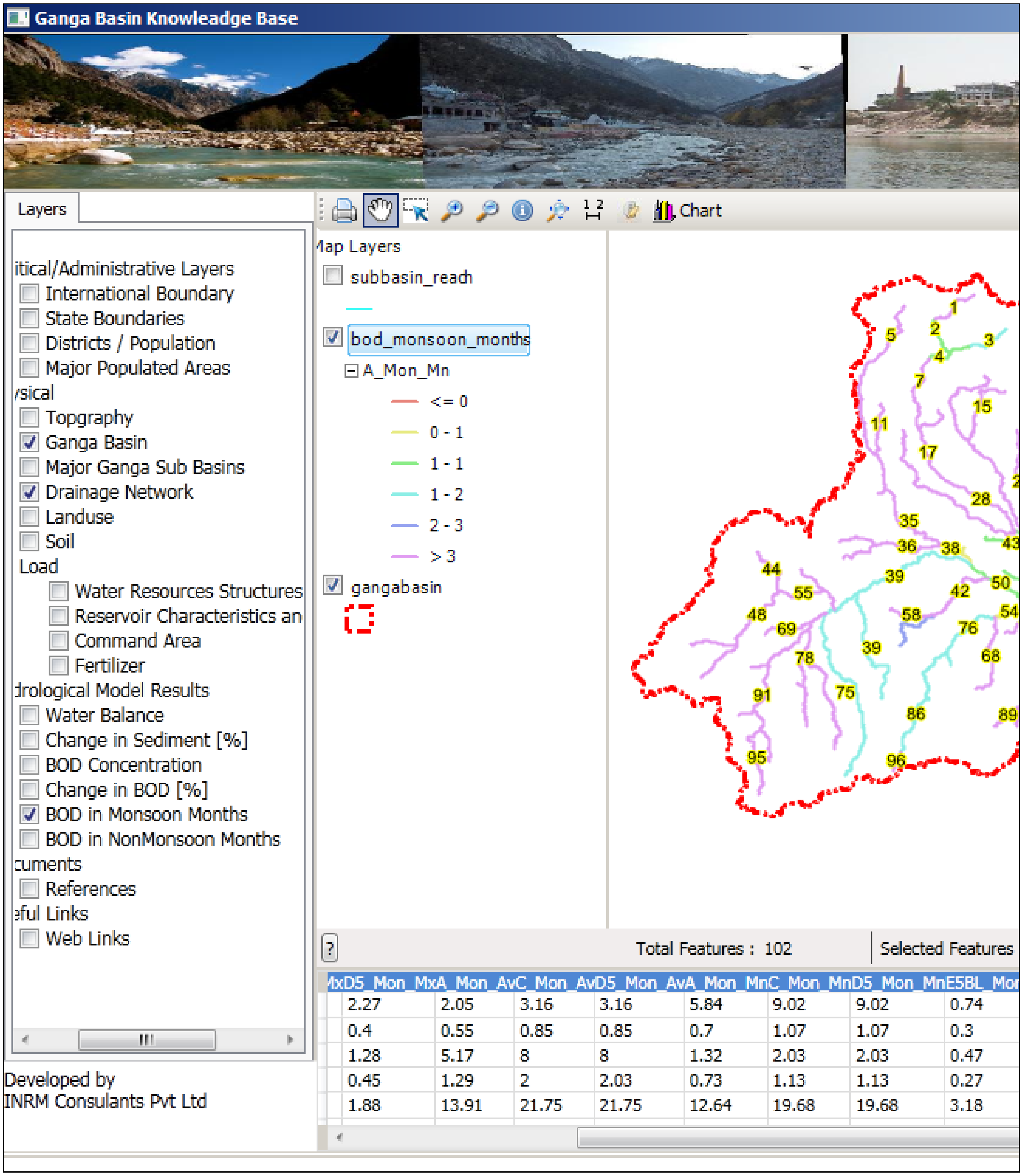
Topgraphy
Ganga Basin
Major Ganga Sub Basins
Drainage Network
Landuse
Soil
Load
Water Resources Structures
Reservoir Characteristics an
Command Area
Fertilizer
drological Model Results
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
BOD in NonMonsoon Months
cuments
References
eful Links
Web Links
Developed by
INRM Consulants Pvt Ltd
Chart
Map Layers
subbasin_reach
Water Balance
Water Yield (mm)
<= 356
356 - 599
599 - 842
842 - 1,085
1,085 - 1,328
1,328 - 1,571
1,571 - 1,814
1,814 - 2,058
> 2,058
gangabasin
Total Features : 100
Selected Features : 0
SubbasinArea ScenarioSUBMONAREAkm2PCP SNOM PET ET SW
1 4632.566 WB_A 1 40 4632.6 780.915 119.863 1597.743 345.239 32.275
2 1240.866 WB_A 2 40 1240.9 1388.189 0.907 1790.615 567.927 47.581
3 10384.94 WB_A 3 40 10385 835.581 148.562 1352.672 302.209 40.706
4 5613.153 WB_A 4 40 5613.2 1346.089 0.92 1829.184 566.308 43.331
5 13791.44 WB_A 5 40 13791 1383.424 0 1953.235 628.601 82.196


Ganga Basin Knowleadge Base
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International Boundary
State Boundaries
Districts / Population
Major Populated Areas
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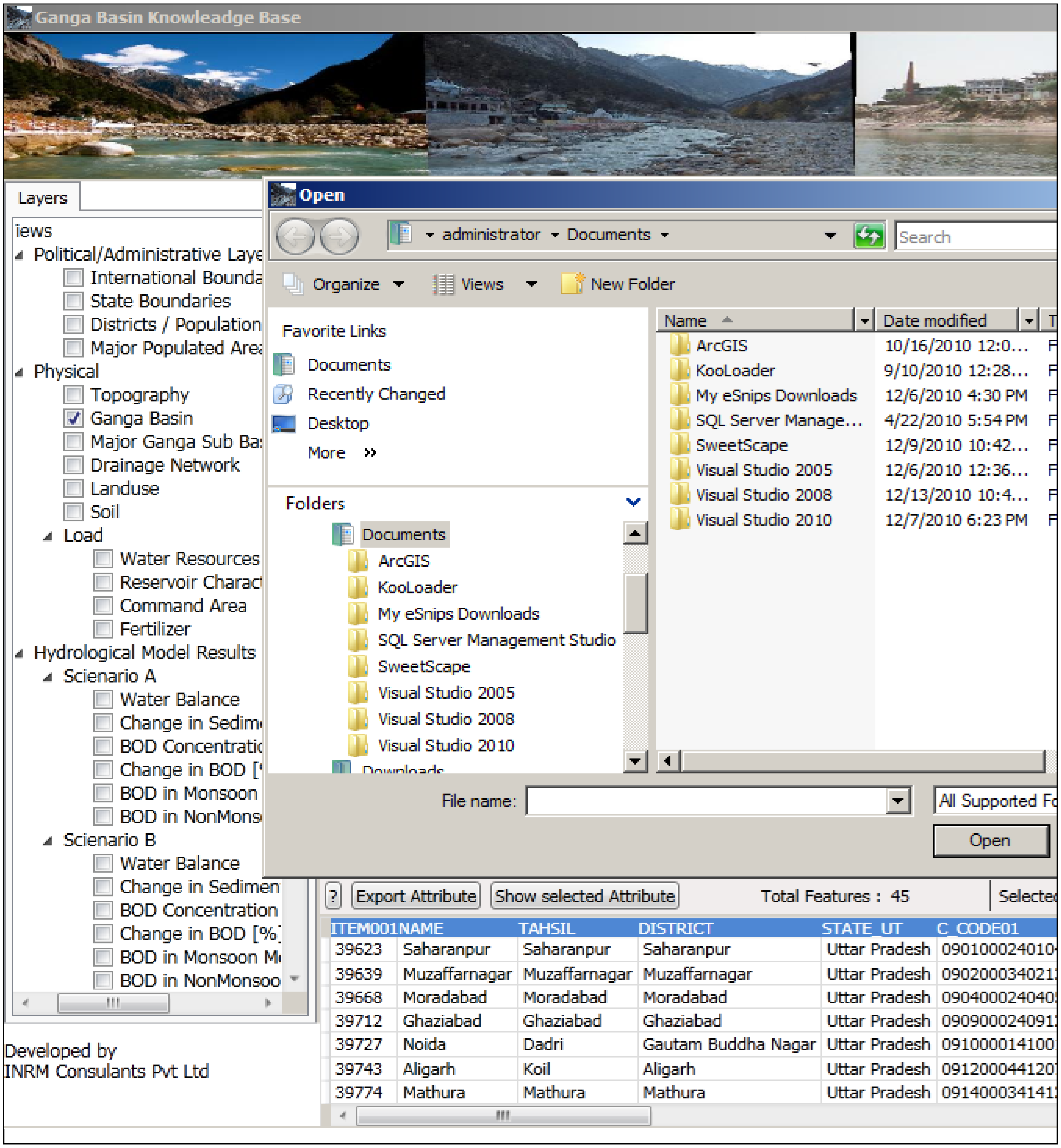
Topgraphy
Ganga Basin
Major Ganga Sub Basins
Drainage Network
Landuse
Soil
Load
Water Resources Structures
Reservoir Characteristics an
Command Area
Fertilizer
drological Model Results
Water Balance
Change in Sediment [%]
BOD Concentration
Change in BOD [%]
BOD in Monsoon Months
BOD in NonMonsoon Months
cuments
References
eful Links
Web Links
Developed by
INRM Consulants Pvt Ltd
Chart
Map Layers
subbasin_reach
bod_monsoon_months
A_Mon_Mn
<= 0
0 - 1
1 - 1
1 - 2
2 - 3
> 3
gangabasin
Total Features : 102
Selected Features
MxD5_Mon MxA_Mon AvC_Mon AvD5_Mon AvA_Mon MnC_Mon MnD5_Mon MnE5BL_Mon
2.27 2.05 3.16 3.16 5.84 9.02 9.02 0.74
0.4 0.55 0.85 0.85 0.7 1.07 1.07 0.3
1.28 5.17 8 8 1.32 2.03 2.03 0.47
0.45 1.29 2 2.03 0.73 1.13 1.13 0.27
1.88 13.91 21.75 21.75 12.64 19.68 19.68 3.18


Ganga Basin Knowleadge Base
Layers
Political/Administrative Laye
International Bounda
State Boundaries
Districts / Population
Major Populated Area
Physical
Topography
Ganga Basin
Major Ganga Sub Ba
Drainage Network
Landuse
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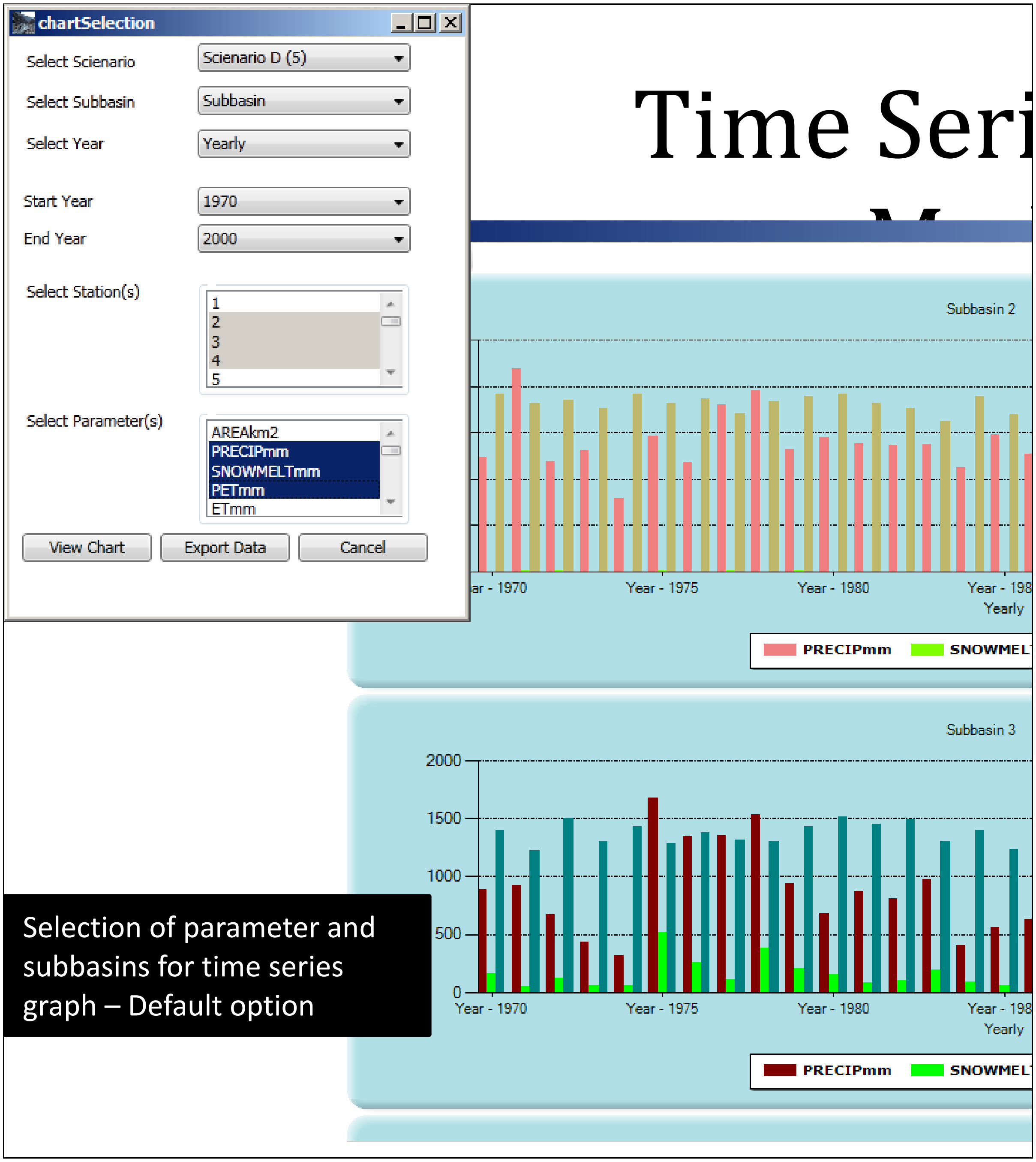
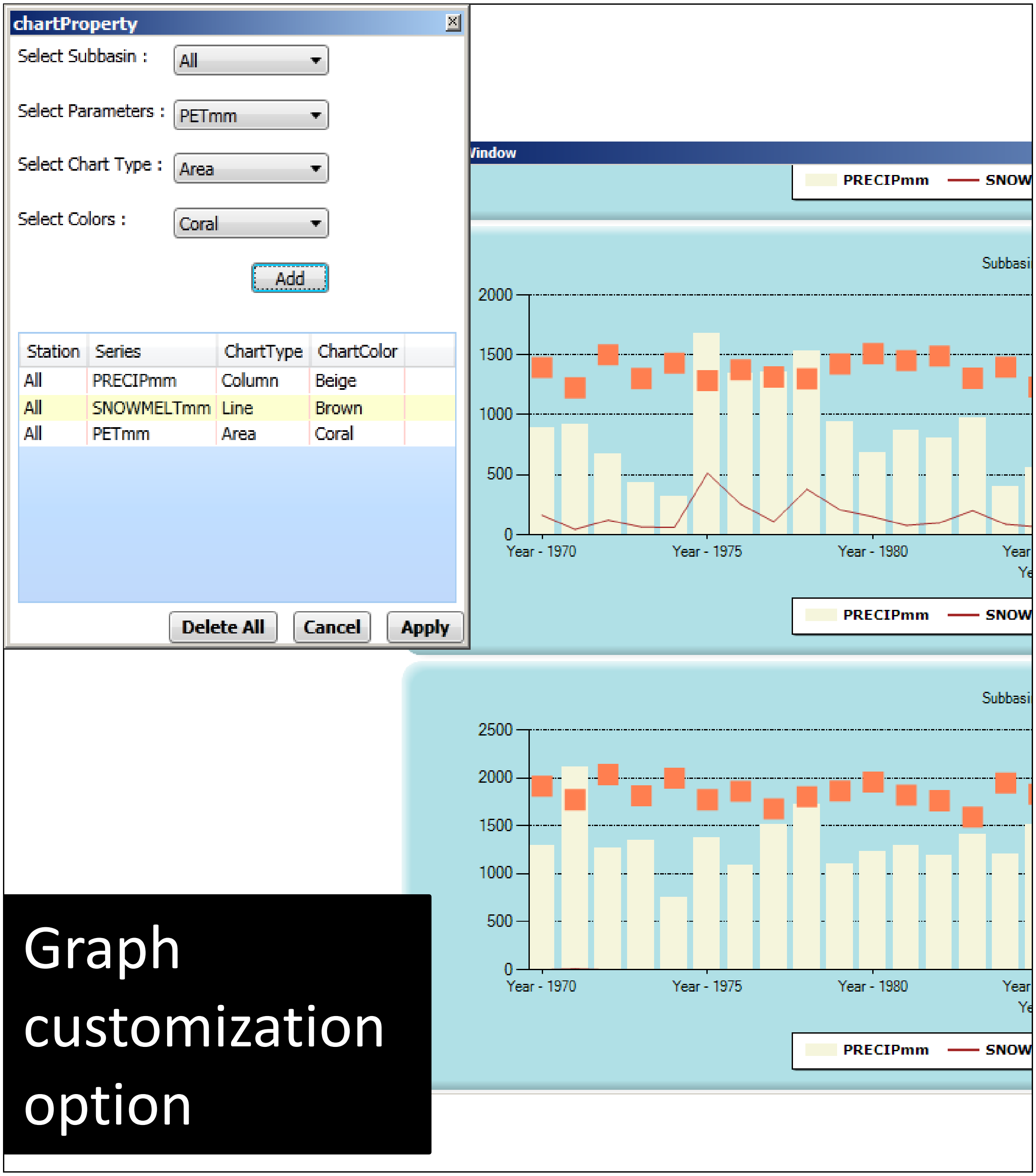
Water Resources
Reservoir Charact
Command Area
Fertilizer
Hydrological Model Results
Scienario A
Water Balance
BOD in Monsoon
Scienario B
Water Balance
Change in Sedimen
BOD Concentration
Developed by
INRM Consulants Pvt Ltd
Open
administrator
Documents
Search
Organize
Views
New Folder
Favorite Links
Documents
Recently Changed
Desktop
More
Folders
Name
Date modified
ArcGIS
KooLoader
My eSnips Downloads
SQL Server Management Studio
SweetScape
Visual Studio 2005
Visual Studio 2008
Visual Studio 2010
10/16/2010 12:0...
9/10/2010 12:28...
12/6/2010 4:30 PM
4/22/2010 5:54 PM
12/9/2010 10:42...
12/6/2010 12:36...
12/13/2010 10:4...
12/7/2010 6:23 PM
File name:
Open
Export Attribute
Show selected Attribute
Total Features : 45
ITEM001NAME
TAHSIL
DISTRICT
STATE_UT
C_CODE01
39623 Saharanpur Saharanpur Saharanpur Uttar Pradesh
39639 Muzaffarnagar Muzaffarnagar Muzaffarnagar Uttar Pradesh
39668 Moradabad Moradabad Moradabad Uttar Pradesh
39712 Ghaziabad Ghaziabad Ghaziabad Uttar Pradesh
39727 Noida Dadri Gautam Buddha Nagar Uttar Pradesh
39743 Aligarh Koil Aligarh Uttar Pradesh
39774 Mathura Mathura Mathura Uttar Pradesh




Selection of parameter and subbasins for time series graph – Default option


chartProperty
Select Subbasin : All
Select Parameters : PETmm
Select Chart Type : Area
Select Colors : Coral
Add
Station Series ChartType ChartColor
All PRECIPmm Column Beige
All SNOWMELTmm Line Brown
All PETmm Area Coral
Delete All
Cancel
Apply
PRECIPmm
Year - 1970
Year - 1975
Year - 1980
Graph customization option